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MARINE SHRIMP CULTURE: PRINCIPLES AND PRACTICES

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PREFACE

According to Pliny the Elder (23-79 A.D.), "No book is so bad but some good might be got out of it." With that possible worst case scenario in mind, we can only hope and expect that this volume will do some good. We hope, however, that it will do much more. We hope that it will provide you with facts and observations about the art and science of marine shrimp culture; but more importantly we hope that it will also provide genuine insights. We hope that such insights will inspire better understandings and further advancements.

Emerson (1803-1882) caught the essence of what we are after when he said, "Books are the best of things, well used: abused among the worst. What is the right use? What is the one end which all means go to effect? They are nothing but to inspire."

If necessity is the mother of invention, then inspiration is the father. By including both, chances of success are good. We hope that our book will provide insight and inspiration for the development of better shrimp culture technology. This technology development depends not only on a thorough understanding of underlying principles, but the reduction of these principles to practice through creation of appropriate technology.

We will try to point out this idea of appropriate technology at different places in our book. It is an important idea since it includes elements of economic, social, biological and environmental influences. A technology which was appropriate last year at some place, may not be appropriate today. Appropriate technology today may be inappropriate tomorrow as conditions change, all the time driven by economic considerations. The culture system that produces shrimp at the lowest cost will capture a large market share. New knowledge and innovations will lead to shifts in culture system profitability and changes in culture methods. This system evolution is now accelerating at a rapid pace. We are living in exciting and interesting times for shrimp culture enthusiasts. Each year, new events arouse the interests of participants and observers alike.

Our book is intended to provide a description of principles and practices of shrimp culture at one point in time. It documents some of the important historical events, and describes conditions that exist now. We will also try to look into the future.

Like channel catfish and salmon culture in colder climates, commercial culture of marine shrimp in tropical areas has grown at a phenomenal rate during the last 10 to 15 years. Growth of these industries is driven by people's tastes in food and by economic factors. Market demands, coupled with intellectual curiosities in both the private and public sectors have lead

to breakthroughs in culture technologies. This in turn resulted in exponential growth of these commodities; trends which have yet to peak.

In the U.S., which vies with Japan as the principal shrimp consuming country, per capita shrimp consumption has tripled from 1 lb/person in 1950 to 3 lbs/person today. Shrimp prices have more than tripled during this same period.

The full impacts of increased cultured shrimp production on traditional catch fisheries have not yet been fully realized. We can expect that they soon will be, however, since the world's population and per capita consumption of shrimp are growing slower than cultured shrimp production increases. We can and have speculated in the present volume about what will happen to both the shrimp catch fishery and shrimp culture industry as world shrimp supply exceeds demand and prices fall.

This book is about penaeid shrimp culture. We have tried to produce a comprehensive volume which will be of value to the researcher, consultant, practitioner and potential investor. We have tried to provide practical information about the particulars of shrimp culture, as well as basic information on shrimp biology. By so doing, we feel that we have broadened the information base on shrimp culture and helped fuel further advancements.

Advancement, in the view of some, is most often accomplished by someone erecting an idea, model or conceptual framework. This is followed by testing and proposing alternative ideas, models or conceptual frameworks, while the testing process is repeated. If the newer concepts are better they replace the first. With this also in mind, we have produced this book. We hope and expect that it will be replaced by better ones later. There are recognized deficiencies in some areas, which must await later attention. Some subject areas will soon deserve full volumes of their own.

With all of these thoughts in mind, we produced this book with the hope that, "... some good might be got out of it."

Arlo W. Fast
Sichang Island, Chonburi
Gulf of Thailand
Kingdom of Thailand
May, 1989

As you read these chapters, it will be apparent that the scientific foundation of shrimp aquaculture is in a very early stage. Thomas Kuhn describes a level of scientific development in The Structure of Scientific Revolutions (1962, p. 15) which I believe applies to aquaculture.

"In the absence of a paradigm or some candidate for a paradigm, all of the facts that could possibly pertain to the development of a given science are likely to seem equally relevant. As a result, early fact-gathering is a far more nearly random activity than the one that subsequent scientific development makes familiar." "Because the crafts are one readily accessible source of facts that could not have been casually discovered, technology has often played a vital role in the emergence of new sciences."

Being representative of this stage of development, our book is a mixture of science, technology and craft. Scientific advances in aquaculture are presently limited by the level of available technology.

Shrimp culture will experience, no doubt, the type of technological breakthroughs seen in agriculture. Science often advances in spurts or "revolutions" which alter the conceptual foundations; therefore, the picture of shrimp culture we present may not endure for long. We have done our best to capture the "state of the art". There is a cornucopia of information in these pages, but most of it will be revised and the next generation of scientists and culturists will paint a different, more detailed picture of shrimp biology, water chemistry, pond dynamics, etc.

A single book could not incorporate all of the important contributors to the development of shrimp culture technology. The editors have attempted to compensate for the lack or surfeit of qualified authors in certain areas through personal contributions. This was simply the most efficient approach. We hope that these areas have been faithfully summarized.

As one can see from the dates on the preface by Arlo Fast and this one, it has taken two years to complete the editing of this book. Some of the authors were not able to complete their contributions until late in 1990. During final editing and formatting, I went through several changes in job responsibilities which made it very difficult to give this project the time it deserved. The publisher, my fellow editor and the authors have been very understanding. I regret the delays that occurred in production of the final draft of this manuscript; however, I believe this book is still very timely and will make a significant contribution to the literature on shrimp culture.

L. James Lester
Houston, Texas
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CHAPTER 1

Arlo W. Fast

INTRODUCTION

1.1 EARLY SHRIMP CULTURE

The history of marine shrimp culture is not well documented. Its origin undoubtedly traces to the earliest brackishwater and marine ponds. These primitive ponds, which date back thousands of years in the Mediterranean area (Brown 1983), and to the 15th century A.D. in Indonesia (Ling 1977) were typically stocked with fish, shrimp, and other biota through passive flooding. Desirable seed, as well as unwanted predators and competitors were all carried into the pond with source waters where they grew for some time, and were then harvested. These culture methods, perhaps more properly termed "catch and hold" culture, are still commonly used today (Fig. 1). Where land and labor costs are low, and pond improvement costs have been largely depreciated, this approach can still be profitable with low risk.

1.2 POND STOCKING WITH WILD SEED

While the catch and hold approach is simple, requires minimal labor, capital and skill, it is also low yield and unpredictable. Neither stocking densities nor species composition are controllable. An improvement over catch and hold is a growout system where the pond source water is screened to control unwanted entrants, and the pond is then stocked with a known quantity of known species. This approach was perfected in Indonesian and Philippine brackishwater ponds with milkfish (*Chanos chanos*) and various shrimp species (Bardach et al. 1972). Shrimp seed collected from the wild are normally late postlarvae (PL) and juveniles which are either stocked directly, or nursed to a larger size before pond stocking (Fig. 1). Although additional labor and skill are required for this controlled stocking approach with wild caught seed, greater control is exercised over survival, growth and size at harvest of both shrimp and fish. The growout location can also be far removed from the seed source, thus greatly expanding potential farm sites.

Although controlled stocking with wild caught seed is still commonly used today, it does have limitations. In particular, it depends on seed availability. During certain times of year and during certain years, wild seed is scarce. Farms that depend on this seed source would then be understocked, or perhaps not stocked at all. This can cause economic hardships. In addition,

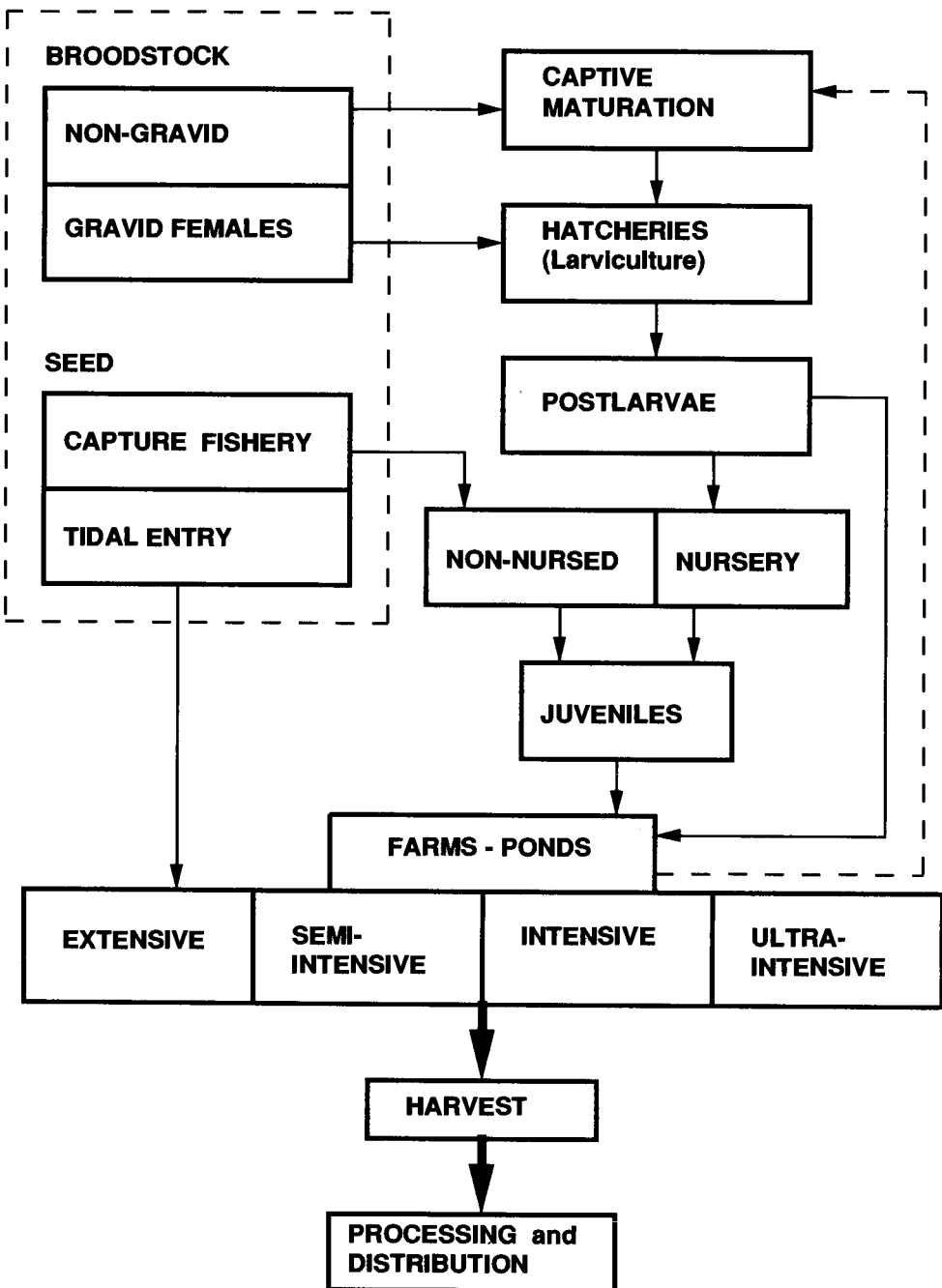
OCEAN RESOURCES

Figure 1. Conceptual model of marine shrimp culture systems. Primitive culture techniques involve passive stocking of extensive ponds with wild seed. Advanced culture technologies use intensive pond culture and hatchery produced seed.

it is sometimes difficult to distinguish desirable from undesirable seed species. Ponds are often stocked with seed mixtures that are less than optimal, with reduced yields.

1.3 CAPTIVE REPRODUCTION WITH WILD GRAVID SHRIMP

The evolution of modern shrimp culture required captive reproduction and seed production through larviculture in hatcheries. The Japanese scientist Motosaku Fujinaga (published under the name Hudinaga 1935, 1942) can be credited with laying the technical groundwork for this development. Fujinaga was able to obtain gravid female Penaeus japonicus from fishermen, spawn these in the laboratory, hatch the eggs, and rear the larvae to PL suitable for pond stocking (Fig. 1). This was a major breakthrough in shrimp culture technology, but it was not widely recognized and applied until the late 1960's and early 1970's.

Although hatchery produced shrimp seed from gravid females taken from the wild is still the major source of high quality hatchery seed today, it has problems. Perhaps the two biggest problems are that; first, gravid females (like wild seed) are not consistently available. This involves both seasonal inconsistencies, as well as year to year inconsistencies. Secondly, gravid females of a preferred species may not be found in places where their pond culture is practiced. While gravid females can be imported, this complicates matters and introduces major risks. Further improvements were needed. This came in the form of eye stalk ablation.

1.4 CAPTIVE REPRODUCTION FROM NON-GRAVID SHRIMP

During the 1970's, researchers found that non-gravid female shrimp could be induced to mature and spawn in captivity by a technique known as eye stalk ablation or enucleation, where the eye stalk is destroyed (Caillouet 1972, Chamberlain and Lawrence 1981). This was one of the most important developments leading to increased world shrimp culture. Using ablation, non-gravid female shrimp could be captured from the wild, transported to the culture area, matured and spawned in captivity, and seed produced at will (Fig. 1). Although ablated females produce lower quality spawns, the large increase in egg production, on demand, more than compensates for reduced quality. Viable eggs can now be produced year around at locations far from the natural range of many shrimp species.

With a few species, such as Penaeus vannamei in Hawaii, pond reared stock have been matured, spawned, and commercially viable seed produced under closed-cycle culture (Fig. 1). Results with other species, such as P. monodon has been largely unsuccessful. Pond-reared broodstock produce eggs

of low quality. Improved egg quality from pond reared broodstock is one of the major goals for improved culture technology.

1.5 EVOLUTION OF POND CULTURE

With the catch and hold approach, only extensive pond culture is possible (Fig. 1A). Ponds are normally stocked with less than 1 PL/m². Once hatchery seed became available in quantity, and sources of abundant wild seed were identified and collected, more intensive culture systems evolved; including semi-intensive, intensive, and ultra-intensive (Fig. 1). The latter two depend almost totally on hatchery seed, since their profitability depends on a large supply of known age seed on a timely basis. These higher intensity culture systems all evolved during the 1970's in response to seed availability and high profits from shrimp culture. Development of mass culture techniques for seed, and pond growout system development during the 1970's can thus be credited with laying the groundwork for the large increase in cultured shrimp production during the 1980's.

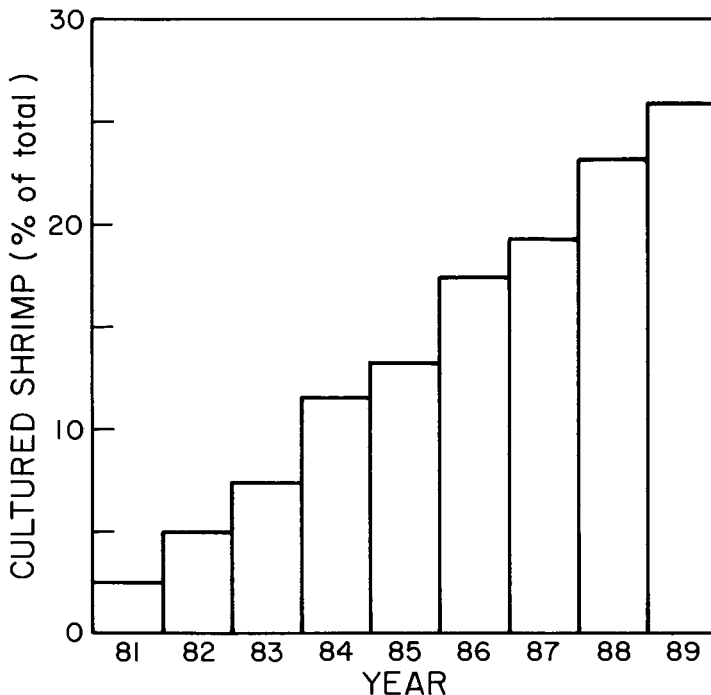


Figure 2. World production of cultured shrimp as a percentage of total world production from 1982 through 1989 (Rosenberry 1990).

Large-scale culture of marine shrimp to supply the world markets is now firmly established. Large-scale, commercial culture methods now exist for broodstock maturation, larviculture, nursery, and growout to market. This knowledge and development has contributed to increases in farmed or cultured shrimp, from less than 2% of the world's production in 1980, to more than 26% in 1989 (Fig. 2). To be sure, there are still some problems with culture technology, as we will see in this volume, but these will not prevent continued expansion of the culture industry. Resolution of these problems will simply improve culture techniques, making shrimp products less costly and more widely consumed.

1.6 CRUSTACEAN AQUACULTURE PRODUCTION

Production of cultured aquatic species increased nearly 100% between 1975 and 1986, from 6.1 million metric tons (MT) to 12.1 million MT respectively (Table 1). The 1987 estimate is 13.1 million MT, and still increasing (Anonymous 1990). Of the four major aquaculture commodities, crustaceans experienced the greatest relative increase during this period from 16 to 399 thousand MT.

The world's total production of crustacean from both culture and capture increased from 2.4 to 3.2 million MT between 1975 and 1985, or 34% overall (Table 2). Marine shrimp and freshwater crustacean demonstrated the greatest increases of 43% and 63% respectively. Most of these latter two increases came from increased culture production of marine penaeid shrimp, freshwater prawns (*Macrobrachium* spp.) and freshwater crayfish. The share of cultured crustaceans in world crustacean production increased from 1.2% in 1975 to 8.2% in 1985. By 1988, cultured crustacean production accounted for perhaps 15% or more of the total (Csavas 1988).

Clearly, cultured production of all aquatic food commodities is rising. These increases are driven by market demands from an increasing world population, production limits on the wild fisheries, and by improved techniques for cultured production. Economic considerations increasingly favor cultured production of aquatic species, just as they favored land based agricultural crops centuries ago.

1.7 FUTURE TRENDS

Even if shrimp culture technology development could be frozen at its present level, changes are now underway within the industry which will cause major upheavals. These upheavals are related to economics. Large potential profits, and the foreign currency exchange aspects of shrimp culture have led both private and government interests to invest in shrimp farming. The large

Table 1. World production of aquaculture products from 1975 to 1986. Data from Kungvankij and Kongkeo (1988) and Anonymous (1990).

Product	Production (x 1,000 MT)			
	1975	1980	1985	1986
Finfish	3,981	3,233	5,697	5,455
Mollusc	1,051	3,196	2,886	3,478
Crustacean	16	71	282	399
Seaweed	1,055	2,206	3,526	2,742
Total	6,103	8,706	12,391	12,074

production increases that occurred as a result are leading to a long-term downward trend in shrimp prices and profit margins. This in turn will create consolidation and shifts towards culture methods that remain profitable.

Total world shrimp production from pond culture will continue to increase, and prices will continue to decrease. Improved knowledge about shrimp will lead to improved culture techniques and better performing domestic stocks, as happened with other animal crops such as chickens, cattle, and hogs.

Perhaps we are jumping ahead of the story too much at this point with speculation about future developments. Before we do that, we should consider the large amount of information contained within the following chapters. These chapters review many aspects of shrimp biology and culture. Shrimp culture is indeed multi-faceted and complicated. We will try to dissect it into its component parts herein, and examine each. In the last chapter we will continue our speculations about the future of shrimp culture.

1.8 TERMINOLOGY: SHRIMP VS. PRAWNS

A few words may be in order about the use of the terms shrimp and prawns before we proceed. The editors fully agree with FAO's attempts to establish clear cut distinctions for these terms where "prawns" refer to freshwater creatures (especially Macrobrachium spp.), while shrimp refer to their marine and brackishwater relatives (Csavas 1988). Common usage has often resulted in reference to large shrimp as "prawns" and to small shrimp as "shrimp" regardless of the salt content of their habitat. The latter applications are so deeply imbedded in common and scientific usage in some countries that we have permitted this usage here as well; most noticeably in the Philippines and Taiwan chapters.

Table 2. Estimated world production of captured and cultured crustaceans from 1975 to 1985 (Csavas 1988).

Crustacean group	Production (x 1,000 MT)			1975-1985 % Increase
	1975	1980	1985	
Freshwater prawn and crayfish	93	98	152	63
Crabs, sea spiders	754	793	887	18
Lobsters	174	165	211	21
Marine shrimp	1,332	1,657	1,903	43
Other marine	60	63	75	25
Total	2,413	2,776	3,228	34
% Cultured	1.2	2.7	8.2	

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CHAPTER 2

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PENAEID TAXONOMY, BIOLOGY AND ZOOGEOGRAPHY

2.1 INTRODUCTION

The Food and Agriculture Organization of the United Nations lists 343 shrimp species that are actually or potentially important commercially (Holthuis 1980). Of these, 110 species belong to the family Penaeidae and account for about 80% of the world's wild-caught shrimp (Dore and Frimodt 1987).

A number of penaeid species have been matured, mated, and spawned in captivity to produce viable nauplii (Lawrence et al. 1985). This technology is critical to the success of the shrimp culture industry, for it can provide farmers with a predictable supply of postlarvae of a known species for growout. Among those species that reproduce in captivity, eight have significant importance in aquaculture (Rosenberry 1989, Table 1). These species include: Penaeus chinensis, P. indicus, P. japonicus, P. merguensis, P. monodon, P. stylirostris, P. vannamei, and Metapenaeus ensis.

It is beyond the scope of this chapter to review all published literature on penaeid shrimp taxonomy, biology, and zoogeography. We have therefore limited our review to the eight species listed above. This chapter is divided into three major sections. The first section provides an overview of penaeid shrimp taxonomy, including a description of the external morphology of a generalized penaeid shrimp and illustrations of important diagnostic features. Brief descriptions are given of the principal diagnostic features of the eight selected species. The second section covers aspects of penaeid shrimp biology of particular interest to culturists, including an overview of penaeid reproduction and feeding biology. Most of the information in this section is from published literature on Penaeus merguensis, P. monodon, and P. vannamei. The third section provides information on the geographical distributions of natural populations of the eight penaeid species, and on the habitats where these species commonly occur. Finally, a glossary is provided at the end of the chapter that includes technical terms used in discussions on taxonomy and reproduction.

TABLE 1. List of commercially important penaeid shrimp species and those countries principally engaged in their culture. Food and Agriculture Organization (F.A.O.) names are listed in English (E), French (F), and Spanish (S). Percentage of the world production by species is based on 1989 data (after Rosenberry 1989).

Species	F.A.O. Names	% Production	Country ^a
<u>Penaeus chinensis</u>	(E) Fleshy prawn (F) Crevette charnue (S) Camaron carnososo	28%	China, North Korea
<u>Penaeus indicus</u>	(E) Indian white prawn (F) Crevette royale blanche (S) Camaron blanco de la India	6%	India, Indonesia, Vietnam
<u>Penaeus japonicus</u>	(E) Kuruma prawn (F) Crevette kuruma (S) Camaron kuruma	<1%	Japan
<u>Penaeus merguensis</u>	(E) Banana prawn (F) Crevette banana (S) Camaron banana	8%	Indonesia, Thailand, Philippines, China, Vietnam
<u>Penaeus monodon</u>	(E) Giant tiger prawn (F) Crevette geante tigre (S) Camaron tigre gigante	33%	Indonesia, India, Thailand, Vietnam, Philippines, Taiwan, China, Bangladesh
<u>Penaeus stylirostris</u>	(E) Blue shrimp (F) Crevette bleue (S) Camaron azul	1%	Panama, Columbia Honduras, Ecuador
<u>Penaeus vannamei</u>	(E) Whiteleg shrimp (F) Crevette pattes blanches (S) Camaron patiblanco	10%	Ecuador, Mexico, Panama, Columbia, Honduras
<u>Metapenaeus ensis</u>	(E) Greasyback shrimp (F) Crevette glissante (S) Camaron resbaloso	2%	China, Vietnam, Philippines, Taiwan

^aCountries listed are those that produced $\geq 2,500$ MT live weight of shrimp in 1989 (after Rosenberry 1989). Sources used include: Shigueno 1975, Liu 1983, Hirono 1983, Apud 1985, New and Rabanal 1985, Liao 1986, and Rosenberry 1989.

2.2 TAXONOMY

Penaeid shrimp belong to the largest phylum in the Animal Kingdom, the Arthropoda, characterized by jointed appendages and an exoskeleton or cuticle that is periodically molted. There are thousands of terrestrial species in this phylum, and a large, predominately aquatic subphylum, the Crustacea.

The more highly evolved crustaceans (Class Malacostraca) include the penaeid shrimp (Order Decapoda).

The subphylum Crustacea contains about 42,000 species belonging to 10 classes. The class Malacostraca contains about three-fourths of the known species and includes crayfish, lobsters, shrimps and crabs. The following outline of crustacean taxonomy is adapted from Barnes (1987).

Subphylum Crustacea

Class Cephalocarida

C. Branchiopoda (e.g. fairy shrimps and brine shrimps)

C. Remipedia

C. Ostracoda (e.g. mussel or seed shrimps)

C. Mystacocarida

C. Tantulocarida

C. Cirripedia (e.g. barnacles)

C. Copepoda (e.g. calanoids and harpacticoids)

C. Branchiura

C. Malacostraca

Subclass Phyllocarida

Order Leptostraca

Subclass Eumalacostraca

Superorder 1. Syncarida

Order Bathynellacea

O. Anaspidacea

Superorder 2. Hoplocarida

O. Stomatopoda (e.g. mantis shrimps)

Superorder 3. Peracarida

O. Mysidacea (e.g. opossum shrimps)

O. Cumacea

O. Tanaidacea

O. Isopoda

O. Speleogriphacea

O. Amphipoda

O. Thermosbaenacea

Superorder 4. Eucarida

O. Euphausiacea (e.g. krill)

O. Decapoda (e.g. crayfish, lobsters, shrimps and crabs)

Superorders Peracarida and Eucarida are the most speciose Malacostraca, and are distinguished from one another by a number of morphological and life-history traits. Peracarida are characterized by direct development (i.e. no independent larval stage), a ventral brood pouch or "marsupium" for retaining

developing young, and the presence or absence of a carapace uniting the head and thoracic segments. Eucarida have indirect development (i.e. one or more independent larval stages), no brood pouch (developing eggs are usually attached to appendages), and a distinct carapace. Shrimp-like species are found in both superorders, and some peracarids are important to world fisheries (e.g. the Mysidacea); although the most desirable fishery species are decapod eucarids (e.g. lobsters, shrimps, and crabs).

2.3 THE APPENDAGES

Decapods can be distinguished from other higher crustaceans by examining differences in the thoracic appendages. The first three pairs of thoracic appendages, the maxillipeds, are modified for feeding and the remaining five pairs are the walking legs, hence the name Decapoda or "ten-legs". Penaeid appendages typically consist of two branches (biramous), the exopodite and endopodite. These structures are variously developed for feeding, locomotion or burrowing; or they bear feathery gills (modified epipodites) contained beneath the carapace, or sensory structures on the antennae and antennules (Fig. 1A).

Appendages associated with the head region include the antennules, antennae, mandibles and two pairs of maxillae. The thorax bears three pairs of maxillipeds and five pairs of walking legs (pereopods). The endopodites of the walking legs are attached to the cephalothorax by a short joint, the coxa (Fig. 1A,C). Legs consist of a number of articulating sections that terminate at the dactylus which may be chelate (first, second and third walking legs) or simple (fourth and fifth walking legs). Sections between the coxa and dactylus are called the basis, ischium, merus, carpus and propus. The presence of a spine or row of spines on the ischium is of taxonomic importance for some species (Fig. 1C). The six-segmented abdomen has five pairs of swimmerets (pleopods) and a pair of uropods that form the tail fan with the telson (Fig. 1A).

Morphological features used to identify the commonly cultured penaeid species are shown in Figure 1. Shape and number of rostral teeth, carapace spines and grooves, and antennal scale length are useful diagnostic features for species identification. Pigmentation patterns on adults and larvae are also used for species identification, especially by farmers when stocking ponds with wild-caught postlarvae.

2.4 MORPHOLOGY OF EIGHT CULTURED SPECIES

(Based on Dore and Frimodt 1987, Grey et al. 1983.) See Figure 1 and Glossary.

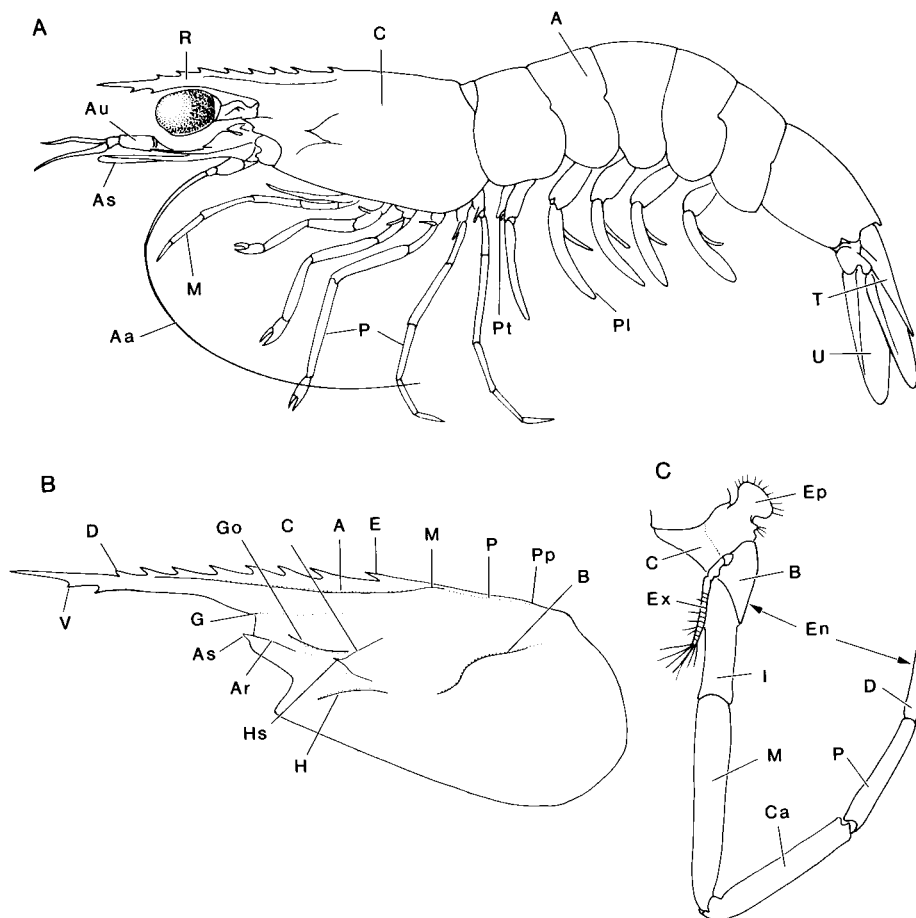


Figure 1. A) Lateral view of a male *Penaeus vannamei*. A, Abdomen; Aa, Antenna; As, Antennal scale; Au, Antennule; C, Carapace; M, Third maxilliped; P, Pereopod (walking leg); Pl, Pleopod (swimmeret); Pt, Petasma; R, Rostrum; T, Telson; U, Uropod.

B) The anterior region (cephalothorax) of a typical penaeid shrimp indicating spines, grooves and other features that are useful for species identification. A, Adrostral ridge and groove; Ar, Antennal ridge and groove; As, Antennal spine; B, Branchiocardiac ridge and groove; C, Cervical ridge and groove; D, Distal or last rostral tooth; E, epigastric or first rostral tooth; G, gastro-frontal ridge and groove; Go, Gastro-orbital ridge and groove; H, Hepatic ridge and groove; Hs, Hepatic spine; M, Median groove; P, Postrostral ridge; Pp, Position of the post-rostral groove; V, Ventral rostral tooth.

C) A biramous appendage from the thorax of *Penaeus vannamei* showing the two differentially developed rami. B, Basis; C, Coxa; Ca, Carpus; D, Dactylus; En, Endopodite; Ep, Epipodite; Ex, Exopodite; I, Ischium; M, Merus; P, Propus. (Figure 1A and AB modified from Grey et al. 1983).

2.4.1 Penaeus chinensis (Osbeck, 1765)

Rostral crest is low and projects horizontally with 7-9 dorsal teeth and 3-4 ventral teeth. Telson forms a narrow triangle, is shorter than the uropods and lacks lateral spines.

Color: Overall creamy white with darker rostrum and uropods.

Remarks: This species is often referred to by the synonym P. orientalis Kishinouye; or its common names, the Korean shrimp or Japanese shrimp.

2.4.2 Penaeus indicus Milne Edwards, 1837

Rostral crest is elevated with 7-9 dorsal teeth and 4-5 ventral teeth. Adrostral groove is distinct, but close to the median groove and reaches almost to the middle of the carapace. Gastro-orbital ridge is well defined and hepatic ridge is absent. Telson is broadly triangular and has a median longitudinal groove which lacks spines.

Color: Overall creamy white with small specks of blue, legs may be red and the rostral region brown.

Remarks: This species is very similar to P. merguensis and juveniles of the two species are difficult to differentiate.

2.4.3 Penaeus japonicus Bate, 1888

Smooth, shiny carapace without hairs. Rostrum is almost horizontal but curves down very slightly, and has 8-10 dorsal teeth and usually a single ventral tooth. Adrostral and median grooves reach the posterior margin of the carapace. Adrostral groove is narrower than the postrostral ridge. The anterior plate of the thelycum is rounded at the apex in females. Telson has moveable lateral spines.

Color: Brown bands (usually 10 or more) are especially conspicuous on the abdomen, but also apparent on the dorsal part of the carapace, legs and uropods. Legs are red and the telson and uropods are tinged with red, blue and yellow.

2.4.4 Penaeus merguensis de Man, 1888

Rostrum extends horizontally and has an elevated crest with 6-10 large teeth dorsally and up to 6 ventral teeth. Median and adrostral grooves are shallow and diminish at the middle of the carapace. Gastro-orbital ridge is absent or weakly defined and there is no hepatic ridge so the carapace appears smooth.

Color: Overall creamy white

2.4.5 Penaeus monodon Fabricius, 1798

Rostrum has 7-8 dorsal teeth and 3-4 ventral teeth and curves down very slightly. Rostral ridge lacks a distinct groove behind it, and the hepatic ridge is long and curved. Telson has a groove but is without lateral spines.

Color: Carapace and abdomen have black bands giving a tiger-striped appearance to this species. Pereiopods may be red.

Remarks: P. monodon is the largest of the commercial species, reaching 330 mm or more in length.

2.4.6 Penaeus stylirostris Stimpson, 1874

Rostrum projects horizontally and has about 7 dorsal teeth and one weakly developed ventral tooth. There is a small spine on the posterior margin of the fifth abdominal segment.

Color: Overall white with a blue or blue grey tinge to the rostrum, carapace, legs and telson.

2.4.7 Penaeus vannamei Boone, 1931

Rostrum curves down slightly and has 8-9 dorsal teeth and 1-3 ventral teeth.

Color: Overall white, with white or pale legs.

Remarks: P. vannamei may be difficult to distinguish from P. stylirostris (the blue shrimp). Both species have a similar geographic distribution, although P. vannamei can be found in deeper waters.

2.4.8 Metapenaeus ensis (de Haan, 1844)

Rostrum is horizontal and narrow with about 8-9 dorsal teeth. Branchiocardiac ridge is distinct and is bordered by a shallow groove with short hairs. Ischia of the first pair of walking legs bear a spine. Telson has a broad groove and lacks spines.

Color: Overall pale brown to bright pink with bright red antennae. Uropods are red and legs are pink to red and may be striped.

2.5. BIOLOGY

2.5.1 Reproduction

The penaeid life cycle includes several distinct stages found in a variety of habitats. Juveniles often prefer brackish waters of estuaries and coastal wetlands, while adults are usually found off-shore at higher salinities and greater depths. Larval stages inhabit plankton-rich surface waters off-shore, with an on-shore migration as they develop (Fig. 2).

Penaeids are dioecious and the external structures of the genital system are the major dimorphic features. The male has two pairs of modified

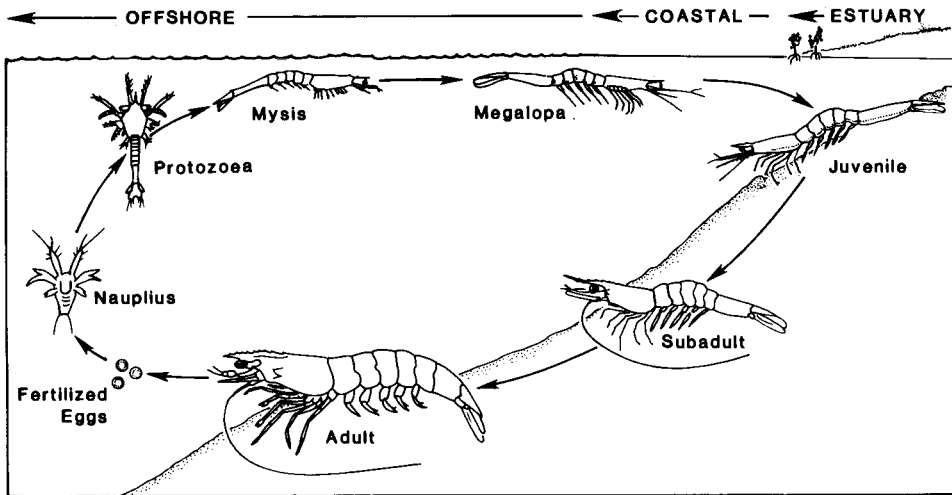


Figure 2. The life cycle of a typical penaeid species with stages in different habitats.

abdominal appendages on the first and second abdominal segments (the petasma and appendix masculina) that deliver sperm to the female's external receptacle (the thelycum) located between the bases of the fifth walking legs. The petasma, appendix masculina and thelycum are located on the ventral surface (Fig. 1A, 3, and 4).

The petasma is formed by the endopodites of the first pair of pleopods which are modified as interlocking structures for spermatophore transfer (Fig. 3A and 4A). The appendix masculina (Fig. 3B and 4B) are on the endopodites of the second pair of pleopods and serve to separate the petasma into two component halves. The thelycum may be "open" or "closed", depending on the species (Fig. 3D and 4C). "Closed" thelyca are those where the spermatophore is placed by a male in the groove below the plates while the female is in the soft exoskeleton stage following molting. The spermatophore is stored for some time before spawning. "Open" thelyca are not enclosed by plates, and the spermatophore must be placed on it by a male when the female's exoskeleton is hard; usually within hours of spawning. The presence of a spermatophore on the female is evidence that she has successfully mated (see Chapter 5 for a detailed discussion). Open thelyca are found in some shrimp species endemic to the Western Hemisphere, such as *P. stylirostris* and *P. vannamei*; while closed thelyca are characteristic of most Asian species, such as *P. monodon*, *P. chinensis*, *P. japonicus*, *P. indicus*, *P. merguensis* and *Metapenaeus ensis*.

Internal organs of the male reproductive system include a paired testes, vas deferens and terminal ampoules for spermatophore storage. The female

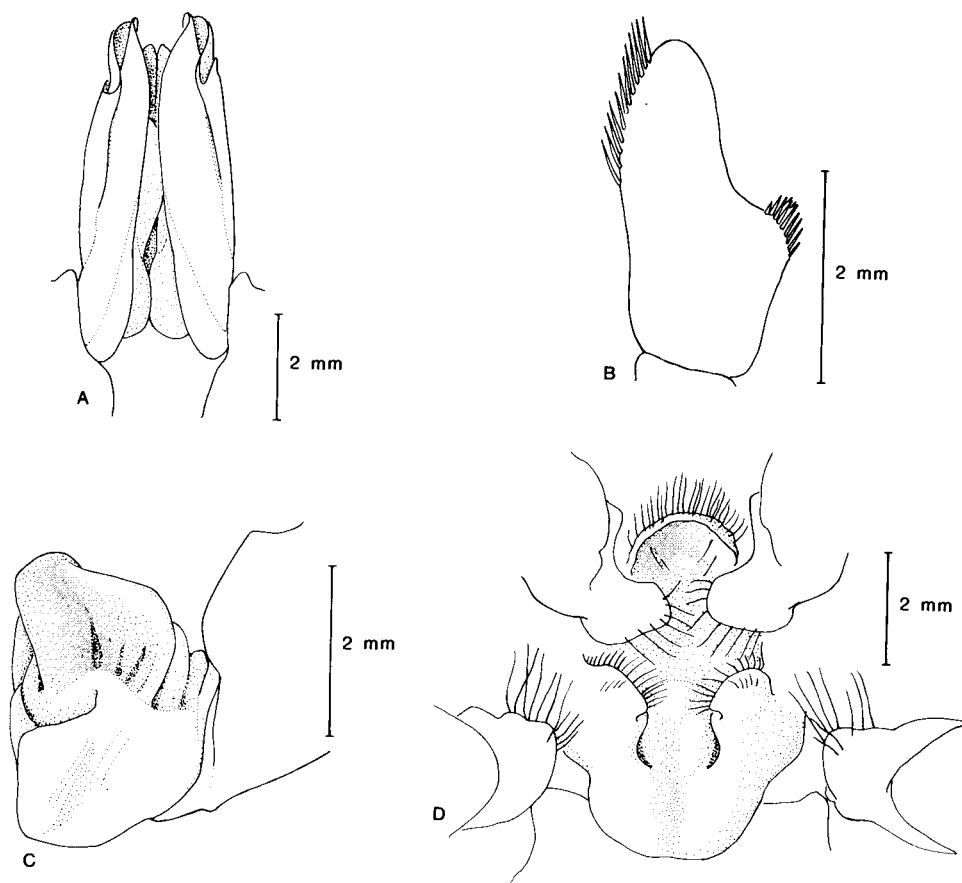


Figure 3. External reproductive structures of *Penaeus vannamei*.

A) The petasma of a male (modified endopodites of the first pair of pleopods) is hooked together forming a single structure.

B) One of a pair of appendix masculina of a male *P. vannamei*. These modified endopodites of the second pair of pleopods separate the petasma into two halves.

C) One of a pair of terminal ampoules at the base of the fifth pereopod a male that stores the spermatophores before mating.

D) Open thelycum of a *P. vannamei* female located between the bases of the fourth and fifth pereopods.

reproductive system includes paired (but partially fused) ovaries that extend from the mid-thorax to the posterior end of the abdomen, and oviducts terminating adjacent to a single thelycum. Ovaries increase in volume and change color as the eggs accumulate yolk and increase in diameter. Five stages of ovarian maturation have been described for penaeid species (see Chapter 5). Egg diameter increases from 35 μ or less in immature (stage I)

ovaries, to greater than 235 μm in ripe (stage IV) ovaries. These changes can often be viewed through the carapace and are useful indicators for farmers to assess ovarian development.

Courtship and mating generally occur at night, and have been described for *Penaeus monodon* (Primavera 1979) and *P. vannamei* (Yano et al. 1988). (See Chapter 5 for a more complete description of courtship behavior.) The behavior of these species is very similar, even though they have closed and open thelyca, respectively. Mating behavior of *P. vannamei* differs from *P. monodon* in that the spermatophore is transferred while the pair are ventrally opposed with the male beneath the female, rather than curled around her. Mating and spermatophore transfer take place just before spawning in open thelycum penaeids, but usually days or weeks before spawning in closed thelycum species.

During spawning, eggs and sperm are simultaneously released from the female while she is swimming. Fertilization is external, and egg development occurs in the water column. The first larval stage, the nauplius, hatches from the egg membrane and molts five or six times before becoming a protozoa. Nauplii are nourished on yolk stored in the egg cytoplasm. Three protozoa stages are followed by three mysis stages, and a number of megalopa or postmysis stages before reaching the juvenile stage (Motoh 1981). These are all active-feeding stages (after nauplius), where the shrimp require an appropriate sized phyto- and zooplankton diet.

2.5.2 Feeding Biology

The following discussion on the feeding biology of penaeid shrimp relates only to the postlarval through adult stages. Discussions on larval feeding are presented later in this volume, and in Emmerson 1980, Emmerson 1984, Chu and Shing 1986, and Wong et al. 1989.

Feeding behavior, mechanisms of food ingestion, and the structure and function of feeding appendages have been extensively studied in the banana prawn, *Penaeus merguensis* (Hindley 1975, Hindley and Alexander 1978, Alexander et al. 1980, Alexander and Hindley 1985). Shrimp foraging activity is stimulated by low concentrations of organic compounds in the water. These compounds include proteins, protein derivatives such as amino acids, ammonium compounds such as trimethylamine, compounds rich in highly unsaturated fatty acids, and others (Hindley 1975, Bryant et al. 1989). Cuticular chemosensory structures, such as fine hairs or setae, can detect these compounds in concentrations as low as 10^{-6} Molar, although the range of sensitivity and the threshold concentrations for individual compounds may vary among species. Chemosensory structures are most concentrated at the anterior end of the body on antennules, mouthparts, chelae, antennae, and maxillipeds. Vision does not seem important for the detection or location of

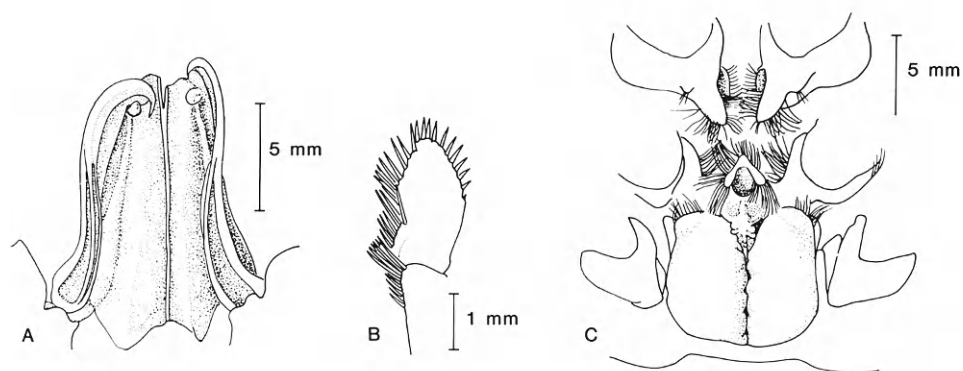


Figure 4. External reproductive structures of Penaeus monodon. A. The petasma of P. monodon. B. Appendix masculina. C. Closed thelycum of a P. monodon female, with lateral plates where spermatophores are inserted.

food (Hindley 1975), and form vision is considered rudimentary in crustaceans (Bullock and Horridge 1965).

During foraging, shrimp rapidly probe the substratum using the first three pair of chelate pereiopods. Once food is located, it is grasped by the pereiopods which pass it to the mouthparts (Hindley and Alexander 1978). Small particles are placed directly in a pre-oral cavity, while larger items are held to the mouthparts by the third maxillipeds for further manipulation (Alexander et al. 1980). Sand grains and other inedible items are usually rejected (Alexander and Hindley 1985), although some items may be ingested and aid in food grinding (Suthers 1984).

Preliminary digestion occurs after ingested food enters the elastic foregut, or proventriculus, where enzyme addition, trituration, and storage take place (Dall and Moriarty 1983). Food passage through the foregut is rapid and it empties at a declining logarithmic rate (Marte 1980, Leber unpublished data). Partially digested food then passes to the midgut, or digestive gland, where the dual functions of enzyme secretion and absorption of digested food occur. Digestive enzymes secreted from the midgut include proteinases, carboxypeptidases, lipases, amylases, chitinases, and others (Dall and Moriarty 1983). It may be possible for some penaeid species to alter their digestive enzyme profiles depending on their dietary history (J. M. Wigglesworth pers. comm.). Gut flora may be an important source of digestive enzymes for penaeids (Hood and Meyers 1973, Dempsey and Kitting 1987), although their role is not well established. While most soluble products of digestion are absorbed in the midgut and midgut diverticula, undigestible items pass through a simple tubular hindgut where longitudinal, muscular pads grasp the

fecal string by its peritrophic membrane and rhythmical contractions expel it (Dall 1967).

Penaeid shrimp are known to ingest a variety of items and have been described as omnivorous scavengers (Dall 1968), opportunistic omnivores (Ruello 1973, Cockcroft and McLachlan 1986), detritus feeders (Dall 1968), carnivores (Hunter and Feller 1987), and predators (Marte 1980, Leber 1985, Wassenberg and Hill 1987). While some interspecific differences in the trophic status of penaeids may exist, ontogenetic changes in food preference and food availability can account for much of the reported variation in their diets (Chong and Sasekumar 1981). Epibenthic postlarvae and juveniles consume both animal and plant matter, including microalgae, detrital aggregates, macrophytes, foraminiferans, nematodes, copepods, tanaids, larval molluscs, and brachyuran larvae (Chong and Sasekumar 1981, Gleason and Wellington 1988). As shrimp grow, many of the small invertebrates in their diet are replaced by larger invertebrate prey, such as mysid and caridean shrimp, amphipods, polychaetes, and molluscs, as well as fishes (Chong and Sasekumar 1981, Leber 1985, Stoner and Zimmerman 1988).

Subadult and adult shrimp also consume significant amounts of detrital aggregates (Chong and Sasekumar 1981, Cockcroft and McLachlan 1986). Depending on its source and age, detritus can be efficiently assimilated (Qasim and Easterson 1974). The relative contribution of detrital particles per se (as defined by Wetzel et al. 1972) versus attendant microbes (i.e. fungi, bacteria, and protozoans) to shrimp nutrition is not clear. Detritus originates mostly from primary producers, and is largely composed of structural polysaccharides and other polymers (Fenchel and Jorgensen 1977, Lee 1980). The ability to hydrolyze these compounds is rare among marine invertebrates (Hylleberg Kristensen 1972), and is not well documented for penaeid shrimp (Yokoe and Yasumasu 1964).

Bacteria rapidly colonize and decompose detritus in marine and brackishwater ecosystems (Fenchel and Jorgensen 1977, Lee 1980), and were thought to be important components in penaeid diets (Moriarty 1976, Moriarty 1977, Moriarty and Barclay 1981). Recent evidence indicates, however, that bacterial biomass associated with detritus or sediments accounts for a relatively small fraction of total organic carbon and nitrogen (Ruble 1982, Blum et al. 1988), and animals using this resource generally do not consume these bacteria rapidly enough to meet their energetic requirements (Cammen 1980). Furthermore, bacteria are conspicuously lacking in long chain polyunsaturated fatty acids, sterols, and the sulfur-containing amino acid methionine (Phillips 1984), all of which are important dietary components for penaeid shrimp (New 1976).

Less is known about the potential nutritional importance of other microbial groups. Protozoans are considered important bacterial grazers in

planktonic food chains, capable of consuming a large fraction of the bacterial biomass and channeling energy to higher trophic levels (Azam et al. 1983). A similar situation may occur in sediments and on detrital aggregates, where protozoans (especially ciliates) are thought to be important bacterial grazers (Fenchel and Jorgensen 1977). Although protozoans are presumed to synthesize their own long chain polyunsaturated fatty acids (Phillips 1984), thus making them desirable dietary items for penaeid shrimp, virtually nothing is known about macrofaunal consumption of these potential food items (Berk et al. 1977, Sherr et al. 1986). Fungi are considered to play a minor role in the decomposition of detritus in marine and brackish water ecosystems (Fenchel and Jorgensen 1977), and are probably nutritionally unimportant to shrimp.

Recent studies using stable carbon isotope techniques have helped to clarify food web relationships between penaeid shrimp and potential food items in coastal habitats (Fry 1984, Gleason and Zimmerman 1984, Gleason 1986, Gleason and Wellington 1988, Stoner and Zimmerman 1988). These techniques are useful in determining the origins and transformations of organic matter that is channeled through benthic food webs by providing a time-integrated dietary history of the species under study (Fry and Sherr 1984). Penaeid shrimp inhabiting coastal mangroves and saltmarshes appear to derive little carbon from macrophytes or macrophyte-derived detritus and associated heterotrophic microbes. Instead, a substantial portion of carbon ending up in shrimp biomass originates from planktonic microalgae (Gleason and Wellington 1988), epiphytic algae (Fry 1984), or benthic algae (Stoner and Zimmerman 1988). These studies provide evidence that microalgae, or organisms feeding on microalgae, can be a major source of nutrition for penaeid shrimp in coastal habitats.

2.6 ZOOGEOGRAPHY

The genus Penaeus occurs in tropical and subtropical waters around the world, from about 40°N to 40°S latitude. Known geographical distributions and typical habitats of adults and juveniles of the eight selected species are listed in Table 2. Six of the species are from the Indo-Pacific region, while two are endemic to the eastern Pacific. Adult shrimp of these species are rarely found below 180 m and typically inhabit off-shore waters, while juveniles generally occur in protected coastal habitats (Table 2, Fig. 2).

Penaeid shrimp may exhibit specific behaviors depending on the type of habitat they occupy (Penn 1984). For example, Penaeus merguensis typically inhabits areas characterized by soft, muddy bottoms and high turbidity (Munro 1975). This type of habitat may confer some protection from visual predators because of the restricted light penetration into the water. In these conditions,

Table 2. Geographical distributions of commercially important penaeid shrimp species and the types of habitats where they commonly occur. Water depths are expressed in meters (modified from Holthuis 1980).

Species	Distribution	Habitat
<u>Penaeus chinensis</u>	Indo-West Pacific: China, Hong Kong, Korea	depth 90-180 m; marine.
<u>Penaeus indicus</u>	Indo-West Pacific: E. and S.E. Africa to S. China, Indonesia, New Guinea, N. and N.E. Australia	depth 2-90 m; bottom: mud or sand; adults marine; juveniles estuarine.
<u>Penaeus japonicus</u>	Indo-West Pacific: from the Red Sea, E. and S.E. Africa to Korea, Japan, southward to Indonesia, N. and N.E. Australia, eastward to Fiji. This species has entered the eastern Mediterranean Sea through the Suez Canal to the south coast of Turkey.	depth 0-90 m; bottom: sand or sandy mud; marine.
<u>Penaeus merguensis</u>	Indo-West Pacific: from the Persian Gulf to Thailand, Hong Kong, the Philippines. Indonesia, New Guinea, New Caledonia, W., N. and E. Australia	depth 10-45 m; bottom: mud; estuarine and marine.
<u>Penaeus monodon</u>	Indo-West Pacific: E. and S.E. Africa and Pakistan to Japan, southward to Indonesia and N. Australia	depth 0-162 m; bottom: mud or sand; adults marine; juveniles estuarine.
<u>Penaeus stylirostris</u>	Eastern Pacific: from N. Mexico to Peru	depth 0-27 m; bottom: mud, clay or sandy mud; marine; adults marine; juvenile estuarine.
<u>Penaeus vannamei</u>	Eastern Pacific: from N. Mexico south to Northern Peru	depth 0-72 m; bottom: mud; adults marine; juveniles estuarine.
<u>Metapenaeus ensis</u>	Indo-West Pacific: Sri Lanka and Malaysia to S.E. China, Japan, southward to Indonesia, New Guinea, and W., N. and E. Australia	depth 18-64 m; bottom: mud; marine and estuarine.

P. merguensis does not exhibit strong burrowing behavior, and can forage at any time throughout a diel cycle.

During periods of the tidal cycle when turbidity falls to a minimum, Penaeus merguensis can form dense schools and generate intense, turbid patches known as "mud boils" (Lucas et al. 1979). This schooling behavior and turbidity generation may have survival value for this non-burrowing

species by reducing predation pressure at times of low turbidity. The majority of penaeid species, however, do not exhibit schooling behavior except possibly during emigration from estuaries.

In contrast, shrimp inhabiting clearer waters, with more intense predation from visual predators, often exhibit stronger burrowing behavior and are active only at night. Penaeus japonicus and P. duorarum exhibit these characteristics.

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2.8 GLOSSARY

Antennule, antenna (pl. antennae): the first and second pairs of appendages are the "feelers" at the anterior end; the first pair are the antennules which consist of two basal parts each with three segments and bearing a pair of fine flagella at the tip. The second pair are the antennae which consist of two scales and two very long whip-like flagella (Fig. 1A).

Appendage: any structure growing out of the body; usually movable paired leg-like structures (Fig. 1A, C).

Appendix masculina: a flattened segment of the endopod of the second pair of pleopods in males. The margins bear a number of stout spines. Part of the male reproductive system (Fig. 3B).

Basis, basial: On an appendage, the segment nearest the body. It is very short and seems almost fused with the body. The first freely movable segment is the basis, or basial segment (Fig. 1C).

Cuticle: the hard covering or shell of a shrimp.

Distal: away from the body, usually the part farthest away; as opposed to proximal.

Epigastric tooth: a rostral tooth above the gastric region (Fig. 1B).

Exopod, exopodite: a small structure arising from the basial segment of an appendage (Fig. 1C).

Flagellum (pl. flagella): literally, a whip. The name given to the thin flexible feelers of a shrimp's antennae.

Ischium, ischial: the third segment of a pereopod that follows the basis (Fig. 1C).

Maxilliped: the thoracic appendages in front of the walking legs; there are three pairs but only the third can be easily seen (Fig. 1A).

Megalopa (postlarvae, postmysis): technically the postlarval stages that are still pelagic; follows the mysis.

Mysis: the third larval stage, becoming shrimp-like in appearance (see nauplius, protozoa, megalopa).

Nauplius (pl. nauplii): the first larval stage; nauplii swim by antennal propulsion and are nourished by the yolk originally stored in the egg.

Petasma: the male appendage used for transferring sperm packets (spermatophores) to the thelycum of the female. It looks like a penis and is formed from the inner parts of the first pair of pleopods (Fig. 3A). The shape of the petasma is of taxonomic importance.

Pleopods: the swimming appendages on the abdomen (Fig. 1A).

Postlarvae (postmysis): the early juvenile stages that follow the mysis, may include the megalopa or specifically refer to the first benthic stage in the life cycle.

Process: a projecting part, may be a spine, tooth, ridge, keel or rostrum (Fig. 1A, B).

Protozoa: the second larval stage; protozoa feed on small phyto- and zooplankton (see nauplius, mysis, megalopa).

Ridges, keels and grooves: ridges on the carapace of shrimp are usually low, and vary from quite sharp to blunt. Very sharp ridges are sometimes called keels. The grooves on the carapace may be filled with fine hairs.

Spermatophore: soft package containing sperm that is transferred by the petasma of the male to the thelycum of the female.

Tooth: a hard, immovable, broad-based and usually sharp projection of the cuticle.

Telson: the sharp triangular spike at the end of the abdomen (Fig. 1A).

Thelycum: the female external receptacle for sperm packets (spermatophores) situated between the fourth and fifth pairs of legs; may be closed by two flaps, or consist of a series of open plate-like structures (Figs. 3D, 4C).

Uropods: the two pairs of flattened appendages on either side of the telson; (Fig. 1A).

CHAPTER 3 L. James Lester and Ma. Josefa R. Pante

GENETICS OF PENAEUS SPECIES

3.1 INTRODUCTION

A thorough knowledge of the genetics of a cultured organism is extremely important for understanding the responses of that organism to culture environments and management techniques. An organism develops in response to and under the control of its genes and the environment. Modifying the gene pool of a cultured stock to obtain a greater yield or higher quality animals is one of the primary objectives of the domestication process. The need for genetics in aquaculture programs has been addressed previously (Kirpichnikov 1981; Moav 1979; Wilkins 1981). Some authors emphasize the need to focus on the traditional approaches to improvement through selective breeding (Newkirk 1981) while others call attention to applications of modern techniques of biochemical and molecular genetics (Hedgecock 1977; Moav et al. 1978; Maclean and Penman 1990).

This chapter will cover all information that is currently available on the genetics of penaeid shrimp, whether it is basic information on the biochemical or molecular genetics of members of the family Penaeidae or data collected on commercial traits such as growth rate.

3.2 GENETICS OF WILD POPULATIONS

Studies of genetic variation within and among species of penaeid shrimp in nature began over 15 years ago for purposes of fishery management. The results of these studies are of interest to culturists. They provide information about genetic differences among potential founder populations for initiation of aquaculture stocks. All of the findings on penaeid species will be reviewed here whether or not the subject species is currently used in aquaculture.

3.2.1 Levels of variation within species

Although some studies of single loci show high numbers of allozymes, the general pattern among shrimp species and other large decapod crustacea is lower levels of electrophoretic variation than would be expected based on studies of terrestrial animals and other marine invertebrates. Nelson and Hedgecock (1980) have tried to explain this apparent lack of genetic variation using a hypothesis based on differences in adaptive strategies. Another

possibility is that this difference in genetic variation is more associated with the technique of electrophoresis than a real lack of allelic variation.

Some labs have applied to penaeids the techniques of restriction fragment length polymorphisms of mitochondrial DNA (Palumbi and Brand 1991; Davis 1990), DNA probes for Southern hybridization with genomic DNA (Palumbi and Brand 1991) and extraction of nuclear DNA for amplification by polymerase chain reaction (Palumbi and Brand 1991). Palumbi and Brand (1991) have applied all three techniques to the problems of phylogenetic relationships and differentiation of natural and domestic populations. They conclude that the level of mtDNA variation within penaeid species is small.

Studies of phenotypic variation do not suggest a lack of additive genetic variance in quantitative traits. The estimates of heritability discussed below indicate normal levels of allelic variation underlying the growth process of the penaeid species studied.

3.2.1.1 Biochemical genetic variation

The earliest report of electrophoretic variation in a species of Penaeus was by Proctor et al (1974) of the phosphoglucosmutase polymorphism in Penaeus aztecus with five allozymes. This report was followed in 1976 by two others on the same locus in P. setiferus, P. brasiliensis and P. subtilis (Marvin and Caillouet, 1976; Lansford et al. 1976). These species exhibited the same allozymes as P. aztecus, except that P. brasiliensis lacked the most cathodal allozyme. The heterozygosities (H) were different in the Gulf of Mexico species, P. aztecus: $H = 0.37$ ($n=600$) and P. setiferus: $H = 0.37$ ($n = 1048$), and Caribbean species, P. subtilis: $H = 0.16$ ($n = 310$) and P. brasiliensis: $H = 0.14$ ($n = 390$). Marvin et al. (1977) also found phosphohexose isomerase to be polymorphic in the penaeids, P. setiferus and P. duorarum. This locus had four allozymes in both species.

Reports which used multiple loci to investigate geographic differentiation and the level of genetic variation began to appear in 1979. Lester (1979) reported that the three common species of Penaeus in the Gulf of Mexico exhibited no geographic variation in the gene frequencies of polymorphic loci among 26 loci studied. The heterozygosities were between .079 and .092. Redfield et al. (1980) found a very low heterozygosity in P. merguensis ($H = 0.008$) using 25 loci. The most emphatic report of low heterozygosity in penaeid species is that by Mulley and Latter (1980) who surveyed seven Penaeus species and six Metapenaeus species. The heterozygosities reported for these penaeids ranged from a low of 0.006 in P. longistylus to 0.033 in P. esculentis. P. monodon was reported to have an H of 0.008. The same phenomenon was reported for the Metapenaeus species with H starting at 0.01 in M. insolitus ranging up to 0.03 in M. endeavouri. This study used

electrophoretic data to confirm the taxonomic relationships among these species.

Two studies of intraspecific variation of cultured penaeid stocks have been performed (Lioe 1984; Sbordoni et al. 1987, 1988). Lioe (1984) studied Penaeus chinensis, P. indicus, P. stylirostris, P. vannamei, P. kerathurus, P. japonicus, and P. monodon. Most of the samples of these species are from cultured stocks held at the Centre IFREMER de Tahiti or at the Centre Oceanologique de Bretagne. The samples were surveyed for electrophoretic variation at 29 loci. Penaeus japonicus was obtained from a cultured stock and showed a heterozygosity of 0.015 from one polymorphic locus. Two cultured stocks of P. stylirostris were sampled which had similar heterozygosities, 0.035 and 0.045. However one stock was highly polymorphic at a malate dehydrogenase locus (MDH-2) ($h = 0.343$) and a mannose-6-phosphate isomerase locus (MPI) ($h = 0.403$) and monomorphic at the phosphoglucumutase (PGM) locus while the other was the reverse (PGM: $h = 0.466$). Thus considerable genetic differences existed between these stocks. P. vannamei was also examined from two cultured stocks and similar observations were made. One stock was polymorphic at the amino aspartate transferase locus (AAT-2: $h = 0.403$) and the other was not.

Four cultured stocks of P. monodon were examined, one of unknown origin, one originating from Taiwan, one from five individuals captured near Fiji, and another from the Philippines. The Taiwan stock appeared to have lost genetic variation and had no detectable heterozygosity. The Fiji stock which originated from the smallest number of founders had maintained the greatest heterozygosity, $H = 0.023$, which is nevertheless low. The other two stocks showed lower H , 0.016 and 0.011. One wild and one captive sample were examined for P. indicus. The cultured stock had only one polymorphic locus while the wild stock was found to be polymorphic at five loci. The heterozygosity of the wild stock was approximately twice that of the cultured stock ($H = 0.025$ vs. $H = 0.014$). Only one cultured stock of P. orientalis (chinensis) was studied and it had 3 polymorphic loci out of 29 and a heterozygosity of 0.021. Two wild stocks of P. kerathurus were collected from the Mediterranean coasts of France and Spain. This species had the highest average polymorphism and average heterozygosity among all the species in this study. Penaeus kerathurus from additional Mediterranean localities have been examined for electrophoretic variation (Mattoccia et al. 1987). Allele frequencies at 10 polymorphic loci are reported for four populations around Italy and Tunisia. The levels of heterozygosity are relatively high for penaeids, ranging from 0.052 to 0.089.

Penaeus japonicus has been cultured in Italian lagoons for seven generations. Sbordoni et al. (1986, 1987) have examined the change in electrophoretic variation over time in this cultured population.

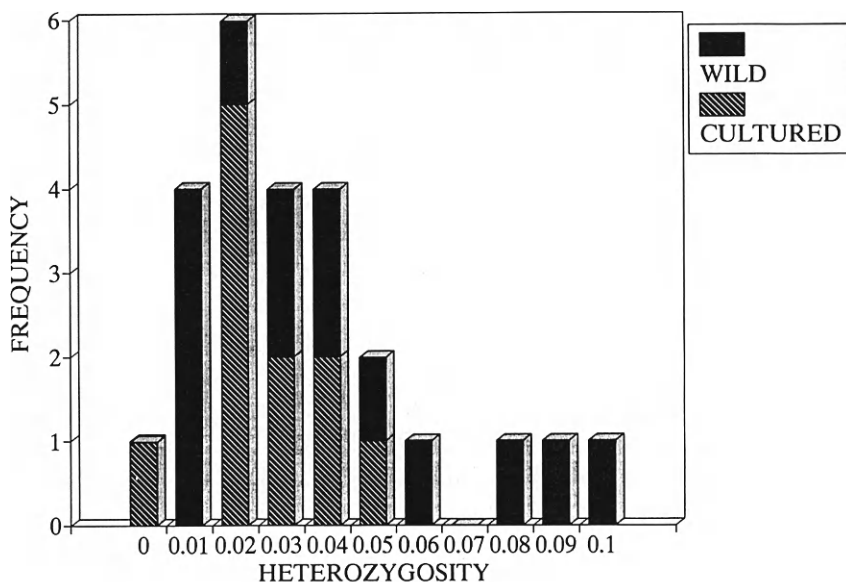


Figure 1. Distribution of heterozygosities reported for species of Penaeidae. Values obtained from cultured stocks are indicated by shading.

Heterozygosity has declined from 0.102 in the first captive generation to 0.036 in the seventh. All lagoons are stocked with offspring from broodstock obtained from the same lagoon each generation. Broodstock management has not been satisfactory for maintenance of genetic variation. In addition to a known bottleneck of only four broodstock for production of the second generation, there have been unrecognized reductions in effective population size causing continued strong genetic drift.

The H values of all penaeid species discussed in this section are summarized in Figure 1, which illustrates the differences between wild and cultured collections. It appears that there is a strong tendency for captive breeding to result in a lessening of genetic variation in penaeid stocks. This is a serious problem.

3.2.1.2 Morphological variation

Aside from deformities which are discussed below, there are no reports of morphotypes segregating in populations of Penaeidae. The morphological variation detected in morphometric studies of penaeid species is of a continuous nature whether the character in question is metric or meristic. Thus studies of morphological variation are based on statistical analysis of measurements and counts not the frequency of morphotypes.

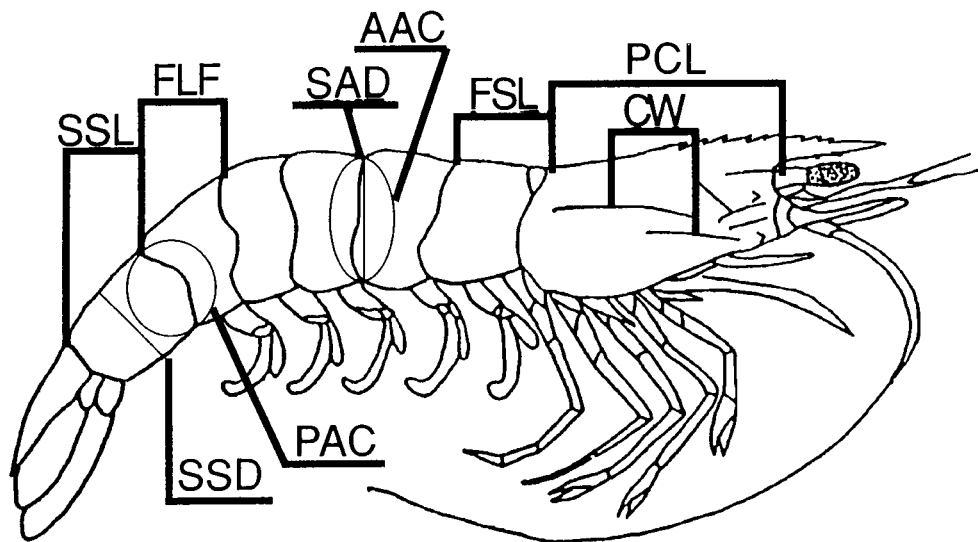


Figure 2. Morphological variables collected by hand and used in the studies on correlation with tail weight by Goswami et al. (1986) and Lester (1983)

The first multivariate morphometric study of penaeid species was by Horton (1982). Museum specimens were used to investigate Penaeus stylirostris and Penaeus vannamei for univariate and multivariate morphological variation within sex and age classes and among geographic localities. Horton used 11 metric and two meristic variables to detect variation among age and sex classes. The univariate results show significant differences between adult males and females of P. vannamei for medial and proximal lateral antennular flagella length and differences between adult males and females of P. stylirostris for medial antennular flagella length. Also, some of the ratios change significantly over age (size) classes due to allometric growth.

Several applied studies of morphometric variation in Penaeus species have been performed with the objective of determining the metric trait with the highest covariation with abdomen weight. This trait could then be used in a selection program in place of tail weight which can not be measured from live shrimp. Lester (1983) studied nine measurements taken on body dimensions (Figure 2) of P. stylirostris and P. vannamei reared in culture ponds and concluded that sixth segment depth would be the best substitute for abdomen weight. Goswami et al. (1986) examined 17 measurements from

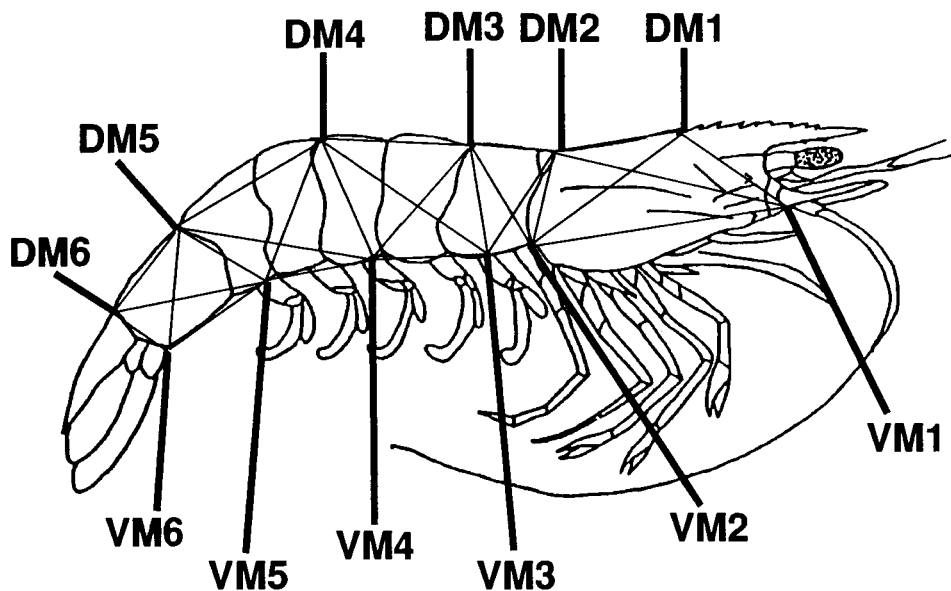


Figure 3. Morphological variables collected by digitizing a photographic image and used in a study of morphological variation among species (Lester et al. 1990).

P. merguensis collected from two localities and determined that partial carapace length, exopod of uropod length, or posterior abdominal circumference were the most accurate estimators of abdomen weight depending upon the population being analyzed.

Dimensions collected from photographs of shrimp in either lateral or dorsal view, either alive or dead, have been used in recent studies. The photographs are used in concert with a computer and a digitizing tablet to determine the location of landmark points around the periphery of the shrimp (Figure 3). Entry of a scale permits the use of these coordinates to calculate the distances between combinations of landmark points. This results in a truss network (Strauss and Bookstein 1982) of dimensions across the body of the shrimp (Figure 3) (Lester et al. 1990). Four species of *Penaeus*, *P. monodon*, *P. setiferus*, *P. stylirostris*, and *P. vannamei*, have been investigated with this methodology. The results indicate that nearly all of the morphometric variation within populations and species of *Penaeus* is related to the size of the shrimp. In most analyses, less than five percent of the variation in the data set is attributable to differences in a particular region of the body, i.e. shape differences.

3.2.2 Genetic differences among species

Any two populations which have not exchanged genes for a long period of time will accumulate different mutations, some of which may rise in frequency and contribute to morphological, physiological or biochemical differences between members of these populations. Based on fossil evidence, the genus Penaeus has been extant since the Cretaceous, at least 65 million years (Moore 1969), and many of the species have been reproductively isolated gene pools for millions of years. There are no reports of interspecific hybridization between Penaeus species in the wild. Thus we expect to find genetic differences among penaeids, some of which will be significant to culturists.

3.2.2.1 Biochemical differences among species

Although there is limited allozymic variation within species of Penaeus, studies of biochemical genetic differences among species have reported significant genetic divergence, even between closely related species. Mulley and Latter (1980) compared 13 species, six of Metapenaeus and seven of Penaeus from Australian waters for 37 presumptive gene loci common to all the species. The average genetic distance (D, Nei 1972) between species of different genera was 0.95 and the average genetic distance between Penaeus species was 0.44. Lioe used D to compare seven species of Penaeus, six of which were sampled from cultured stocks. It is interesting to note that the average genetic distance among Penaeus species in the Lioe study is larger than in the Mulley and Latter study, 0.63 versus 0.44. This could be attributed to the analysis of different species pairs and/or the effect of genetic drift caused by culture-related population bottlenecks.

The loci that are most commonly polymorphic in the penaeids are MPI and PGM. Phosphoglucose isomerase (PGI) is also commonly polymorphic and can be scored from the same electrophoretic buffer system as MPI and PGM. These loci then are useful tools for tracking the genetic variation of a cultured stock. The type of variation which exists at these loci is shown in Table 1 which summarizes results reported by Mulley and Latter (1980) and Lioe (1985), as well as results from the authors' laboratory.

Isoelectric focusing is a very precise way of detecting amino acid sequence differences between species for a limited range of proteins. The resulting patterns are difficult to quantify. King and Grey (1991) have examined the isoelectric focusing patterns of 13 species of Penaeus for sarcoplasmic proteins. Every species is clearly distinguishable by isozymic pattern. Penaeus setifersu and P. subtilis and P. marginatus have the most distinctive electropherograms from this technique.

Data from restriction fragment length polymorphisms in mtDNA show specific differences as large as those detected by electrophoresis. Palumbi

Table 1. Allozyme frequencies of ten Penaeus species at three enzyme loci.

LOCUS	ALLELE	AZT ¹	DUO	SET	SCH	VAN	STY	OCC	MON	JAP	ORI
PGI	140	.003		.005						.125	
	120	.050	.013	.130	1.00				1.00	.875	
	100	.722	.945	.847		.006	.002	1.00			1.00
	80	.220	.042	.010		.988	.991				
	60	.005		.008		.006	.007				
	N	346	302	316	17	271	214	19	20	4	4
PGM	120	.005	.003					1.00			
	110	.200	.027	.140	.054		.026			.125	.500
	100	.790	.952	.802	.910	.002	.911		1.00	.875	.500
	90	.005	.018	.045	.036	.974	.063				
	80		.003	.010		.022					
	N	340	302	298	28	267	213	12	20	4	4
MPI	115		.025	.008							
	110	.008	.068	.055	.091		.027				
	105	.065	.820	.110	.909		.234			.125	
	100	.112	.058	.777		.029	.715	.055	1.00	.875	.375
	95	.757	.023	.040		.929	.023	.945			.625
	90	.030	.006	.010		.042					
	85	.028									
	N	310	302	342	22	191	128	19	20	4	4

¹ AZT = Penaeus aztecus; DUO = P. duorarum; SET = P. setiferus; SCH = P. schmitti; VAN = P. vannamei; STY = P. stylirostris; OCC = P. occidentalis; MON = P. monodon; JAP = P. japonicus; ORI = P. orientalis

and Brand (1991) describe a $9\% \pm 1.2\%$ difference between the mtDNA of P. vannamei and P. stylirostris. Partial sequences of a ribosomal RNA gene segment yielded a 9.6% difference between these two species. They report that these are "surprisingly high genetic differences among morphologically and ecologically similar species" (Palumbi and Brand 1991).

It is usually possible to identify penaeid species by their morphological characteristics. Thus biochemical characteristics are not really needed for classifying species. These differences are useful for determining the phylogenetic relationships among species.

3.2.2.2 Chromosomal differences among species

Few cytogenetic studies of Penaeus species have been published. This is probably due to the daunting number of small chromosomes reported for other decapods. Milligan (1976) reported the chromosome number ($2n$) of

P. setiferus to be 90, P. aztecus as 88 and P. duorarum as 88. Chow et al. (1990) confirm these numbers although their data on P. setiferus has a modal haploid number (n) of 44. This study included P. vannamei for which $n = 44$. Cytological study of P. chinensis and P. monodon yielded the same diploid number of 88 (Xiang 1988 and Xiang et al. 1990 in Liu 1990). A diploid number of 86 has been reported for P. japonicus (Hayashi and Fujiwara 1988). If $2n = 88$ is the correct chromosome number for P. setiferus (Chow et al. 1990), then one could conclude that the genus is conservative for chromosome number because only one of seven species has a diploid number different from 88.

The genus also appears to be relatively consistent in nuclear DNA content, although one study does differ considerably from the rest. Hemocytes of P. aztecus, P. duorarum, P. marginatus and P. vannamei have estimated nuclear DNA contents of 66 to 74% of the DNA content of human lymphocytes (Bachmann and Rheinsmith 1973; Rheinsmith et al. 1974; Chow et al. 1990). An early study of P. setiferus reported a nuclear DNA content that was 101% of human lymphocytes (Vaughn 1976), but Chow et al. (1990) report a value of 72% which is more consistent with its congeners.

3.2.2.3 Morphological differences among species

There is an indication of a lack of genetic differences among the species of Penaeus in the control of basic developmental patterns determining body shape. However, it is difficult to associate such evolutionary conservatism with a lack of genetic variation. It could be the result of stabilizing selection.

Species of Penaeus differ in a variety of morphological characteristics that are the expression of genetic differences among them. There are, of course, numerous studies of the morphological differences among species which can be used for taxonomic distinctions. These types of studies generally focus on the structures of genitalia, appendages, rostra, or sculpturing of the carapace. While it is important for culturists to recognize the species that might be contained in their ponds, these taxonomic characters have no known commercial value. Studies of the variation among species in morphological characters related to size, shape or other commercial characters are quite limited.

Morphometric studies of several species of Penaeus have been performed in the authors' laboratory using two approaches to the collection of measurements. In the early studies, the relationship was examined between various morphological measurements and abdomen weight. (See section 3.2.1.2)

The motivation for these morphometric studies changed from providing guidance for choosing traits to be used in selection programs to investigating the limits for detecting size and shape differences among species or

individuals of Penaeus. One rationale for this change is that deformities, which are gross changes in shape, may simply be an extreme expression of variation along a shape continuum. An understanding of shape variation may help us determine the inheritance of deformities.

Most morphometric variation is due to size differences, both within and among species. There is usually very little variation among members of a species in shape. Size differences are sometimes difficult to measure accurately because of measurement error. Multivariate analysis of shrimp body dimensions has proven to be useful as a very accurate method of size measurement (Lester et al. 1990)

The first step in our study was to determine whether a multivariate morphometric approach could discriminate among species of Penaeus in shape. Using the nine measurements which are shown in Figure 2. Data from six species have been examined. Both principal component and discriminant analysis techniques were used in attempts to find a methodology that would allow the description of shape differences in a biologically meaningful way. Figure 3 shows the results of this analysis expressed as a graph of the first principal component versus the sheared second principal component with each species shown by an ellipse representing the 95% confidence interval of the species centroid. The sheared second PC should define the differences among the species in shape with size removed as a factor (Humphries et al. 1981). PC 1 expresses the variation in size. Clearly some differences in shape exist, but this approach does not permit them to be partitioned into variables which have clear morphological meaning.

3.2.3 Geographic differentiation within species

There is much interest in genetic differences among geographically separated stocks within species. Farmers growing P. vannamei and other species are concerned that a different source of broodstock or seedstock might have a better growth rate, better reproductive characteristics, etc. The first step in investigating the possibility of such differences is usually to study the biochemical or morphological variation of samples from several geographic stocks.

3.2.3.1 Biochemical variation

Statistics can be calculated that express the level of genetic differentiation among geographically separated populations. Most studies of biochemical genetic variation employ genetic distance, typically D (Nei 1972), or the fixation index, F_{ST} (Wright 1965). Most penaeid species show insignificant variation in allozyme frequencies across large geographic distances (Lester 1979; Mulley and Latter 1981a, 1981b). There are no indications of genetic differences among stocks from the Gulf of Mexico and the Atlantic coast of

Florida of P. setiferus, P. aztecus and P. duorarum (Lester 1979, 1983). However, P. stylirostris appears to have a genetically distinct population in the northern Gulf of California (Lester unpublished data). This may be the source of the population in Fiji which was studied by Lioe (1984) and showed a high genetic distance (0.113) from the other Aquacop stock derived from Ecuador. Lioe also describes a large genetic distance (0.193) between two stocks derived from P. indicus populations on the coasts of the Philippines and Kenya. A moderate genetic distance (0.083) was reported by Lioe between stocks of P. kerathurus from the Mediterranean coasts of France and Spain. However, Mattoccia et al. (1987) calculate pairwise genetic distances between four populations of P. kerathurus from Italy and Tunisia as between 0.001 and 0.011. Thus it does not appear that P. kerathurus has a subdivided population in the Mediterranean.

The reports by Mulley and Latter (1981a, b) described the lack of geographic variation among localities of most Australian penaeid species, P. esculentis, M. ensis, P. semisulcatus, P. merguensis and P. plebejus. However, populations of M. endeavouri and P. latisulcatus showed significant differences between Gulf of Carpentaria and the localities in other parts of their ranges (Mulley and Latter, 1981b). Metapenaeus bennettiae and M. macleayi exhibited minor genetic differences among localities in Eastern Australia (Mulley and Latter, 1981a). In the case of species with genetically differentiated stocks which have different growth potential or disease susceptibility, electrophoresis could be useful to determine whether a sample came from the desired population.

Recently a comparison of electrophoresis and restriction fragment length polymorphism (RFLP) has been completed using geographic populations of P. vannamei and P. stylirostris (Dr. Scott Davis, Texas A&M University, unpublished data). The two techniques yield very different conclusions about the level of geographic differentiation among populations of these species. The F_{ST} based on electrophoretic variation is close to zero for P. vannamei and low (>0.05) for P. stylirostris. When RFLP is analyzed, the level of geographic differentiation rises more than 20 fold in P. vannamei to approximately 0.1. For P. stylirostris the increase in F_{ST} is only six fold, but the value (0.28) indicates very significant genetic differences between populations from Mexico and Ecuador. Electrophoretic characters may be too evolutionarily conservative to demonstrate genetic differences among natural populations that could be useful to culturists.

3.2.3.2 Morphometric variation

Clustering and principal component techniques can be used on morphometric data to compare geographic populations. Horton (1982) is the only investigator who has looked carefully at geographic variation of

morphological variables. Samples from throughout the ranges of P. vannamei and P. stylirostris exhibited differences in principal component scores and UPGMA clustering, but the results did not permit the development of an explanation based on geographic separation and changes. Horton reaches the conclusion that his morphometric study does not support the existence of subspecies within these species or of genetically differentiated stocks.

3.2.4 Implications for foundation broodstock

Currently data on genetic and morphometric variation and differentiation are not considered in the choice of species or stocks for culture. The choice seems to hinge on availability of seedstock or broodstock, market potential or value, tolerance of the culture environment, and growth rate. These last two criteria have genetic components, but species are rejected on these criteria without considering possible genetic modification of environmental tolerance or growth rate. Genetic variation and genetic differences should be considered in deciding whether a stock should be the source of future broodstock. Genetic improvement should be viewed as an option to rejection of a candidate for culture.

A large sample of wild animals should be used to start a captive stock so that genetic variation in the natural population is adequately sampled, thus avoiding any founder effect. There are indications from electrophoretic studies of captive populations that some past founding events employed inadequate samples (Lioe 1984).

3.2.4.1 Species and stock selection

Nelson (1977) makes several suggestions concerning genetic considerations prior to choosing a crustacean species for aquaculture. The first consideration is adaptation to environmental conditions similar to the culture conditions. The second consideration could be described as a high evolutionary potential. An indication of this may be the number of species in the genus and the number of geographic races in the species. Third, one should consider the heritability of important traits. If this information is not available, then the heterozygosity as determined by electrophoresis could be substituted.

Refstie (1990) comments on the early advantage which can be obtained in a domestication program by surveying the available genetic (geographic) stocks of the species to be cultured and choosing the one with the best performance. In the Western Hemisphere, this has been a consideration with P. vannamei and P. stylirostris, but no data exists on experimental comparisons of geographic stocks reared under comparable conditions.

For penaeid aquaculture, the choice of species for culture is determined by many factors, but based on little scientific data. The family Penaeidae has

110 species and the genus Penaeus contains 27 species (Holthuis 1980), some of which have been studied very little. In general, a choice of species can only be based on very general information about natural temperature and salinity conditions. Dietary requirements are known for only a few species and ecological studies are very limited. One can not assume that indigenous species will be best adapted to the culture environment because so many variables are changed in culture systems, particularly in intensive systems.

P. monodon has the highest growth rate under natural conditions, but heritability of growth has been estimated only for P. vannamei (Lester 1988; Lester and Lawson unpublished). Using heterozygosity levels as a substitute for heritability (h^2) may be misleading because most decapod crustacea have low levels (see above). Based on heterozygosity, P. monodon would be a very poor choice.

Genetic differences between conspecific stocks can be detected by biochemical differences (e.g. differences in allozyme frequency or restriction fragment length polymorphism) or morphological differences (e.g. shape differences detected by morphometric techniques or changes in meristic variables). The choice among genetically differentiated stocks within species should be based on performance and economic considerations, but the existence of stocks must be known for that choice to be made. Studies of geographic differentiation in penaeid species have yielded very few examples (see above). Thus there is little indication that comparison of geographic stocks for performance as recommended by Refstie (1990) would be useful. However, there is a case of performance differences between two stocks of P. stylirostris in an intensive culture system. The two stocks of P. stylirostris appear to have different environmental optima as related to culture conditions. The change from a stock originating from Guaymas to one sourced from Puerto Penasco was associated with a large increase in growth rate at one culture facility, some of which was attributed to the source of the stock (Neal Hicks, Environmental Research Lab, pers. comm.) There has been no study of geographic differentiation across the range of P. monodon, but one is needed.

3.2.4.2 Effective population size

The effective population size (N_e) of a population can be viewed as the calculated equivalent of the number of wild genomes contributing to the next generation. This number is reduced from the actual number of broodstock producing nauplii by recent historical constrictions in the population size, very unequal production of larvae among parents, unequal sex ratios and inbreeding (Crow and Kimura 1971). Reduction in N_e causes unplanned, irreversible loss of genetic variation. Broodstock management should be planned to maintain N_e in a cost effective manner. Monitoring of broodstock

performance should be conducted because genetic drift can occur despite large numbers of broodstock, as in the sea bream in Japan (Taniguchi et al. 1983). Once a significant bottleneck has occurred efforts should be made to restore genetic variation. An early generation bottleneck of a P. japonicus population in Italy resulted in a decrease of heterozygosity over the next five generations (Sbordoni et al. 1986, 1987). This decline in H is consistent with a N_e of less than 4 in all generations (Sbordoni et al. 1987). The decline in genetic variation was strongly correlated with a decrease in hatching percentage (Sbordoni et al. 1986). Loss of genetic variation from hatchery stocks of cutthroat trout (Allendorf and Phelps 1980) has resulted in an increase in the frequency of morphological deformities which result from developmental instability (Leary et al. 1985). No study has been published on the relationship between deformity and genetics in penaeid shrimp.

3.3 QUANTITATIVE GENETICS OF COMMERCIAL TRAITS

Quantitative genetics is used to determine the best approach to modifying traits of commercial value. The phenotypic variation of a trait (V_P) can be partitioned into its environmental (V_E) and genetic (V_G) components. There are three possible sources of genetic variance, but among them additive genetic variance is of significance for selective breeding. If the variance of a trait has a large additive component, it implies that the mean of the trait can be increased by increasing the frequency of certain alleles. Heritability (h^2) is the proportion of the phenotypic variance attributed to additive genetic variance. The response to selection (R) is determined by the heritability and the selection differential (S), i.e. $R = S h^2$. Thus the higher the heritability the greater the improvement one will attain from a given selection plan. When more than a single trait contributes to the commercial value of the shrimp (e.g. disease resistance, survival at low temperature), the genetic correlation of traits should also be studied.

3.3.1 Growth

Growth of crustacea can be viewed as size increments occurring primarily at molting events or as the increase in weight resulting from added tissue mass. The molting process and changes in exoskeleton size are at least partially independent of muscle growth, the most commercially important component of growth (Hartnoll 1982). The studies of larval growth described below use linear measures of size, not weight, and control for the effect of molting by comparing equivalent stages regardless of the time differences in reaching those stages. The studies of postlarvae and juveniles examine size increase over a particular time period and contain the effects of both size increment at molt and molting frequency (Hartnoll and Dalley 1981).

Table 2. Heritabilities of size at P1, M1 and PL1 in Penaeus vannamei and Penaeus stylirostris (Lester 1988).

Species	Experiment	Developmental Stage		
		P 1	M 1	PL 1
<u>P. vannamei</u>	1	0.00	0.00	0.33
	2	0.58	0.18	0.36
	3	0.64	0.09	0.15
<u>P. stylirostris</u>	1	1.00*	1.00*	0.84
	2	1.00*	0.64	1.00*

* The estimated heritability was greater than 1.0.

3.3.1.1 Larval growth

Shrimp larvae do not begin to feed until protozoa 1, therefore the h^2 at P1 is an expression of the utilization of the maternal contribution to the egg by the zygotic genotype. All of the studies of larval growth are based on full-sib families obtained as nauplii reared under controlled conditions in small volumes. Maternal effects are not partitioned out of V_G in these experiments.

Lester (1988) reported h^2 of length at protozoa 1, mysis 1 and postlarva 1 of Penaeus stylirostris and P. vannamei. Two sets of P. stylirostris families and three sets of P. vannamei families were studied. The resultant heritabilities are shown in Table 2. Heritabilities greater than 1.0 are impossible, but appear in four places in the table for P. stylirostris. This is probably due to the genetic effect plus an effect of common mother or common environment occurring before the larvae were divided into experimental units. Penaeus vannamei heritabilities are lower. In seven of nine cases, the heritability is zero or has a standard error greater than the estimated heritability. Thus in P. stylirostris there is a strong indication of genetic determination of size at the three larval stages, but for P. vannamei these studies give weak support of genetic contribution to larval size.

3.3.1.2 Postlarval growth

Postlarval studies are performed in small cages at high densities under artificial conditions. Therefore, the results reported here may not be representative of those observed in ponds. Studies of P. vannamei were conducted on PL2 grown to PL30 and on PL15 grown to PL43. Under standard culture conditions, the h^2 of size was 0.23 (S.E.=0.20) in the early growth study and 0.0 in the latter.

Table 3. Estimates of heritability of growth rate of *P. vannamei* (Lester and Lawson 1988).

Experiment	Stage	Number of Families	Mean N per Family	Heritability (Standard deviation)
V387	EARLY JUVENILE	8	16.0	0.53 (0.27)
	LATE JUVENILE	8	25.1	0.60 (0.25)
V188	POSTLARVA	10	24.6	0.35 (0.17)
	LATE JUVENILE	9	27.3	0.05 (0.06)

3.3.1.3 Juvenile growth

The studies performed on juvenile growth were done in two stages. First, shrimp were grown in cages set in tanks as described above for PL growth. Then the animals were transferred to net cages set in a 0.1 ha pond. The animals were reared at high densities, equivalent to 1235 PL's per m², in the small cages in tanks and low densities, 16 or 20 per m², in the net cages in the pond. They were fed ad lib at both stages. The first experiment began late in 1987 and finished with cage growth at the end of the growing season in Texas. The shrimp encountered water temperatures which fluctuated below 24°C. The second experiment started in early spring of 1988 and pond growth occurred under better conditions. There were high survivals above 90%, except for the second postlarval growth study which registered 48% survival. The heritabilities estimated from these studies are given in Table 3. Shrimp were stocked into the pond cages at a larger size in experiment 1 than in experiment 2. Yet the harvest size from the pond cages was greater in experiment 2 after the same growth period. Note the pattern of high heritability under poor end-of-year conditions and low h² under better (spring) conditions.

3.3.1.4 Stressful environments

If a trait has been subjected to selection in nature, the genetic variance of that trait will be reduced from its potential level. This expression of genetic variance holds under "normal" environmental conditions. However, if the genotype is exposed to a novel or stressful environment, the expression of the genotype will change and the genetic variance can be increased (Parsons 1986, 1988). In some circumstances, selection of shrimp for growth in stressful environments could be useful both for increasing tolerance to

these stresses and for increasing the response to selection. Studies of growth of *P. vannamei* at low temperatures has shown that h^2 of larval and postlarval growth increases at temperatures that affect survival (22 to 24 °C) (L.J. Lester and K.S. Lawson, unpublished data). These experiments were done on families split between normal and low temperatures. When the normal temperature of 28°C was compared to 22°C, h^2 increased from 0.02 to 0.03 for size at PL 1 and from 0.23 to 0.45 for size at PL 30. When 28°C was compared to a larval temperature of 24°C and a postlarval temperature of 22°C, the h^2 of PL 2 size rose from 0.12 to 0.16 and the h^2 of size at PL 43 increased from 0.0 to 0.29.

3.3.2 Survival

There are two factors that determine the yield of a culture unit at harvest, the survival and the growth rate. Evidence for the genetic contribution to growth is described above. The genetic component of survival is less understood and less studied. One reason for less attention to this factor is the self-regulating nature of mortality due to genotype. If there is genetic variance for resistance to mortality-causing agents, e.g. disease organisms or low dissolved oxygen, natural selection will operate to improve the survival of the population. In the course of experiments on inheritance of size, survival data has been collected. These data are not ideal because they are collected from full-sib families. The maternal contribution to survival through egg provisioning can not be factored out. This contribution should be less important in postlarval studies than in larval studies.

3.3.2.1 Larval survival

The mortality experienced in shrimp hatcheries is sometimes epidemic resulting in catastrophic loss of larvae, but most often is attritional resulting in a gradual decline in numbers of larvae passing through the system. It is the latter that may provide information on the genetic contribution to survival under particular conditions. In the cone system for rearing larvae (see Chapter 11), it is simple to collect survival data and, because each cone receives water and food from a communal source, to attribute differences among families in survival to the characteristics possessed by the shrimp when they entered the system. Whether or not these are genetic attributes is subject to debate.

There are significant differences among families in survival during larval rearing. For all experiments in our laboratory, the mothers of the larvae have been treated similarly in the same maturation facility, the nauplii have been shipped under the same conditions, and the acclimation and rearing procedures are the same. Yet survivals of families may range from 0 to 96% within the same experiment (Lester 1988). In recent studies on the effect of

temperature on growth, families held at two different temperatures during larval rearing can show very different mortality patterns. One experiment on seven families of *P. vannamei*, had two families suffer complete mortality at 28 °C, but the same families at 22 °C differed considerably in their mortality. The first suffered a high mortality resulting in a final PL survival of 18.7%; the other had a PL survival of 63.0% which was not significantly different from the survival of four other families (Lester and Lawson 1988). These families are grown in triplicate cones in a randomized placement. The patterns are not due to simple random contamination of single cones. Non-parametric statistical analysis of the survival patterns in two experiments involving the same families grown at two temperatures showed a significant effect due to family differences in one experiment, but not the other (Lester and Lawson 1988).

3.3.2.2 Postlarval survival

Postlarval survival has been followed in two different types of experiment. In the first, groups of PLs belonging to the same full-sib family are stocked into 20 cm diameter cages with screened openings which are immersed in a large water bath. These experiments run for 28 days to determine the heritability of postlarval growth. Survivals are seldom high, but range from 0% to 67%. There is no consistent relationship between survival to PL and survival from PL to juvenile. Families may change their rank within an experimental group from first to last. In two experiments on temperature effects (described above), there is a significant effect of family on survival rank in one experiment, but not in the other.

Postlarval survival has also been followed in experiments using PLs isolated in individual growth chambers of 500 ml.

3.3.3 **Deformities**

The most common deformities reported for harvested shrimp in the U.S. and Panama are bent and blunted rostrum, knobby exoskeleton on abdominal segments, misshapen uropods, bubble-head (a greatly expanded carapace which does not lie in proper contact with the dorsal tissue of the cephalothorax), and scoliosis (twisting of the exoskeleton along the mid-dorsal line) (Fritz Jaenicke, Laguna Madre Shrimp Farm, pers. comm.; Steve Hopkins, Waddell Mariculture Center, pers. comm.; Rolland Laramore, Granada Mariculture Technologies, pers. comm.). There is no evidence to attribute the causation of any of these deformities to single gene inheritance. All of them could be environmentally induced by teratogens or physical factors. Whether there is a quantitative genetic determination of these as threshold traits remains to be investigated.

3.3.4 Other traits

Among the other types of traits which will be of interest for genetic improvement in cultured stocks, disease resistance is the most important. There have been anecdotal reports of *P. stylirostris* stocks that have developed resistance to IHHN viral infection. This phenomenon has impacted the application of a bioassay which uses *P. stylirostris* to determine whether *P. vannamei* is infected with IHHN. One observation of dramatic differences in survival among full-sib families of *P. stylirostris* during an IHHN epidemic has been reported to one of the authors (Chris Brand, Environmental Research Laboratory, pers. comm.).

3.4 DOMESTICATION AND GENETIC MANIPULATION

Culture of penaeid shrimp has in most areas not progressed beyond the rearing of wild caught PL or the rearing of offspring from wild adults. This will change as the practice becomes more integrated into the common pattern of agriculture and animal husbandry. Genetic improvement of cultured stocks has contributed to the success of domestic animal husbandry and will eventually make a significant contribution for shrimp. There are genetic issues which must be decided at each stage of the development of shrimp culture from extensive culture to intensive animal husbandry.

The basic issue is one of control over the genetic changes which will occur during domestication. Once the life cycle is closed and a cultured stock is isolated from other gene pools, there will be genetic changes that occur as the stock adapts itself to the culture system. Some of the selective factors about the culture system are not recognized by the managers and result in genetic deterioration of the stock or selection for negative characteristics (Doyle 1983; Doyle et al. 1983). For example, selection of all future broodstock from a single pond will result in a certain probability of inbred matings in the next generation which would not occur if male and female broodstock were selected from ponds stocked from different larval-rearing tanks.

The basic issues to be considered in the development of a cultured stock of shrimp are common to all new domestications. First, which species should be chosen? Second, what should be the source of the original foundation population and how many animals should be used? Third, how large should the broodstock be to satisfy the commercial needs and maintain the genetic quality of the stock? Fourth, which commercial traits should be considered in the selection process and under what conditions should these traits be assessed? Fifth, how should the broodstock be selected each generation and how should they be mated?

3.4.1 Changes in cultured broodstocks

Very few shrimp stocks have been isolated sufficiently long for the process of domestication to begin. Obviously, the stocks analyzed by Lioe (1984) and Sbordoni et al. (1986, 1987) have begun domestication as indicated by the dramatic genetic changes which have occurred. There are two P. vannamei stocks undergoing domestication in U.S. commercial farms, Laguna Madre Shrimp Farm (LMSF) and Amorient. LMSF has grown these two stocks in side-by-side comparisons with offspring from wild adults collected from Guatemalan waters. The results suggest that domestication has produced shrimp stocks with higher survival and growth rates than wild stocks under culture conditions (Fritz Jaenicke, LMSF, pers. comm.).

The authors have compared the larval survival and growth of nauplii obtained from wild parents matured under culture conditions and from domesticated broodstock of LMSF. These studies found that under the controlled culture conditions employed in our laboratory, larvae from domesticated (LMSF) stock had a higher survival rate and produced larger PL (Lester unpublished data).

3.4.2 Manipulation of reproduction

Production of fertile eggs from captive broodstock has often been a problem for shrimp hatcheries. The ability to control maturation and reproduction is desirable for many reasons. These reasons and the techniques that have been developed are discussed in Chapter 5. Artificial insemination and in vitro fertilization make possible crosses between shrimp that would not normally mate. There have been four cases of interspecific hybridization accomplished by artificial insemination. P. setiferus (PS) has been crossed with P. stylirostris (PY) (Lawrence et al. 1984) and with P. schmitti (PT) (Bray et al. 1990). P. chinensis has been hybridized with P. monodon (PM) (Yang et al. 1988 in Liu 1990). P. penicillatus and PM have been hybridized in Taiwan. The crosses of PS x PY and PS x PT were confirmed by electrophoretic patterns.

Only in the P. penicillatus x PM cross have the hybrid offspring been tested for performance. Morphological differences between the hybrids and the parental species included some eye deformities, smaller carapace, shorter rostrum length and a different rostral spine formula. The hybrids exhibited lower survival than the parentals, but faster growth. None of the hybrid females matured after ablation and there were no matings observed. This suggests a combination of heterosis for growth and hybrid sterility, but further study is needed.

3.4.3 Selective breeding

Lester (1983) made some recommendations concerning selective breeding programs for marine shrimp. Recent studies of the heritability of growth rate of P. vannamei provide support for the improvement of performance via selective breeding. (See section 3.3.1 above.) We are only aware of one shrimp farm in the Western Hemisphere that has implemented such a program. All of the shrimp farms maintaining closed broodstock of P. vannamei are practicing some form of selection, but, in most cases, it is a visual comparison of adult individuals. Selection of P. vannamei for spawning frequency and fecundity has been practiced at one research institution with positive results (U.S. Marine Shrimp Farming Program: Progress Report 1990). Selection is being performed on the Italian population of P. japonicus for size of female and, indirectly, for early spawning under maturation conditions (Sbordoni et al. 1987). There may be some selective breeding programs for P. japonicus in Asia or Brazil of which we are unaware. As shrimp culture comes to depend more upon captive stocks and hatchery production, selective breeding programs will become more widespread.

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CHAPTER 4

Ernest S. Chang

ENDOCRINOLOGY

4.1 INTRODUCTION

This chapter will examine endocrine regulation of several important life processes in shrimp. Hormones are chemical messages synthesized and secreted by an endocrine gland and released to circulating blood. Blood carries the hormone to a (usually) distant target cell(s) where the hormone alters that cell's physiology. Usually, hormones mediate long-term, pervasive physiological alterations; as opposed to short term, localized events that are usually mediated by the nervous system.

Although this book focuses on penaeid shrimp, by necessity other decapod crustaceans will also be discussed in this chapter due to our limited knowledge about certain aspects of shrimp endocrinology. This is especially true for molting. We have good reason to believe that data from other crustacean species generally apply to shrimp.

Throughout this chapter I will refer to several procedures that are tools and techniques for the study of shrimp endocrinology. These are as follow:

- 1) Extirpation and reimplantation. These classical manipulations are often the initial experiments conducted to determine if an endocrine factor is involved in a particular function. Suspected endocrine tissue is removed and the effects observed. Tissue from other donors is then reimplanted to see if the original function recurs.
- 2) Endocrine gland extract injection. Glands are removed and homogenized to release stored hormone. Cellular fragments are centrifuged out and the supernatant containing the hormone is injected into test animals (often lacking the suspected gland).
- 3) Bioassay development for the hormone. This is often the most difficult step in the subsequent characterization of a putative hormone. A reliable, reproducible, rapid, and sensitive assay must be developed that shows some biologically relevant response (morphological, physiological, or biochemical change).
- 4) Hormone purification. Using the bioassay, various fractionation and chromatographic steps are used to purify the putative hormone. These can include solvent fractionation, thin-layer (TLC), gas-liquid (GLC), and high-performance liquid (HPLC) chromatography. The purified hormone

can then be characterized by its molecular weight, structure (if it is a steroid), or sequence (if it is a peptide or protein).

5) Chemical assays. For routine, rapid determination, a chemical assay is often developed. This may involve specific antibodies developed against the purified hormone. A common immunological assay that utilizes radiolabeled hormone is the radioimmunoassay (RIA).

4.2 ENDOCRINE REGULATION OF MOLTING

4.2.1 Biology of Molting

Rapid, controlled growth is a primary goal of all shrimp culturists. For growth to occur, shrimp (and all other arthropods) must first periodically loosen the connectives between their epidermis and the extracellular cuticle; rapidly escape from the confines of this rigid cuticle; take up water to expand the new, flexible exoskeleton; and then quickly harden it with minerals and

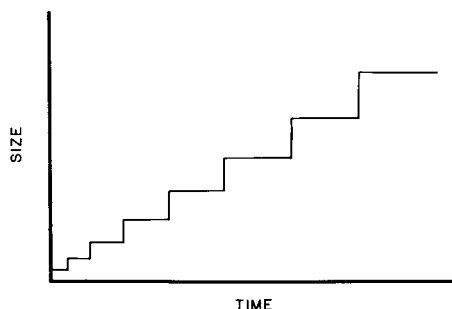


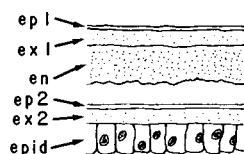
Figure 1. Diagram showing the discontinuous nature of crustacean growth.

proteins. This molting process results in discontinuous size increases (Fig. 1). At each molt, represented by vertical increases in size, water is taken up to expand the soft new exoskeleton. Between molts, water is replaced by tissue and the exoskeleton hardens.

If a crustacean has initial difficulties shedding its exoskeleton, subsequent progress (i.e. escape from the old exoskeleton) is made even more difficult by expansion of tissues under the soft, new exoskeleton. In addition to potential physical problems associated with ecdysis, crustaceans are also at great risk during molting because they release a molting fluid composed of amino acids, enzymes, and other organics from the partially digested old exoskeleton. Molting fluid is a very strong feeding stimulant and attractant. The newly ecdysed animal is often unable to move or defend itself. Considering these problems and vulnerabilities, it is remarkable that shrimp and other crustaceans are so evolutionarily successful.

ECDYSIS

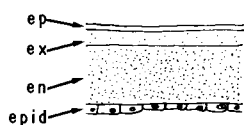
LATE PREMOLT



POSTMOLT



INTERMOLT



EARLY PREMOLT

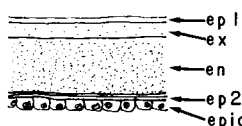


Figure 2. Schematic of a crustacean exoskeleton. en, endocuticle; ep1, old epicuticle; ep2, new epicuticle; epid, epidermal cells; ex1, old exocuticle; ex2, new exocuticle (modified from Skinner 1985)

Ecdysis is the completion of a complex process which began days or even weeks before. Essentially every tissue is involved in preparation for the impending molt. Lipid reserves are mobilized in the midgut gland (also known as the hepatopancreas; a combination digestive and storage organ). Cell division increases. New mRNA is produced, followed by new protein synthesis. Behavior changes. Not surprisingly, these complex processes over a prolonged time course require close coordination and are hormonally mediated.

The molt cycle has several stages, some with substages. Different species often have their own stage definitions (see Skinner 1985, for a more thorough discussion). For simplicity, I will refer to only four general stages (Fig. 2). Postmolt is the stage just following exuviation (shedding of the old exoskeleton). It is the period when the exoskeleton expands due to increased hemolymph volume from water influx. Water influx occurs across the epidermis, gills, and gut. After several hours or days (depending upon total length of the molt cycle), the new exoskeleton hardens and retains its rigidity. Next, during intermolt, the exoskeleton becomes much harder through mineral and protein deposition. Shrimp exoskeleton is relatively thin and soft

compared to crabs and lobsters. Premolt (proecdysis) stage occurs just prior to exuviation, and is characterized by separation of the old exoskeleton from the underlying epidermal layer. The old exoskeleton is partly reabsorbed, and energy reserves are mobilized from the midgut gland. Premolt begins with an increase in concentration of molting hormone in the hemolymph. Ecdysis, as a stage, only lasts a few minutes. It begins with the old exoskeleton opening at the dorsal junction of the thorax and abdomen in decapod crustaceans, and is completed when the animal escapes from its confines.

There is little information about the endocrine regulation of shrimp molting. This deficiency is likely due to unusually large conspecific variation in wild-caught crustaceans; and difficulty in conducting controlled physiological experiments in crustaceans because of confounding effects of molt and reproductive cycles. The availability of cultured shrimp stocks and the intense interest in shrimp aquaculture will lead to a better understanding of ecdysis in shrimp.

Several reviews have appeared recently and should be consulted for other aspects of crustacean molting (Kleinholz and Keller 1979; Spindler et al. 1980; Kleinholz 1985; Skinner 1985; Mattson 1986; Chang and O'Connor 1988; Chang 1989).

4.2.2 Ecdysteroids (Arthropod Molting Hormones)

4.2.2.1 Isolation and Characterization

Kopeck (1922) first studied hormonal regulation of arthropod molting. Since then, much information has accumulated on various aspects of molting, mostly with insects. Most of the work with Crustacea has not been with marine shrimp.

The steroid molting hormone, ecdysone, was isolated from hundreds of kilograms of moth pupae, (Butenandt and Karlson 1954) and its structure elucidated (Karlson et al. 1965; Huber and Hoppe 1965). Although the secreted product of the molting gland was determined to be ecdysone, it appears that, in most cases, the metabolite 20-hydroxyecdysone (20-HE) is the physiologically active form of the arthropod molting hormone.

Soon after the ecdysone structure was determined from insects, Horn and his colleagues (Hampshire and Horn 1966; Horn et al. 1966) isolated and determined the structure of 20- hydroxyecdysone (20-HE) from the lobster *Jasus lalandei*. They demonstrated the identity of the arthropod molting hormone from both insects and crustaceans.

Additional ecdysteroids have since been identified in various tissues of different crustacean species. These include ponasterone A (25-deoxy-20-HE); inokosterone (25-deoxy-20,26-dihydroxyecdysone); makisterone A (24-methyl-20-HE); 20,26-dihydroxyecdysone; and 2-deoxyecdysone (reviewed in Chang 1989). Concentration comparisons of different ecdysteroids between species

are difficult due to different detection methods and lack of molt stage standardization in donor animals.

Various synonyms have appeared in the literature: α -ecdysone for ecdysone; β -ecdysone, crustecdysone, and ecdysterone for 20-HE; ecdysones for ecdysteroids. By convention, the following are the presently used terms: ecdysone, 20-hydroxyecdysone, and the generic term ecdysteroids for compounds with molting hormone activity and similarity to the polyhydroxylated steroid structure of the parent compound ecdysone.

4.2.2.2 Y-Organ (Molting Gland)

Early experiments indicated that the molting hormone source was a gland located in the anterior branchial chamber, called the Y-organ (Echalier 1959). This molting gland may exist as a compact mass (in crabs), or as diffuse strands (in crayfish and lobsters). Morphologically and histologically described by Gabe (1953), the role of the Y-organ in successful molting initiation has been demonstrated in many brachyuran and macruran species (for review see Chang 1989). Relatively few studies, however, have addressed the structure and function of the Y-organ in shrimp (Bourguet et al. 1977).

Although there were ample reports of both the necessity of the Y-organ for successful ecdysis in reptantian decapods, and that 20-HE was the active ecdysteroid, the relationship between the Y-organ and the molting hormone required in vitro techniques for eventual elucidation. The small, yet significant amounts of ecdysone isolated from circulating hemolymph (Chang et al. 1976) suggested that ecdysone might be a precursor for 20-HE. In addition, previous work with insect molting glands in vitro suggested that ecdysone, and not 20-HE was the secretory product of insect molting glands. Similar approaches were taken with crustacean Y-organ cultures.

Y-organs from crabs, Cancer antennarius and Pachygrapsus crassipes (Chang and O'Connor 1977), remained viable for several weeks in culture (based upon gross morphological appearance) and continued to secrete a product which possessed immunoactivity when assayed with an ecdysteroid-specific RIA (Borst and O'Connor 1972). After culturing hundreds of crab Y-organs, a RIA-active ecdysteroid was observed co-migrating with an authentic ecdysone standard on several chromatographic systems. Definitive characterization of ecdysone as the secretory product of the Y-organ of the crabs C. antennarius and P. crassipes was established by mass spectrometry (Chang and O'Connor 1977). Using similar procedures, Keller and Schmid (1979) found ecdysone was the primary secretory product of the macruran Y-organ. Analogous data are presently lacking for the natantian decapods.

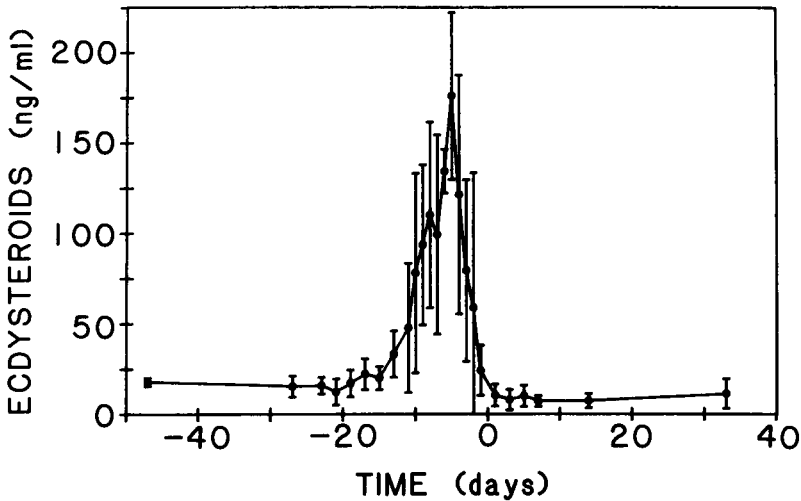


Figure 3. Ecdysteroid titers of the penaeid shrimp *Sicyonia ingentis* at various times before and after molt. Molt occurred on day 0 (Chang et al. 1991)

4.2.2.3 Regulation of the Y-Organ

Not unexpectedly, molting hormone concentration varies dramatically during the molt cycle. At postmolt, just after ecdysis, the titer is negligible. There is an initial rise in ecdysteroids upon entry into premolt followed by a large peak which drops precipitously just prior to ecdysis (Fig. 3). In the study described in Fig. 3, hemolymph was removed and ecdysteroids quantified with RIA ($n = 3$ to 16) (Chang et al. 1991).

It is apparent, however, that crustaceans must possess some mechanism for regulating the circulating and active form of the molting hormone (20-HE). Alterations in hemolymph hormone concentrations could be regulated by either changes in the synthesis and/or secretion of ecdysone by the Y-organ, the hydroxylation rate of ecdysone to 20-HE, and the degradation and clearance rates of the hormone from the hemolymph.

Indirect studies indicate that changes in the synthesis and/or secretion rates of ecdysone by the Y-organ may be the predominant mechanism of controlling hemolymph ecdysteroids. Supporting evidence for this conclusion is that the *in vitro* secretory rate of ecdysteroids by Y-organs is correlated with the amount of hemolymph ecdysteroids in the crab *P. crassipes*. Just prior to the substage of premolt when the highest concentration of ecdysteroids was observed in the hemolymph, explanted Y-organs secreted the greatest amount of ecdysone (Chang and O'Connor 1978). Whether this phenomenon is true for other crustaceans is unknown.

The effects of eyestalk ablation on Y-organ secretion, and of co-culture of Y-organs with eyestalk extracts, however, lend strong support to the

supposition that Y-organs, under the control of eyestalk factors, do vary ecdysone production during the molt cycle.

The rate of ecdysone hydroxylation to 20-HE may also vary during the molt cycle. As much as a three-fold increase in ecdysone 20-hydroxylase activity occurred in crab testes following eyestalk ablation (Chang and O'Connor 1978).

Differential degradation and elimination of ecdysteroids during the molt cycle has not been adequately monitored for any crustacean. We found, however, that lobsters excrete significant amounts of ecdysteroids via the urine (Snyder et al. 1988) and that the pattern of secretion is stage dependent (Snyder and Chang 1989).

4.2.2.4 Effects of Exogenous Ecdysteroids In Vivo

Not surprisingly, administrated ecdysteroids promote molting in some Crustacea. Other experiments of this type, however, resulted in incomplete molts with either death or developmental abnormalities. Regardless of how the hormone was administered (injection or addition to the surrounding water), induced molting was most successful when the ecdysteroids were administered in small, frequent doses or in a slow release form, as opposed to massive, single injections.

4.2.2.5 Ecdysteroids and Reproduction

Some evidence exists that ecdysteroids are involved in crustacean egg and embryonic development. With RIA detection after HPLC separation, ecdysone, 20-HE, ecdysteroid conjugates, and (in some cases) ponasterone A have been identified in follicle cells, oocytes, and embryos of various species, including the shrimp, Palaemon serratus (Spindler et al. 1987). Embryonic ecdysteroid concentrations were low after fertilization, but increased rapidly following the appearance of the embryonic Y-organ.

The actual function of these ovarian ecdysteroids is uncertain. There are correlations between vitellogenesis and increasing hemolymph ecdysteroids (Lachaise et al. 1981; Chaix and DeReggi 1982) in some species but not in others. Experiments have shown that Y-organ removal can result in either stimulatory or inhibitory effects on vitellogenesis. These conflicting results are difficult to interpret due to species differences, animal age, and stage in the molt and reproductive cycle. Adiyodi (1985) gives more thorough discussion.

Ecdysteroid concentration changes have been observed in developing embryos of various species. These observations support the hypothesis that they are at least partially of embryonic origin, and not entirely sequestered from the mother during vitellogenesis. These embryos, which were spawned at fertilization, and in some cases incubated on the female's abdomen, were without any cytoplasmic connections to the parent. Ecdysteroid concentration

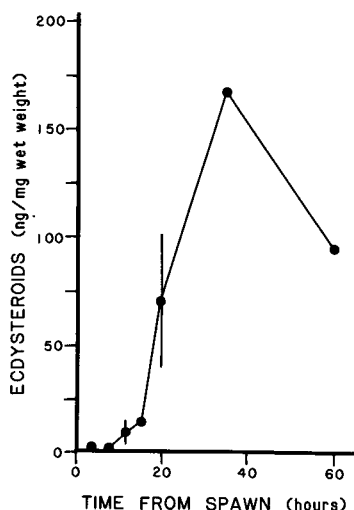


Figure 4. Concentrations of ecdysteroid in egg and larval extracts of Sicyonia ingentis from spawning to early nauplii. Hatching occurred at approximately 20 hrs.

increases were most likely due to endogenous synthesis. Figure 4 displays ecdysteroid levels during the embryonic life of the penaeoid Sicyonia ingentis. The data indicate a low concentration of ecdysteroids initially deposited in the eggs, and synthesis and secretion by the embryo begins soon after fertilization.

Further evidence for larval ecdysteroid synthesis is the Y-organ description in larval crab Cancer anthonyi (McConaughy 1980). The function of these embryonic ecdysteroids are not known. It is plausible, however, that they are involved in the deposition of embryonic envelopes and in embryonic molting (Burkenroad 1947; Cheung 1966).

4.2.2.6 Mode of Action of Ecdysteroids

4.2.2.6.1 *Hormone Receptors*: Hormones must be released, circulated, and transported to their target tissue. In general, this means that the hormone, which is sometimes bound to a low affinity binding protein, will be found throughout the body. This begs the question: What is the biological determinant of a particular hormone's target tissue, since all tissues are in contact with the blood and hence the hormone? The apparent answer is that although most hormones can freely enter most cells, only target cells have an intracellular protein that binds with the specific endocrine factor. This protein is the receptor.

The following basic criteria generally apply to all intracellular receptors: 1) affinity for the hormone should be higher by an order of magnitude than for the hormone carrier protein in the blood; 2) the intracellular binding sites should be saturable (limited binding capacity); and 3) the binding should be

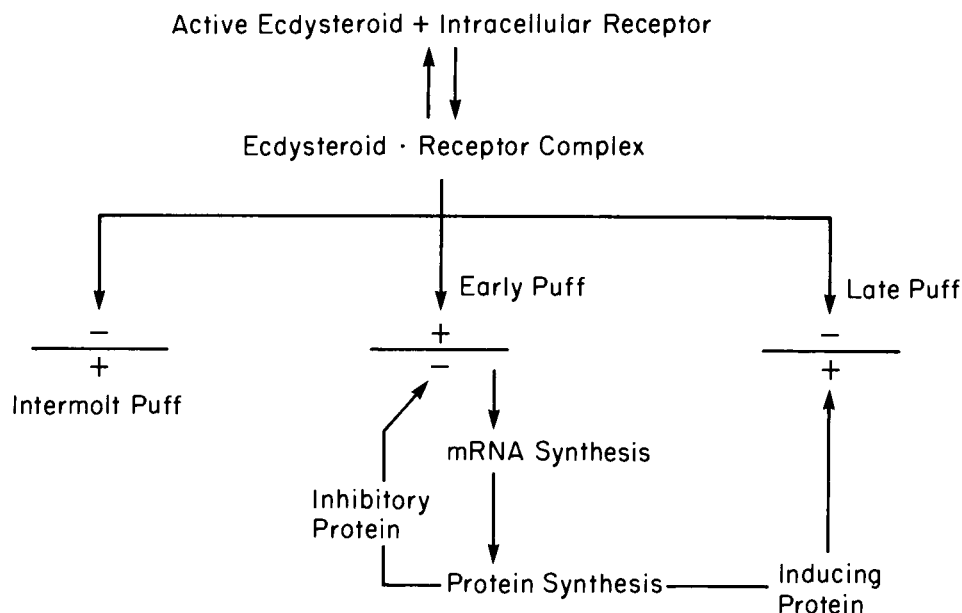


Figure 5. Model of the mode of action of ecdysteroids (after Ashburner 1974).

specific for the particular hormone or its analogs.

Until recently, the model for molecular action of a steroid hormone was as follows: 1) the hormone passively diffuses across the plasma membrane into the cytoplasm; 2) the steroid binds to the cytoplasmic receptor at a specific site; 3) the structure of the receptor is modified in an allosteric manner such that it and the steroid are able to enter the nucleus; 4) the activated receptor - steroid complex then binds to a specific chromatin site; 5) this binding alters the configuration of the chromatin and exposes specific sites on the DNA for subsequent transcription; and 6) these hormone-specific transcripts then either further regulate the genome or else enter the cytoplasm for translation into specific proteins. Recently, however, data indicate that cytoplasmic binding activity may be due to artifacts generated by the isolation procedure of this subcellular compartment (for a review see Gorski et al. 1986).

4.2.2.6.2 Ecdysteroid Receptors in Insecta: Current understanding of the mode of action for ecdysteroids and for steroids in general is mostly due to research

on insects. In particular, polytene chromosomes of flies have provided an ideal model system in which to examine steroid hormone interaction with the genome. Subsequent studies on the ecdysteroid-inducible puffing phenomenon (localized unwinding of chromatin) in fruit fly Drosophila melanogaster larvae led to a testable model of how a hormone can exert both positive and/or negative effects at different times at different genetic loci (Ashburner et al. 1974). This model is summarized in Fig. 5. Puffs are sites of mRNA transcription on polytene chromosomes of Drosophila and other insects. Stimulation of transcription is indicated by a "+"; inhibition by a "-".

4.2.2.6.3 Ecdysteroid Receptors in Crustacea: Indications are that ecdysone molecules circulate freely in the hemolymph following synthesis and secretion by the Y-organ without attachment to a carrier protein (Chang et al. 1976; Kuppert et al. 1978). This statement may be true for the two crustacean species thus far examined (P. crassipes and Orconectes limosus), and contrasts with demonstration of plasma carrier proteins for vertebrate steroid hormones. This discrepancy may result from reduced polarity and lower solubility of vertebrate steroid hormones that then require carrier proteins to provide sufficient concentrations of hormones at the target site. Reversible binding of the hydrophobic ligand to its particular carrier protein then permits it to be dispersed in an aqueous medium. Since crustacean ecdysteroids are particularly polar steroids (20-HE has six hydroxyl groups and one keto group), carrier proteins may not be needed.

Most of the information on the uptake and binding of ecdysteroids in crustaceans is from Spindler and colleagues (see Spindler et al. 1984 for review). They have concluded that in addition to simple diffusion of ecdysteroids into target cells, there is also an energy dependent, carrier-mediated process of hormone entry. These observations have been made on both the crayfish Astacus leptodactylus and the crab Carcinus maenas.

Nuclear binding sites have been found in crustaceans, consistent with the original hypothesis on the mode of action of steroid hormones (Karlson and Sekeris 1966). Affinity of the nuclear binding sites is similar to those in the cytoplasm (Spindler et al. 1984), lending further evidence to the hypothesis that steroid hormones mediate their action by differential transcription of DNA.

4.2.3 Molt-Inhibiting Hormone (MIH)

4.2.3.1 Biological Characterization

Early in this century Zeleny (1905) performed a simple experiment by removing both stalked eyes of the fiddler crab, Uca pugilator. Zeleny observed a decreased molt cycle interval. This observation, plus the replacement experiment of implanting eyestalk contents (Brown and

Cunningham 1939), led to the postulation of an endocrine factor present in the eyestalks that normally inhibits molting; or in other words a molt-inhibiting hormone (MIH). This simple eyestalk ablation procedure has been repeated on a large number of different crustaceans, especially decapods (reviewed in Skinner 1985).

Bliss (1951) and Passano (1953) described a neurohemal organ (storage gland for neurosecretory products) in the eyestalks of decapod crustaceans. This organ, called the sinus gland, serves as a storage site for neurosecretory products and it consists of the enlarged endings of a group of neurosecretory neurons, collectively called the X-organ (Bliss and Welsh 1952; Passano 1953). It was postulated that some of the stored neurosecretory material is MIH, and that MIH is responsible for inhibiting the secretion and/or synthesis of ecdysone by the Y-organ.

Other observations implicate the sinus gland - X-organ complex as a source for MIH. In crayfish (Jegla et al. 1983), lobsters (Chang and Bruce 1980), and crabs (Chang et al. 1976), eyestalk removal results in a dramatic and rapid elevation in the concentration of circulating ecdysteroids.

Molt interval decrease can result in dramatically accelerated increased size and weight (Conklin and Chang 1983). Whether these laboratory results can be applied to culture systems remains to be seen.

4.2.3.2 Chemical Characterization

An extensive review of crustacean hormone biochemistry, including MIH, was recently published (Kleinholz 1985) which stresses the need for pure hormones in order to determine biological activities. A generalized scheme for hormone isolation and characterization was also presented.

Not much information exists concerning the chemical nature of MIH. Many of the isolations used whole eyestalks. Use of whole eyestalks for X-organ - sinus gland peptide isolation should generally be avoided since the whole eyestalk is so much more massive than the sinus gland (ca. 3000x larger), and hence, introduces large amounts of contaminants.

From crab Ocypode macrocera eyestalk ganglia, Rao (1965) isolated a fraction with MIH activity using solvent extractions and precipitations. The isolate was bioassayed with eyestalk-ablated O. macrocera, and the time to molt was observed. Controls were either uninjected, or injected with seawater. They concluded that the MIH activity was due to a peptide.

With crab eyestalks or barnacle central nervous systems, Davis and Costlow (1974) demonstrated increased length of molt cycle in experimentally injected barnacles. These researchers also concluded that the MIH activity was due to a peptide.

With the shrimp Palaemonetes pugio, whole eyestalk extracts were found to contain MIH activity that eluted from a molecular sieve chromatography

column in fractions that indicated an apparent molecular weight of 1,000 to 5,000 (Freeman and Bartell 1976). In subsequent work, Freeman and Costlow (1979) isolated a fraction from eyestalks of the shrimp P. vulgaris that was able to antagonize 20-HE activity when added to barnacle explants in culture. Molting hormone alone stimulated apolysis in these explants of barnacle inner mantle tissue. This material had an apparent molecular weight of 2,300 to 3,400. These novel reports (Freeman and Bartell 1976; Freeman and Costlow 1979) indicated that an eyestalk factor may directly antagonize the action of the molting hormone in stimulating premolt activity at the cellular level. Whether this activity was a specific antagonism, as opposed to non-specific inhibition of epidermal cell metabolism, remains to be seen. In addition, the identity of MIH with this ecdysteroid-antagonistic activity remains unknown.

Soyez and Kleinholz (1977) partially characterized a small molecule (<1000 daltons) obtained from eyestalks of the shrimp Pandalus jordani. They observed that this material prolonged premolt in the amphipod Traskorchestia traskiana. This material may be either a hormonal releasing factor or a neurotransmitter that mediates release of MIH. The existence of the latter was suggested by Mattson and Spaziani (1985). While assaying for MIH and gonad-inhibiting hormone (GIH), Quackenbush and Herrnkind (1983) observed distinct fractions with apparent molecular weights of approximately 5,000. The two different activities, as assayed in the crab U. pugilator, were thought due to two distinct molecules.

Our laboratory has concentrated on the isolation and characterization of MIH from American lobster, Homarus americanus. Sinus glands and non-sinus gland eyestalk neural tissue controls were obtained from juvenile lobsters that were hatched and raised in our laboratory (Chang and Conklin 1983; Conklin and Chang 1983; Hedgecock 1983). The glands were excised and homogenized in acid for subsequent chemical characterizations. Following HPLC separation of sinus gland peptides, eight predominant peaks were identified. These peaks were tested for MIH activity; and only one was active (Chang et al. 1987). The complete amino acid sequence of the active peak was established by gas-phase microsequencing techniques (Chang et al. 1990).

4.2.4 Other Aspects on the Endocrinology of Molting

4.2.4.1 Larval Molting

Many marine Crustacea have planktonic larvae that are dramatically different in morphology from juvenile and adult forms. These larvae usually undergo several true molts prior to metamorphosis. Experiments indicate that molting in larval crustaceans may also be under the control of a neurosecretory hormone - ecdysteroid system.

Molting has been stimulated in crab (Rhithropanopeus harrisi) (McConaughy and Costlow 1981) and lobster (H. americanus) (Hertz and

Chang unpublished) larvae that were placed into water containing 20-HE. Not unexpectedly, developmental abnormalities have also been observed when larvae were reared with various concentrations of ecdysteroids (McConaughy 1979; Cheung 1974).

Ablation of crab larvae resulted in accelerated molting (Freeman and Costlow 1980). This indicates that larval eyestalks may contain MIH activity that affects the activity or concentration of circulating ecdysteroids.

Using the ecdysteroid RIA, lobster (*H. americanus*) larvae were shown to contain cycling titers of molting hormones which peaked approximately midway during the larval molt cycles and dropped to basal levels just prior to ecdysis (Chang and Bruce 1981). The predominant whole-body ecdysteroid was 20-HE. As with *R. harrisi* (Freeman and Costlow 1980), eyestalk removal in larval lobsters increased molting. Molting was accompanied by ecdysteroid peaks that occurred sooner relative to controls (Snyder and Chang 1986a). Injections of extracts from juvenile lobster sinus glands into eyestalk-ablated lobster larvae resulted in molt cycles that were not significantly different from controls.

Intact eyestalks were thought necessary for normal metamorphosis. This was based on abnormal metamorphosis following ablation. Recent data from our laboratory, however, indicate that these previous abnormalities may have been due to trauma or accelerated metabolism induced by eyestalk removal. When we reared lobster larvae communally and fed them frozen brine shrimp (suboptimal conditions), intermediate larval morphologies were sometimes observed. These intermediates possessed traits common to both third and fourth stage larvae whereas the intact controls had distinct fourth stage morphologies.

When similarly ablated lobster larvae were reared in isolation and fed live brine shrimp (optimal rearing conditions), we rarely observed these intermediate forms. Thus, although eyestalks did regulate both the timing and growth increment of larval molting, they did not appear to mediate the morphological aspects of lobster metamorphosis (Snyder and Chang 1986b).

4.2.4.2 Limb Factors

4.2.4.2.1 Limb Autotomy Factor, Anecdysial (LAF_{an}): Although multiple limb loss effects on the molt interval duration was observed by others (see review by Skinner 1985), this phenomenon was not thoroughly defined until the work of Skinner and Graham (1970, 1972). They observed in crabs (*Gecarcinus lateralis*) that multiple limb autotomy was in some ways a greater stimulus to molting than eyestalk removal. Skinner (1985) has termed this molt-promoting substance limb autotomy factor, anecdysial (LAF_{an}). Both the chemical nature and the source of this factor are unknown.

4.2.4.2.2 Limb Autotomy Factor, Proecdysial (LAF_{pro}): Additional observations on the interaction between limb regeneration and molting were made by Holland and Skinner (1976). They observed that the loss of limbs or primary regenerates (the limb buds of regenerating limbs) was able to inhibit the progress of premolt, as measured by the growth of the remaining primary regenerates. When the secondary regenerates (the limb buds formed following autotomy of the primary regenerates) reached a size that was comparable to the remaining primary regenerates, premolt events resumed. The modes of action of both LAF_{an} and LAF_{pro} are not known at this time. LAF_{an} could either inhibit the secretion of MIH or antagonize MIH action at the level of the molting gland. LAF_{pro} could either promote the secretion of MIH or inhibit the secretion of ecdysone by the Y-organ. As with LAF_{an} , the chemical nature and the source of LAF_{pro} are not known.

4.3 MALE SEX DETERMINATION AND REPRODUCTION

This section will examine the endocrine regulation of sex determination in shrimp and other decapod crustaceans. This includes not only primary sexual characteristics (i.e. whether the gonad produces eggs or sperm), but also secondary sexual characteristics (i.e. morphology and behavior). The role of other endocrines in the regulation of male reproduction will also be discussed.

The endocrine basis of female reproduction will be examined in the next chapter. Early experiments on female Crustacea will also be mentioned in this section, however, since much of the experimental characterization of the endocrine basis of sex determination involved both sexes.

Recent reviews should be consulted for further information on the topics discussed here (Adiyodi 1985; Charniaux-Cotton and Payen 1985, 1988; Sagi 1988).

4.3.1 Biological Studies of the Androgenic Gland

Very little work has been conducted on the penaeid shrimp androgenic gland. The first experimental evidence for a sex-determining hormone in crustaceans was obtained from the amphipod Orchestia gammarella. Charniaux-Cotton (1954a) observed that when an ovary was transplanted into an intact male, the ovary was subsequently transformed into a testis. Since an ovary was also transformed in a gonadectomized male, the conclusion was that the source of the masculinizing substance could not come from the testis.

In a series of elegant experiments, Charniaux-Cotton (1955) identified the responsible organ (the androgenic gland; AG) on the distal portion of the vas deferens of the amphipod O. gammarella. Additional experiments confirmed the obligatory role of the AG in determining maleness. Ovaries were

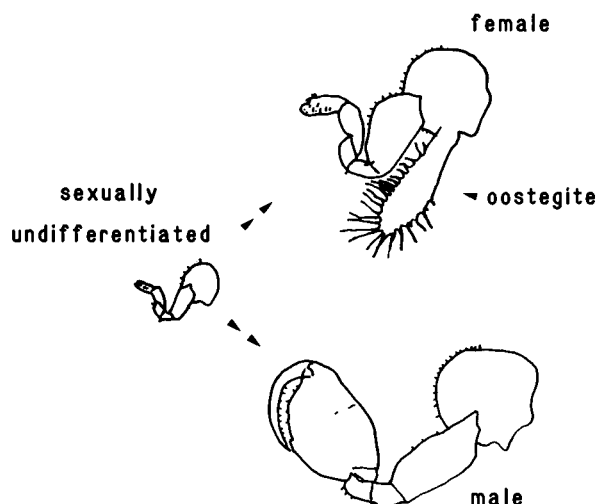


Figure 6. Sexual differentiation of the second gnathopod of the amphipod Orchestia gammarella. (modified from Charniaux-Cotton 1957)

implanted into males that had their AGs removed. These ovaries did transform into testes (Charniaux-Cotton 1954b, 1955, 1957). In addition, following removal of the AGs, spermatogenesis diminished and oocytes began to develop (Charniaux-Cotton 1964).

The degree of appearance of experimentally-induced altered sexual characters in a particular species appears more pronounced in those species that are normally hermaphroditic. Although sexual transformation in hermaphroditic species had been observed for several decades, it was not until recently that feminization was demonstrated in an andrectomized (AG removed) male prawn Macrobrachium rosenbergii, a gonochoristic species (Nagamine et al. 1980). In addition, success in sexual transformation depends upon the animal's age when ablation and/or implantation occurs. In general, greater transformation occurs the younger the animal. For example, Malecha et al. (1991), using very young juveniles (<10 mm carapace length) transformed female M. rosenbergii into fully functional males. They achieved a relatively high degree of success compared to Nagamine and Knight (1980), who used older juveniles (8.6-32.8 mm carapace length).

Amphipods and isopods also apparently possess an endocrine factor in the ovary that determines female secondary sexual characters. For example, if an ovary is implanted into a male O. gammarella that has been andrectomized, oostegites (a female secondary sexual characteristic; Fig. 6) develop from the second gnathopod. Simple andrectomy does not produce oostegites in males. Ovariectomy in a female amphipod results in the lack of development of oostegites (Charniaux-Cotton 1957). The undifferentiated

gnathopod normally develops into a robust claw in the male. If an androgenic gland is implanted into a female, the second gnathopod is transformed into a male claw. If both the androgenic gland and the second gnathopod are removed from a male, the appendage regenerates into the undifferentiated form (modified from Charniaux-Cotton 1957).

4.3.2 Chemical Studies of the Androgenic Gland Hormone (AH)

Chemical identification of the androgenic hormone (AH) has been hampered by the lack of a rapid assay. There are differing reports as to the nature of AH. Berreur-Bonnenfant et al. (1973) isolated a terpenoid fraction from the AG of the crab *C. maenas*. This group identified the active fractions as hexahydrofarnesylacetone and farnesylacetone (Ferezou et al. 1977a,b, 1978). They characterized these molecules based on their ability to inhibit vitellogenesis in *O. gammairella* ovaries.

In addition, these terpenoids were reportedly able to inhibit incorporation of radiolabeled leucine and uridine into cultured ovaries (Berreur-Bonnenfant and Lawrence 1984). Although these two molecules can inhibit some of the normal functions of the ovary, they apparently cannot induce masculinization. Thus, it is unlikely that these compounds are AH.

In contrast to the terpenoids isolated from the AG, Katakura et al. (1975) isolated a protein from the AG of the isopod *Armadillidium vulgare*. Subsequent work has characterized two distinct active proteins (Hasegawa et al. 1987). These AHs masculinized the first pair of pleopods in females (Katakura et al. 1975) as well as the genital apparatus (Katakura and Hasegawa 1983).

From this same isopod, Juchault et al. (1978, 1984) also isolated an active fraction that promoted the appearance of male secondary sex characteristics when injected into females. This particular factor, however, had a smaller molecular weight than the factors isolated by Hasegawa et al. (1987).

4.3.3 Other Endocrine Regulators of Male Reproduction

There are indications that the AG is regulated by an eyestalk neurohormone. Precocious spermatogenesis can be induced in some eyestalk-ablated males (Table 1). The AG cells of eyestalk-ablated males of some species are enlarged and appear to be more active than in intact males (Table 1). The nature of this regulation is unknown.

There are many reports on the role of molting hormones (ecdysteroids) in the regulation of female reproduction (see Chang 1989, for review). There are few indications, however, about the role of these steroids in male reproduction. To explore this and other subjects further, our laboratory has established a long-term primary cell culture system for crustaceans (Chang and Brody 1989). Testicular cells are especially amenable to culture. In

Table 1. Effects of eyestalk ablation on the male reproductive system in decapod Crustacea (from Adiyodi 1985).

Species	State of Animal at Ablation	Precocious Testicular Development ^a	Hypertrophy of Androgenic Gland ^a	References
<u>Lysmata seticaudata</u>	Functional adult	(-); precocious development of ovary	(?)	1
<u>Pandalus gracilis</u>	Functional adult	(-)	(?)	2
<u>P. borealis</u>	Functional adult	Spermatogenesis arrested; germinal zone oogenesis, no vitellogenesis	(+)	3
<u>P. platyceros</u>	Adult, summer Adult, early autumn	(-) (+)	(-) (+)	4
<u>Carcinus maenas</u>	Immature or nonbreeding males Adult males	(+) No change in the testis	(+) (+)	5, 6 7
<u>Potamon dehaani</u>	Young and adult	(+)	(?)	8
<u>Parathelphusa hydrodromus</u>	Medium-sized, mature males	(+)	(?)	9
<u>Callinectes sapidus</u>	Beginning of megalopa stage	Precocious sex differentiation	(+)	10

^a (+) positive effect; (-) negative effect; (?) unknown effect.

References: 1 = Carlisle 1953; 2 = Aoto and Nishida 1956; 3 = Charniaux-Cotton 1967; 4 = Hoffman 1968; 5 = Demeusy 1953, 1967a,b; 6 = Payen 1968; 7 = Charniaux-Cotton unpublished; 8 = Otsu 1961, 1963; 9 = Gomez 1965; 10 = Payen et al. 1967.

addition, they are responsive to exogenously added ecdysteroids. For example, lobster (H. americanus) testicular cells undergo mitoses in our culture system. Exposure of one-month old lobster primary cell cultures to 10^{-7} M

20-hydroxyecdysone caused mesodermal cells to die and spermatogonia to proliferate. After 7 days, the hormone was withdrawn. Mesodermal cells were absent, while the spermatogonia continued to proliferate for 10 days (Brody and Chang 1989). Some insect testicular cells also appear responsive to ecdysteroids (Takeda 1972; Dumser and Davey 1975).

4.4 FEMALE REPRODUCTION

One of the major constraints still facing shrimp culture is control of female reproduction. Most of the world's seed producers still depend upon the catch of gravid female shrimp from the wild to supply larvae. This practice, of course, makes scheduled production unreliable and prevents sustained selective breeding.

Reproduction and molting are often antagonistic events since both require large energy expenditures and are often mechanically incompatible. It is therefore not surprising that female reproduction is under endocrine regulation. What is surprising, perhaps, is the relative lack of information on the identification of regulating factors and their mode of action. In the previous section on molting, I discussed the purported role of ecdysteroids in both male and female reproduction. This section is concerned with the putative neuropeptide called the gonad-inhibiting hormone (GIH). The literature also discusses an ovary-inhibiting hormone (OIH), and a vitellogenesis-inhibiting hormone (VIH). There is presently no reason to suspect that these are all different factors.

4.4.1 Gonad-Inhibiting Hormone (GIH)

The primary action of GIH in females apparently occurs during secondary vitellogenesis, the time when the ovary increases dramatically in size due to synthesis and uptake of yolk produced in either follicle cells or at extraovarian sites. Detailed reviews have been published recently by Adiyodi (1985) and Charniaux-Cotton and Payen (1985, 1988).

Observations were first made by Panouse (1943, 1944). He observed that, depending upon the molt stage, eyestalk removal in the shrimp P. serratus resulted in accelerated ovarian development and spawning. Similar observations have repeatedly been made in a number of natantians, including Crangon crangon (Klek-Kawinska and Bomirski 1975), Metapenaeus dobsoni (Muthu and Laxminarayana 1977), Palaemon paucidens (Kamiguchi 1971), P. serratus (Meusy et al. 1983), Pandalus hypsinotus (Aoto and Nishida 1956), Parapenaeopsis hardwickii (Kulkarni and Nagabhushanam 1980), Parapenaeopsis styliifera (Muthu and Laxminarayana 1977), Penaeus chinensis (Arnstein and Beard 1975), Penaeus esculentus (Crococ and Kerr 1986), Penaeus indicus (Muthu and Laxminarayana 1977; Emmerson 1980), Penaeus

japonicus (Yano 1984), Penaeus kerathurus (Lumare 1979), Penaeus monodon (Muthu and Laxminarayana 1977; Santiago 1977; Halder 1978; Primavera 1978; Emmerson 1983; Hillier 1984), and Penaeus plebejus (Kelemec and Smith 1980).

Purifications and characterizations of GIH have begun, including: 1) Bomirski et al. (1981) characterized a factor with a molecular weight of approximately 2000 from eyestalks of the crab Cancer magister. Their assay animal was the shrimp C. crangon. 2) A 5000 dalton factor was characterized from the spiny lobster Panulirus argus and was assayed in the fiddler crab U. pugilator (Quackenbush and Herrnkind 1983). 3) A 7500 dalton peptide was isolated from sinus glands of the lobster H. americanus and assayed in the shrimp Palaemonetes varians (Soyez et al. 1987). Antisera have been raised against the lobster VIH (= OIH?) (Meusy et al. 1987). It appears to crossreact with sinus gland extracts from a number of different decapods. 4) A 3300 dalton factor was characterized from eyestalks of Penaeus setiferus as assayed in vitro using fiddler crab ovaries. The assay utilized precipitation of radiolabeled leucine by an antibody that had been generated against fiddler crab vitellogenin (Quackenbush and Keeley 1988).

The study by Quackenbush and Keeley (1988) suggests that the target of GIH may be synthesis of yolk protein. There are other data, however, that suggest that GIH may inhibit binding and uptake of yolk by the oocyte. Whether the same or different factors are responsible for these activities is unclear. Purification and amino acid sequencing of GIH is one of the most active areas of research in crustacean endocrinology.

4.4.2 Methyl Farnesoate

Based on endocrine regulation of molting analogies between crustaceans and insects (mediation by 20-hydroxyecdysone with ultimate regulation of ecdysone secretion from the molting gland by a neuropeptide), it is reasonable to hypothesize that an analog to the insect juvenile hormone (JH) is present in crustaceans. The insect JH plays important roles in regulating morphological development and reproduction. Evidence for the presence of the precursor to JH, methyl farnesoate (MF), has recently been presented (Laufer et al. 1987).

There are reports of insect JH, or related compounds having biological activity in crustaceans, and of crustacean tissue extracts having JH activity in insects. Schneiderman and Gilbert (1958) first observed JH activity in eyestalks of the lobster using an insect biological assay. More recently, additions of JH or analogs to culture water have been shown to affect normal development of barnacle larvae (Balanus galeatus, Gomez et al. 1973; Ramenofsky et al. 1974; Elminius modestus, Tighe-Ford 1977); cladoceran Daphnia magna (Templeton and Laufer 1983); crab Rhithropanopeus harrisi

(Costlow 1976; Christiansen et al. 1977a,b); and lobster H. americanus (Hertz and Chang 1986). There are also reports that JH analogs affect crustacean reproduction (Payen and Costlow 1977; Hinsch 1981; Templeton and Laufer 1983).

Although JH has not been isolated in significant concentrations from crustaceans, MF was isolated from several tissues of the crab Libinia emarginata (Laufer et al. 1987; see Laufer and Borst 1988 for review). It was further determined that the secretory source of MF was the mandibular organ (MO). This gland is located at the base of the tendon associated with one of the mandibular muscles (Le Roux 1968). The MO cells contain numerous mitochondria and have an extensive system of endoplasmic reticulum (Yudin et al. 1980). These are features characteristic of steroid/terpenoid secreting cells. Similar observations (secretion of MF by the MOs) were made with lobster H. americanus, crayfish Cambarus bartonii, and crabs Cancer borealis and Carcinus maenas (Borst et al. 1987). As with JH in insects, indications are that MF has effects upon both larval development and adult reproduction.

4.4.2.1 Effects of MF upon Larval Development

When added to lobster culture water (10^{-6} M) there was a small yet significant ($P < 0.01$) increase in larval metamorphosis time compared to control larvae (22.0 ± 1.3 versus 20.8 ± 1.5 days, respectively; Borst et al. 1987). Control larvae were dosed with farnesol to prevent potential non-specific toxicity of these terpenoids. These observations were consistent with the hypothesis that MF was acting as a crustacean JH by promoting retention of juvenile characteristics. There were, however, no measurable changes in morphology of larval lobsters.

4.4.2.2 Role of MF in Female Reproduction

There are correlations between secretory activity of the MO and vitellogenesis. In the spider crab L. emarginata, MOs from juvenile females secreted small amounts of MF in culture (0.5 ng/gland/hour). Low levels were also observed in females at the beginning of their ovarian cycles. During the later stages of ovarian development, however, when vitellogenesis was most pronounced, secretion of MF by the MO increased to 3.2 ng/gland/hr. At completion of vitellogenesis, MO secretion dropped to 1.6 ng/gland/hr (Laufer et al. 1987). The precise role of MF in vitellogenesis remains unclear.

There are indications that eyestalk neuropeptides may regulate the MO secretory rate. Both inhibitory and stimulatory effects have been observed when assayed either in vitro (Laufer et al. 1986) or in vivo (Borst et al. 1988). Identity of these eyestalk factors with GIH, and the putative gonad-stimulating hormone remains to be seen.

4.4.2.3 MF Binding Proteins

Additional evidence for an endocrine role of MF in crustaceans is the demonstration of binding proteins for MF in lobster blood (Li and Borst 1991). Binding protein presumably prevents premature degradation of the putative hormone and may facilitate entry into target cells.

Our laboratory has used a radiolabeled and photoaffinity-labeled analog of MF called farnesyl diazomethyl ketone (FDK) (Ujvary and Prestwich 1990). With this analog we have demonstrated specific binding to a protein with an approximate molecular weight of 42,000 in the blood of adult female H. americanus (Prestwich et al. 1990). The same binding protein has been detected in adult male, juvenile, and larval lobsters. Similar binding proteins have been seen in the blood of the crab C. magister and the shrimp S. ingentis (Chang et al. 1991).

4.4.3 Other Factors

There is reportedly a vitellogenin-stimulating ovarian hormone (VSOH) in an amphipod. Following ovariectomy, vitellogenesis ceased after 5 to 8 days (Junera et al. 1977). Vitellogenesis was restored by ovary reimplantation. The target is likely the fat body. Analogous experiments have not yet been conducted in shrimp or any other decapods.

There may also be a reproductive role for steroid hormones other than ecdysteroids. Various estrogens and progesterones have been identified in crustaceans by means of bioassay, chromatography, and reactivity against antisera (Donahue 1948; Lisk 1961; Jeng et al. 1978; Couch et al. 1987; Fairs et al. 1989). In addition, the presence of 17 α -hydroxyprogesterone significantly increased oocyte diameters in Penaeus vannamei ovaries when cultured in vitro (Tsukimura and Kamemoto 1988).

4.5 PIGMENTATION

Regulation of coloration has important implications for not only understanding the basic biology of shrimp and other crustaceans, but also for the eventual application of this information to culture systems. This is one of the few areas of crustacean endocrinology where most of the experimental work has been conducted on shrimp (although mainly carideans).

There are two types of pigmentary effectors in Crustacea: chromatophores, and retinal pigment cells. Chromatophores are located primarily in the integument, and their activities affect in the body color. Retinal pigments are located in the compound eyes. They regulate the amount of light impinging on the rhabdom, which is the light-sensitive portion of each ommatidium (the functional unit) of the compound eye. The physiology and morphology of these two types of pigmentary effectors are

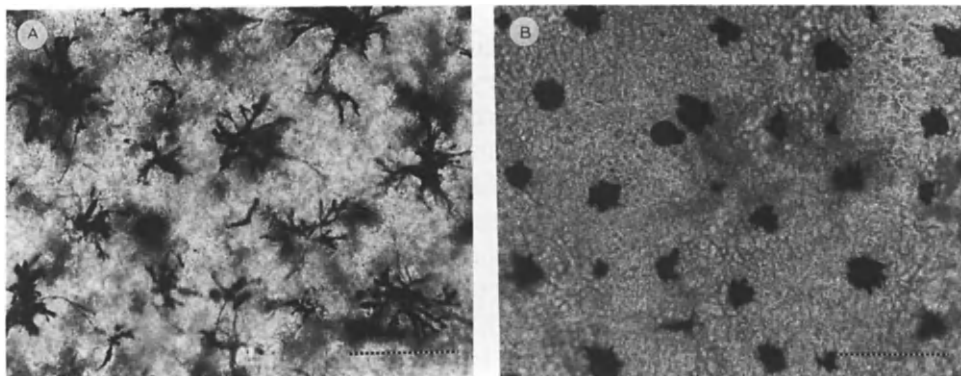


Figure 7. Photograph of chromatophores from the shrimp *Sicyonia ingentis*: A) maximally dispersed, B) maximally condensed (Scale = 20 μm).

quite different. Several excellent reviews have appeared recently and should be consulted for more detailed discussions (Kleinholz and Keller 1979; Fingerman 1985; Kleinholz 1985; Rao et al. 1985; Fingerman 1988).

4.5.1 Color Adaptation

4.5.1.1 Biology

Chromatophores are pigment-containing cells that exist not only on the external surface of the crustacean, but are also present in some internal tissues as well. Their function is to adjust the body coloration to its surroundings, depending upon the situation (e.g. protection, mating behavior, antagonistic displays; Fig. 7). The chromatophores are single cells with numerous extensions. Pigment granules of various colors migrate into and out of these extensions. The most common pigment granules are black, red, white, and yellow.

When pigment granules are spread out along the chromatophore extensions, they are said to be dispersed. In this state, the granules are most visible and give the chromatophore its characteristic color (Fig. 7A). When the granules are withdrawn from the chromatophore extensions, they are in a concentrated state and are not as visible (Fig. 7B).

As discussed in a recent review (Fingerman 1988), different body colors that arise from differential activities of chromatophores have been demonstrated to serve several important functions. First, they provide camouflage to match background color and pattern (Brown 1950). This is useful for both prey capture and predator protection. Second, there is evidence that differential body coloration can affect body temperature. Thus, light coloration on hot days and dark coloration on cold ones may assist thermoregulation (Wilkins and Fingerman 1965). Third, pigment dispersion

may protect the living cell layers from damage by ultraviolet irradiation (Coohill et al. 1970). Fourth, differential coloration may be utilized for intraspecific communication (e.g. courtship or antagonism; Crane 1944).

4.5.1.2 Chemistry of Hormones

As discussed earlier, crustacean eyestalk ablation results in not only precocious molting, but a dramatic alteration of the body color as well (Koller 1925, 1928). In some genera (e.g. Crangon, Palaemon, and Palaemonetes), the body color darkens following eyestalk ablation. In others (e.g. Uca), the body color lightens. An indication that body coloration was under hormonal control was the demonstration that injection of eyestalk extracts could reverse color changes induced by eyestalk ablation (Koller 1928; Perkins 1928).

Early observations indicated that the eyestalk sinus gland was a storage site for neurosecretory material that regulated color change (chromatophorotropins). It now appears that the chromatophorotropins are not only located in the X-organ-sinus gland complex, but in other neural tissue, both within the eyestalk and at other body locations as well (see Rao et al. 1985, for a more thorough discussion).

Because of the number of different chromatophores, the diversity of suspected sources of the chromatophorotropins, and because of the likely presence of both concentrating and dispersing hormones in the same tissues, it is difficult to make any overall generalizations about the diverse physiological observations on the chromatophorotropins (see Rao et al. 1985, for review). There has been, however, much recent work on two specific classes of pigmentary effector hormones: the red pigment-concentrating hormone (RPCH) and the pigment-dispersing/ light-adapting hormone (PD/LAH) families. The chemistry of PD/LAH will be discussed in more detail in the following section on the retinal pigment hormones.

The first crustacean chromatophorotropin that was sequenced was RPCH from the eyestalks of the shrimp Pandalus borealis (Fernlund and Josefsson 1968, 1972; Fernlund 1974a,b). Its sequence is



Some publications refer to this molecule as erythrophore (red chromatophore) concentrating hormone or ECH. In addition to the erythrophores, however, there are observations that other types of chromatophores are concentrated with RPCH (Josefsson 1975, 1983a,b).

RPCH is a member of a family of structurally related peptides. Another member of the family, adipokinetic hormone (AKH), has been isolated from several different insect species. Interestingly, although there is biological crossreactivity between the insects and crustaceans (i.e. RPCH has some

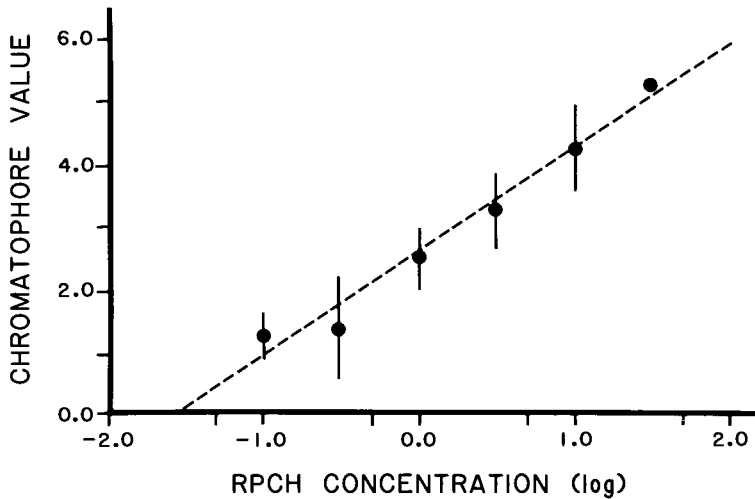


Figure 8. Dose response curve (in ng) of RCPH activity in *Sicyonia ingentis*. (Hertz and Chang unpublished)

AKH activity in insects and AKH has some RCPH activity in crustaceans), the functions of the hormones are quite distinct in the two taxonomic group (i.e. AKH does not appear to alter lipid mobilization in crustaceans).

A bioassay for the activity of chromatophorotropins has been developed (Hogben and Slome 1931). An example of a dose-response curve for RCPH on the red chromatophores of *S. ingentis* is shown in Fig. 8. In the study described in Fig. 8, the indicated amounts of synthetic RCPH (in ng) were injected at time 0 into shrimp that had been eyestalk-ablated several weeks previously. The hormone was solubilized in 10 μ l of sterile seawater. At 45 and 90 min after injection, the score of the condensed chromatophores was subtracted from the zero time score (Hogben and Slome 1931). The chromatophores of the meropodite of the first walking leg were used (Hertz and Chang unpublished).

There are several studies on correlations between the structure of the peptide and physiological activity (Christensen et al. 1978, 1979; Carlsen et al. 1979).

4.5.2 Retinal Pigments

4.5.2.1 Biology

There are three retinal pigments in the compound eyes of shrimp and other decapod crustaceans. Distal retinal pigment is found within cells that extend from the distal ends of the reticular cells to the cornea. Proximal retinal pigment is contained within reticular cells. Reflecting retinal pigment

is contained within cells that are variously located between the neighboring ommatidia, depending upon the species.

Depending on the ambient light, these three pigments alter their cellular locations in concert such that their combined activities result in modulating the amount light impinging upon the rhabdom. In dim light or darkness, the light-sensitive rhabdom is exposed by the movement of the distal and proximal pigments. Reflecting pigment is located distally to the basement membrane in a position that permits light to be reflected onto the rhabdom. In bright light, the distal and proximal pigments move to screen the rhabdom from excess light. In addition, the reflecting pigment is positioned adjacent to the basement membrane. In this position, it does not reflect light onto the rhabdom.

4.5.2.2 Chemistry of Hormones

PD/LAH was first isolated and its structure determined from the eyestalks of the shrimp Pandalus borealis (Fernelund 1976). Its amino acid sequence is Asn-Ser-Gly-Met-Ile-Asn-Ser-Ile-Leu-Gly-Ile-Pro-Arg-Val-Met-Thr-Glu-Ala-NH₂. At the time it was referred to as the distal retinal pigment light-adapting hormone (DRPH) because of its action on the distal retinal pigment (Fernelund 1971). Later studies (Kleinholz 1975) demonstrated that this same molecule was able to disperse pigment granules in several types of chromatophores. Since the chromatophore assay is easier to conduct than the characterization of the distribution of the retinal pigments, this hormone is now referred to as the pigment-dispersing hormone (PDH). Structure-function studies will likely elucidate the active site of the hormone (Riehm and Rao 1982).

A second PDH (β -PDH) was recently isolated and characterized from the fiddler crab U. pugilator (Rao et al. 1985). Its amino acid sequence is Asn-Ser-Glu-Leu-Ile-Asn-Ser-Ile-Leu-Gly-Leu-Pro-Lys-Val-Met-Asn-Asp-Ala-NH₂.

4.6 METABOLISM AND WATER BALANCE

4.6.1 Crustacean Hyperglycemic Hormone (CHH): Biological Aspects

Observation that eyestalk factors may regulate blood glucose concentrations in a crustacean was made by Abramowitz et al. (1944). They observed that injection of eyestalk extracts from the crab Uca were able to elevate the blood glucose in the crab Callinectes. In addition, they localized this activity in the sinus gland. This factor was originally called the hyperglycemic hormone (HGH) but recently it is referred to as the crustacean hyperglycemic hormone (CHH). For recent reviews see Kleinholz and Keller (1979), Keller et al. (1985), Kleinholz (1985), Sedlmeier (1985), and Keller

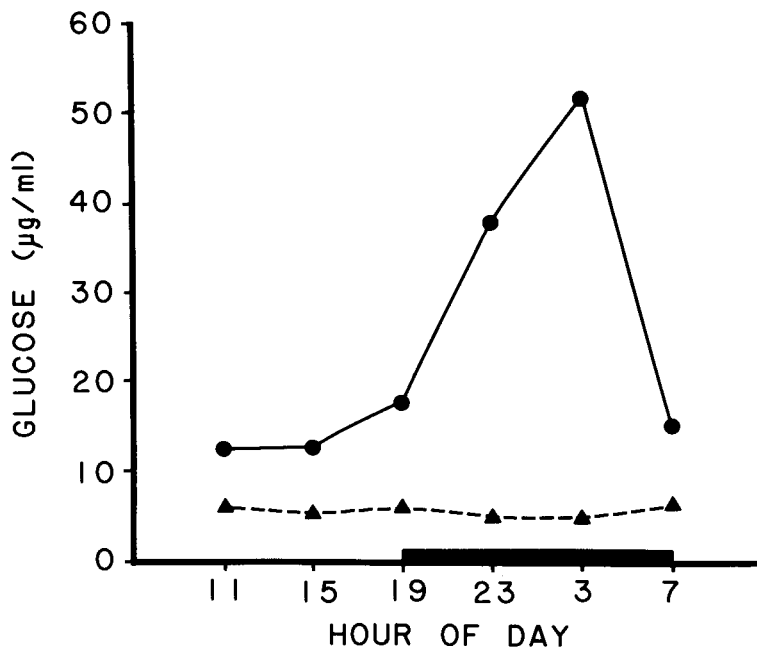


Figure 9. Hemolymph glucose concentrations in *Orconectes limosus* during 24 hrs in animals with (solid line, circles) and without (broken line, triangles) sinus glands. N=18 for each point (modified from Hamann 1974).

and Sedlmeier (1988).

Sinus gland removal, leaving the remainder of the eyestalk neural tissue and vision intact, clearly demonstrated that an endocrine factor was mediating not only an elevated blood glucose concentration, but was also responsible for a circadian rhythm in blood glucose (Hamann 1974; Fig. 9).

4.6.2 Chemical Aspects of CHH

CHH has been isolated from a number of different crustacean species using various procedures, including solvent precipitation, electrophoresis, gravity column chromatography, and high-performance liquid chromatography. The amino acid composition of CHH has been determined from the crab *Carcinus*, crayfish *Orconectes*, and isopod *Porcellio* (Keller 1981; Martin et al. 1984). The complete amino acid (Kegel et al. 1989) and nucleotide (Weidemann et al. 1989) sequences of the *Carcinus maenas* CHH have recently been reported.

Although there are differences in the amino acid composition of the three CHHs, they are all blocked at the N-terminus, have a molecular mass of 6,000 - 7,000, and have three disulfide bridges. There appears to be species

specificity in the different CHHs. For example, injection of 36 pmol of CHH from the crayfish Orconectes results in a 8-9 fold increase in circulating blood glucose in the crayfish. When this same dose of crayfish CHH is injected into the crab Carcinus, there is no effect (Keller and Sedlmeier 1988).

Antisera have been raised against CHH isolated from Carcinus. Using these antisera, a highly sensitive radioimmunoassay has been developed for the detection and determination of cross-reactivity of CHH from a number of different species (Jaros and Keller 1979a; Keller et al. 1985). These sensitive antisera have also been useful for the mapping and identification of neurons that synthesize CHH (Jaros and Keller 1979b).

The mode of action of CHH is not clear at this time. It may act via glycogenolysis since decreased glycogen was observed in the abdominal muscle and the gonads of Orconectes and Uca following CHH administration (Keller and Andrew 1973). In addition, Schwabe et al. (1952) found an increase in glycogen content in abdominal muscle and integument of the lobster Panulirus following eyestalk ablation. Action of CHH is likely mediated in target tissues through specific hormone receptors. These membrane receptors, in concert with adenylate and guanylate cyclase, mediate an increase in cAMP and cGMP concentrations. These compounds act as second messengers to activate protein kinases. These kinases then phosphorylate glycogen synthase that results in an inhibition of this key enzyme. In addition, the enzyme phosphorylase is also phosphorylated by a protein kinase and hence activated (see Keller and Sedlmeier 1988, for review). These combined actions result in decreased glycogen, and a concomitant increase in glucose concentration in the hemolymph.

CHH appears to have activity at a site other than abdominal muscle. Sedlmeier (1988) observed a significant increase in amylase released from the midgut gland of Orconectes following injection of eyestalk extract. The mode of action of CHH on the release of amylase from the midgut gland is not clear at this time, although it appears to involve the release of Ca^{2+} ions.

There is also evidence for a crustacean hypoglycemic hormone. Sanders (1983a,b,c) characterized a fraction from the lobster H. americanus that had immunological cross-reactivity with vertebrate insulin. Although this fraction increased radiolabeled glucose incorporation into glycogen in vitro, it did not appear to decrease the concentration of hemolymph glucose when injected in vivo. Clearly, further work needs to be done on the possible bihormonal regulation of glucose metabolism in crustaceans.

4.6.3 Cardioactive Peptides

The pericardial organs (POs) are paired nerve networks located laterally in the heart cavity. They are neurohemal structures that store and release factors that influence heart contraction rate (see Cooke and Sullivan 1982, for

review). Two active peptides have recently been identified from the POs. The first is proctolin (Schwarz et al. 1984), which is also an insect neuropeptide. Its amino acid sequence is Arg-Tyr-Leu-Pro-Thr. A second, novel neuropeptide has been isolated and characterized from the POs. It has been termed the crustacean cardioactive peptide (CCAP) and has not yet been found in any other taxonomic group. The amino acid sequence is Pro-Phe-Cys-Asn-Ala-Phe-Thr-Gly-Cys-NH₂ and is a cyclic peptide due to a disulfide bridge between the Cys residues (Stangier et al. 1987).

Immunocytochemical studies indicate the presence of both proctolin and CCAP throughout most of the central nervous systems of crustaceans examined (Schwarz et al. 1984; Dirksen and Keller 1988; Stangier et al. 1988). Precise mode of action and physiological significance of proctolin and CCAP are not yet clear and are currently under investigation by several laboratories. These peptides most likely act as neurohormones to regulate the activity of the heart.

The above studies have been conducted on crabs and lobsters. The existence of cardioactive peptides in shrimp is presently uncertain; they will likely be found when looked for, however.

4.6.4 Water and Ion Balance

Water and ionic regulation is of critical importance to shrimp and all other organisms. Several features of crustacean biology add complexity to water and ion regulation: 1) ability of many crustaceans to regulate their osmolarity over a wide range of environments; 2) distinct preferences for different salinities at different life stages; and 3) need for rapid uptake of large quantities of water at ecdysis to expand the new, soft exoskeleton.

Salt and water transport occur across many different sites, including excretory organs, gills, mouth, anus, and surface epithelium. Not surprisingly, control of salt and water balance is under endocrine control. However, the details of the factors involved and their modes of action are far from clear. The literature contains contradictory results, sometimes from the same laboratory. Extracts of eyestalks, pericardial organs, thoracic ganglia, or brains have resulted in either increases and/or decreases in water, sodium, and/or chloride in the hemolymph (for a recent review see Muramoto 1988; other reviews by Kamemoto 1976; Mantel and Farmer 1983). Other than indications that the responsible factors are neuropeptides, it is difficult to make any further generalizations. As with the other aspects of crustacean metabolism, very little attention has been devoted to water/ionic balances in shrimp.

4.7 CONCLUSIONS

As catch per unit of effort steadily decreases, and total catch fails to increase for most of the world's fisheries, it is apparent that culture techniques will increase in importance. This is especially true for marine shrimp. Economical manipulation of growth and reproduction will contribute significantly to this enterprise. For these applications to come to fruition, however, a great deal of basic information about the endocrine regulation of growth and reproduction in shrimp and other crustaceans must first be obtained.

Basic understanding of crustacean endocrinology has advanced rapidly in recent years since the pioneering classical endocrinological experiments involving glandular ablation and reimplantation. This rapid advancement has been due primarily to the development of new assay (e.g. RIA), separation (e.g. HPLC), and detection (e.g. mass spectrometric) methods. In addition, the cooperation between basic scientists and applied culturists has been mutually beneficial. Use of cultured stocks, reared under controlled temperature, photoperiod, and nutritional regimes, have made possible some of the studies discussed in this review.

Future research will be aided by recombinant DNA, monoclonal antibody, and peptide microsequencing techniques. Although much additional research is needed to elucidate some of the very basic questions in shrimp biology, it seems likely that routine commercial application of endocrinological techniques will occur within the next decade.

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CHAPTER 5

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REPRODUCTION OF PENAEUS SPECIES IN CAPTIVITY

5.1 INTRODUCTION

Striking growth in marine shrimp culture has occurred over the past decade, especially in China, Ecuador, Taiwan, Indonesia, Thailand, and the Philippines, but also in other tropical and sub-tropical areas worldwide. The world market share of cultured shrimp has grown from 2% in 1980 to 25% in 1989, representing 663,000 metric tons of heads-on shrimp entering world markets (Rosenberry 1991). This explosive growth in shrimp culture has been accompanied by the construction of several hundred maturation/reproduction facilities, and perhaps another 2,000 "hatcheries" which function only as spawning and larval rearing facilities for wild-matured females. True domestication (continued captive generations) of marine shrimp is still rare and accounts for only a handful of operations. Although technically feasible, complete reliance on captive populations by the shrimp culture industry has not occurred due to: 1) the regional availability of natural breeding stocks from wild populations, and 2) the often lower quality of larvae produced through captive reproduction, which discourages development of reproduction technology when other options are available.

The reasons for the less-than-complete success of captive penaeid reproduction fall into the following categories:

- 1) Lack of criteria for early determination of offspring quality.
- 2) Poor definition of nutrition requirements for reproduction.
- 3) Poor definition of culture water requirements.
- 4) Lack of standards for disease identification, prevention and treatment.
- 5) Lack of standards for broodstock culture.
- 6) Incomplete understanding of environmental influences.

The lack of criteria in these areas is partly due to the infancy of the industry and partly due to a paucity of thorough research. Reproduction research is expensive: the systems are large and labor intensive, and variability within shrimp populations is great, requiring thorough replication. Additionally, testing of breeder and larval viability requires long-term tracking

of individual adults and spawns. The literature concerning reproduction is often observational, or else experimental conditions are so poorly defined that replication of results is hit-and-miss. Furthermore, the literature which does exist is scattered across a broad array of journals and specialties, involving 23 geographically diverse species within the genus Penaeus alone, over a period of years, and it is difficult to achieve a comprehensive overview of the status of captive reproduction. In spite of these factors, many of the hurdles to consistent production of high quality larvae have been overcome or are understood well enough to be managed around. If environmental and nutritional parameters are optimized, high quality offspring can be produced through captive breeding.

It is important to first differentiate among the various systems available for larval production, as all of these systems loosely qualify as definitions of "captive reproduction," and yet are truly different culture systems, each with advantages as well as limitations. These include:

- 1) Collection of females with completely mature ovaries from a wild population for immediate spawning in captivity;
- 2) Ovarian maturation and spawning achieved in a laboratory environment; and,
- 3) Management of a breeding population in ponds or large outdoor culture vessels and simple transfer of females to a laboratory situation for spawning.

The first system is extremely reliable in terms of larval quality. Healthy females are collected from their natural spawning grounds where they have had the advantages of appropriate nutrition and oceanic water quality, have been subject to natural selection processes, and have not been exposed to environmental stresses which may occur in captivity. The disadvantages are the regional availability of suitable indigenous species, the changing seasonal and daily availability of mature females, the expense of capture and transfer, and the lack of potential for offspring improvement through genetic selection. The mechanics of this system are simple--mature wild females are placed in suitable spawning vessels with high quality, oceanic-character water, and allowed to spawn. After spawning, the females are not used again and the healthy, nature-prepared larvae are reared through well understood techniques.

The second system, that of achieving ovarian maturation and fertile spawns in a laboratory environment, utilizes adult shrimp either captured in the wild or cultured, and exposes them to appropriate environmental conditions and nutrition to stimulate spawning. Unilateral eyestalk removal, or ablation, of females is used almost invariably as a requirement to obtain adequate levels of ovarian development. This system is demanding (and more so for some species than for others) in terms of water quality, disease

prevention, nutrition, and environmental standards. Multiple spawnings are achieved from females, which are held for periods of three weeks to six months.

The third type of system involves maintenance of a breeding population in a relatively natural environment such as an outdoor pond, and then transfer of gravid females to controlled conditions for spawning. While the basis for this type of extensive system exists in the literature, this system is little used. It provides preferential grazing of natural productivity, a low-stress, more natural environment, and may be used with or without the alteration of physiological processes which accompanies eyestalk ablation. High quality larvae can be produced through this system. However, it is very limited to use in warm climates, and larval production is subject to natural rhythms, and therefore, inconsistent availability.

The first system is derived from contributions of the late Dr. Motosaku Hudinaga of Japan, who made some of the most important contributions to understanding reproduction in marine shrimp early in this century. Hudinaga captured wild P. japonicus females with mature ovaries, spawned them in captivity, and reared the resulting larvae through to subadulthood (Hudinaga 1942). The practice of capturing wild females with mature ovaries for immediate spawning in captivity, sometimes referred to as "sourcing," is still common in Japan today, with a total output of some 600 to 700 million postlarval shrimp annually. About 80% of these are used to restock coastal fisheries and the remainder are used in commercial culture (Liao and Chao 1983a). This system (captive spawning of wild-matured females) is also used extensively today in Taiwan and the Philippines with P. monodon, with P. vannamei in Ecuador, and with P. chinensis and P. penicillatus in China. Because the collection of females which are ready to spawn limits culturists to indigenous species which may not be the most suitable, and is dependent on seasonal availability, migratory movements, weather, and natural rhythms, this system is not feasible in many locations. Furthermore, this method does not allow the longer-term goal of developing improved domestic stocks with strong growth and survival characteristics, or of maintaining disease-free captive stocks, and may disrupt fishery production.

The second major system of larval production involves the achievement of ovarian maturation as well as spawning in a laboratory or greenhouse-type environment. This system is almost invariably dependent on use of unilateral eyestalk ablation (ablation=a surgical removal; thus, "unilateral eyestalk ablation" indicates one eyestalk has been operated) of females. Panouse (1943) first demonstrated that ovarian development in the shrimp, Palaemon serratus, was inhibited by a hormone from the eyestalk sinus gland, but the practical application of this technique as a means to diminish inhibition of gonadal development and to accelerate secondary vitellogenesis in captivity

was not seen until the mid-1970's. The use of unilateral eyestalk ablation to achieve ovarian maturation and spawning in captivity spread rapidly around the world, and now has been tested, at least on a preliminary basis, in almost all of the species in the genus Penaeus, including all of the most important commercial species. However, there are many instances in which offspring produced by eyestalk-ablated females have been perceived to be of poorer quality than those produced by wild-developed females. Indeed, in captive stocks, the following are sometimes observed:

- smaller spawns (lower number of eggs/spawn)
- lower hatch rates
- larval deformities, especially abbreviated or missing setae, and sometimes clubbing of the posterior or other abnormality
- retarded metamorphosis between larval stages
- lower survival to postlarval stage
- lower survival in growout
- ovarian color somewhat altered from natural coloration
- increased larval susceptibility to disease
- higher variation in size frequency distributions in captive-derived stocks
- morphological aberrations such as curved or abbreviated rostra, "bubble heads," humped backs, etc., observable in growout, usually minor but significant percentages of populations.

Interestingly, there are few data indicating that eyestalk ablation, per se, is the cause of any of these conditions, and circumstantial evidence indicates that these conditions are often related to nutritional state or environmental conditions, and/or pathogens. For example, the extent to which these conditions are related to incomplete diets, unable to provide nutrients quickly enough for the accelerated ovarian development induced by eyestalk ablation, is not defined. It is certainly true that as practical diets have been improved, so has the performance of penaeid broodstock and their offspring. In spite of some quality questions, a substantial number of postlarvae (PL's) derived from captive maturation are being cultured worldwide. We are not familiar with any estimate of worldwide postlarval production derived specifically from captive maturation, but we would estimate that the total is at least several billion postlarvae annually.

The third type of larval production system involves management of a breeding population in a relatively natural environment such as outdoor ponds or raceways. We are aware of only a few commercial operations worldwide which have used this system, but the basis for using it is clear. Adult marine shrimp breed without exception in oceanic or ocean-influenced seawater. A pond environment which roughly simulates their natural environment (e.g., in temperature, in salinity, in light parameters, in natural feed organisms and benthos, with or without natural feed supplementation),

stocked at a very low density, will induce penaeids to develop ovaries and spawn, without the requirements of eyestalk ablation (although eyestalk ablation could also be used). Because natural breeding under pond conditions has been observed for a number of species, it is logical to speculate that the inhibitions to ovarian development which are associated with captivity are greatly intensified by the final step into a laboratory environment, where potential breeders are subjected to unnatural noise levels, close confinement, frequent handling, different substrate, unnatural lighting and photoperiod, unavailable live natural animal and plant food organisms, and often markedly different water quality. In outdoor breeding systems, the shrimp population receives many natural cues and diet components, and develops ovaries spontaneously. The primary shortcomings are: a) the system can only be used in tropical areas to guarantee a somewhat predictable larvae supply, and b) the mechanics of retrieval of mature females for spawning are often tedious.

Of these three systems currently used, the first is simply a collection and spawning system, and the third is geographically limited and hardly used. The focus of this review is on the second system, which is demanding in terms of environmental and nutritional conditions. It is our intent in this review to provide a practical discussion of known influences on Penaeus species reproduction, and to characterize the general biology of the reproductive system. Because of the breadth of the topic, an exhaustive review in the space of one chapter is impossible. Our attempt is rather to generally characterize Penaeus reproduction as currently understood and practiced, to highlight the more important considerations, to speculate from the vantage point of hindsight, and to draw together some of the apparent patterns where enough isolated observations have been made to warrant speculation. Only briefly will the endocrine systems in crustacea be described, as well as disease considerations, as both of these topics are treated separately in this volume.

Table 1 is a bibliographical summary, by species, of literature pertaining specifically to maturation and spawning in captivity in the genus Penaeus. Of the 27 species within this genus (Holthuis 1980), at least 21 species have been matured and spawned in captivity, and viable eggs produced, including: P. aztecus, P. brasiliensis, P. californiensis, P. canaliculatus, P. chinensis, P. esculentus, P. indicus, P. japonicus, P. kerathurus, P. marginatus, P. merguensis, P. monodon, P. notialis, P. paulensis, P. penicillatus, P. plebejus, P. schmitti, P. semisulcatus, P. setiferus, P. stylirostris, and P. vannamei. Limited information on captive breeding is also available for P. duorarum and P. occidentalis. Even a casual student of the literature quickly observes it is discontinuous and incomplete. For many species only limited references are available, and may represent only initial attempts at captive maturation. Furthermore, there are numerous unexplained occurrences throughout the

Table 1. Compendium of published literature in which reproduction in captivity of Penaeus species is reported, by species.¹

Species	References
<u>P. aztecus</u>	AQUACOP 1975; Duronslet et al. 1975; AQUACOP 1977a
<u>P. brasiliensis</u>	Martino 1981; Brisson 1986
<u>P. californiensis</u>	Moore et al. 1974
<u>P. canaliculatus</u>	Choy 1987
<u>P. chinensis</u>	Arnstein and Beard 1975; Liu 1983; Gao 1980; Main and Fulks 1990; Hu 1990; Rho 1990a
<u>P. duorarum</u>	Eldred 1958; Caillouet 1972
<u>P. esculentus</u>	Crococ and Kerr 1986
<u>P. indicus</u>	Muthu and Laxminarayana 1977; Alikunhi and Hameed Ali 1978; Emmerson 1980; Primavera et al. 1982; AQUACOP 1983a; Emmerson et al. 1983; Muthu et al. 1984; AQUACOP 1986a; Muthu et al. 1986; Makinouchi and Honculada-Primavera 1987; Galgani et al. 1989b
<u>P. japonicus</u>	AQUACOP 1975; Laubier-Bonichon 1975; AQUACOP 1977a; Laubier-Bonichon 1978; Caubere et al. 1979; Laubier-Bonichon and Laubier 1979; Lumare 1981; Yano 1984a; Yano 1984b; Yano and Tanaka 1984; Kanazawa 1990; Rho 1990b
<u>P. kerathurus</u>	Lumare 1979; Rodriguez 1981; Luis 1989
<u>P. marginatus</u>	Frogner and Klemetson 1987
<u>P. merguensis</u>	Alikunhi et al. 1975; AQUACOP 1975; Nurjana and Yang 1976; AQUACOP 1977a; Beard et al. 1977; Alikunhi and Hameed Ali 1978; Lichatowich et al. 1978; Primavera and Yap 1979; AQUACOP 1983a; Nair 1987
<u>P. monodon</u>	Alikunhi et al. 1975; Arnstein and Beard 1975; Wear and Santiago Jr. 1976; AQUACOP 1977a; AQUACOP 1977b; Muthu and Laxminarayana 1977; Santiago Jr. 1977; Alikunhi and Hameed Ali 1978; Halder 1978; Primavera 1978; Primavera and Borlongan 1978; AQUACOP 1979; Primavera 1979; Primavera and Yap 1979; Primavera et al. 1979; Beard and Wickens 1980; Primavera and Gabasa, Jr. 1981; Pudadera and Primavera 1981; Vicente and Valdez 1981; Simon 1982; AQUACOP 1983a; AQUACOP 1983b; Emmerson 1983; Poernomo and Hamami 1983; Liao and Chen 1983; Hillier 1984; Millamena et al. 1985a; Millamena et al. 1985b; Ruangpanit et al. 1985; Lin and Ting 1986a; Lin and Ting 1986b; Treece et al. 1987; Bray et al. 1988; Enriquez 1988; Menasveta et al. 1989; Kittiwattanawong et al. 1990

literature which render impossible a comprehensive understanding of captive reproduction influences. For example, an observational report that spawning was achieved, but that no fertilization occurred, or that fertilization occurred initially, but no nauplii were achieved beyond a certain point. While it is not

Table 1. (continued)

Species	References
<u>P. notialis</u>	Ramos-Trujillo and Gonzales-Flores 1983
<u>P. occidentalis</u>	Arnstein and Beard 1975
<u>P. paulensis</u>	Marchiori and Boff 1983
<u>P. penicillatus</u>	Liao and Chen 1983; Liao and Chao 1983a,b; Dong 1990; Hu 1990; Main and Fulks 1990
<u>P. plebejus</u>	Kelemac and Smith 1980; Kelemac and Smith 1984
<u>P. schmitti</u>	Nascimento et al. 1986; Bueno 1990
<u>P. semisulcatus</u>	AQUACOP 1975; Browdy and Samocha 1985a,b; Browdy et al. 1986; Browdy 1989; Browdy et al. 1989
<u>P. setiferus</u>	Johnson and Fielding 1956; Duronslet et al. 1975; Conte et al. 1977; Brown et al. 1979; Lawrence et al. 1980; Bray et al. 1982; Bray et al. 1983; Bray and Lawrence 1984; Bray et al. 1985; Wurts and Stickney 1984; Chamberlain and Lawrence 1986
<u>P. stylirostris</u>	AQUACOP 1977a; Conte et al. 1977; AQUACOP 1979; Brown et al. 1980; Chamberlain and Lawrence 1981a,b; Magarelli, Jr. 1981; AQUACOP 1983a; Liao and Chao 1983a; Brown et al. 1984; Chamberlain and Gervais 1984; Bray and Lawrence 1988; Chamberlain 1988; Ottogalli et al. 1988; Galgani et al. 1989a; Bray et al. 1989; Bray et al. 1990; Robertson et al. 1991
<u>P. vannamei</u>	AQUACOP 1977a; AQUACOP 1979; Chamberlain and Lawrence 1981a,b; AQUACOP 1983a; Liao and Chao 1983a; Kawahigashi et al. 1986; Goguenheim et al. 1987; Gomez and Arellano 1987; Yano and Wyban 1987a,b; Wyban et al. 1987; Ashmore 1988; Chamberlain 1988; McGovern 1988; Yano 1988; Galgani et al. 1989a; Oyama et al. 1989; Arellano 1990; Cahu and Fakhfakh 1990; Chen et al. 1990; Fakhfakh and Cahu 1990; Wyban et al. 1990
<u>Penaeus</u> Reviews	Wickens 1976a; Sandifer 1986; Chamberlain 1985; Primavera 1985; Harrison 1990; Main and Fulks 1990

¹ Authors' note: Abstracts are often the only references on recent research. Table 1 contains many abstracts from the past five years and some older abstracts published only in conference program format. Any inconvenience to the reader is regretted.

always obvious, experience and familiarity with mainstream and peripheral literature provide clues to these voids. Such problems can occur due to lack of mating, immature or infertile males, inadequate diet of females, poor quality seawater, toxicity, environmental fluctuation, or stress. If a thorough description of methods and seawater system has been provided, it is often possible to understand, or at least suspect, in retrospect, the probable cause. It is also noteworthy that tremendous variation exists among species in their

responses to captive conditions. Some species, such as P. indicus, copulate, mature, and spawn readily under captive conditions, while others, such as P. vannamei, are far more difficult to breed.

Captive reproduction in Penaeus species has made the transition from art to science. The ultimate milestone of quality for captive reproduction will be reached when shrimp farmers who have an option request captive-maturation source postlarvae for their growout operations. This milestone will be reached when we have better defined criteria for larval and postlarval quality, better defined diets, well defined broodstock management systems, defined ranges for seawater composition, and better disease prevention, diagnosis, and treatment. Thorough understanding of these areas will allow routine reliance on closed stocks, a year-around postlarvae supply, and an end to exotic species dependence and competition for fishery resources. Additionally, captive reproduction allows the benefits of classical genetics research in agriculture: improved yield through selection for such traits as improved growth, disease resistance, and environmental tolerance.

5.2 BIOLOGICAL CHARACTERIZATION

5.2.1 Age/Size of Breeding Adults

The best age for broodstock of various species is not defined, but as a general rule the size of animals capable of breeding corresponds to the size at which onset of maturation occurs in the wild for a given species. Because size of a poikilotherm at a given age is extremely dependent on culture temperature, as well as adequate nutrition, age alone is not a good predictor of breeding readiness. In nature, as well as in ponds, attainment of potential for sexual maturity and breeding usually occurs in 8 to 10 months. This age category corresponds with sizes of about 40 g in P. vannamei and slightly larger in P. stylirostris. P. vannamei appears to perform best in captive breeding when a size of 45-50 g has been attained. Wyban et al. (1987) suggested that P. vannamei females greater than 45 g and males greater than 40 g be used. In P. monodon, the largest species of the genus, males of about 60 g and females of about 90 g are recommended. Small species, such as P. indicus, are reproductively active at a size of 10 g or less. The youngest reported spawning in captive penaeids is five-month-old P. monodon (Primavera 1978). A simple indicator of breeding readiness is appearance of ovarian development in some females in a population. Sexual dimorphism for size is generally exhibited in mature Penaeus sp., with females being larger than males. Broodstock cultured in captivity, especially males, sometimes appear to require a larger size than size at first maturity in the wild to be reproductively viable.

While the relationship has not been demonstrated in penaeids, Charnov (1990) found in pandalid shrimp a correlation between size at onset of maturity and the asymptotic size, independent of species or latitude (relative size at onset of maturity divided by asymptotic size ≈ 0.55).

5.2.2 Male Reproductive System

The male reproductive system is composed of paired testes and paired vasa deferentia terminating in ampoules containing spermatophores, or sperm packets, at gonopores at the base of the fifth walking legs (pereiopods). The multi-lobed, transparent testes are located above the heart, which is situated dorsally over the digestive gland. The milky-colored vasa deferentia extend posteriorly from the testes, then ventrally to connect with the gonopores. In mature males, spermatophores are clearly visible through the exoskeleton (except in species with extremely dark exoskeletons, such as P. monodon) from ventral or lateral views at the fifth pair of pereiopods. The two spermatophores, one from each terminal ampule, become fused longitudinally at the time of extrusion (mating with a female) and then are referred to as the "compound spermatophore" or simply the "spermatophore" in open thelycum species.

Males have a specialized structure called the petasma which is presumed to be used in spermatophore transfer. The petasma is a roughly triangular, membranous flap which connects the first pair of pleopods ("swimming legs"). The petasma in young animals is unjoined, but becomes "zippered" in subadulthood, about 105-107 mm total body length in P. setiferus (Perez-Farfante 1969) and as small as 91 mm in P. duorarum (Eldred et al. 1961). Spermatophores are approximately 5-7 mm longitudinally, and their structures vary somewhat, especially between members of the Litopenaeus subgenus and the other subgenera. The more complex spermatophores of the Litopenaeus members (P. setiferus, P. vannamei, P. stylirostris, P. schmitti, and P. occidentalis) have been described by Perez-Farfante (1975). Distinctions between mating characteristics of litopenaeids and other subgenera are discussed in section 5.2.4.

Spermatozoa are contained within the spermatophore in a viscous, slightly grayish or milky medium. These sperm are non-motile, and are shaped much like a golf ball on a tee, with characteristic spherical portion (the "golf ball") and "tee" or cap, with spike extending outward from the spherical portion (King 1948). Trujillo (1990) has shown that number of sperm is positively correlated with male total weight in P. setiferus. An adult male P. setiferus of 35 g may carry some 70 million sperm per compound spermatophore.

5.2.3 Female Reproductive System

The female reproductive system consists of two bilaterally symmetrical, partly fused ovaries which extend almost the entire length of the female. Later stages are visible dorsally in those species with light-colored exoskeletons. In the carapace (head), the anterior lobes extend to the anterior portion of the gastric mill and laterally in the cephalothorax area, while posterior lobes extend the length of the abdomen dorsally. Oviducts terminate in gonopores at the base of the third pair of pereiopods. Ovarian development is categorized by an external staging system developed by King (1948) for P. setiferus, Tuma (1967) for P. merguensis, or variation thereof:

Stage 1. Undeveloped. Found only in young shrimp; ovaries are small and translucent.

Stage 2. Developing. Ovaries are larger, opaque, and yellowish, with scattered melanophores over surface.

Stage 3. Nearly ripe or yellow stage. Ovaries larger and yellow to yellow-orange.

Stage 4. Ripe. Ovaries fill virtually all space among other organs, and are drab olive-brown.

Stage 5. Spent. Spawned ovaries are flaccid and muddy-colored. Often, microscopic examination is required to accurately determine this stage, although areas of unspawned ova can sometimes be seen.

The general color sequence described by King, and later, Brown, Jr. and Patlan (1974) holds true for the Litopenaeus subgenus, with variations of yellow-orange-brown among species. All of the other subgenera begin with yellowish-green ova which mature to a true dark green to dark olive-drab final color stage. Tan-Fermin and Pudadera (1989) recently recommended a simplified ovarian staging system for P. monodon which includes previtellogenic (P stage), vitellogenic (V), cortical rod (C), and spent (S) stages. The final flush of color change during ovarian maturation seems to occur within hours of spawning, and may be associated with breakdown of follicle cells surrounding the ova in preparation for spawning. Browdy (1989) found a strong correlation between external staging and histological and biochemical evaluation of P. semisulcatus. Ovarian evaluation (viewing of females to determine maturity of ovaries and readiness for isolation to spawning tanks) is usually conducted from half an hour to two hours after dark in open thelycum species. Because in closed thelycum species the females are already bearing spermatophores, evaluation and isolation of females for spawning can be conducted earlier. Ovary evaluation is implemented with a powerful light source such as a handheld spotlight, underwater dive flashlight, miner's type headlamp, or bright overhead illumination. Use of undertank lighting to silhouette ovaries has also been used (Emmerson et al. 1983).

Under captive conditions, particularly over time, ovary colors vary somewhat from wild-matured ovaries, possibly due to dietary differences such as carotenoid content, hormonal changes related to eyestalk ablation, or the tank color in which the females are cultured. Emmerson (1980) found that unablated *P. indicus* females in white and black tanks generally took on a color similar to the background color, as did their ovaries, eggs, and nauplii. White-tank females developed pale green to cream-colored ovaries, while black-tank females developed dark olive ovaries. AQUACOP (1977a) has noted that ovary color, although varying from the wild state, can be fairly dependable as a staging determinant in *P. vannamei* and *P. stylirostris*, but that the size of the gonad in the first thoracic segment, compression of the posterior cephalic lobes observed at the thoracic abdominal junction, and a "granular" texture, must be used as determinants of immediate spawning in *P. monodon*, *P. merguensis*, and *P. japonicus*. Of course, the presence of an external spermatophore, spermatophore portion, or sperm mass, is an obvious indication of spawning readiness in those species with external spermatophore placement (see section 5.2.4). All of these judgments in ovarian staging are somewhat subjective, and best guided by experience, except the latter. In addition to ovarian color, fullness of captive females' ovaries also may be noticeably different. It is not uncommon to see eyestalk-ablated females of some species with ova filling only the anterior portions of ovaries, even in Stage 4, or for there to be a gap between ova-filled lobes of the carapace and abdomen.

External staging, then, is used to monitor the internal process of oocyte development, or "ovarian development," which includes oocyte proliferation in a germinal zone of the ovary, development of previtellogenic oocytes surrounded by round follicular cells outside of the germinal zone, and primary and secondary vitellogenesis, in which egg yolk is produced and accumulated. The final stage is retraction of follicle cells from around mature oocytes (ovulation, and spawning). The hormonal control of crustacean reproduction and sites of synthesis of nutrients for ova production remain active areas of research. Research over these fundamental areas can be found in: Adiyodi and Adiyodi (1970); Fingerman (1970); Fyffe and O'Connor (1974); Kleinholz (1975); Klek-Kawinska and Bomirski (1975); Silverthorn (1975); Bomirski and Klek-Kawinska (1976); Lui and O'Connor (1977a,b); Soyez and Kleinholz (1977); Kleinholz (1978); Andrew and Saleuddin (1979); Kleinholz and Keller (1979); Meusy (1980); Charniaux-Cotton (1980); Kulkarni and Nagabushanam (1980); Bellon-Humbert et al. (1981); Bomirski et al. (1981); Andrew (1983); Adiyodi and Subramoniam (1983); Quackenbush and Herrnkind (1983); Berreur-Bonnenfant and Lawrence (1984); Meusy and Charniaux-Cotton (1984); Chang (1984); Adiyodi (1985); Charniaux-Cotton (1985); Fingerman (1985); Kleinholz (1985); Laufer et al. (1986); Quackenbush (1986); Vazquez-

Bouchard et al. (1986); Chan et al. (1987); Fingerman (1987); Laufer et al. (1987); Meusy et al. (1987); Tom et al. (1987a,b); Paulus and Laufer (1987); Soyeux et al. (1987); Yano and Chinzei (1987); Chang and O'Connor (1988); Charniaux-Cotton and Payen (1988); Quackenbush (1988); Quackenbush and Keeley (1988); Tsukimura and Kamemoto (1988a,b); Yano et al. (1988a); Tobe et al. (1989); Chang (1989); Quackenbush (1989a,b); Rankin et al. (1989); Browdy et al. (1990); Fainzilber et al. (1990); Fairs et al. (1990); and Harrison (1990).

5.2.4 Mating Characteristics in Open v. Closed Thelycum Species

Penaeus species are grouped into two broad categories based on differences in morphology of the female genital area, or thelycum, which occupies the area from the third to the fifth pereopods. The "open-thelycum" species include only the five members of the Litopenaeus subgenus; they receive a spermatophore or sperm packet from the male, and then retain it externally for a few hours prior to spawning. In contrast, the "closed thelycum" species are those which mate each time the female molts (approximately each two to three weeks in adults at breeding temperature). The closed thelycum female receives the spermatophore into her thelycum, her new exoskeleton hardens over it, and she retains the spermatophore until she utilizes the sperm in one to several spawnings, or until she molts again. The subgenera Farfantepenaeus, Fenneropenaeus, Marsupenaeus, Melicertus, and Penaeus, have the closed, or internal-type thelycum. Thus, open thelycum females follow a sequence of molt-mature-mate-spawn, while closed thelycum species follow a sequence of molt-mate-mature-spawn. In both groups, males with hardened exoskeletons transfer spermatophores to females. Multiple spawns may occur within one intermolt period for both open and closed thelycum species. An example of the female genital structure in a closed thelycum species, P. monodon, is shown in Fig. 4 of Chapter 2, along with the male specializations, petasma and appendix masculina.

In closed thelycum species, when the spermatophores are inserted into the thelycum, a portion remains visible protruding from the thelycal opening (seminal receptacle) for about 24 hours until the exoskeleton hardens. In a few species, such as P. japonicus, a portion of the spermatophore (sometimes referred to as a "plug") remains visible externally throughout the intermolt period, making it obvious that a female is bearing sperm. Contrary to the scenario with open thelycum shrimp, multiple spawns can occur utilizing the same sperm mass for egg fertilization within the same intermolt period. Mating of closed thelycum species seems to very closely follow molting in time sequence. Primavera (1979) observed a female P. monodon in the laboratory which molted, and then remated within an hour. Browdy (1989) observed an even briefer period, from 1 to 2.5 minutes, elapsing between molting and

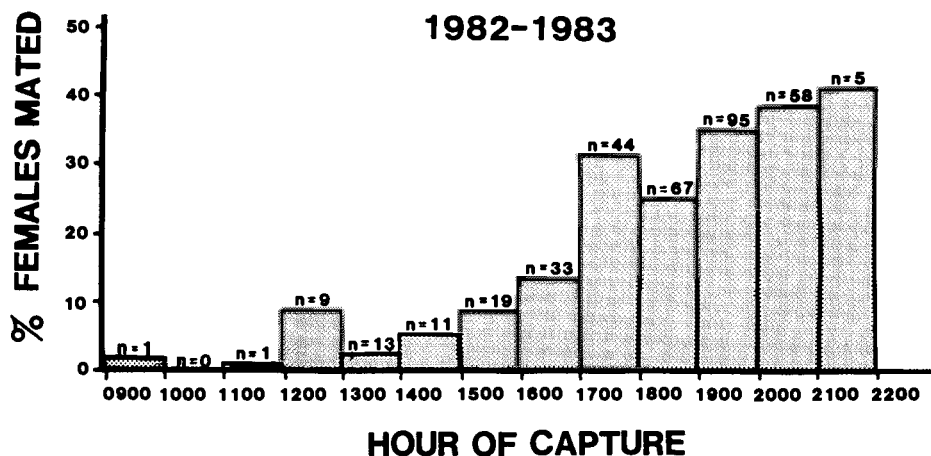


Figure 1. Percentage of Penaeus setiferus females which were mated, by hour of capture, in trawls over two-year period (from Bray and Lawrence 1984).

mating in P. semisulcatus. Hudinaga (1942) described "chasing" of a female P. japonicus even prior to molting, and mating closely followed the molting process.

The stimulus for courtship behavior in Penaeus sp. is believed to be a sex pheromone secreted in the female's urine and received by the male's antennules (Bauchau and Fontaine 1984) or antennular flagella (Young 1959). Although not demonstrated in Penaeus, such a sex pheromone has been demonstrated in several decapod crustaceans, including Palaemonetes vulgaris, Palaemon paucidens, and Macrobrachium kistnensis (Hazlett 1975; Dunham 1978; and Sarojini et al. 1982).

Mating in closed thelycum species, in conjunction with molting, occurs at night. Browdy (1989) observed matings between 2230 and 0200 hours in P. semisulcatus. Primavera (1979) found that 88% of P. monodon molting occurred between 1800 and 0600 hours over a five-month period. The molting-mating sequence was first observed by Hudinaga (1942) in P. japonicus, and the sequence appears universal among the subgenera except for Litopenaeus.

In open thelycum species, mating occurs mainly in the evening of the night spawning (as opposed to molting) will occur. Bray and Lawrence (1984) showed that most mating activity in wild populations of P. setiferus occurred from 1900 to 2100 hours during two years of observation (Fig. 1). This pattern is maintained in captive breeding, and mated females are normally isolated to spawning tanks within one to two hours of darkness. AQUACOP

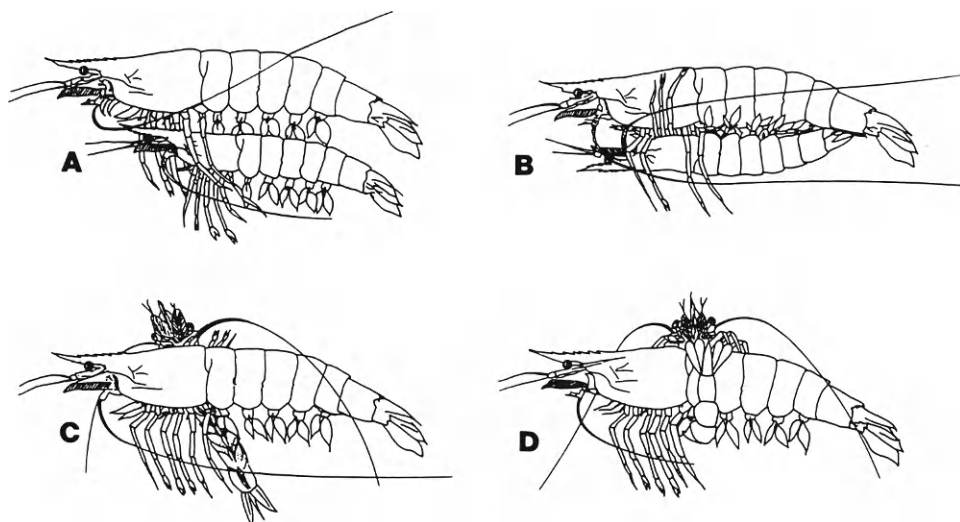


Figure 2. Mating of *P. monodon*. A) parallel swimming; B) male ventral side up, attached to female; C) male perpendicular to female; D) male curves around female, flicks head and tail (from Primavera 1979).

(1977a) observed that the elicitation of sexual activity seemed to be related to the intensity of light and occurred much earlier when the sky was overcast with *P. vannamei* and *P. stylirostris*.

Relatively few descriptions of copulation or "mating" exist in the literature, but the general sequence for both open and closed thelycum species is the same: 1) one or more males are attracted to a receptive female, often approaching the female from behind, and a male may gently slide his rostrum/anterior-most parts underneath a female's tail; 2) the female rises from the bottom, and "chasing" or "parallel swimming" ensues, with the male closely following the female's movements precisely. The male is often slightly posterior, and below the female; 3) below the female, the male turns ventral side up (head-to-head/ventral-to-ventral). In *P. monodon*, *P. paulensis*, *P. semisulcatus*, and *P. stylirostris*, the male has been observed to then rotate his body 90° , and then from this perpendicular orientation, flick his head and tail several times to effect spermatophore ejaculation and attachment (Primavera 1979; De Saint-Brisson 1985; Browdy 1989; AQUACOP 1977a). In *P. vannamei*, *P. schmitti*, and *P. japonicus*, the ventral-to-ventral/head-to-head orientation has been described, and also sometimes ventral-to-ventral/head-to-tail orientation, without the 90° rotation (Yano et al. 1988b; Bueno 1990; Hudinaga 1942). The exact role of the

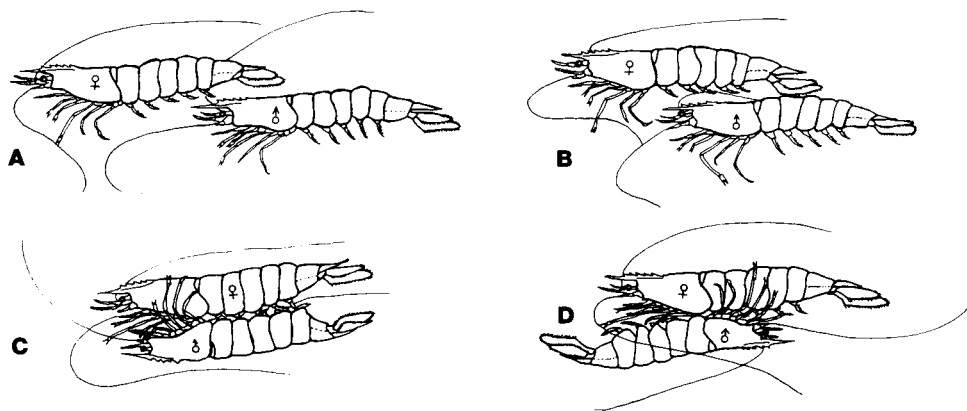


Figure 3. Mating of *P. vannamei*. A) male slips carapace under abdomen of female; B) male chases in parallel; C) male attaches to female; D) 180° rotation of male was observed (from Yano et al. 1988b).

petasma, and perhaps the appendix masculina, in spermatophore transfer is not understood. The mating sequence in *P. monodon*, from Primavera (1979), and in *P. vannamei*, from Yano et al. (1988), are shown in Figs. 2 and 3, respectively. Courtship in *P. brasiliensis* has also been described (Brisson 1986).

The complex spermatophores of the open thelycum species have been described by Perez-Farfante (1975). In *P. vannamei*, the "wings" (perpendicular anterior processes of the longitudinal body) are not present. Spermatophores are often easily dislodged from the female in open thelycum shrimp, and in some species the spermatophore may break down sequentially prior to spawning. In offshore collections (as well as in the laboratory), three spermatophore conditions are observed in mated *P. setiferus*: 1) the full compound spermatophore; 2) the "wings" portion only (anterior processes of the spermatophore only) present just posterior to the third pereopods; and 3) a sperm mass only is present, obscured from vision when walking legs are in normal position, but visible when the third pereopods are folded posteriorly (Figure 4, from Bray and Lawrence 1984). High levels of fertilization can be achieved with any of these positions, leading to speculation that the sperm mass is deposited from the spermatophore rather quickly after spermatophore transfer occurs in at least some of the open thelycum species (*P. setiferus*, Bray and Lawrence 1984; *P. schmitti*, Bueno

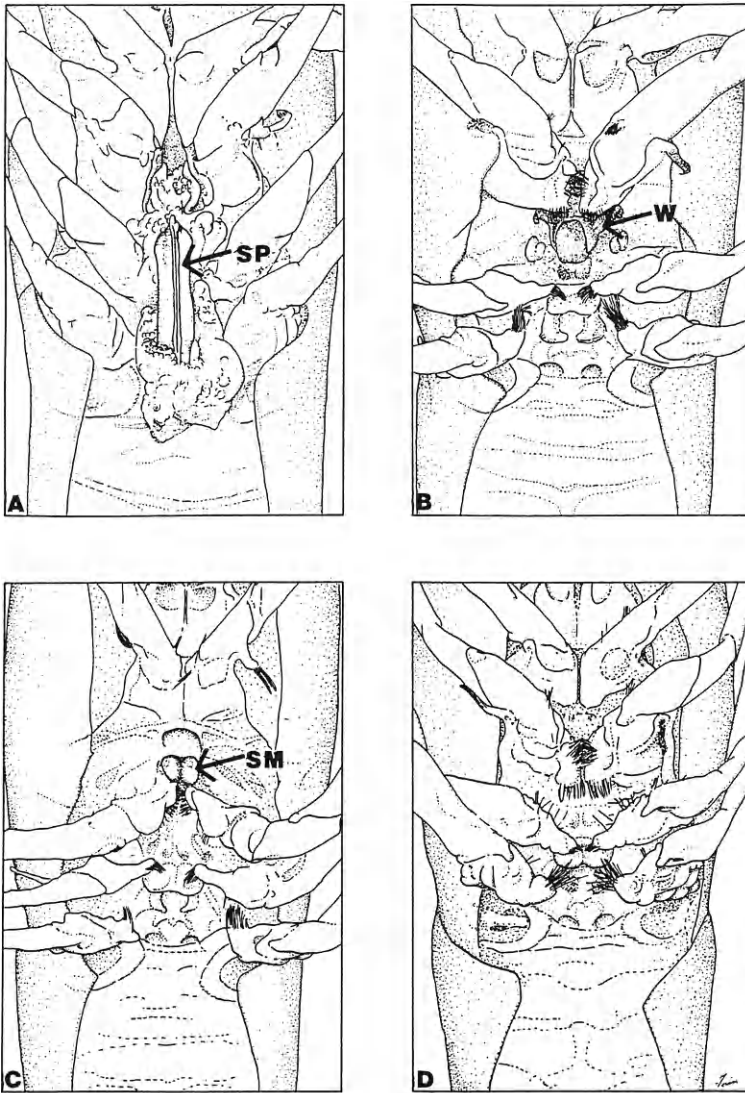


Figure 4. Mated conditions of *Penaeus setiferus* include: A) Full compound spermatophore (designated SP) on thelycum of female, extending from just posterior to the third pereopods to posterior to the fifth pereopods; B) "Wings" (W) or anterior portion of spermatophore retained just posterior to third pereopods. Fourth and fifth pereopods are folded posteriorly in this view; C) Sperm mass only (SM), with no structural portion of spermatophore remaining, may be observed by folding the third pair of pereopods posteriorly; and D) No sperm mass is visible with pereopods in normal position (from Bray and Lawrence 1984).

1990).

5.2.5 Fecundity

Penaeids are extremely fecund, and may produce from 100,000 to over 1,000,000 eggs per spawning in the wild (Rao 1968; Perez-Farfante 1969; Martosubroto 1974). There is a positive correlation between female size and number of eggs produced, and larger species, such as P. monodon, produce higher numbers of eggs per spawn than smaller species such as P. indicus. An example of the relationship between female weight and fecundity in wild P.

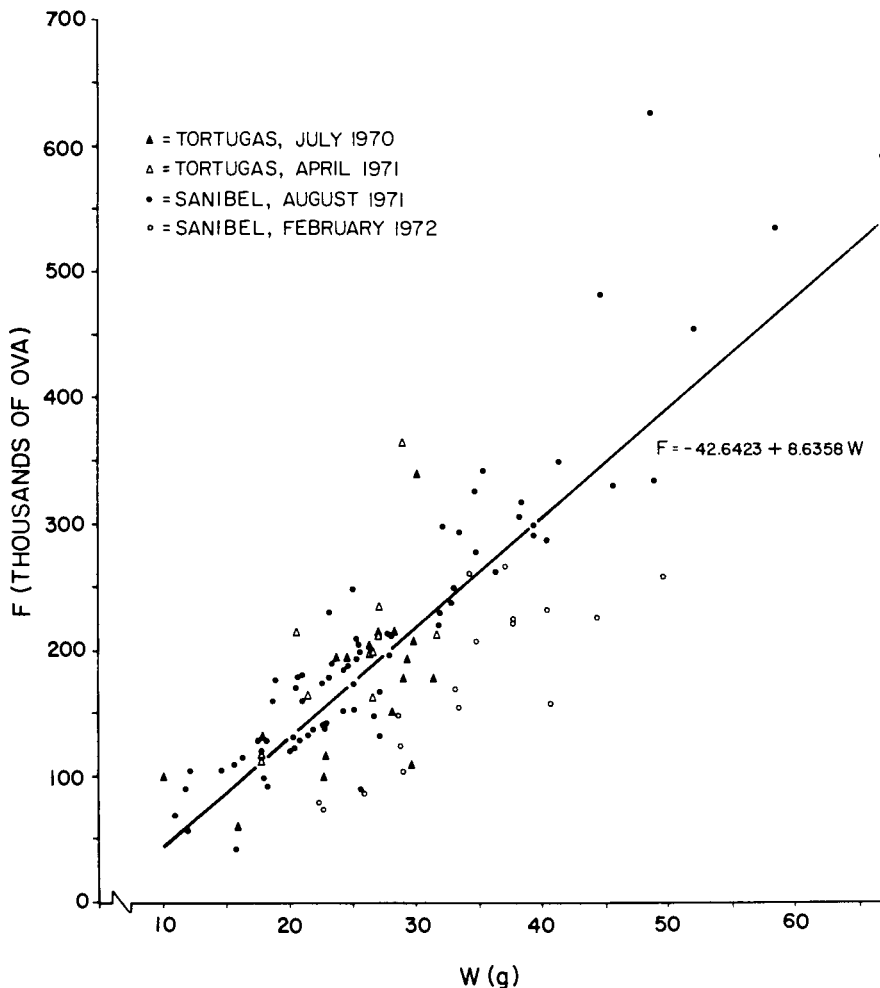


Figure 5. Relationship between fecundity, F, and body weight, W, in four wild populations of Penaeus duorarum (from Martosubroto 1974).

Table 2. Selected examples of spawn results obtained in captivity with five species, of various mean female sizes, demonstrating species variation in fecundity and female size.

Species	Female Size (approx.)	Eggs/Spawn (mean)	Nauplii/Spawn (mean)	Broodstock Source	Ref.
<u>P. indicus</u>	27 g	59,000	30,000	Ablated; wild	1
<u>P. monodon</u>	146 g	315,000	195,000	Ablated; pond	2
<u>P. semisulcatus</u>	45 g	61,000	55,000	Ablated; pond	3
<u>P. stylirostris</u>	62 g	189,000	103,000	Ablated; pond	4
<u>P. vannamei</u>	50 g	146,000	60,000	Ablated; pond	6

^a Reference: 1, Emmerson 1980; 2, Bray et al. 1988; 3, Browdy and Samocha 1985b; 4, Bray et al. 1990a; 5, Ashmore 1988.

duorarum is shown in Figure 5. (from Martosubroto 1974), $r=0.84$. Examples of the species differences in total weight and fecundity in captive spawns are demonstrated in Table 2. In captivity, spawns usually range from 50,000 to 300,000 eggs. Some species such as P. monodon consistently produce larger spawns than others, such as P. indicus and P. merguensis.

Precise data concerning the number of spawns produced by a female in nature are unavailable. However, evidence of repeated spawning in nature has been presented for a number of species. "Several" to more than five times have been predicted for P. indicus (Subramanyam 1965; Rao 1968; Emmerson 1980), P. semisulcatus, five spawns per lifetime (Badawi 1975), and at least two spawns per season for P. setiferus (Lindner and Anderson 1956), P. duorarum (Cummings 1961; Eldred et al. 1961; Burukovski 1970), and P. japonicus (Hudinaga 1942). In captive animals, without the stimulus of eyestalk ablation, multiple spawning has been shown by Laubier-Bonichon and Laubier (1976) and AQUACOP (1975) in P. japonicus, as well as in P. indicus (Emmerson 1980) and P. semisulcatus (Browdy and Samocha 1985a,b). Unablated P. merguensis have been noted to spawn each 2.6 months in captivity (Beard et al. 1977) compared with an average of 2.8 months for P. japonicus (Laubier-Bonichon and Laubier 1976). Browdy (1989) observed one unablated P. semisulcatus to spawn 11 times in a 133-day period, and an ablated female to spawn 14 times over a 176-day period. Browdy found unablated females spawned up to 4 times per molt cycle, and ablated, up to 6. Beard and Wickens (1980) have also observed ablated P. monodon to spawn up to 6 times in one molt cycle. Attributing the incidence to overstimulation of spawning under captive conditions, Emmerson (1980) noted spawning of one unablated P. indicus female 19 times in 7 months.

Two estimates of reproductive performance in captivity, average number of spawns per female per month, and average percentage of females spawning (mating and spawning in open thelycum species), are sometimes cited. Both can provide useful production projections, although both are quite misleading because often only a minor percentage of the population produces the great percentage of production. Average number of spawns per ablated female per month often ranges from 1 spawn per female per month to about 3 spawns per female per month. These estimates correspond to approximately 3% to 10% per night of females spawning.

5.2.6 Spawning and Egg/Nauplius Development

The act of spawning or egg expulsion occurs in one to several minutes and usually occurs between 2230 and 0030 hours in both open and closed thelycum species. Similar descriptions are available for several species, e.g., as in AQUACOP (1977a): A female initially is resting on the bottom of a spawning tank. She begins to swim upward just before spawning, sometimes with rapid flexing of the abdomen. Her swimming slows, and eggs are expelled freely from the oviducts into the water. Pleopods are beating rapidly. Spawning is frequently observed at the water surface. If a female is interrupted during spawning, sometimes spawning will occur without appropriate movement of the female, leading to a pile of eggs being deposited on the bottom. Such eggs adhere together and never hatch (Hudinaga 1942; Villaluz et al. 1972; AQUACOP 1977a). Spawning usually occurs several hours after dusk. Makinouchi and Honculada-Primavera (1987) found 72% of *P. indicus* spawned between 2000 and 2200 hours.

Fertilization of spawned eggs apparently occurs as the eggs are expelled. In open thelycum species, the sperm mass is external, leading to the conclusion that eggs would be exposed to sperm as the eggs brush past the sperm mass, or else the sperm matrix and sperm are dispersed into the water column at the time of spawning, requiring a mechanism for chemical attraction and fertilization to occur freely in the water column. In the closed thelycum species *P. japonicus*, Hudinaga (1942) described tiny apertures through which sperm could be conducted at time of spawning from the internal thelycum. Since eggs are discharged from gonopores at the base of the third pereopods, and these apertures are at the bases of the pereopods, this observation indicates fertilization also occurs externally in closed thelycum species, as or immediately after eggs are released.

Spawned eggs go through a striking process of changes immediately after extrusion, and accompanying the fertilization process (Clark, Jr. et al. 1980). A coating of egg jelly disappears about 30 to 40 minutes after spawning and eggs have achieved their spherical shape, and the zygote begins its first cleavage, lasting 2 to 3 minutes. The second division begins 12 to 15 minute

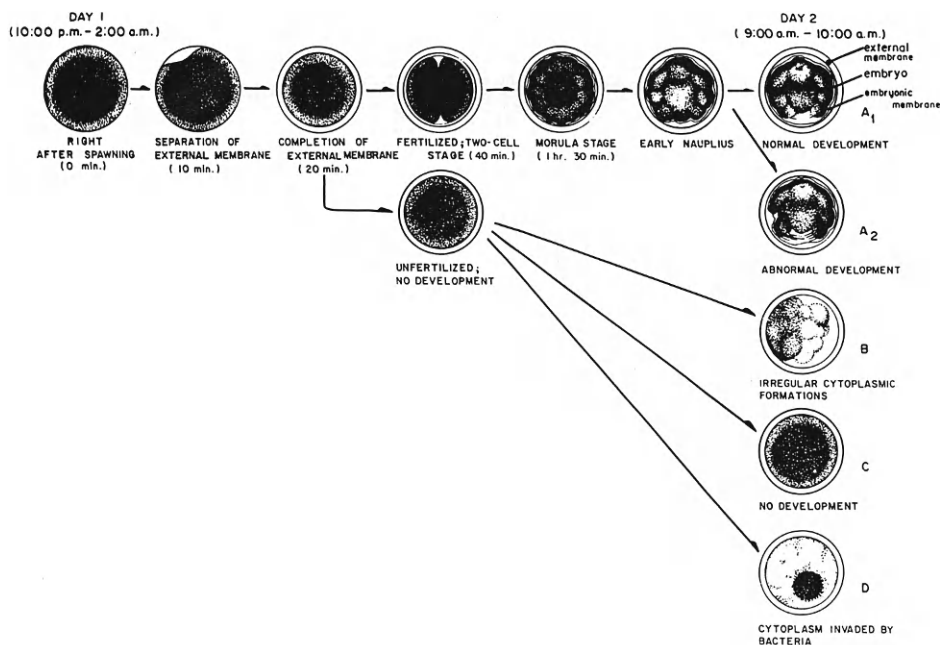


Figure 6. Egg development sequences of fertilized and unfertilized eggs of *Penaeus monodon* over approximately 12-hour period (from Primavera and Posadas 1981).

later, and also takes several minutes, as does the third division. Egg diameter reported for various species is fairly consistent (e.g., 260 to 280 micron, *P. japonicus*, Hudinaga 1942; 270 to 310 micron, *P. monodon*, Motosh 1985; 310 to 330 micron, *P. duorarum*, Dobkin 1961). An embryonic membrane surrounds the developing embryo about 2 to 2.5 hours after spawning. Hatching occurs about 12 to 14 hours after spawning. Eggs are slightly negatively buoyant, and will stay suspended in the water column with little circulation. Egg fertilization and classification have been described by AQUACOP (1977a) and Primavera and Posadas (1981) for *P. monodon*. Fertilized and unfertilized eggs of *P. monodon* are shown in Fig. 6 (from Primavera and Posadas 1981). The first stage larva, or Nauplius I, convulses free from the egg, remains in a resting phase for about 3 to 4 minutes, and then begins sporadic locomotion. Locomotion becomes brisk after about 20 minutes, and the nauplius already displays positive phototaxis, or attraction to light. Both five and six nauplius substages have been reported for various *Penaeus* species, depending on researcher and species. More recent literature, and some of the oldest literature, appears to confirm six, rather than five nauplius substages, which are designated Nauplius I through Nauplius VI. Recent larval keys recognizing six nauplius substages have been

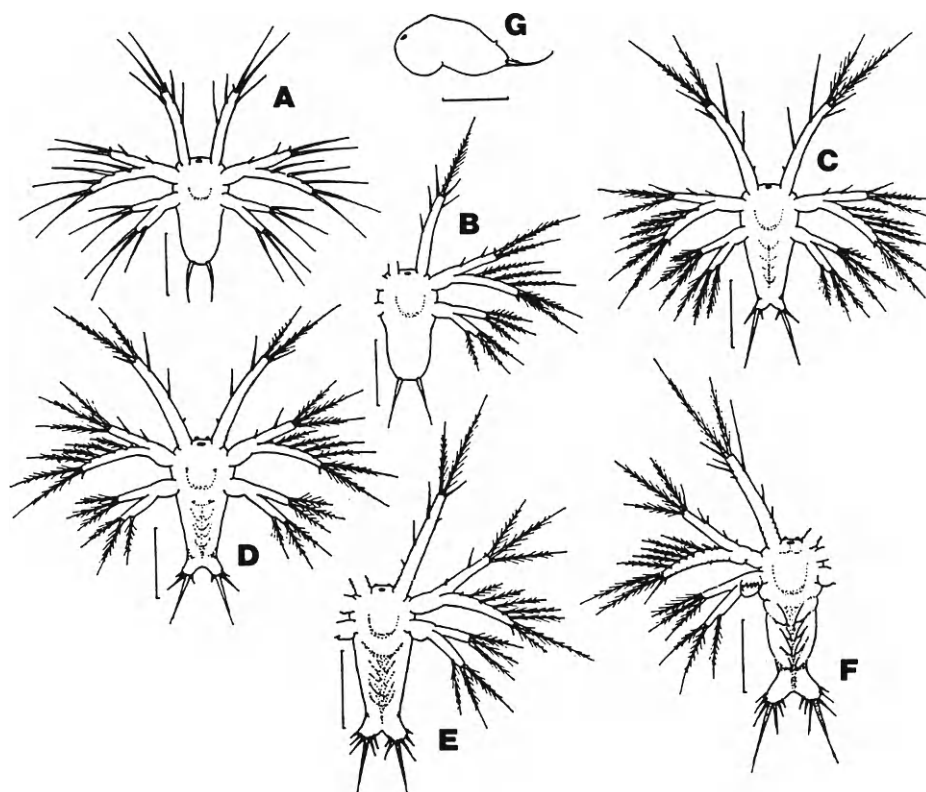


Figure 7. Six nauplius substages of *Penaeus vannamei*, designated Nauplius I-VI, in ventral views A-F. Lateral view of Nauplius I, drawing G. Scale=0.2 mm (from Kitani 1986c).

published for *P. merguensis* (Motoh and Buri 1979) and for *P. aztecus*, *P. stylirostris*, and *P. vannamei* (Kitani 1986a,b,c). Nauplii (all substages) subsist on yolk from the egg, require no feeding, and do not exhibit mouthparts or anus. Nauplius developmental stages in *P. vannamei* are shown in Figure 7 (from Kitani 1986c). Major changes which occur between nauplius substages (molts) include length increase, increasing number of furcal spines, progressive bifurcation of the abdomen, and development of ventral appendages. Length at the final nauplius substage is approximately 500 microns.

While it is commonly accepted that body length increases occur after molting in crustacea, there is evidence that substantial body length increase occurs at least within some substages. Hudinaga (1942) found that body length of early Protozoa I *P. japonicus* larvae increased from an average of 0.92 mm to 1.3 mm in the late Protozoa-I substage, a body length increase of 41%.

The major metamorphosis from the final nauplius stage to the first Protozoaea stage (also called Zoea) occurs at about 30 to 36 hours after hatching. With transition to Protozoaea I, the larvae begin feeding immediately. It is the feeding stages of Protozoaea (I-III) and Mysis (I-III), and early days as postlarvae, which are referred to as the "hatchery phase" or larviculture phase of shrimp culture.

5.2.7 Unilateral Eyestalk Ablation

The process of unilateral eyestalk ablation is used in almost every marine shrimp maturation/reproduction facility in the world, both research and commercial, to stimulate female shrimp to develop mature ovaries and spawn. This method of inducing females to develop mature ovaries is used for two reasons: 1) most captive conditions cause inhibitions in females which keep them from developing mature ovaries in captivity, and 2) even in conditions where a given species will develop ovaries and spawn in captivity, use of eyestalk ablation increases total egg production and increases the percentage of females in a given population which will participate in reproduction.

The relationship between removal of one (or both) eyestalks of a female decapod crustacean and ensuing gonadal development was first discovered by Panouse (1943) in the shrimp Palaemon serratus. However, the importance of this finding to shrimp culture lay dormant for thirty years until the eyestalk removal/gonad development principle was applied to Penaeus spp. in the early to mid-1970's. A flurry of research activity resulted over the next decade and continues to some extent today, applying unilateral eyestalk ablation to various species, under various conditions. Eyestalk ablation has also been shown to stimulate precocious gonadal development in males (e.g., Demeusy 1967 a,b).

The most commonly accepted theory is that a gonad inhibitory hormone (GIH) is produced in the neurosecretory complexes in the eyestalk. This hormone apparently occurs in nature in the non-breeding season and is absent or present only in low levels during the breeding season (Bomirski and Klek 1974; Kulkarni and Nagabushanam 1980). By inference, then, the reluctance of most penaeids to routinely develop mature ovaries in captivity is a function of elevated levels of GIH, and eyestalk ablation lowers the high hemolymph titer of GIH. Eyestalk ablation in crustaceans has been reviewed by Adiyodi and Adiyodi (1970), Fingerman (1970), Highnam (1978); Kleinholz and Keller (1979), and Charniaux-Cotton (1985). The effect of eyestalk removal is not on a single hormone such as GIH, but rather effects numerous physiological processes. The X organ/sinus gland complex (see Andrew 1983) is also implicated in regulation of various other metabolic processes: sugar transport, respiratory functions, carbohydrate metabolism, molting, osmoregulation, thermal acclimation, heart rate, color change, and retinal

pigment migration (Kamemoto et al. 1966; Lockwood 1968; Adiyodi and Adiyodi 1970; Fingerman 1973; Fernlund 1974; Silverthorn 1975; Kleinholz 1978; Dores and Herman 1980).

Considering that eyestalk ablation affects the hormone balance for numerous physiological processes in addition to stimulation of gonadal hypertrophy, what are the practical effects of this operation, and at what cost do we achieve induced ovarian development using eyestalk ablation? The following observations have been made concerning use of eyestalk ablation in captive reproduction, and may be related to either captive conditions, eyestalk ablation, or both:

- 1) Captive spawn size (number of eggs per spawn) is smaller than in wild-matured females, regardless of whether eyestalk ablation is used (e.g., Moore et al. 1974; Nurjana and Yang 1976; Primavera and Yap 1979; Beard and Wickens 1980; Emmerson 1980; Lumare 1981; Browdy et al. 1986; Choy 1987).

- 2) Eyestalk ablation increases total egg production in captivity by producing more frequent spawnings, but not larger spawns. For example, Browdy and Samocha (1985b) found ablated females produced double the number of eggs of unablated females. Usually, somewhat larger individual spawns are reported for unablated females, but frequency of spawning is considerably higher in eyestalk ablated animals (e.g., Emmerson 1980; Browdy and Samocha 1985a,b; Browdy et al. 1986).

- 3) There is not a strong trend toward diminishing spawn size over time (Poernomo and Hamami 1983). Browdy and Samocha (1985a) found decline in eggs/spawn in both ablated females and unablated females in 80 and 110 days, respectively.

- 4) Reduced fecundity has been observed with successive captive generations in P. stylirostris (Magarelli, Jr. 1981) and P. semisulcatus (Browdy et al. 1986). This appears to be correlated with captive conditions, not eyestalk ablation. In P. vannamei, Jaenike (1990, personal communication, F. Jaenike, Harlingen Shrimp Farm, Ltd., formerly Laguna Madre Shrimp Farm, Inc., Box 4043, Los Fresnos, TX, USA, 78566) has noted increased rather than decreased fecundity with successive generations, probably due to selection.

- 5) Molt cycle duration is shorter in eyestalk-ablated females than intact females (e.g., Kelemac and Smith 1980; Chamberlain and Lawrence 1981; Poernomo and Hamami 1983; Browdy and Samocha 1985a; Robertson et al. 1987).

- 6) Higher mortality of eyestalk ablated females is often, but not always, reported (Primavera et al. 1982; Chamberlain 1981b; Poernomo and Hamami 1983; Makinouchi and Honculada-Primavera 1987).

7) Eyestalk ablation has been suggested to deteriorate female condition, measured as Kn, a relative condition factor (Emmerson 1980).

8) Eyestalk ablation in some instances has been observed to produce lower hatch rate of eggs than unablated females (Emmerson 1980; Lin and Ting 1986a; Choy 1987). Primavera and Posadas (1981) found that wild P. monodon females had the highest hatch rate, followed by ablated wild stock, followed by ablated pond stock.

9) Hatch rate has been observed to decline over time under captive conditions (AQUACOP 1979; Simon 1982) and has been shown to be partly diet related (Bray et al. 1990a). Hatch rate is sometimes reported to decline within an intermolt period (Beard and Wickens 1980).

10) Ovarian color in captive females, especially in eyestalk ablated females, is often rather different than wild-matured (AQUACOP 1977a; Emmerson 1980).

11) Nauplii of captive females are sometimes observed to be transparent, rather than having a brownish-olive tint (Emmerson 1980).

12) Slow larval development times (metamorphosis rates into Protozoa, Mysis and PL) are sometimes noted in captive stocks.

13) Physical abnormalities are sometimes observed in nauplius stages. Symptoms range from missing or abbreviated caudal setae to crimping of abdomen, clubbed abdomen, or in some cases, two heads (AQUACOP 1977a; AQUACOP 1979).

14) Survival from Nauplius (or Protozoa I) to Postlarva is sometimes lower in captivity-produced larvae vs. wild-produced.

15) Survival (during growout) of PL's produced in captivity is often, but not always, inferior, and survival is less predictable than in PL's produced from healthy wild females.

16) A higher incidence of physical abnormalities in growout is correlated with captive reproduction. Common abnormalities include curved rostra, abbreviated or blunted rostra, disfigurement of one or more tail segments, and enlarged carapace, especially over gills. Holloway et al. (1990) and Kalagayan et al. (1990) have reported a positive correlation between incidence of IHVN virus and physical abnormalities.

17) Some offspring of captive-matured females are clearly inferior in terms of growout performance, exhibiting "runting" (arrested or lower growth) or variability in size frequency distributions (Holloway et al. 1990; Kalagayan et al. 1990).

Observations 13-17 are barely documented in the reproduction literature, but are in fact frequently encountered. Interestingly, a biochemical basis for these differences resulting from captive reproduction, and particularly, from eyestalk-ablation induced, captive reproduction, has not been identified. It is clear, however, that as diets for reproduction have improved, so also have

reproduction results. There is strong circumstantial evidence that part of the problems seen with captive reproduction are related to a simple inability of current diets to supply required nutrients as rapidly as required for the gonadal hypertrophy stimulated by eyestalk ablation. In nature, an organism would not be anticipated to develop eggs, constituting some 10% of female body weight, unless nutrients are available for first, metabolism, second, growth, and third, reproduction. Eyestalk ablation accelerates the production of ova, regardless of whether the proper types and balance of nutrients are available, and regardless of whether those ova are even capable of fertilization. Dietary factors clearly have been shown to influence percentage hatch and percentage of females spawning (see Nutrition section).

While many of the undesirable characteristics sometimes observed in captive reproduction do not appear to be related to eyestalk ablation per se (e.g., a nutritional deficiency may cause lower hatch, larval deformities, or slowed development times; lower survival of ablated females appears related to an associated bacterial pathogen, rather than ablation per se; high variability in growout size frequency distributions has been correlated with IHHN virus presence, not ablation per se, etc.), there is some evidence that eyestalk ablation does cause abnormal ova development which could be expected to reduce the quality of offspring. While several studies of penaeid shrimp have found no histological or biochemical distinctions between ovaries produced with or without eyestalk ablation (Duronslet et al. 1975; Lawrence et al. 1979), Teshima et al. 1988; Browdy 1989), Anilkumar and Adiyodi (1980) induced ovarian development in the crab, Paratelphusa hydrodromus, during the non-breeding season, and observed the following differences in ovaries of ablated and unablated females:

- 1) Levels of all organic substances were drastically lower in ablated Vitellogenesis II ovaries compared with normal Vitellogenesis II ovaries from the regular breeding season.

- 2) Abnormally high numbers of Vitellogenesis I stage oocytes were found sandwiched among Vitellogenesis II oocytes. Thus, there appeared to be a pattern of unequal yolk deposition among oocytes in ovaries of destalked crabs from the non-breeding season, resulting in apparent disruption of natural synchrony.

- 3) The proportion of lipid to protein in ovaries of destalked crabs was higher than in intact crabs.

- 4) Observed differences were not believed to be related to nutritional availability.

These observations, although made on a crab rather than a shrimp, lend considerable credence to the likelihood that certain biochemical deficiencies, affecting at least a portion of ova, are related to eyestalk ablation per se. The extent to which such deficiencies are also produced during the actual

breeding season, the extent to which better maternal and larval diets can compensate, and the extent to which deficiencies may be individual species related, are not known. Lawrence et al. (1979) found some evidence that spawned eggs of captive P. setiferus had higher percent lipid than wild-spawned eggs.

Higher mortality of females sometimes associated with use of eyestalk ablation (Emmerson 1980; Primavera et al. 1982; Chamberlain 1981b; Poernomo and Hamami 1983; Makinouchi and Honculada-Primavera 1987) appears to be associated with bacterial infection allowed by invasive surgery, i.e., eyestalk ablation. In support of this, Poernomo and Hamami (1983) found greatly improved survival of ablated females after introducing an antibiotic regime of Streptomycin at 1.5 to 2.0 ppm or Malachite Green at 0.01 to 0.05 ppm, as well as chlorination during tank cleaning. Browdy (1985b) found that an initial one hour 5 ppm Nitrofurazone bath, and additional treatment about each 10 days, reduced mortality in ablated P. semisulcatus females. Thus, while no definitive research has been conducted to pinpoint causes of the mortality in eyestalk ablated animals sometimes reported, there is circumstantial evidence that bacterial infection is a primary cause. This is a strong argument for using either the cauterization or ligation techniques, which close the wound, or antibiotic treatment (topical or dip) in conjunction with eyestalk ablation. Makinouchi and Honculada-Primavera (1987) compared survival 15 days following eyestalk ablation of P. indicus females using three techniques of eyestalk ablation (pinching, cauterization, and ligation) against unablated controls. They found 100% survival of unablated controls, compared with 91 and 95% survival for cauterized and ligated treatments, and 76% survival for the eyestalk-pinched treatment. Assuming these data are not confounded by molt stage differences, they indicate a strong advantage to using an eyestalk ablation technique which closes the wound, reducing hemolymph loss and avoiding potential bacterial invasion. Cauterization has been used with good success by Muthu and Laxminarayana (1977), Browdy and Samocha (1985a,b), Browdy et al. (1986), and Makinouchi and Honculada-Primavera (1987).

5.2.8 Eyestalk Ablation Techniques

Unilateral eyestalk ablation is accomplished in the following ways:

- 1) Simple pinching of the eyestalk, usually performed half to two-thirds down the eyestalk. This method may leave an open wound.
- 2) Slitting one eye with a razor blade, then crushing eyestalk, with thumb and index fingernail, beginning one-half to two-thirds down the eyestalk and moving distally until the contents of eyes have been removed. This method, sometimes called enucleation, leaves behind the transparent exoskeleton so

that clotting of hemolymph, and closure of the wound, may occur more rapidly.

3) Cauterizing through the eyestalk with either an electrocautery device or an instrument such as a red-hot wire or forceps. If correctly performed, this method closes the wound completely and allows scar tissue to form more readily. A variation of this technique is to use scissors or sharp blade to sever the eyestalk, and then to cauterize the wound.

4) Ligation by tying off the eyestalk tightly with surgical or other thread. This method also has the advantage of immediate wound closure.

A more complete discussion of eyestalk ablation techniques can be found in Makinouchi and Honculada-Primavera (1987).

5.2.9 Molt Cycle v. Eyestalk Ablation

Since molting and ovarian development occur at different times of the molt cycle, it has been theorized that the timing of eyestalk ablation might influence reproductive performance. While it has long been observed that eyestalk ablation of a female which happened to be in late premolt would cause mortality, timing of ablation within the intermolt period has not been tested until recently. With a mean molt cycle duration of 22 days, Browdy and Samocha (1985a) compared reproductive performance of females ablated 8, 9 and 10 days postmolt (roughly in the second quarter of the molt cycle) with females ablated 13, 14, and 15 days into the molt cycle (toward the latter part of the third quarter of the molt cycle). They found that in the first 11 days, females ablated early produced about twice as many eggs as those in the latter ablation group. However, in the next 11 days, the pattern was reversed. The authors concluded that animals ablated early in the molt cycle had time to mature and spawn before molting, while most females ablated later in the molt cycle began to spawn only after molting. There appeared to be a possible trend toward increased total egg production from females ablated late in the molt cycle.

Molting (ecdysis) is a cyclical pattern of shedding of cuticle, or exoskeleton, which occurs throughout the life of marine shrimp. As one exoskeleton is shed, a new and larger exoskeleton hardens, allowing growth to continue. In the earliest life stage, larvae molt between substages in a matter of hours. As shrimp grow, the molt cycle lengthens to approximately three weeks under optimal temperature during adulthood. In decapod crustaceans, the molting process is an energy demanding process, with numerous physiological and biochemical changes affecting the entire body of the organism. Because molting and reproduction, especially in females, are both energy-demanding processes, they appear to be antagonistic in terms of biological programming (Adiyodi and Subramoniam 1983). Observations in wild populations of P. indicus, P. merguensis and P. semisulcatus support this

concept. For example, Read and Caulton (1980) found no mature ovaries in P. indicus with molt stage D₃ or A₁. Crocos and Kerr (1983) found no recently molted females with developed ovaries, beginning vitellogenesis during the intermolt period, and the majority of ripe ovaries occurring during premolt. Schlagman et al. (1986) correlated ovarian development with cuticle hardness in P. semisulcatus, and also concluded that ovarian development and spawning occurs between two successive molts. In summary, the energy-demanding processes of spawning and molting appear to occur discretely, with spawning or resorbing of ovaries occurring during the late intermolt or early premolt stages of the molt cycle.

5.2.10 Latency Period: Eyestalk Ablation to Ovarian Development

Once females have been subjected to eyestalk ablation, complete ovarian development often ensues within as little as 3 to 10 days, assuming the animals were removed from a breeding or ready-to-breed population, of adequate size for reproduction, and not subjected to too much transfer stress. If the animals have been removed from non-conductive environmental conditions (e.g. cold, non-breeding season temperatures, or hypersaline conditions), a longer than normal latency period between eyestalk ablation and ovarian development can be anticipated, probably due to seasonal hormonal cycling. Duration of the latency period between eyestalk ablation and maturation of ovaries is determined by the readiness of the population at the time of eyestalk ablation. Ruangpanit et al. (1985) found a population of P. monodon from a natural breeding area began spawning 4-5 days after eyestalk ablation, while a second population took 20 to 30 days to begin spawning. Similarly, Bray et al. (1988) reared P. monodon in a hypersaline pond; mating occurred regularly, but ovarian development and spawning did not occur until the adults were exposed to oceanic-salinity culture water for about 30 days.

5.2.11 Artificial Insemination, in vitro Fertilization

Because one of the troublesome obstacles to accomplishing penaeid reproduction in captivity has been the achievement of spermatophore transfer, some research has focused on artificial insemination. Artificial insemination is routinely used in some laboratories, (e.g., AQUACOP 1983a), to accomplish fertilization when environmental conditions (either water quality or exogenous influences such as light, noise, etc., are inhibitory to mating. While artificial insemination can be useful in increasing production in a maturation laboratory, or in the collection of wild spawners (in open thelycum species), it also has long-term significance in its potential for interspecific and intraspecific pairings of individual males and females for genetic selection of desirable traits in domestic stocks. Because of the

physiological differences in the genitalia of open and closed thelyca species, the procedures are distinct for each group.

In open thelycum species, artificial insemination is accomplished by removal of spermatophores from a male, manually or by electroejaculation (Sandifer et al. 1984), removal of sperm from spermatophores, and placement of the sperm mass externally near the female gonopores prior to spawning. This method of fertilization has been utilized by Persyn (1977); Laubier-Bonichon and Ponticelli (1981); Bray et al. (1982); AQUACOP (1983a); Bray et al. 1983; and Bray and Lawrence (1984). In the closed thelycum species, spermatophores can be implanted into the thelycum while the female is soft (at molt, prior to ovarian maturation) or during the intermolt period (Laubier-Bonichon and Ponticelli 1981; Lumare 1981; Ponticelli 1981; Muthu and Laxminarayana 1984; and Lin and Ting 1986). Designs for restraining devices for use in artificial insemination have been reported by Tave and Brown (1981) and Olivier and Salinger (1984).

Lin and Ting (1986b) accomplished in vitro fertilization in P. monodon by introducing a sperm suspension into a spawning tank just prior to release of eggs by the female. This procedure apparently requires tedious synchronization of addition of the sperm suspension with spawning, but might be a practical method for use in interspecific hybridization with either closed or open thelycum species. In vitro fertilization of P. merguensis has been recently reported by Nair (1987). Clark et al. (1973) reported one instance of in vitro fertilization in the brown shrimp, P. aztecus, although the results have not been replicated. Successful in vitro fertilization has also been reported recently in palaemonid shrimp (Berg et al. 1986). In the penaeid shrimp Sicyonia ingentis, cryopreservation of sperm has been reported (Anchordoguy et al. 1988).

Interspecific hybridization to achieve heterosis, or stock improvement, is not yet a commercial reality, although artificial insemination has been used to produce hybrids of P. stylirostris and P. setiferus (Lawrence et al. 1984), and P. schmitti and P. setiferus (Bray et al. 1990).

Genetic manipulation of domestic stocks is still very primitive today. However, closing of life cycles opens the way for stock improvement through selection for traits such as growth rate, disease resistance, and tolerance of specific environmental parameters. Selection for improved growth will likely succeed, as in other domestic stocks, despite relatively low levels of genetic variation in penaeid populations (Lester 1979a,b; Lester 1983; Mulley and Latter 1980, Mulley and Latter 1981a,b; Redfield et al. 1981). Considerable genetic variation in the growth rate of larval penaeids is indicated by the heritabilities reported by Lester (1988) for size of P. vannamei postlarvae ($h^2 = 0.15 \pm 0.32 - 0.36 \pm .40$) and P. stylirostris ($h^2 = 0.84 \pm 0.79 - 1.02 \pm 0.60$). In the American lobster, Homarus americanus, Hedgecock and Nelson

(1978) suggested that up to 30% of the variation in juvenile growth may be heritable.

5.2.12 Percent Females Participating in Nauplius Production

From studies in which reproductive performance of individual females has been compared, it is clear that even using the stimulus of eyestalk ablation, participation in breeding is extremely variable among females (McGovern 1988). Bray et al. (1990a) found in a population of *P. stylirostris* about 70% of nauplii were produced by only 25% of females. This pattern also has been seen in populations of other species, and Wyban et al. (1990) indicated that a great deal of the variability among *P. vannamei* females in reproductive performance may be due to genetic factors. Knowledge of participation vs. non-participation in breeding can be utilized to cull and replace non-performing females from a population, thereby increasing the percentage of females participating and larval production. Additionally, knowledge of participation in breeding is helpful in avoiding decreased gene pool (Sbordoni et al. 1986).

5.3 SEAWATER PARAMETERS FOR REPRODUCTION

Because an organism tends to thrive best in its natural medium, it is the job of the culturist working with reproducing penaeids to provide seawater of basically oceanic character. Seawater is a complex medium consisting of primary and trace elements, and its elemental composition may vary in dramatic to subtle ways from location to location, from estuary to nearshore water to offshore water, and among different ocean-fronting locations. Even temporary storage of seawater has been shown to alter its ability to support bacteria, which indicates the subtle changes which may occur in water treatment systems.

It is instructive to remember that in nature, all members of the genus *Penaeus* migrate to generally oceanic character water by adulthood, and reproduction occurs in this life cycle phase. The reasons for this shift in habitat are not known, but the result of this migration is to place the organism in a medium in which temperature and salinity are relatively stable, and land-derived trace minerals are relatively scarce. The following are very basic water quality requirements for reproduction which must be addressed in order to achieve *Penaeus* spp. reproduction.

5.3.1 Salinity

Salinity should be maintained from 28 to 36 ppt for most species. Optimal salinity by species has not been experimentally determined, but this range is widely used in penaeid research and commercial laboratories. This

range also generally matches the oceanic-character water to which penaeids are exposed during breeding. There is a preference among some P. vannamei culturists for 32 ppt culture water, which might indicate a positive stimulus of fresh water run-off to near-shore breeding areas for some species. Conte et al. (1977) observed mating and subsequent spawning, but no hatching, in P. stylirostris at 44 ppt. However, slight hypersalinity probably is not detrimental, and may be beneficial in those species which naturally inhabit higher salinity bodies of seawater such as the Mediterranean Sea. Browdy and Samocha (1985a,b) and Browdy et al. (1986) had excellent reproduction results with P. semisulcatus at 40 ppt. In the case of P. monodon, Bray et al. (1988) found that broodstock cultured in hypersaline ponds (45 ppt and slightly higher) were mating, but required 3-5 weeks conditioning to 35 ppt seawater to develop ovaries, achieve normal exoskeleton coloration, and begin spawning.

5.3.2 Temperature

While many aspects of temperature regimes have not been tested, the range of 27 to 29° C is believed to be almost universally optimal. Generally, temperature below 26° C will greatly reduce reproductive performance in most species. Slightly lower optima are probable in more temperate and deeper water species. Laubier-Bonichon (1978) stimulated spawning in unablated P. japonicus at 24 to 26° C, with 14.75 to 16.0 hours light. Penaeus chinensis reportedly matures at 18°C, quite unusual within the genus (Liu 1983; Dong 1990). Increasing temperature and day length are considered to be important cues in nature for onset of spawning in a number of species, although response to natural stimuli may be lessened by use of eyestalk ablation. Stability of temperature during the maturation process is considered important for some species, such as P. vannamei, and less important for others, such as P. stylirostris and P. indicus.

One technique which is sometimes used as a mild stimulus to spawning (when females are transferred to isolation tanks for spawning) is to use slightly elevated (by 1.0 to 1.5°C) temperature in the spawning tank water (Laubier-Bonichon and Laubier 1976). This technique may help overcome handling stress which could cause resorption of ovaries rather than spawning, or at least hasten the spawning process.

Interestingly, Magarelli, Jr. (1981) showed a negative correlation between time in spawning tank prior to spawning and percentage hatch of ova in P. stylirostris. As time in spawning tanks prior to spawning increased, percentage hatch decreased. This phenomenon may be an argument for using slightly increased temperature in spawning tanks as a stimulus to spawning, so long as other factors relating to temperature, e.g. bacteria levels, are not detrimental.

5.3.3 pH

It is strongly recommended that pH for reproduction be maintained at oceanic values of 8.0 to 8.2. Higher than 7.8 is probably acceptable. In flow-through systems, pH adjustments are not normally required. Low pH, common in recirculating seawater systems, is associated with decreased inorganic carbon, which has been shown to effect metabolism of calcium and several other minerals (Wickens 1976b; Wickens 1984a,b). Greater than 12 mg C/l is recommended by Wickens (1976b). Frequent additions of sodium hydroxide and/or calcium carbonate can be used to maintain pH/alkalinity levels.

With *P. indicus*, considered to be one of the penaeids most amenable to reproduction, Muthu et al. (1984) found a complete inhibition to maturation and spawning in eyestalk-ablated females whose recirculated culture water went from pH 8.2 to 7.2 over a 10- to 12-day period. Controls treated daily with sodium carbonate began spawning 3-4 days after ablation. In untreated tanks, some females achieved Stage 2-3 ovaries, but resorbed before spawning.

5.3.4 Dissolved Oxygen

As a general rule, dissolved oxygen should be maintained close to saturation to provide the best culture conditions, with greater than 5 ppm a reasonable rule of thumb. In practice, dissolved oxygen is not usually limiting if a) maturation tank stocking density is low; b) relatively high seawater flow is provided; and c) high levels of organics (e.g., from excess food, feces, and spawned eggs) are not present in tanks.

Aeration (usually supplied by regenerative blowers) is commonly used in maturation tanks, and from two to four airstone diffusers or one to two microporous strip diffusers are commonly used. Air diffuser types and configurations vary. One consideration in air diffuser placement is to make certain air lines do not interfere with the chasing and spermatophore transfer aspects of courtship, especially in open thelycum species. It is common practice to reduce or discontinue aeration during the evening mating period to reduce turbulence, although a requirement for this has never been shown experimentally.

5.3.5 Nitrogen Standards

Normal seawater values (oceanic) are 0.02-0.04 mg/l $\text{NH}_4\text{-N}$; 0.01-0.04 mg/l $\text{NO}_2\text{-N}$, and 0.1 to 0.2 mg/l $\text{NO}_3\text{-N}$. In the absence of empirical data demonstrating actual tolerances, we recommend that ammonia and nitrite values for reproduction be kept as close as possible to oceanic seawater values. Suggested guidelines are $\text{NH}_4\text{-N}$, < 0.1 mg/l, and $\text{NO}_2\text{-N}$, < 0.05 mg/l.

Nitrate buildup, common in recirculating systems, is considered relatively harmless but actual tolerance is not known.

Under general culture conditions for growout, higher nitrogen levels are quite acceptable, but it is recommended that water quality standards for reproduction be maintained at much higher standards. The actual toxic values for nitrogen (48-hour LC_{50} for seven species of penaeids) are 1.29 mg/l unionized NH_3 -N; 170 mg/l NO_2 -N and 3,400 mg/l NO_3 -N (Wickens, 1976). The Wickens "maximum acceptable level" for culture (not reproduction) which reduced growth by 1-2% of that of controls was 0.1 mg/l NH_3 -N (which corresponds to approximately 1.8 mg/l NH_4 -N at 28° C, pH 8.0, and 27 ppt).

5.3.6 Seawater Composition

Table 3 provides values for primary components of seawater (from Riley and Chester 1971), and Table 4 provides selected trace element levels (adapted from Quinby-Hunt and Turkian 1983). These values are useful to assess non-oceanic water sources such as deep wells or for evaluation of contaminants in seawater systems. Reported values of trace elements in seawater are sometimes suspect, due to use of obsolete techniques, interferences, or lack of familiarity with current methods of preconcentration of metals.

5.3.7 Heavy Metals

Exact standards for heavy metals as an influence on reproduction, either lethal or sublethal, do not exist, but review of available data (mostly short-term toxicity tests on species other than Penaeus) indicates a need to be extremely cautious in siting of reproduction facilities as well as in possible contamination of seawater systems by construction materials (pipes, pumps, walls, etc). Standards which may be roughly extrapolated from existing literature suggest that generally oceanic water quality is necessary. Nimmo et al. (1977) found that Penaeus duorarum would accumulate cadmium from seawater at levels of 30 ug/Cd/l or less. Mandelli (1971, c.f. Couch 1979) found copper to be toxic to P. aztecus and P. duorarum larvae at 0.05 mg/l, and normal growth occurred at 0.025 mg/l Cu. Inhibition of reproduction in the brine shrimp Artemia salina has been shown after exposure to extremely low levels of $CuSO_4$. While the 48-hour LD_{50} for this Artemia species, which is considered far more hardy than Penaeus, is about 25 ppt, adverse effects on reproduction were found at levels 24,000 to 156,000 times lower (Browne 1980). Other reported toxicity values for copper within the genus Penaeus and in other marine shrimp include: 1.3 mg/l, lethal in 24 hours to 100% of P. stylirostris larvae (Lawrence et al. 1981); 0.1 mg/l, toxic to lobster adults (McLeese 1974); 0.14 mg/l, reduced survival in the shrimp Mysidopsis bahia (Gentile et al. 1982); and 0.0777 mg/l, reduced reproduction in M. bahia

Table 3. Primary components of seawater (from Riley and Chester 1971).

Ion	g/kg of water, salinity 35 ppt
Chloride	19.344
Sodium	10.773
Sulphate	2.712
Magnesium	1.294
Calcium	0.412
Potassium	0.399
Bicarbonate	0.142
Bromide	0.0674
Strontium	0.0079
Boron	0.0045
Fluoride	0.0013

(Gentile et al. 1982). It is clear from these examples that care should be taken to avoid heavy metals toxicity from municipal, agricultural, and industrial sources, as well as contamination within a laboratory system. The TAMU Maturation/Reproduction lab has routinely used 10 ppm EDTA as a prophylactic chelator in semi-closed systems for penaeid reproduction, and has observed this additive used in flow-through systems as well, without apparent detrimental effects.

5.3.8 Pesticides

Synthetic organic chemicals used for industrial or agricultural purposes are extremely toxic to shrimp, and it is well to bear in mind their potential for reducing reproduction or reducing viability of offspring. Potential sources are land runoff, aerial spraying, and feedstuff contamination. Shrimp are closely related biologically to insects, and are vulnerable to pesticides throughout their life cycle. Vitellogenesis and egg and larval development may be expected to be more susceptible than later life stages for which some toxicity literature exists. Toxicity values of some pesticides to penaeid shrimp are shown in Table 5 (see Couch 1978 and Couch 1979 for discussion). Polychlorinated biphenyls, organochlorines, organophosphates, and carbamates are extremely toxic to shrimp, generally in parts per billion concentrations. Sublethal effects on reproduction could be anticipated at levels well below these actual toxicity values.

5.3.9 Organics

Table 4. Currently accepted values for concentrations of selected trace elements in seawater, mean ocean concentration, at salinity 35 ppt with standardized nutrient levels. (from Quinby-Hunt and Turekian 1983).

Element	Concentration (ng/kg)	Reference ¹
Chromium (Cr)	330	A
Manganese (Mn)	10	B
Iron (Fe)	40	C
Cobalt (Co)	2	D
Nickel (Ni)	480	E
Copper (Cu)	120	E
Zinc (Zn)	390	E
Selenium (Se)	170	F
Cadmium (Cd)	70	E
Mercury (Hg)	6	G
Lead (Pb)	1	H

¹ References: A, Cranston (1979); B, Landing and Bruland (1980), C, Gordon et al. (1982); D, Knauer et al. (1982); E, Bruland (1980); F, Measures and Burton (1980); G, Mukherji and Kester (1979); H, Schaule and Patterson (1981).

Coastal waters vary considerably in levels of dissolved organics, but these do not appear to be normally problematical to reproduction in flow-through seawater systems. In closed or semi-closed systems, opportunities are greater for elevated organics levels from food nutrients added into the system as well as feces and eggs. Uncontrolled, they form an excellent substrate for bacteria, fungi, and protozoans which can either be pests or potential pathogens. Additionally, it is possible, although certainly unproven, that excessive organic loading is associated with lack of mating sometimes reported, either from buildup of metabolites or by masking of pheromones required for courtship.

5.4 ENVIRONMENTAL AND BEHAVIORAL INFLUENCES

The following section summarizes a number of environmental and behavioral influences which have either been shown experimentally or are commonly believed to affect reproduction in captivity. It is probably safe to assume that with any particular parameter, shrimps' tolerances for less than optimal conditions are somewhat overcome by using the artificial stimulation of eyestalk ablation. Thus, because the organism's natural response to an adverse or unnatural environment is suppressed or overshadowed by eyestalk ablation, the animal can be expected to perform reproductively under less than optimal conditions. However, while reproduction will clearly proceed under less stringent environmental requirements, it is also logical to assume

Table 5. Examples of pesticide levels toxic to penaeid shrimp or related species. These values are taken from short term toxicity tests, and lower levels can be expected to influence reproduction.

Compound	Level	Period	Effect	Species	Reference
Aroclor 1016	0.9 ppb	96 hr.	8% mortality	<u>P. aztecus</u>	A
Aroclor 1016	10.0 ppb	96 hr.	43% mortality	<u>P. aztecus</u>	A
Aroclor 1254	0.9 ppb	14 days	some mortality	<u>P. duorarum</u>	B
Aroclor 1254	3.0 ppb	30 days	50% mortality	<u>P. duorarum</u>	C,D,E
DDT	0.1 ppb	8 days	mortality	<u>P. setiferus</u>	F
DDT	>0.1 ppb	28 days	mortality	<u>P. duorarum</u>	F
Diazinon	4.8 ppb	96 hr.	50% mortality	<u>Mysidopsis bahia</u>	G
Diazinon	3.2 ppb	96 hr.	low growth	<u>Mysidopsis bahia</u>	G
Diazinon	28.0 ppb	96 hr.	50% mortality	<u>P. aztecus</u>	G
Dibrom	2.0 ppb	48 hr.	50% mortality	<u>P. aztecus</u> PL's	H
Dibrom	5.5 ppb	48 hr.	50% mortality	<u>P. aztecus</u> adult	H
Dieldrin	0.9 ppb	96 hrs.	50% mortality	<u>P. aztecus</u>	I
Heptachlor	0.11 ppb	96 hr.	50% mortality	<u>P. duorarum</u>	J
Malathion	14.0 ppb	48 hr.	mortality	penaeids	K
Metamidophos	10.0 ng/l	24 hr.	50% mortality	<u>P. stylirostris</u> nauplii	L
Mirex	1.0 ppb	7 days	25% mortality	<u>P. duorarum</u>	M,N,O
Parathion	0.2 ppb	48 hr.	mortality	<u>P. duorarum</u>	K
Parathion	1.0 ppb	96 hr.	25% mortality	<u>Crangon septimspinosa</u>	P
Parathion	2.0 ppb	96 hr.	25% mortality	<u>Palaemonetes vulgaris</u>	P

¹ References: A, Hansen et al. 1974; B, Couch and Nimmo 1974; C, Duke et al. 1970; D, Nimmo et al. 1971; E, Nimmo et al. 1975; F, Nimmo et al. 1970; G, Nimmo et al. 1981; H, Butler and Springer 1963; I, Parrish et al. 1973; J, Schimmel et al. 1976; K, Couch 1978; L, Juarez and Sanchez 1989; M, Lowe et al. 1971; N, Tagatz et al. 1974; O, Markin et al. 1974;

that use of eyestalk ablation notwithstanding, more optimal environmental conditions will cause less stress to the breeding population and improve health and reproductive performance. While there is no comprehensive understanding of hierarchical or interactive effects of environmental and nutritional factors, there is clearly an interrelationship between biological needs (in terms of environmental and nutritional variables) and reproduction (e.g., accomplishment of mating, egg fertilization and hatching rate, disease vulnerability).

5.4.1 Maturation Vessel Size and Shape

Circular tanks with a minimum diameter of 3.65 m are recommended, and a slightly greater diameter may be preferable. In terms of configuration, round tanks are by far the most typical; however, rectangular, oval, or other shapes can be used. Circular tanks have the advantage of being somewhat

self-cleaning, by moving suspended particulates toward a central drain, and are sometimes designed with a slight bottom slope to facilitate movement of particulates to drain. Circular, rectangular, ovoid, or other configurations may be used so long as water flow is efficient, courtship distance is satisfied, and females can be readily observed and captured for isolation daily.

The most limiting factor in tank design for reproduction is a minimum width, which seems to be related to the "run" distance required during the courtship ritual prior to mating. Magarelli, Jr. (1981) reported that a 3 m "run" distance was required by P. stylirostris, and observations at the Texas A&M Shrimp Mariculture Project are similar: P. stylirostris would not mate in 2.4 m diameter tanks, but would in 3.65 m diameter tanks (Bray and Lawrence, TAMU, unpublished data). Crocos and Kerr (1986) found similar results with P. esculentus.

One novel approach to tank design has been used to lessen handling of females while assessing ovarian development. Emmerson et al. (1983) installed a translucent panel in one area of the tank bottom which could be used to backlight or silhouette females' ovaries. Scura (1988, personal communication, E. Scura, Aquatic Farms, Suite 1608, 1164 Bishop St., Honolulu, HI, USA 96813) has used a more elaborate variation of this with P. monodon in using tanks whose entire bottoms could be completely backlighted to silhouette ovaries. Such tank bottom modifications can be used instead of more commonly used methods of viewing ovarian development such as a bright hand-held spotlight, underwater (diver's) flashlight attached to a pole, miner's type headlamp, or bright overhead illumination.

5.4.2 Water Depth in Maturation Tanks

Common water depth in maturation tanks ranges from 35 to 50 cm. This shallow depth is functional in that the animals are clearly visible for ovarian observation and tank bottoms can be readily inspected for excess feed. This water depth seems to be adequate for mating of all Penaeus species, so long as the "run" distance for courtship is satisfied by tank width dimensions. In 2 m diameter tanks, Poernomo and Hamami (1983) found 8.7% of P. monodon spawns fertilized at a water depth of 60 cm, but 53.8% of spawns fertilized at water depth of 120 cm. Yano (1985) observed that P. japonicus mated in 25 m³ tanks, but not in 3 m³ tanks. Crocos and Kerr (1986) found that P. esculentus would mate in 3.2 m diameter tanks, 0.9 m deep, but not in 1 m diameter tanks with 0.3 m depth.

5.4.3 Stocking Density

Common stocking densities for adults in maturation tanks are 3 to 5 individuals per m². Stocking density is somewhat dependent on animal size,

incoming water quality, seawater flow rate, and water depth. AQUACOP (1977b) noted that their best maturation of P. monodon was achieved at densities less than 3 individuals/m², and said their best results were achieved at a density of 1/m². Chen et al. (1990) achieved P. vannamei maturation and mating at 10.4 shrimp/m² in a recirculating seawater system, but did not compare density as an experimental variable. Four to five individuals/m² is common with P. vannamei breeding. Especially small species may be stocked at higher density.

5.4.4 Female to Male Ratio

Because nauplii production is based strongly on female output, it is advantageous to use the lowest possible number of males with the highest number of females while still maintaining a high rate of egg fertilization, i.e., effective spermatophore transfer. Review of available data indicate that optimal female to male ratios are from 2:1 to 3:1 in closed thelycum species (see Primavera 1985 for discussion) and about 1:1 to 1.5:1 in open thelycum species. Because a closed thelycum species maintains spermatophores through several spawns within a molt cycle, while an open thelycum female must re-mate prior to each spawn, apparently fewer males are required to service a given number of females in closed thelycum species. Spermatophore regeneration time in captivity has been documented by Trujillo (1990).

Lack of mating has been a persistent and confusing problem in numerous reproduction trials, and has been the source of a great deal of speculation. In the authors' experience, poor mating can be due to environmental stress, use of immature or impotent males, inadequate tank size, poor water quality, and sometimes seems to be related to buildup of metabolites / organic substances in culture water. It is clear that some species are far more tolerant of water quality and environmental fluctuations than others. Species such as P. vannamei are especially susceptible to environmental quality, and mating is easily disrupted.

5.4.5 Substrate

No requirement has been established for a sand or other soil substrate in conjunction with shrimp maturation and spermatophore transfer. Although such a requirement has been postulated for several closed thelycum species, it has largely been disproved by later studies which were successful using bare tank bottoms. It appears that no tested species requires a substrate, with the probable exception of P. japonicus, a strongly burrowing species. Maturation culture vessels are commonly fiberglass, vinyl-lined, or concrete. Use of no-soil substrate in maturation tanks allows easier tank maintenance in terms of excess feed removal, sedimentation buildup, and possible toxicity from anaerobic activity, as well as easier cleaning and disinfection during dryout.

5.4.6 Tank Color

Black is the most commonly used color for inside surfaces of maturation tanks. There is some support in the literature for the idea that black tanks may be beneficial, although effects of tank color might be expected to be more a function of light intensity than tank color, or at least closely tied to available light intensity. Brown et al. (1979) observed that black tank walls reduced the incidence of P. setiferus running into tank walls, thus reducing eyestalk and cuticular damage. While it was not statistically significant, Emmerson (1980) reported twice the number of spawns of P. indicus in a black tank as were achieved in a white tank under light intensity of 70 $\mu\text{Wsec}/\text{cm}^2$. Average number of eggs per spawn and hatch rate were also higher in the black tank. General pigmentation, ovary, egg, and nauplius color were also observed to be dependent on background color. On the other hand, excellent reproduction results with P. semisulcatus were achieved by Browdy and Samocha (1985a,b) using black-walled tanks with white bottoms, at low light intensity. A light intensity of 0.1 to 0.3 microeinsteins / m^2 / sec was used.

5.4.7 Light Intensity

Reproduction of marine shrimp has been accomplished under such a broad variety of light intensity and other light conditions that it is difficult to suggest optima. Few empirical data exist, and some literature pertains to eyestalk ablated females only, which might be anticipated to have different responses to environmental cues. Also, optima may be expected to vary somewhat by species.

Although early success was seen in unablated P. japonicus at 500 to 4,000 lux (Laubier-Bonichon and Laubier 1979; Caubere et al. 1979), the tendency for some years has been to greatly reduce light intensity for maturation. AQUACOP (1983a) has used 10% incident light for several eyestalk-ablated species. Browdy and Samocha (1985a,b) had excellent results with ablated and unablated P. semisulcatus at 0.1 to 0.3 microEinsteins / m^2 / sec. Emmerson (1983) utilized 45-50 microWatts / cm^2 for unablated P. indicus. A trend toward lower light levels seems to agree with the calculation of Wurts and Stickney (1984), who estimated a light intensity of less than 12 microWatt / cm^2 / sec in the natural spawning habitat of P. setiferus.

However, it should be emphasized that eyestalk ablated females respond at a broad range of light intensity. For example, the authors have observed high levels of P. vannamei mating occurring in systems utilizing from 8 to 12, 4' fluorescent lamps (40-watt, usually "cool white") at peak lighting, and have also observed good mating when the only light regime provided was incidental light leaking through joints of an opaque roof, providing extremely dim conditions. It seems that when acclimated to a particular light level, ablated

P. vannamei as well as other species will reproduce over a broad range of light levels.

5.4.8 Light Spectrum

Values for spectral irradiance calculated for the ocean environment in which members of Penaeus spawn indicate that little light would be available except for shorter spectra (greens and blues) because of the rapid attenuation of longer wavelengths (such as red) in seawater. However, the majority of published research and commercial labs have utilized either cool white fluorescent lamps (mixed spectra) or diffuse natural light, which at appropriate intensities, do elicit maturation response and mating. At the TAMU maturation reproduction facility, we also have used "blue" fluorescent lamps with good results with P. stylirostris.

Emmerson et al. (1983) compared reproductive performance, animal condition, and growth of unablated P. indicus under green, blue, and diffuse natural light at 45 to 50 uWatt / cm² over a five-month period. They observed the highest mean number of females spawning per month in the natural light treatment, due to high spawning in months 1-3, but extremely poor reproduction performance in months 4 and 5. However, growth under the natural light had a negative slope and a "condition" factor, Kn, a relationship between fresh weight mass and carapace length, declined in the natural light treatment throughout the five months. Under green light, females spawned poorly in months 1 through 4, but at a high rate in month 5. Additionally, growth and Kn improved in months 2 through 5. Under blue light, month 1 spawning was high, but spawning declined in months 2 to 4 before rising again in month 5, as occurred under green light. Growth slope was positive only in month 5, and Kn improved in months 3-5. The authors interpreted these results to indicate that a) overstimulation of maturation occurred initially in the natural light treatment, adversely affecting animal condition, and b) over 4 to 5 months, it was possible to achieve simultaneous growth and maturation (1.3 to 1.75 spawns per female per month) using blue and green light. The immediate applications for these results are not clear, and the results raise further questions: After simultaneous growth and maturation are achieved, how long would this pattern continue? How applicable are the results to eyestalk-ablated females? From a practical standpoint, is it preferable to "overstimulate" maturation with natural lighting for three months, sacrificing growth, or to maintain breeders for four months before spawning begins? Clearly, many questions remain concerning light quality for reproduction.

5.4.9 Light Level Pattern

Most maturation literature describes systems using artificial light with simple on/off timers such that only one light intensity is used. However, it has become common in artificial lighting regimes to use several banks of fixtures on different timers to roughly approximate natural increasing and diminishing light levels. While there are no experimental comparisons of static v. staggered light levels, staggered lighting (or more elaborate light control) is probably beneficial. It seems logical that a more natural lighting regime would be less stressful, which might enhance reproductive performance, especially in more sensitive species.

Particularly in open thelycum species, courtship ritual and time of mating seem closely related to afternoon diminution of light intensity (AQUACOP 1977a). They noted that on cloudy days, mating and courtship occurred earlier than on bright days in tanks provided natural light. Speculation by AQUACOP that controlling intensity might increase the period of sexual activity and enhance chances of successful fertilization has not been pursued experimentally. However, because numerous examples of successful reproduction have been published using only static artificial lighting, mating time may be related to anticipation of darkness rather than diminishing intensity.

5.4.10 Photoperiod

Various light:dark regimes have been utilized in maturation experiments, and no clear optimum is suggested. Observational evidence suggests that the appropriate day-length is equal to or greater than the day-length during the natural breeding season of a given species. A 14 to 16 hour "day" period is frequently used. With unablated *P. japonicus*, Laubier-Bonichon (1978) found that a 12 hour light:12 hour dark regime led to an arrest of spawning. Renewal of spawning was initiated 15 days after lengthening the light period to 15 hours. In spite of these findings, spawning has been shown to occur year-around in captive ablated animals when other culture conditions such as temperature are held constant.

Photoperiod reversal is practiced in some commercial maturation facilities which utilize artificial lighting in order to lessen the labor intensive nighttime activities (evaluation and isolation of mature and/or mated females). Photoperiod reversal accomplished over a several week period is probably less stressful than abrupt change.

5.4.11 Turbulence

Turbulence in maturation vessels is usually kept to a minimum and incoming seawater is often introduced below the water to help reduce turbulence. Excessive turbulence is thought to be disruptive to courtship and

spermatophore transfer in open thelycum species. Water flow (as well as aeration) is sometimes reduced or discontinued during mating hours.

5.4.12 Noise/Environmental Stress

Shrimp do exhibit stress response to noise, and care should be taken to place activity and mechanical areas well removed from culture areas. Mechanical areas can often be located on a separate slab. While no research has been conducted with Penaeus spp., studies with Crangon crangon have shown decreases in reproductive activity, feeding, and growth, and increases in mortality, aggression, and cannibalism (Lagardere and Sperandio 1981; Lagardere 1982), as well as increased metabolic response (ammonia excretion) when comparing ambient lab noise levels with controls in soundproofed culture tanks (Reynault and Lagardere 1983).

Stress from environmental sources other than noise should also be avoided whenever possible. Shadows, handling, tank cleaning, environmental fluctuations, etc., should be kept to a minimum.

5.4.13 Seawater Flow Rate

Water exchange rate required is dependent on factors such as animal size, stocking density, feed type, number of feedings/day, organic load of the water supply, and other factors relating to the biological load on the culture system. In flow-through systems (once-through) seawater systems, this usually translates to roughly 100% to 400% exchange rate per 24 hours. There has been a feeling among some culturists that lower flow rates are preferable in order to reduce turbulence and increase mating. However, we feel that improvement of water quality using higher flow rates is often beneficial to animal health generally, decreases stress, and benefits reproductive performance. We have received reports that P. vannamei has performed well at continuous flow up to 600% per 24 hours. Bray et al. (1990a) reported high mating rates with P. stylirostris at 350% exchange per 24 hours. In recirculating seawater systems, recirculation rates are normally 300 to 500% per 24 hours, or higher, and required flow rate is dependent on efficiency of biological and mechanical filtration. A behavioral limitation related to water flow rate, such as water velocity as a limitation to mating, has not been established. Flow rate is often reduced during mating hours with open thelycum species.

5.4.14 Lunar Effects

Lunar effects on penaeid reproduction are not well demonstrated, and are not currently utilized in reproduction laboratory management. However, there is some evidence that such influence exists. Hanson and Goodwin (1977) reported that several species seem to have peak reproduction in

conjunction with lunar cycles. AQUACOP (1977a) noted that with captive unablated P. merguensis exposed to a portion of incident natural light there seemed to be a one-week reproduction peak linked to lunar period.

It is clear that in the wild lunar phase is related to biological rhythms in shrimp. Boddeke et al. (1976) has shown that sensitivity to stimuli triggering migration (such as temperature) decreases the farther the shrimp is away from the next molt. Thus, different waves of migrating shrimp in nature exhibit close molt synchronization. He also found that berried Crangon crangon are more sensitive to migratory stimuli than non-berried females. Boddeke found striking patterns in both C. crangon and P. brasiliensis suggesting extremely rigid migration and distribution patterns, strongly tied to physiological condition (especially molt cycle). Boddeke speculated that moonlight may have a directly inhibitory effect on migration, and observed in P. brasiliensis an apparent relationship in which the inhibiting effect of moonlight (or associated tides?) would gradually become stronger, practically blocking migration during the two-week period around full moon. Such strong response to environmental cues could be expected to have a strong influence on reproductive rhythms as well.

5.4.15 Phytoplankton

Evidence has been presented that spawning in a number of invertebrates other than shrimp appears to be correlated with or stimulated by phytoplankton blooms. In the sea urchin, Strongylocentrotus droebachiensis, and the chitons Tonicella lineata and T. insignis, Himmelman (1975) induced spawning by addition of phytoplankton to culture vessels. Miyasaki (1938) induced spawning in the oyster Crassostrea gigas with a substance found in a macroalga, Ulva sp. Barnes (1957) and Barnes and Stone (1973) have presented evidence that release of barnacle nauplii is causally related to the spring diatom bloom. The theory is elegant in logic: that organisms whose larvae require phytoplankton as food would be cued to spawn by blooms of those phytoplankton. However, no evidence has been presented which lends support to this theory in shrimp. One study, Chamberlain and Lawrence (1981b), attempted to stimulate reproduction in P. stylirostris and P. vannamei by daily additions of Chaetoceros gracilis, but no effect was seen.

5.4.16 Spawning Tanks

In virtually all commercial schemes for maturation laboratories, females are isolated from large, group culture tanks into small individual spawning tanks the evening spawning will occur. Females which are ready to spawn (complete ovarian development) and mated naturally or through artificial insemination are gently netted, carefully handled for inspection and then immediately transferred to a spawning tank. This technique allows one to

follow performance data of individual females, allows segregation of the best spawns for continued culture, and isolates a female prior to spawning into water which has been highly filtered, often disinfected, and often prophylactically treated with a gram negative antibiotic. It is presumed that spawning of females in isolation tanks of this type will increase hatch rate and nauplii performance by decreasing susceptibility of eggs to bacterial and fungal invasion. Frequently, gram negative antibiotics and EDTA at 10 ppm are added as a prophylactic measure (see Licop 1988 for discussion).

Individual spawning tanks are usually a minimum of 75 l, and are often 100 to 150 l, with circular tanks with lids preferred. Low aeration is recommended (Emmerson 1980). Primavera (1985) recommended that egg density in spawning tanks not exceed 2,500 to 3,000 eggs/ liter, or hatch rate would be adversely affected. Primavera also suggested using the same rule of thumb for incubation tanks as well, although incubation tanks of 20 to 50 l are often used. The morning following spawning (or if animals are on reversed photoperiod, some 3 to 6 hours after spawning), females are carefully removed and returned to their respective maturation tanks. The spawned eggs remain in the spawning tanks, and can be left there to hatch or may be collected, rinsed, and transferred to a smaller hatching vessel of 20 to 40 l. Advantages of using the latter method include: a) large spawning tanks are vacated, to be refilled for the new day, b) eggs are separated from the water in which the female spawned, which also contains feces and what has been referred to as a "proteinaceous scum" which is often extruded by the female along with spawned eggs. The smaller vessels into which the eggs are placed can be more easily transported to larval rearing tanks prior to larval metamorphosis to Protozoa I. An alternative to static or non-flowing spawning tanks sometimes used is gentle flow-through, which may aid in nauplii recovery through light attraction. There are also several examples in the literature of direct egg or nauplii collection from maturation tanks (e.g., Laubier-Bonichon and Laubier 1979; Lawrence et al. 1980; Simon 1982; Chen et al. 1990). This is highly desirable in a commercial situation, as it can obviate the need for nightly evaluation of females, subsequent isolation of females, and maintenance of numerous spawning vessels. However, such systems are not in common usage, as it is usually necessary to assess individual spawns.

5.5 NUTRITION

5.5.1 Practical Diets

Nutrition is profoundly important to reproduction of Penaeus, and the success of reproduction is closely related to nutrient ingestion accompanying ovarian development. It is illustrative of this point that many culturists have

observed hatch rates dropping to zero within a week after altering females' diets with inadequate food sources. This is not to imply that nutrition during pre-gonadal development is unimportant, but to stress the importance of immediate ingestion of nutrients for building of ovarian tissue. While the hepatopancreas, or digestive gland, is often referred to as a storage organ, in many respects it serves as a processing, rather than long-term storage, organ. Using radioactive tracers, Teshima et al. (1988) showed labelled palmitic acid (C16:0) and linolenic acid (C18:3(n-3)) increases in the ovaries of P. japonicus with concomitant decrease in labelled hepatopancreas tissue within 24 hours. Galois (1984) and Castille and Lawrence (1989) have estimated the potential contribution of lipid from the hepatopancreas at 40% in P. indicus and 57.5% in P. setiferus, respectively. Millamena and Pascual (1990) have also presented evidence of a storage role of the hepatopancreas in P. monodon.

In view of the critical importance of proper nutrition to captive breeding, it is surprising that dietary needs are not better defined either in terms of nutrient requirements, practical ingredients for compounded diets, or at least in terms of the most appropriate fresh food organisms. However, nutrient requirements and fresh-food diets are only crudely defined, and we are not familiar with any prepared maturation diet which serves alone to accomplish successful reproduction. Diets used for reproduction consist of one or more fresh (or fresh-frozen) marine organism ingredients, with the most common being squid, mussels, clams, shrimp, brine shrimp, and polychaete worms. Additionally, fish, shark, mysids, trocha, krill, cockles, crab, and other items have been reported as breeding diets. These ingredients are often chopped into approximately 0.5 to 1.0 cm pieces, rinsed, and fed two to five times daily to breeding populations. Usually only one item is fed per feeding so that a preferred item is not selected. In addition to feeding between one and four fresh feed ingredients, a high quality commercial or prepared diet is often fed, usually around 25% of diet (dry weight basis), and occasionally higher, to around 50%. Even though prepared rations do not serve as a complete substitute for fresh food components at this time (e.g., Primavera et al. 1979), they can provide valuable vitamin/mineral supplements as well as help balance macronutrients.

In addition to fresh (or fresh-frozen) marine animal food sources, a macro alga, Enteromorpha sp., has also been introduced as a supplement for P. stylirostris (Bray et al. 1990a) and P. monodon (Bray and Lawrence 1988). Of these species, P. monodon especially seemed to graze the Enteromorpha. Enteromorpha sp. meal has been added into a prepared ration by Emmerson (1980) and Emmerson et al. (1983) for P. indicus. It is noteworthy that the nutritional value of fresh or fresh-frozen animal or plant components can vary in nutritional quality with species, lifestage, season of collection, nutritional condition, freezing method, and storage. Additionally, most published studies

report only short term results, rather than following the breeders and their offspring over time, which would put more pressure on diets and confirm viability of offspring into growout.

Choice of feed items is often based more on regional availability rather than proven success, but there are widespread beliefs in the benefits of certain feed items with certain species. In the Western Hemisphere, P. vannamei is usually fed a portion (25% to 35%, dry weight basis) of bloodworms, commercially available polychaete worms obtainable from Panama (Americanuphus reseii) or from the fishing bait industry in the U.S. state of Maine (Glycera dibranchiata). In the South Pacific, AQUACOP (1977a) observed that fresh Trocos niloticus appears to hasten the final maturation of ovaries in several species of penaeids. They also recommended that fresh food organisms used in broodstock diets should themselves have mature gonads. Squid is a common denominator of many diets, and brine shrimp adults have been found to produce a dramatic feeding response in P. stylirostris. (Bray and Lawrence, TAMU, unpublished data).

5.5.2 Influence of Diet

While literature relating to diets is sparse, a number of useful observations have been published. Middleditch et al. (1979) and Middleditch et al. (1980a) compared fatty acid profiles of ovaries in P. setiferus, P. stylirostris, and P. vannamei, and then induced spawning in P. setiferus while feeding a supplement of polychaetes rich in long carbon chain polyunsaturated fatty acids which were also predominant in the shrimp ovaries, C20:4(n-6), C20:5(n-3), and C22:6(n-3) fatty acids. They suggested, circumstantially, that it was the fatty acid component of bloodworms that was responsible for the ovarian stimulation. They cautioned that the diet was not optimal and observed that laboratory-reared females' hepatopancreases contained 2.0 to 4.4 times higher percent lipid than wild female controls. Proportions of 20- and 22-carbon fatty acids were also altered. Additionally, Middleditch et al. (1980b) surveyed five species of marine annelids, four species of bivalves, two species of crustaceans, and a gastropod, and concluded that almost all of these displayed substantially similar fatty acid patterns. The balance of n-3 and n-6 fatty acids (Lytle et al. 1990) and the possible role of arachidonic acid as a precursor of prostaglandins (Middleditch et al. 1980; Croz et al. 1988) have been suggested to be limiting factors. Chamberlain and Lawrence (1981a) found that growth and maturation of P. vannamei and P. stylirostris were enhanced with a combination diet consisting of squid, shrimp, bloodworms, and clams, over any single-food diet. Magarelli, Jr. (1981) compared reproductive performance in unablated P. stylirostris and found correlations with several fatty acid levels in ovaries. The level of C20:1(n-9) correlated positively with number of eggs spawned; linoleic acid

C18:2(n-6) content was negatively correlated with number of eggs spawned in a P1 but not an F1 population; and C22:6(n-3) level was positively correlated with hatch in the F1 but not P1 population. Cahu et al. (1986) confirmed that dietary fatty acids were reflected in spawned eggs and found that eggs of females fed a pelleted diet only were lower in C20:4(n-6), C20:5(n-3), and C22:6(n-3), and higher in C18:2(n-6), and had different ratios of n-3/n-6 fatty acids compared with diets containing part or all fresh mussel. Gomez and Arellano (1987) reported that addition of 11% bloodworms to diets of squid, oysters, and pellets improved reproductive performance of P. vannamei. Cahu et al. (1987) found that mean number of eggs per spawn was related to dietary phospholipid content, and also confirmed that fatty acid content of the diet was reflected in eggs.

Browdy et al. (1989) produced evidence that an Artemia supplement increased reproductive performance of P. semisulcatus. Galgani et al. (1989a) tested four diets with P. vannamei and P. stylirostris: one composed of mussels, gastropods, fish, and squid, and three diets with 88% prepared ration:12% fresh component diets. A high spawning rate (up to 2.8 spawns per female per 30 days in P. vannamei, and 4.7 spawns for P. stylirostris) was achieved in some of the 88% prepared:12% fresh regimes as well as with the 100% fresh organism diet, although egg fertilization rates were generally low across the board (16-30% in P. vannamei, 21-27% in P. stylirostris). Actual enhancement of reproduction with a prepared diet was shown recently by Galgani et al. (1989b) with P. indicus after surveying 10 diets, including three single-component fresh diets (mussel, gastropod, squid) and a multiple component fresh diet. They found best results with a diet containing all three fresh components at 40% dry weight, and 60% of the diet as a prepared ration. This diet outperformed others tested for mean number of spawns per 30 days, eggs per spawn, and fertilization rate. Bray et al. (1989) found evidence that a soy lecithin supplement increased nauplius production in P. stylirostris.

Additionally, Bray et al. (1990a) compared six diets using fresh and compounded dry diets with P. stylirostris. Three total dietary lipid levels, as well as squid-only at 40% of diet versus multiple fresh components, were compared. Diets containing the multiple fresh supplement generally outperformed the squid-only supplement, and 7.8% or 11.1% total lipid produced better results than 13.9%. Kanazawa (1990) reported recently that the substances in clam meat which induced ovarian development in P. japonicus are both lipid and protein fractions.

5.5.3 Biochemical Characterization of Diets

Nutritional guidelines for reproduction are only crudely defined, but it is possible to generally characterize diets in use. They are high in protein (45-

65% protein), utilize primarily marine animal sources of protein, often with amino acid profiles similar to shrimp, and have high protein:energy ratios. Additionally, the importance of the lipid component of diets for breeding is unquestioned, although precise recommendations for essential fatty acid levels, ratios of n-6 (linoleic family) to n-3 (linolenic family) fatty acids, phospholipid requirements, and cholesterol requirements are not available. Vitamin and mineral requirements have not been defined, although some recent work with breeders suggests a definite Vitamin E requirement. Additionally, in the absence of data specifically for broodstock, vitamin and mineral requirements established for larvae might be used as a guide.

The need for attention to the lipid portion of the breeders' diets is clear. Because of the rapid rate of ovarian tissue synthesis (ovaries may comprise 10% or more of female weight), accelerated rate of ovarian development with eyestalk ablation, and limited storage function of the digestive gland ("hepatopancreas"), the large amount of lipid in ovary tissue, and limited ability of shrimp to synthesize long carbon chain, polyunsaturated fatty acids predominant in ovaries, inability of shrimp to synthesize sterols, and high phospholipid requirement, the importance of lipid quality is overwhelming. Studies with *P. japonicus*, *P. monodon*, and *P. merguensis* have established linoleic, C18:2(n-6), linolenic, 18:3(n-3), eicosapentaenoic, C20:5(n-3), and docosahexaenoic, C22:6(n-3) as essential fatty acids for growth. In other words, dietary sources of these fatty acids are required for growth, as they can either not be synthesized by shrimp or can only be synthesized on a limited basis (Kanazawa and Teshima 1977; Kanazawa et al. 1977; Deshimaru et al. 1979; Kanazawa et al. 1978; Kanazawa et al. 1979a,b,c,d,e,g; Kanazawa and Teshima 1981; see also Castell 1981 and Harrison 1990 for reviews). In addition to these essential fatty acids, we suggest that arachidonic acid, C20:4n-6, is often deficient in diets for breeding. Lilly and Bottino (1981) reported about 9% arachidonic acid in *P. setiferus* lipids, and reported only a low degree of endogenous synthesis. Bottino et al. (1980) and Kayama et al. (1980) also reported slow conversion rates of dietary linoleic acid to arachidonic acid.

The fatty acid profiles of shrimp ovaries themselves can be used as a clue to appropriate fatty acid constitution of breeders' diets. It is noteworthy that fatty acid profiles of various species are strikingly similar (Table 6). These data suggest that roughly mimicking these proportions in dietary lipids will aid successful reproduction, and radical departures from these proportions are likely to be detrimental.

Two other aspects of lipid metabolism believed to be important to broodstock are the dietary levels of phospholipids and cholesterol. Many of the natural diet components which are at least somewhat successful for reproduction are high in phospholipids, and particularly phosphatidyl choline.

Table 6. Selected fatty acid composition (% of total fatty acids) of late developing ovaries of several *Penaeus* species, compiled from literature (wild-collected samples).

Fatty Acid	<i>Penaeus japonicus</i> ¹	<i>Penaeus indicus</i> ²	<i>Penaeus setiferus</i> ³	<i>Penaeus stylirostris</i> ⁴	<i>Penaeus vannamei</i> ⁴
C18:1(n-9)	11.9	13.0	15.2	17.5	13.1
C18:2(n-6)	1.5	2.5	NR	3.0	0.9
C18:3(n-3)	0.6	1.1	NR	1.8	0.6
C20:4(n-6)	3.3	6.1	4.1	1.3	4.1
C20:5(n-3)	12.6	9.5	9.9	7.6	5.6
C22:6(n-3)	9.4	11.9	7.0	11.3	3.9
fatty acid %	39.3%	44.1%	36.2%	42.5%	28.3%

¹⁻⁴ Reference 1, Guary et al. (1974); 2, Read (1977); 3, Middleditch et al. (1980a); 4, Araujo (1991). Values for *P. indicus* are whole body, oceanic location samples rather than ovaries. Great similarity has been shown between whole body and ovary fatty acids (e.g., see Guary et

Shrimp ovaries are typically rich in phospholipids (e.g., Gehring 1974; Read 1977; Teshima et al. 1977) and there are indications that dietary phospholipid quantity and quality may be limiting (Kanazawa et al. 1979f; Chapelle 1986; Kanazawa 1985; Galois 1984; Teshima et al. 1986a,b,c,d; and O'Leary and Matthews 1990). A cholesterol (or other sterol) requirement for reproduction has not been determined, but dietary sources of sterols have been shown to be required for growth in crustaceans and are implicated as precursors for synthesis of steroid hormones (Kanazawa et al. 1971a,b; Castell et al. 1975; Teshima and Kanazawa 1986). Cholesterol comprises around 20% of the lipid in crustacean eggs (Zagalsky et al. 1967), yet crustaceans cannot synthesize sterols from lower units (Zandee 1962; 1964; 1966; 1967; Van den Oord 1964; Whitney 1969; Teshima and Kanazawa 1971a,b) and it is logical to assume there will be an optimal level for breeding adults, as there is for growth (Kanazawa et al. 1971a,b; Teshima and Kanazawa 1971a,b; Teshima and Kanazawa 1973; Kanazawa et al. 1976a; and Teshima and Kanazawa 1986).

Kanazawa (1985) summarized *P. japonicus* larvae requirements for vitamins as follows: vitamin E, nicotinic acid, choline, pyridoxine, biotin, folic acid, ascorbic acid, cyanobalamin, vitamin D, inositol, riboflavin, thiamine, and beta carotene. Until experimental testing of breeding adults has been conducted, recommendations for larvae might be used as a guide for vitamin supplementation of broodstock diets. Some recent work by Cahu and Fakhfakh (1990) and Fakhfakh and Cahu (1990) does indicate a high Vitamin E requirement: Vitamin E increased hatch rate in *P. indicus* when females

were spawned multiple times. In a study by Chamberlain (1988), a vitamin E deficient diet produced a significantly lower percentage of normal sperm than diets containing vitamin E.

5.5.4 Natural Diets of Adults

In addition to diet studies and biochemical analyses of tissues, it is also appropriate to review available literature on the natural diets of adult penaeids. All members of the genus Penaeus appear to be omnivorous, to one degree or another. It is noteworthy that as the organism approaches adulthood, strong dietary changes are observed, and some observations on apparent species preferences for particular prey items have been made. This pattern of changing diet, which often involves a shift from plant source dependency (or adaptive capability) to more animal sources at a particular size category, corresponds generally to impending adulthood, breeding readiness, and shift of environment to more oceanic waters. Illustrative of this, Read (1977) noted a tripling of the n-3:n-6 fatty acid ratio in marine versus estuarine P. indicus.

Excellent discussions of gut contents observations in a number of Penaeus species are provided by Boddeke and Kat (1979) and Boddeke (1983). These authors provide evidence of different dietary-adaptive capabilities in various Penaeus species and size categories which would correspond with subadult-adult diets. Table 7 summarizes their observations, with additional data from Moriarty (1977) and Wassenberg and Hill (1987) on adult diets, either in the wild, or in natural circumstances such as ponds where natural productivity is available.

5.6 CULTURE SYSTEMS FOR REPRODUCTION

5.6.1 Seawater Sources

Seawater of high quality is sometimes difficult to obtain for land-based reproduction and larval rearing facilities. Options for seawater abstraction include: 1) raw seawater intakes; 2) shallow subsand abstraction from a location covered by seawater; 3) land-based deep wells; and 4) shallow beach wells. All of these options are used for maturation systems, and each has advantages and disadvantages. Synthetic sea salts have not been successfully used to date for penaeid reproduction. Raw seawater intakes tend to foul, may be difficult to anchor in some locations, and may carry a high particulate load, including organic and inorganic sediment, as well as larger marine organisms, phytoplankton, zooplankton, bacteria, protozoans, fungi, and other potential contaminants. Raw seawater intakes do assure that the seawater quality pumped is at least the same as the oceanic quality water at a given location. Shallow subsand abstraction from a sea floor location has some

Table 7. Observations of ingested food items in subadult to adult penaeids in the wild or in pond environment.

Species	Gut Observations	Size	Reference
<u>P. brasiliensis</u>	Benthic invertebrates, amphipods, small crustaceans (ponds)	≥ 9 cm	A
<u>P. duorarum</u>	94% crustaceans, mostly Malacostraca (wild).	75-165 mm	B
<u>P. esculentus</u>	Bivalve and gastropod molluscs	Adults	C
<u>P. merguensis</u>	Crustacea (wild)	Adults	D
<u>P. monodon</u>	55% crustaceans, 31% molluscs 0.69% polychaetes (wild)	31-69 mm C.L.	E
<u>P. japonicus</u>	Polychaetes favored; some insect larvae, amphipods (ponds)	≥ 9-14 cm	A
<u>P. kerathurus</u>	27% polychaetes, 20% molluscs 18% amphipods (silt bottom); molluscs > polychaetes (sand bottom).	Adults	B
<u>P. vannamei</u>	Polychaetes, almost entirely (ponds)	> 11 cm	A
<u>P. semisulcatus</u>	Bivalves, gastropods, crustaceans	Adults	C
<u>P. stylirostris</u>	Small invertebrates, polychaetes insect larvae (ponds)	105-144 mm	A

References: A, Boddeke (1983); B, Burukovsky 1972 c.f. Boddeke 1983 ; C, Wassenberg and Hill 1987; D, Moriarty 1977; E, Marte 1980.

advantages in that primary filtration occurs at the point of intake, reducing mechanical filtration or settling requirements, but is applicable only in locations with appropriate bottom substrate and in a location not subject to shifting bottom. Land-based deep wells may or may not provide oceanic quality water, and must be carefully evaluated, but can provide very clean water if the mineral composition is appropriate. Shallow beach well points can be reliable in terms of drawing seawater of oceanic character, and are easier to install and maintain than some other options. Use of intakes in strongly estuarine-character locations is possible, but may be far more demanding in terms of water treatment.

5.6.2 Open vs. Closed Seawater Systems

Both open and semi-closed seawater systems are in use for breeding penaeids. In an "open" seawater system (also referred to as "once-through" or flow-through), abstracted water is pumped from its source, filtered or settled for removal of suspended particulates, sometimes disinfected, sometimes prophylactically treated with EDTA, heated as required, and passed through culture tanks at 100 to 500% per day. After flowing through the system, the water proceeds to drain and is not reused. Open systems are

by far the more commonly used systems, but are expensive to operate, particularly if incoming seawater temperature requires substantial adjustment or elaborate filtration is required. In an open system, especially one with an oceanic or estuarine source, the basic standards for water quality in terms of salinity, pH, dissolved oxygen, nitrogen, and general elemental composition, are usually met, and the focus in water treatment is on filtration. Particulate filtration of water accomplishes the following objectives:

- 1) It clarifies the water so that shrimp activity, ovarian development, and excess feed can be monitored regularly, and ready to spawn females can be collected without lowering water level.

- 2) Many potential pathogens and competitors--phytoplankton and zooplankton, protozoans, fungi, and bacteria are removed through filtration, depending on degree of filtration. Fouling organisms such as barnacles and worms can also be removed.

- 3) Removal of organic debris as well as live plant and organisms removes a source of decompositional products, substrate for microorganisms, which helps maintain a healthier environment in the laboratory.

- 4) Removal of inorganic particulates, as well as organic particulates, allows easier, and more effective, disinfection in whichever systems disinfection is applied.

An alternative to elaborate mechanical particulate filtration which is fairly commonly used is a 24-hour alternate-day-use reservoir system, in which one reservoir is in use while the other undergoes particulate settling. Sometimes the functions of settling and mechanical filtration are combined by using reservoirs which recirculate for approximately 24 hours through rapid sand filters prior to use. This combination of settling and multiple-pass rapid sand filtration appears to greatly improve the effective filtration level; only 10 to 15 micron filtration is normally achieved in single-pass rapid sand filters. If 24-hour settling is employed, mechanical filtration needs can be greatly decreased. Additionally, extensive settling and use of conventional particulate removal techniques can be obviated or reduced by recently developed high velocity, 0.5 micron filtration techniques with automatic backwash (e.g., Diamond Water Systems, Inc., 530 Main St., Holyoke, MA, USA).

Disinfection of incoming water is often used only for special use applications such as spawning tanks in the maturation / reproduction area, but is more extensively used in larval rearing applications. However, it is not uncommon for chlorination (at an initial treatment level of approximately 10 ppm) to be used for all seawater applications when an alternate-day-use reservoir system is employed, and disinfection of all incoming seawater, including maturation breeding tanks, seems to be increasingly practiced. Ultraviolet irradiation and ozonation are additional methods of disinfection of seawater. Ultraviolet irradiation has been discussed by Spotte (1979) and

Kinne (1976) in aquaculture applications. The conventional industrial standard for treatment of $30,000 \text{ microwatt sec}^{-1} \text{ cm}^2$ does not appear to always be an effective level for seawater treatment. Additionally, the transmission of UV in seawater is reported to be 83% of UV in freshwater (deionized), so even with use of stringent prefiltration prior to ultraviolet irradiation, higher intensities are required. However, use as a bactericide rather than a bacteriostat may require an even higher dosage rate. Brown and Russo (1979), for example, reported excellent kills at $95,000$ to $155,000 \text{ microWatt sec}^{-1} \text{ cm}^2$ of five bacteria species, but reported that lower levels previously tested were ineffective. A positive correlation has been reported (Spotte 1979) between organism surface area and irradiation exposure required for lethal dosage. However, some organisms such as fungi do not appear to always follow this correlation, and may require higher disinfection levels. In literature provided by Bio Marine, Inc. (P.O. Box 5, Hawthorne, CA, USA, 90250), species of fungi such as Penicillium and Aspergillus species (not reported to be Penaeus pathogens or pests, but the only fungi for which data are readily available) require $88,000$ to $330,000 \text{ microWatt sec}^{-1} \text{ cm}^2$ exposure for complete destruction. These observations suggest that ultraviolet irradiation at dosages considerably higher than normal standards in conjunction with stringent prefiltration may be effective. Ultraviolet irradiation would be more dependable for culturists if pre-filtration requirements were well defined in terms of pore size and turbidity, but such data are scarce. A third available water disinfection system is ozonation. There are two types of ozonation devices available: corona discharge or UV-generated ozone. Ozone is difficult to monitor and is potentially dangerous to cultured animals as well as workers, but it is a potent disinfection technique. At certain levels potentially toxic residuals are created in seawater, and must be considered in system design. However, interest in ozone is currently high, and there are undocumented claims that maintenance of a constant, low-level residual throughout a culture system can produce impressive results. We are not familiar with any ozone toxicity data available for penaeids, or with any comparative study utilizing ozone in penaeid hatcheries, either in reproduction or larval rearing systems. Nonetheless, in theory, the method appears useful and should be tested experimentally to determine treatment levels and possible acceptable residual levels. Rosenthal (1980) reviewed ozonation applications for aquaculture and suggested a number of positive benefits. A bibliography of ozone effects and applications was compiled by Rosenthal and Wilson (1987).

In open seawater systems, seawater progresses (either with or without disinfection) to adult breeding tanks, usually at 100-500% per 24 hours, and then goes to drain. In the case of seawater for spawning tanks, seawater from the incoming system is usually diverted to a treatment reservoir, filtered to 1

micron or less, and often treated with EDTA at 10 ppm. Ultraviolet irradiation or chlorination is often used as well for seawater used in spawning tanks. Prophylactic antibiotics, particularly gram negative, are often used in spawning tanks.

In open seawater systems, antibiotics are sometimes used. Routine antibiotic use in maturation tanks is not as common as in larval rearing, but several observations of their use can be cited. Simon (1982) used antibiotics and formalin on a regular basis in maturation tanks, probably partly in order to be able to collect some eggs directly from maturation tanks from spawns of females not isolated into spawning tanks. More recently Poernomo and Hamami (1983) reported that previously high mortality in P. monodon maturation tanks was reversed by chlorination of tanks while cleaning and also occasional use of Streptomycin and Malachite Green. Only 14% mortality of ablated females occurred over a 7-month period. Browdy and Samocha (1985a,b) used electrocauterization for eyestalk ablation in conjunction with a one-hour Nitrofurazone treatment (5 ppm) initially and then each 7 to 10 days, and they felt that this combination reduced mortality from previous trials.

"Closed" or "semi-closed" seawater systems, in which water is biologically filtered for removal of ammonia excretory products of cultured animals, and then recirculated, can also be used for penaeid breeding systems, and are attractive in temperate locations where large volumes of water must be heated for flow-through systems. Their use, however, is not widespread, and caution is required in use of biological filtration (recirculated systems) for reproduction systems because of subtle water chemistry changes which occur with reuse. Biological filters are diverse in design, including trickling filters of various media; submerged (external or internal) gravel, shell, or sand substrate filters; rotating biological contactors, etc. There are variations in efficiency and disadvantages to each in specific usage, but they all function on the same principle: potentially toxic nitrogen excretions of the cultured animals and decomposing organic matter are converted to nitrite and nitrate by two genera of bacteria, Nitrosomonas and Nitrobacter species, which colonize filter media surfaces. Through this process, however, seawater chemistry is altered, especially by lowered pH and alkalinity, decreased inorganic carbon, increased organic carbon, increased nitrates, increase in phosphorus, and depletion of trace minerals. Decreases in pH and inorganic carbon can be counteracted with chemical additives such as sodium carbonate, bicarbonate, or sodium hydroxide. Buildup of organics which are unaffected by biological filtration is common in recirculating systems, and appears to be correlated with poor reproductive results with some species. Methods of lowering buildup of dissolved organics may include use of activated carbon, foam separation, and oxidation. It is worth mentioning that organics can be

a problem in flow-through systems as well as in closed, although the problem can be more easily dealt with through increasing tank flow rates or routine flushing. The primary sources of dissolved organics in both types of systems include not only feces/ urine, but also large numbers of eggs spawned directly into maturation tanks by females not isolated for spawning, dissolved nutrients from feed items, and decomposition of excess feed. Large amounts of organics in the system may serve as substrate for various bacteria, protozoans, and fungi, which may be present as merely pests, actual pathogens, or competitors in the system. Disease in recirculating systems poses special problems in that health of the organisms composing the biofilter must be maintained.

5.7 QUALITY OF OFFSPRING

Because of the variable quality of penaeid postlarvae produced through captive breeding, it is mandatory that the industry develop simple standardized tests to determine viability. There are many sources of quality problems, but regardless of the source of the variability, if certain characteristics can be correlated with "quality" (growth rate, survival rate, disease resistance, etc.), then strong, healthy animals can be identified early for continued culture. Numerous parameters may have predictive value, including some relating to parental traits, egg and embryo development, larval development, and young offspring. Unfortunately, few parameters have been correlated with any long-term results (the growout phase of culture), which leaves the sensitivity and accuracy of their use as predictors of quality in question. Ultimately, the standards which gain acceptance in the industry should be simple to perform, accurate, and replicatable. The following parameters have been proposed as quality tests, and have varying amounts of evidence to support their use:

- 1) Spawn Size, or number of eggs per spawn. This is an especially poor predictor of larval quality; comparisons of experimental treatments rarely show differences in mean number of eggs per spawn.

- 2) Egg Diameter, an important measurement in fish culture, has not been shown to correlate with viability in shrimp spawns.

- 3) Egg Hatch Rate (percentage hatch). Simon (1982) used a cut-off of 40% hatch; when average hatch dropped below this level, broodstock were switched. This parameter is similar in value to mean number of nauplii per spawn or number of nauplii per female per month, both of which are commonly monitored. Egg fertilization rate may also be monitored in addition to hatch rate.

- 4) Nauplius Phototaxis. Nauplii demonstrate positive phototaxis from hatching onward. It has been suggested that nauplii displaying strongest (most rapid) movement to a light source might be more viable than other

nauplii. However, we are not familiar with any empirical data which demonstrate a practical test for this parameter, or prove the concept. Some nauplii collection schemes do use attraction to light to help concentrate and transfer larvae, and in so doing may accomplish some selection for phototactic response.

5) Larval Survival. Number or percentage of larvae surviving from one larval stage to another, as Nauplii to Protozoae, Protozoae to Mysis, Mysis to Postlarvae, or Protozoae to Postlarvae. This parameter is frequently monitored, and a decline in survival from the norm is considered to be evidence of lower viability. This parameter has not been correlated with long-term predictive value, although intuitively it seems such a correlation would exist.

6) Duration of Larval Stages or Embryo Development. Duration (in hours) of various larval stages, hours until hatching, or the total number of hours (or days) from Nauplius or Protozoa to Postlarva, is variable. Once again, there is an assumed relationship with long-term viability of offspring, but there are no empirical data supporting this.

7) Postlarva Weight. In larval diet studies, several authors have found that postlarval weight is a more sensitive measure of treatment differences than survival or metamorphosis time (Wilkenfeld et al. 1984; Fuze et al. 1985; Kuban et al. 1985; and Samocha et al. 1989). While larger (heavier) postlarvae have not been proven to be more viable, it is a reasonable hypothesis and may parallel the experience of fish growers, where "the bigger, the better," is a rule of thumb.

8) Protozoae Length. Bray et al. (1990a) sampled protozoae length at P-1 and found significant differences among spawns sampled from different diet treatments. Only a very limited number of spawns were sampled in the study, but the parameter appeared to be far more sensitive than others monitored. If further testing shows a correlation between P-1 length and larval, postlarval, juvenile, or growout performance, this would be a simple test to use routinely.

9) Postlarvae Stress Tests. Stress tests for postlarvae have been suggested to be of predictive value in determining viability for growout. Tackaert et al. (1989) exposed postlarvae of *P. monodon*, *P. vannamei*, and *P. japonicus* to abrupt salinity change, and found that postlarval resistance could be enhanced by n-3 highly unsaturated fatty acid (HUFA) enrichment of an *Artemia* sp. food source. Arellano (1990) also conducted pH stress tests with batches of *P. vannamei* PL's, and concluded that higher resistance was present in PL's which had higher tissue HUFA's.

10) Biochemical Composition. Differences in biochemical composition may be indicators of hardiness. For example, Araujo (1991) has documented

differences in the fatty acid composition of wild and laboratory-reared larvae of P. vannamei and P. stylirostris.

11) Postlarvae Muscle:Gut Ratio. Bauman and Scura (1990) described microscopic examination of 12-13 mm postlarvae of P. monodon in which a muscle diameter to gut diameter ratio is found, then used to predict growout performance. They report that postlarvae with muscle to gut ratios of 4:1 or greater consistently demonstrated higher rates of growth and survival than postlarvae with less full tail musculature. Results of stress tests (with salinity and formalin) were also presented to demonstrate a relationship between hardness and muscle-to-gut ratio. The Bauman-Scura muscle-to-gut ratio should be thoroughly tested with P. monodon and other species. If the correlation can be verified, this test would be an important contribution to the industry.

12) Weight Frequency Distributions (Juvenile). Kalagayan et al. (1990) and Holloway et al. (1990) have reported that a higher incidence of IHHN virus can be associated with variability in weight frequencies as well as morphological abnormalities in a population. Measures of variability at about 1 g size appear to be promising as predictors of potential growth, although a test for an earlier life stage is also desirable.

13) Disease Diagnosis. Routine, reliable diagnostic techniques, especially for viral agents, are needed in order to confirm grow-out quality.

14) Pre-Spawning Parameters, Male and Female. In females, measurement of serum protein level has been described to characterize readiness of a population for breeding. In males, spermatophore and sperm morphology, sperm enumeration techniques, and vital stains have been reported. Research is continuing on the sperm activation response.

In pre-breeding females, AQUACOP (1983b) reported that serum protein level was correlated with reproductive potential. However, this technique is tedious, and care must be taken to verify molt stage at the time serum is sampled.

In males, gonad abnormalities and infertility have been reported in captive populations of P. setiferus, P. stylirostris, and P. vannamei. (Brown et al. 1979; Chamberlain and Lawrence 1981a; AQUACOP 1983a; Chamberlain et al. 1983; Chamberlain and Gervais 1984; Bray et al. 1985; AQUACOP 1986b; Leung-Trujillo and Lawrence 1987; Chamberlain 1988; Chamberlain and Johnson 1988; Talbot et al. 1989; Alfaro and Lawrence 1990a,b; Trujillo 1990). Symptoms described include abnormal sperm structure or completely disrupted sperm cells, degradation of spermatophores, and sometimes deterioration of medial vas deferens and testes. In males, external observation can be used as a simple initial determinant of spermatophore maturity and general health. A sperm smear under light microscope can be used to verify presence and morphology of sperm cells. In closed thelycum

species, sperm also can be removed from molted exoskeletons of females to verify percentage of females mating. A sperm enumeration technique was developed by Leung-Trujillo and Lawrence (1987) which can be used as an initial determinant of quality in males. Trujillo (1990) also documented baseline sperm counts for several populations, described abnormalities, and tested a viability stain. These authors also monitored spermatophore regeneration time, and showed a positive correlation between body weight and sperm counts. Spermatophore regeneration time in relation to eyestalk ablation has been reported by Salvador A. et al. (1988). Aquacop (1986b) reported using an acridine orange stain with sperm and then quickly viewing the slide under a fluorescent microscope to evaluate sperm viability by viewing strong color distinctions between live and dead sperm.

Clark, Jr. et al. (1984) and Pillai and Clark, Jr. (1987) have documented the sperm activation response in the penaeid shrimp Sicyonia ingentis, and Lynn and Clark, Jr. (1987) have also reported part of the fertilization sequence in a Penaeus species as well. This research holds promise for a simple test of male viability in that it would be based on a natural biochemical response (sperm activation), rather than morphology, and may provide a good indicator of whether sperm are actually viable.

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CHAPTER 6

PENAEID LARVICULTURE:
GALVESTON METHOD

6.1 INTRODUCTION AND HISTORICAL PERSPECTIVE

The earliest pond grow out studies in the US were initiated in the 1950's by Lunz at the Bears Bluff laboratory in South Carolina (Lunz 1958). The promising future for a U.S. mariculture industry predicted from these early trials was overshadowed by problems associated with observed poorer survival of native species compared with non-native species, inadequate knowledge of nutrition and disease, and the unavailability of a dependable supply of good quality seedstock. On the latter point, the Japanese had described hatchery methodology for *Penaeus japonicus* years earlier (Hudinaga 1942). Attempts to duplicate these methods in the US were mostly unsuccessful. Although both Heldt (1938) and Ewald (1965) were successful in rearing small numbers of larvae to postlarvae, establishing an industry in the US required a predictable supply of mass quantities of larvae. Research to solve the seedstock problem was initiated by the US Government in the 1960's at the National Marine Fisheries Service Laboratory in Galveston, Texas. The techniques developed and modified over the next two decades to intensively mass culture penaeid larvae from nauplii to early postlarva are known collectively as the Galveston Method.

Compared to the Japanese Method (Chapter 7), the Galveston Method is a more controlled form of culture which utilizes small, intensively stocked and managed larval rearing tanks. The Galveston style of culture is characterized by high larval stocking densities (100-150/l) in small indoor tanks (2000 l), grow out to early postlarval stages (PL 5-8), large water exchanges (50-80%/day from protozoa-three), the addition of known quantities of both live algae and *Artemia* to the larval rearing tanks, and the separate culture of live algae (i.e. larval rearing tanks are not fertilized to encourage algal blooms). Careful management of the system leads to high, predictable survival.

Successful mass culture of penaeids under laboratory conditions in the United States was first described by Cook and Murphy (1966, 1969) and Cook (1969). Although initial descriptions included those of spawning tanks and

maturation methodology, spawning and hatching in tanks separate from the larval rearing system, while significantly different from that used in the Japanese system (see Chapter 5), are not considered part of the Galveston Method. Larviculture methodology described by these authors included high nauplii stocking densities (<266/l), use of 10 mg EDTA/l of seawater during all larval stages, and reports that feeding a mixture of algae species gave best production.

Modifications to the physical system were made by Mock and Murphy (1970), Mock and Neal (1974) and Salser and Mock (1974), and were redescribed by Mock et al. (1980a). The major modification was the use of 2000 l cone-bottomed fiberglass larval rearing tanks. Changes were also made in filtration and aeration systems (including the use of airlifts).

Methods to mass culture and preserve algae were described by Mock and Murphy (1970), Mock (1971), Brown (1972), Griffith et al. (1973), Salser and Mock (1973), and Fox (1983). Although the basic techniques to batch culture algae under strong overhead florescent lights has remained the same, aeration techniques to maintain an even cell distribution and sterilization methods have changed (Griffith 1971; Salser and Mock 1973; Fox 1983). The most dramatic change has been in the types of feedstuffs fed to the larvae, from yeast (Mock 1980b), to various forms of preserved and live algae (Mock 1971; Brown 1972; Griffith et al. 1973; Salser and Mock 1974).

In the early 1980's, Texas A&M University began a research program on larval penaeid production at the Galveston larviculture facility, in cooperation with NMFS. The original building and equipment has recently been disassembled; however the Galveston Method techniques can be applied to and modified for present day larviculture. The most recent modifications to the Galveston Method made by the Texas A&M staff were described by McVey and Fox (1983) and Fox (1983). Following are the current techniques used by the Texas A&M staff. The major change to the system has been in the feeding regime.

6.2 ORIGINAL SYSTEM DESCRIPTION

6.2.1 Laboratory

Larval and algal rearing facilities were housed in a single building located on the National Marine Fisheries Service Laboratory property in Galveston, Texas. The larval rearing room contained eight 2000 l conical fiberglass tanks (Fig. 1), four of which were used for larval rearing, three as seawater reservoirs and one for *Artemia* hatching. The algae mass culture room contained fourteen 300 l rectangular, flat-bottomed polypropylene algae tanks, wooden shelves for 16 12-20 l glass carboys, and a 2000 l conical fiberglass reservoir. Separate from the algae mass culture room was a small room for

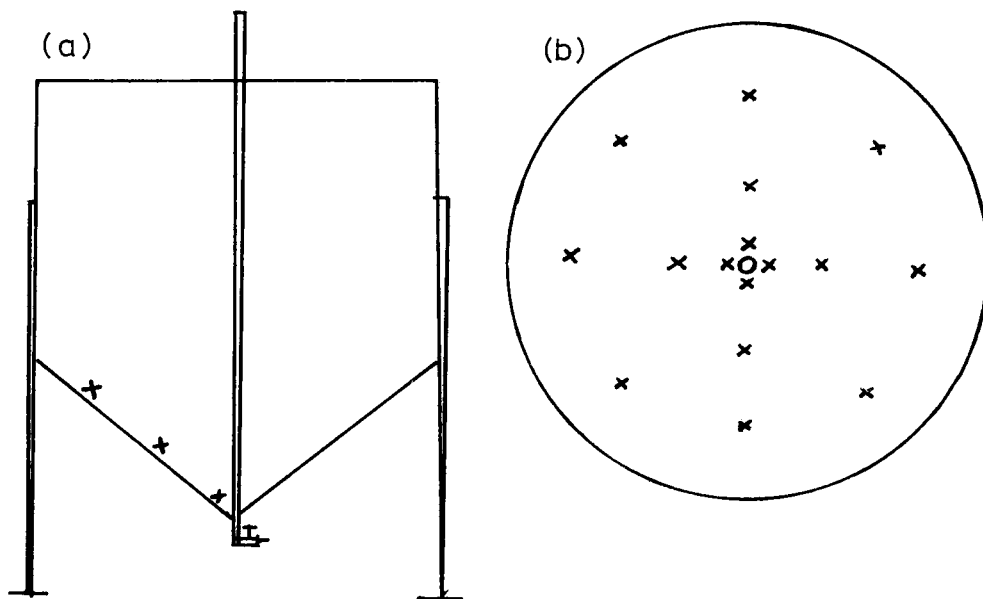


Figure 1. A typical distribution pattern of airstones (x) arranged in three rings on the bottom of a 2000 L cylindroconical larval rearing tank; (a) side view; (b) above view.

algae stock cultures (tubes and flasks). The building also contained two evaluation rooms plus offices.

The four larval rearing tanks (LRTs), stocked with 100 nauplii/l, were each capable of producing a minimum of 100,000 PL-5s (5-day-old postlarva, 50% survival), but most often produced 70-90% survival.

6.2.2 Seawater

Ideally, best production of penaeid larvae is obtained in oceanic quality water having physical parameters in the range of 28-34 ppt salinity, 27-30 C temperature, and a pH of 7.8-8.2. This type of seawater is characterized by relatively stable physical parameters, is nutrient poor and sediment free.

6.2.2.1 Filtration/Disinfection

The entire NMFS complex obtained seawater directly from the Gulf of Mexico. Because of the excessive turbidity, seawater was pumped through a series of offshore buried well points, into a 40,000 l sump tank, into two 12,000 l reservoirs, and finally into the larval rearing building. Once inside the building, sedimentation was further reduced by passing incoming seawater through a sand filter, 5 and 1 micron cartridge filters, and then diverted into

either the larval rearing or algae mass culture room (Section 3), and stored in open-topped reservoirs.

Additional seawater disinfection for larval rearing was accomplished in the indoor reservoir tanks with 2.5 ppm hypochlorite solution; chlorine dissipation was accomplished by vigorous aeration (15-24 hours). Household liquid bleach containing 5.25% hypochlorite (NaOCL solution) was used at a rate of 3.5 ml/100 l seawater. Dechlorination of reservoir seawater with sodium thiosulfate is not recommended because of the risk of toxicity to the larvae. Finally, the chelating agent EDTA was added at a rate of 10 mg/l.

6.2.2.2 Temperature Control

The original system utilized an inline heat exchanger to increase temperature of incoming seawater by 3-5 degrees (bypassed for seawater designated for the algae reservoir), and air heaters to maintain seawater temperature in the uninsulated LRTs between 28 and 30 C. Submersible heaters were not used because of the possibility of electrical shock.

The algae mass culture and algae stock culture rooms were air conditioned to maintain seawater temperatures in mass culture tanks (MCTs), tubes and flasks at 20-21 C.

6.2.2.3 Salinity Control

Because of the proximity of the lab to the Houston ship channel, incoming salinity was greatly influenced by freshwater runoff and, thus, varied seasonally between 16 ppt and 35 ppt. Artificial seasalts were used to raise the salinity to the desired 28-30 ppt. The following brands of seasalts have been used successfully for penaeid larviculture: hW-Marinemix + Bio-elements, Ocean 50, Sera and Tropic Marin (Talley et al. 1988).

6.2.2.4 Aeration

Although aeration was provided by compressors in the original system, blowers are recommended. Blowers are mechanically simple and reliable, and provide high volume of low pressure air free of moisture and oil. Oil and water traps (illustrated in Fox 1983), constructed of 50 cm long x 2 cm diameter PVC pipes stuffed with cotton or charcoal+cotton, were attached to feeder airlines before each LRT, MCT, or carboy shelf.

Between 12 and 16 airlines with airstones, each weighted with a stainless steel nut, were arranged in three concentric rings in each LRT (Fig. 1). Aeration is important, not only for oxygenation, but also to keep all food particles and larvae evenly distributed within the tank.

Three weighted airlines were used in each algae MCT. Aeration was provided primarily to keep algae cells moving to the surface for contact with light.

6.2.2.5 Illumination

Each LRT was illuminated overhead with four 40 W cool white bulbs. Because of the large seawater exchanges, this amount of light was not meant to encourage algae growth, but rather was for human convenience.

6.2.2.6 Chemicals/Additives

The only chemical added to the LRT, other than chlorine for disinfection, is the chelator EDTA at 10 mg/100 l seawater. No antibiotics or other chemicals used to prevent diseases are added.

6.3 CURRENT METHODOLOGY

6.3.1 Larviculture

6.3.1.1 Tank Preparation

As soon as practical after harvesting the larvae, the LRT is sprayed with freshwater to remove organic material and sedimentation. Airlines and airstones are removed and discarded. Stainless steel weights used to hold airstones in place are soaked in dilute (1 N) nitric acid. If cleanup can not be started immediately, the tank can be filled with freshwater and heavily chlorinated (50-200 ppm); however, this wastes freshwater. The inside of the LRT is scrubbed with chlorox and detergent using a long handled, stiff-bristled brush. Entering the tank is dangerous, both from the worker's standpoint and from the introduction of contaminants, and should be avoided. The tank is then rinsed well, and allowed to dry. Airlines are assembled after the tank is dry.

The tank is filled with 1 micron filtered seawater the day before nauplii are stocked. This allowed sufficient time for chlorine dissipation (under strong aeration) and warming of the water to the desired temperature. EDTA is also added after chlorine dissipation. Total seawater volume is 200-300 l less than the final desired volume to allow for live algae addition during the early protozoal stages.

6.3.1.2 Larval Acclimation/Stocking

Seawater containing nauplii should be within 1 ppt and 1 C of that in the larval rearing tank. Nauplii from an on-site maturation source are probably within those characteristics, if not from the same water source, and may need little or no acclimation prior to stocking. Nauplii from outside sources must be acclimated to the temperature and salinity conditions in the larval rearing tank prior to stocking. This can be accomplished in two manners: (a) Seawater dilution method: floating the bags containing nauplii in the tank and adding small volumes of water periodically until both temperature and salinity within the bags are within acceptable ranges, or (b) Seawater replacement

method: placing the nauplii into an acclimation chamber and flowing seawater through the chamber until desired temperature and salinity are reached. The latter method has the distinct advantage that contaminants (ie. debris, bacteria, metabolites, etc.) are reduced or eliminated and, thus, not stocked into the LRT. Seawater temperature and salinity should be raised no faster than 1 C or 1 ppt every 15 min. All bags are gently aerated upon opening. After acclimation, the nauplii are distributed among the LRTs.

A sample of nauplii from each shipping bag is taken for total count estimation and larval quality inspection. Accurate counts of the actual number received are made for several reasons. If there is any question about the viability of the larvae, or suspicion of potential disease problems, it is best to terminate stocking before the nauplii are released into an LRT, risking exposure of the entire larviculture facility. Most reputable suppliers of nauplii will stand behind their counts and adjust bills if the number of viable larvae received is substantially lower than what was ordered. Finally, if more than one LRT is to be stocked, it is important to know the actual number of larvae received so that they can be distributed at proper and efficient densities. Notes are made about incoming temperature, salinity, pH and oxygen level (optional), presence of hatching debris or other contamination (indicates poor separation and rinsing technique from the spawning tank), color of water, general activity of larvae (remembering that nauplii are intermittently active), degree of light attractability, pigmentation, morphology, yolk content (granular appearance) and percent mortality. Abnormalities and developmental substages, if multiple, are determined on a killed larval sample. Once nauplii have been examined and the decision has been made to proceed with stocking, acclimation can begin.

6.3.1.3 LRT Population Estimation

Fifteen to thirty minutes after stocking nauplii into LRT's, strip samples are taken from each tank. A strip sampler consists of a 1.2 to 1.5 meter length of approximately 2.5 to 3.0 cm diameter PVC pipe. The sample is removed by inserting the open ended pipe down into water column, plugging the top end with a rubber stopper, and removing the water "core" by lifting pipe, with the free hand covering the lower end. The contents are poured into a calibrated sample container. Usually two or three strip samples from different areas of the tank are used to achieve the final sample volume (about 1000 ml). Each LRT has its own strip sampler to avoid transfer of potential contaminants and diseases among tanks. The sample is concentrated by pouring the contents through a sieve, which is constructed of a 2 cm length of 5 cm diameter PVC pipe with nitex screen glued across one surface (illustrated in McVey and Fox 1983). During collection procedure, the sieve is held at a slight angle in a petri dish so that the screen is within but not

Table 1. Feeding regime used in larviculture section of Texas A&M University Shrimp Mariculture Project.

Larval Substage	% Water Exchange	Food Type	Food Density ¹ (algae cells/ml/day) (Artemia/ml/day)
N-5	0	<u>Chaetoceros gracile</u>	60,000
		<u>Tetraselmis chuii</u>	15,000
P-1	0	<u>C. gracile</u>	100,000 - 120,000
		<u>T. chuii</u>	30,000
P-2	0	<u>C. gracile</u>	120,000
		<u>T. chuii</u>	35,000
P-3	0-50	<u>C. gracile</u>	120,000
		<u>T. chuii</u>	35,000
		<u>Artemia</u> nauplii	0 - 0.5
M-1	50	<u>C. gracile</u>	100,000
		<u>T. chuii</u>	30,000
		<u>Artemia</u> nauplii	0.5 - 1.5
M-2	50	<u>C. gracile</u>	75,000
		<u>T. chuii</u>	20,000
		<u>Artemia</u> nauplii	1.5 - 5.0
M-3	50	<u>C. gracile</u>	75,000 - 50,000
		<u>T. chuii</u>	20,000
		<u>Artemia</u> nauplii	3.0 - 8.0
PL-1/PL-5	80	<u>C. gracile</u>	50,000 - 20,000
		<u>T. chuii</u>	20,000 - 5,000
		<u>Artemia</u> nauplii	6 - 20

¹Residual algae and residual Artemia estimated twice daily. First Artemia feeding presented in a heat-killed form. Artemia nauplii feeding ranges will have to be adjusted, depending on penaeid species, number of shrimp in the larval rearing tank, and feeding activity of the shrimp larvae.

touching the bottom of a petri dish. (Larvae must be kept in water at all times; angle promotes free flow of water through sieve.) The runoff is collected in a pitcher to catch larvae should the screen overflow. A few mls of the collected runoff is used to rinse original sample container to retrieve any stranded larvae (particularly important during mysis and postlarva stages). Sieve sizes are 100 micron for N through P-2, 200 micron for P-3, and 350 micron for M-1 through PL-5. The contents of the sample are then examined under a dissecting microscope for activity, feeding behavior, presence of fecal strands, development of pigmentation, gut contents, gross deformities, etc. Population within the LRT is estimated based upon the number of larvae obtained in the strip sample.

6.3.1.4 Feeding Practices

The basic feeding regime followed is given in Table 1. This is intended as a guideline, and must be modified according to population demands or species differences. This feeding regime assumes a stocking density of 100 larvae/l, and has been used with P. aztecus, P. monodon, P. schmitti, P. setiferus, P. stylirostris, and P. vannamei. Residual algae and Artemia levels are estimated twice daily. Algae levels are adjusted upwards to maintain the minimum levels suggested in Table 1; Artemia feeding levels in Table 1 are ranges per day (divided into two or more feedings) and must be closely monitored according to demand. Note that dry feeds are not currently part of the standard feeding regime.

Although the nauplius is a non-feeding stage, algae must be added sometime during the N-4 to N-6 substage so that algae is available immediately upon completing the metamorphosis into the first protozoa (P-1) substage. Algae can be fed at half the normal density (see Table 1) to prevent a possible bloom, with additional algae added during the P-1 substage.

6.3.1.4.1 Algae. Two species of algae are fed, Chaetoceros gracile and Tetraselmis chuii. Studies have shown that the use of multiple food sources supplies a more complete nutritional regime than a single source. Generally, diatoms are more nutritious than phytoflagellates. Residual algae levels are estimated twice daily (0800 and 1600) using a hemacytometer. Use of a hemacytometer is described in Fox (1983).

6.3.1.4.2 Artemia. Residual Artemia counts are made twice daily (0800 and 1600) by determining the number of Artemia/ml in three 10 ml samples removed from the LRT with a Henson-Stemple pipet or similar sampling device. The first Artemia feeding is presented in a heat-killed form (microwaving a few seconds or soaking in hot water) to acquaint the protozoa-3 with the new food source. Thereafter, all Artemia are fed live. On an emergency basis, frozen Artemia can be used, however continued use deteriorates seawater quality and larvae which become accustomed to feeding on dead Artemia may not go back to catching live Artemia.

6.3.1.5 Exchanging Seawater in Larval Rearing Tanks

The purpose of the water exchange is two-fold: to reduce metabolite accumulation and remove uneaten Artemia before they grow to a size too large to be removed or consumed. With the exception of an unusual occurrence of a deterioration of water quality, no water is exchanged in the larval rearing tanks from the time nauplii are stocked until the transition from P-3 into the M-1 substage is achieved. Water exchanges start with 50% per day beginning with the M-1 substage, and increases to 80% per day when the

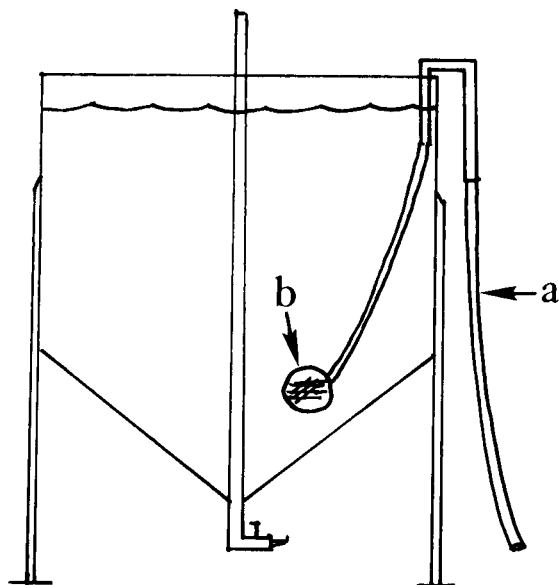


Figure 2: Method for exchanging seawater in larval rearing tank by means of a gravity flow siphon (a) with screened intake (b).

transition to postlarvae occurs. Bottom water is siphoned through a screen dropped into the tank (Fig. 2). The screened intake is constructed from a 12 cm section of 20 cm PVC pipe, with screens glued to both cut sides, and a nipple threaded into the PVC pipe connected to a flexible hose. A 200 micron mesh screen can be used should an exchange become necessary in the later protozoal substages. A 350 micron mesh is used at the M-1 substage. A known volume is removed, trapping larvae in the tank in the residual seawater, and the tank is refilled with fresh seawater from the reservoir.

Artemia are added as soon as the desired amount of water has been removed and refilling has begun. Algae is not added until a sufficient volume of water has been added to the tank such that the volume of cold algae added will not alter the temperature of the LRT, unless the algae is being cultured at the same temperature.

6.3.1.6 Larval Identification

Several good keys are available for identifying larval substages. Refer to those by Cook and Murphy (1971) and Kitani (1986a) for P. aztecus, Kitani (1986b) for P. stylirostris, and Kitani (1986c) for P. vannamei.

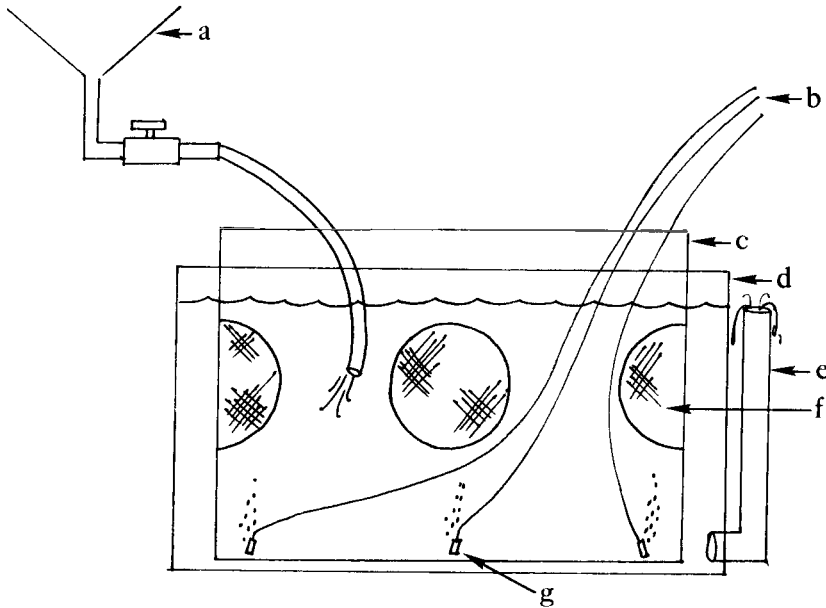


Figure 3. Harvesting chamber: a, larval rearing tank; b, air source; c, circular inner harvesting chamber; d, rectangular outer chamber; e, standpipe; f, screened porthole in inner chamber; g, airstone.

6.3.1.7 Postlarvae Harvesting and Packing Techniques

When the shrimp have reached the age of 5-8 day old postlarva (PL-5 to PL-8), they are harvested from the larval rearing tanks, and packed for transfer to nursery or grow-out ponds. The number of PL packed per box containing about 8-10 liters of seawater (41 x 41 x 23 cm; length x width x height) may vary from 5,000 to 20,000, depending on the size of the larvae and the elapsed time interval from packing to pond stocking. It is best to avoid shipping times greater than 24 hours.

To harvest the tank, water volume is first reduced to about 25% of normal operating level using the water exchange apparatus described in 6.3.1.5 or Figure 2. The standpipe is pulled and PL are released into the harvest chamber (Fig. 3). Clean seawater flows into the chamber to start the rinse procedure. When the tank is completely drained, and all postlarvae have been flushed out of pipes and into the harvesting chamber, residual *Artemia*, cysts and other debris as well as old LRT water is replaced with clean, metabolite free water for packing and shipping. Strong aeration is maintained in inner chamber at all times.

To count postlarvae in the chamber, chamber volume is reduced to a pre-calibrated volume. While stirring contents of inner chamber vigorously with hand or paddle, 3-5 samples of 30-50 ml each are taken by inserting an

inverted glass beaker about half way down into water column, flipping it upright and drawing it rapidly out of chamber. Sample contents are measured into a graduated cylinder, and the postlarvae counted. Postlarvae can be counted by pouring the contents onto a screen held out of the water, or by catching them with the broad end of a pasteur pipet and counting the swimming PL by backlighting the pipet.

Each styrofoam shipping box contains two plastic shipping bags (nested). Once the density of PL/ml in the harvester is known, and a decision has been made as to how many PL to pack per box, a calculation can be made to determine what volume of the harvested concentrate needs to be added to achieve the desired number per box. Normally, the density of postlarvae in the harvesting chamber is so high that not more than 1.5 to 3 liters will be needed to achieve the desired number of PL per box. Clean seawater is added to each box, and the PL added (total volume 8-10 l). As each bag is stocked, ice-filled baggies are added to reduce temperature to 18 C. As each shipping bag reaches the desired temperature, remaining ice is removed, the inner bag is oxygenated, and the shipping box sealed.

6.3.2 Algae Culture

Various aspects of algal batch culture are described by Guillard (1975). The size of the algae culture vessels can be varied to suit the production needs of the particular larval facility. The system used by the Texas A&M staff scales upward in volume from 15 ml screw-capped tubes, to 50 ml foil-capped flasks, to 12 l carboys and finally to 300 l open-topped mass culture. The degree of sterility decreases as the culture volume increases. Original stocks were purchased from an algae supplier. All cultures are grown in f/2 enriched natural seawater.

6.3.2.1 Seawater Disinfection

Seawater passing through the 1 micron cartridge filter is stored in a reservoir tank in the algae mass culture room where it recirculates continuously through a UV sterilization unit and a 0.45 micron cartridge filter to remove small bacteria and algae. This reservoir was painted black to inhibit algal growth. Any additional disinfection was accomplished in the particular culture vessel. All seawater requirements for the various algae culture vessels (tubes, flasks, carboys, MCTs) are supplied from this reservoir.

Autoclaving (steam sterilization) is the most reliable method of sterilizing seawater media in tubes and flasks. Sterilization of media in tubes and flasks can be accomplished with a pressure cooker at 15 psi for 20 min. Larger volumes (1-2 l) require 45 min at 15 psi. Seawater used in carboys and MCTs undergoes 30 min chlorine disinfection (0.035 ml/l seawater) followed by 30

min sodium thiosulfate dechlorination plus vigorous aeration (0.11 ml/l of a solution made from 2 g sodium thiosulfate in 200 ml deionized water).

6.3.2.2 Temperature and Light

Both the stock and mass culture rooms are temperature controlled to 20-21 C. Light is supplied by banks of 40 watt Cool white florescent bulbs. The stock room is maintained on a 20 hr light/4 hr dark photoperiod whereas the mass culture room remains illuminated continuously.

6.3.2.3 Aeration

Aeration is critical since it supplies carbon (in the form of carbon dioxide), stabilizes pH and keeps the algae in suspension so that all algal cells are exposed to the light for photosynthesis. Carboy cultures and mass culture tanks require aeration. Tube and flask cultures are not aerated since diffusion of carbon dioxide is adequate to maintain these cultures. However, flasks must be swirled daily and tubes must be resuspended once a week. Carbon dioxide enrichment is not currently in use, but it is recommended to increase algae production. Guillard (1975) suggests 5% CO₂ (in air) and recommends close monitoring of the pH levels.

6.3.2.4 Cleaning of Glassware

All glassware and pipets used for culturing must be cleaned of organic material and inorganic salt precipitates. Leftover algae is first killed with chlorox and discarded. Glassware is then scrubbed with a biodegradable detergent, such as Alconox, rinsed with tap water, acid washed (1 N nitric acid or 20-30% HCl), rinsed well with tap water and deionized water, covered with foil and allowed to dry. Acid can be reused several times. Carboy aeration apparatus is soaked in the dilute acid bath and rinsed well with deionized water before use.

Serological or pasteur pipets are cleaned by soaking in the dilute acid bath, tip end up, rinsing well with DI water, oven drying, and replugging ends with cotton. Groups of 10-15 pipets are put into a large tube or foil wrap and sterilized. To sterilize in foil bundles, space pipets one inch apart on a piece of foil. Fold edges over the tip and cotton plugged ends. Roll the foil such that when the bundle is unrolled, one pipet can be removed without exposing the others to contamination. Autoclave the bundle.

6.3.2.5 Aseptic Techniques

Standard microbiological aseptic techniques are followed during all tube or flask transfers to reduce the possibility of airborne contamination. These techniques include flaming the moisture from the necks of all flasks and tubes upon opening or after withdrawing or adding a sample. Always flame the tips

Table 2: Summary of ingredients used to prepare the six primary, the four secondary, and the four tertiary nutrient stock solutions used in Guillard's f/2 medium.

Nutrient	Primary Stock Solution ^a	Secondary Stock Solutions ^b	Tertiary Stock Solutions ^c
Nitrate	---	300 g	900 g
Phosphate	---	20 g	60 g
Silicate	---	120 g	360 g
B-1	20 g ^d	20 ml	60 ml
Biotin	0.1 g	(frozen	(frozen
B-12	0.1 g	portion)	portion)
Iron	---	12.6 g ^f	37.8 g ^g
EDTA	---	17.4 g	52.2 g
Trace Metals:			
Copper	9.8 g ^c	4 ml	12 ml
Zinc	22.0 g	4 ml	12 ml
Cobalt	10.0 g	4 ml	12 ml
Manganese	180.0 g	4 ml	12 ml
Molybdate	6.3 g	4 ml	12 ml

^aUsed in the preparation of Secondary and Tertiary Stock Solutions.

^bUsed to enrich Tubes, Flasks and Carboys at f/2 strength (use 1 ml nutrient/L of seawater). Prepare each in a 4 L volume.

^cUsed to enrich Mass Culture Tanks at f/2 strength (use 1 ml nutrient/3 l of seawater). Prepare each in a 4 L volume.

^dMix all three vitamins in 1 L DI. Freeze in 60-ml and 20-ml portions.

^ePrepare each trace metal in a separate 1 L volume of DI.

^fPrepare a 4 L volume with iron, EDTA and 4 ml of each of the five Trace Metal Primary Stock Solutions.

^gPrepare a 4 L volume with iron, EDTA and 12 ml of each of the five Trace Metal Primary Stock Solutions.

of the forceps. A new pipet is used for each species of algae or each time a culture is resampled. Never set a pipet on the table which is still in use. After transfers are complete, check to make sure all foil caps are secure.

6.3.2.6 Estimating Algal Cell Density

Cell counts are made daily from all tanks and carboys in the culture room. The density of the algal culture is determined by counting the algae

cells which fall on a grid of a hemacytometer. Use of a hemacytometer for algae counts is described by Fox (1983).

6.3.2.7 Preparation of Nutrients

To facilitate algal growth, natural seawater is enriched with various inorganic nutrients, most notably nitrates and phosphates. Certain species also require vitamins, trace metals and in the case of diatoms, silicates. McLachlan (1973) lists several types of enriched seawater media preparations. The medium used by Texas A&M is f/2 (Guillard 1975).

The f/2 medium calls for the preparation of four separate nutrient solutions: nitrates and phosphates, silicates, vitamins, and an iron/EDTA/trace metal combination. Because of the low concentration of the vitamins and trace metals needed, these solutions are prepared as Primary Stock Solutions and are diluted to prepare the Working Stock Solutions. For convenience, two sets of Working Stock Solutions are kept, one set for tube, flask and carboy enrichments (Secondary Nutrient Stock solutions, used at 1 ml nutrient solution/1 seawater) and a more concentrated set for mass culture enrichment (Tertiary Nutrient Stock Solutions, used at 1 ml nutrient solution/3 l seawater). The compounds required to prepare these nutrient solutions are listed in Table 2. Table 3 lists the chemical formulas for these compounds.

6.3.2.8 Culture Methodology

6.3.2.8.1 Stock Tube Culture. The algae cultures maintained in tubes are the backbone of the production facility. These cultures are subcultured (tube to tube) every three weeks to indefinitely maintain a low-level growth of contaminant-free (parent) stock, with a minimal amount of effort. Pure, uni-algal cultures can be obtained directly from an algae culture lab, obtained from another larval rearing lab, or isolated from the wild. Isolation techniques are described by Guillard (1973).

Subcultures from tube to flask are made for the initial transfer from a newly obtained culture and then only in emergency situations, such as when the density of the flask culture crashes or the culture becomes heavily contaminated due to improper aseptic transfer techniques.

Three replicates of each species or strain of algae are subcultured (labeled tubes A, B and C). Tubes A and B are kept in the stock culture room, whereas tube C is kept in another room, such as the mass culture room, to assure against total loss of the culture due to an electrical failure or other catastrophe in the stock culture room. Subcultures are made from tube A only; the other two replicates remain unopened. As an extra precaution, the previous two subcultures are also retained so that problems can be back traced. The procedure to prepare and transfer stock tube cultures is as follows:

Table 3: Chemical formulas of compounds used to prepare nutrient stock solutions.

Compound	Chemical Formula
Sodium Nitrate (granular)	NaNO_3
Sodium Phosphate (granular, monobasic)	$\text{NaH}_2\text{PO}_4 \cdot \text{H}_2\text{O}$
Sodium Silicate (meta-soluble)	$\text{Na}_2\text{SiO}_3 \cdot 5\text{H}_2\text{O}$
Thiamine Hydrochloride (B-1)	---
Biotin	---
Cyanocobalamin (B-12)	---
Ferric Chloride	$\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$
EDTA (Disodium Ethylenediamine Tetraacetate)	$\text{Na}_2\text{C}_{10}\text{H}_{14}\text{O}_8\text{N}_2 \cdot 2\text{H}_2\text{O}$
Cupric Sulfate (fine crystal)	$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$
Zinc Sulfate (crystal)	$\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$
Cobalt Chloride (crystal)	$\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$
Manganese(ous) Chloride (crystal)	$\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$
Sodium Molybdate (powder)	$\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$
Sodium hypochlorite	---
Sodium Thiosulfate (anhydrous)	$\text{Na}_2\text{S}_2\text{O}_3$

1. Add 15 ml of f/2 medium to each tube. To facilitate preparation, a 2-3 l volume of unsterilized enriched seawater medium can be prepared and stored in the refrigerator until needed for tubes and flasks. This medium can be (1) sterilized separately from the tubes, and then added aseptically to dry sterilized tubes, or (2) poured into the tubes nonsterile and then autoclaved. Some of the vitamins added to the enrichment medium will be destroyed during sterilization, however Guillard (1975) suggests that a small quantity will still be available for adequate algal cell growth. If this method is not preferred, vitamins can be sterilized separately, and added to the sterilized seawater media in tubes, using sterile transfer techniques, after the media has cooled (add 1 drop from a pasteur pipet per tube). Caps should be screwed on lightly during sterilization and tightened after cooling. (Note: autoclaving new caps may result in chemical release that can contaminate media. New caps can be boiled before use, or autoclaved in a separate container, such as in a petri dish, and screwed onto tubes after sterilization. Tubes sterilized without accompanying screw caps should be covered by inverted vials.)
2. Shake tube A (three week old parent culture) to resuspend any cells on the bottom and withdraw 1/2 of a Pasteur pipet full of culture. Add 4-5 drops of algae into each of the three replicate tubes. Cap loosely. Save algae remaining in pipet for microscopic examination. Record on each

tube the species, date and replicate of the parent tube from which the transfer was made, and the date and replicate of the present transfer.

3. Place all A-C tubes in a rack on the shelf in the stock room in direct light for 1 week to establish growth. After 1 week, transfer all tubes to an indirect light source, integrating the tubes in the proper order and discarding the oldest set of cultures.
4. Resuspend (vortex) tube cultures once a week.

6.3.2.8.2 *Flask Culture.* The flask cultures represent the first step in the sequence of working algae cultures. These cultures are maintained in the stock room and new cultures are started from them twice a week. Flask cultures take 3-4 days to reach a density that can be inoculated into a carboy. The following describes a schedule that can be used to culture and transfer Chaetoceros and Tetraselmis in flasks.

1. Fill flasks with 50 ml of f/2 enriched seawater media following the same preparation notes as in tube culture. Cap with heavy-duty foil. Autoclave and allow to cool.
2. If vitamins were sterilized separately, add 0.05 ml of autoclaved vitamins to each flask using a sterile pipet (approximately 2-3 drops from a pasteur pipet) following aseptic techniques.
3. Resuspend (swirl) the culture in the parent flask. Withdraw a full Pasteur pipet from the flask making sure not to wet the cotton plug. Add 1/4 of the pipet (approx. 1 ml) of algae to each flask. Recap with foil. Save the algae remaining in the pipet for microscopic examination. Record on each flask the species, the date and replicate of the parent flask from which the sample was taken, and the date and replicate of the present transfer. A star "*" will identify the parent flask.
4. Place flasks in direct light in the stock culture room. Swirl flasks daily to resuspend settled cultures.

6.3.2.8.3 *Carboy Culture.* Carboy cultures represent the second step in the sequential batch culture of algae. Carboys are 9 or 12 liters in capacity. All cultures are aerated to keep cells in suspension and in contact with the light. Each carboy is supplied with an aeration apparatus consisting of a rubber stopper, inlet glass tube that extends to near the bottom, and a short glass tube for air escape. Carboys are inoculated twice a week (more often if algae demand is high) from 2 or more 50 ml flask cultures. Normally it takes 4-5 days for a carboy culture to reach a density that can be inoculated into the next step, mass culture. The following describes a schedule which can be used for carboy inoculations with Chaetoceros or Tetraselmis.

1. Rinse a clean carboy with filtered seawater and fill. Sterilize by autoclave, or disinfect seawater with chlorine and dechlorinate with sodium thiosulfate as noted above. Place on carboy rack in continuous light.
2. Enrich seawater with Secondary Stock Nutrients at a rate of 1 ml nutrient/l of seawater (f/2 strength in final concentration).
3. Inoculate with 100 ml (2 flask cultures) of algae. Label and date.

Foaming on the surface indicates that the culture is crashing. Beginning day 3, cultures should be examined daily to monitor growth, cell density and contamination level.

6.3.2.8.4 Mass Culture Tanks. The mass culture tanks (300 liter capacity) are the final step in the sequential culture method in this particular lab. It is from these tanks that algae is taken to feed the shrimp in the larval rearing tanks. The mass culture tanks are maintained under constant light and temperature conditions in the mass culture room. All tanks are aerated with airstones such that a circulation is created which exposes all algae cells to illumination for photosynthesis.

To inoculate a mass culture tank:

1. Fill the tank with 300 l of filtered seawater, disinfect with chlorine, and dechlorinate with sodium thiosulfate.
2. Aerate and enrich seawater with Tertiary Stock Nutrients at a rate of 1 ml nutrient solution/3 l of seawater (f/2 strength in final concentration).
3. Inoculate with the contents of one 12 l carboy. Tetraselmis takes about 6-8 days to reach a density of 1×10^6 cells/ml (denser growth can be obtained with CO₂ enrichment), although this species is usually used to feed larvae when cultured reach a density of $5-8 \times 10^5$ cells/ml. Chaetoceros takes 3-5 days to reach 2×10^6 cells/ml and is usually fed to larvae after reaching a density of $1-3 \times 10^6$ cells/ml. Shrimp are always fed algae that is still in log phase (exponential) growth because the algae is more nutritious during the period of rapid growth than when in the stationary phase of growth.
4. A tank which is in healthy condition, but has half the volume at the end of the day after feeding can be brought back up to full volume by adding reservoir seawater directly to the tank without disinfecting with chlorox; enrich the volume added with the appropriate quantity of Tertiary Stock Nutrients at an F/4 strength, i.e. 1/2 f/2 strength. Diatom cultures can be re-enriched with Tertiary Silicates every 2-3 days (use F/4 strength), if necessary. Cultures should be examined daily beginning day 3 to monitor contamination and growth.

6.3.3 Artemia Culture

An excellent review of the history of Artemia use in aquaculture, and the basic procedures and physical conditions required for hatching cysts can be found in Sorgeloos (1980) and Sorgeloos et al. (1983).

6.3.3.1 Salinity

According to the suppliers, hatching rates are salinity dependent and each recommends a particular salinity from 10 to 34 ppt for the best results. If tap water is used to dilute the hatching media, care must be taken to ensure that sufficient time (24-72 hr) is allowed for the liberation of chlorine by strong aeration prior to use. In the Galveston lab, space was not available to dechlorinate municipal tap water in sufficient quantities to dilute seawater to manufacturer's recommended salinity. Thus, a percentage of the hatchability was sacrificed for the technical ease of using ambient seawater salinity.

6.3.3.2 Temperature

Good hatching results are obtained in the range of 26-30°C, preferably about 28°C.

6.3.3.3 pH

The literature suggests that pH should be kept between 8.0 and 9.0 for best hatching results. Sorgeloos et al. (1983) suggests enriching diluted seawater with 2g of NaHCO₃ per liter of hatching water.

6.3.3.4 Illumination

Best hatching results are obtained in the presence of a fairly strong light source (1000 lux) placed nearby (40-60 watt fluorescent light bulb(s) placed 20cm above water surface).

6.3.3.5 Aeration

Aeration must be very strong, to maintain all cysts in suspension at all times. Cysts settling to the tank bottom simply will not hatch. For best agitation of cysts, the shape of the hatching container should be as close as possible to a steeply-sloped cone.

6.3.3.6 Stocking Density

Experience at this lab is that hatching efficiency is significantly reduced at stocking densities above 2-3 grams of cysts/l of hatching water. Hatchability of a particular brand will vary with the water source and technical conditions used. Always obtain samples from several brands to hatch under both the recommended conditions and the local conditions. Hatchability, in addition to nutritional value and cost, should be used as a basis for brand selection.

6.3.3.7 Hydration, Hatching and Harvesting

Calculating the number of grams of cysts to be hydrated is dependent on desired feeding density (number of nauplii/ml), total volume of water to be fed, and hatching efficiency of cysts (the number of nauplii that can be expected to hatch per gram of cysts). Normally, sufficient cysts will be hydrated to provide for two feedings, one in the afternoon about 28 hours after initiation of hydration procedure, and one additional morning feeding, about 48 hours after hydration began. Artemia nauplii remaining after initial harvest and feeding procedure can be kept refrigerated at 4 C at a density of up to 4,000 nauplii/ml for an additional 12 to 18 hours. While the low temperature will maintain the Artemia in an early metamorphic stage, bacteria will continue to multiply in the organic rich media. All Artemia must be rinsed well with clean seawater prior to feeding.

Artemia culture involves hydration, incubation, hatching and harvesting. The desired quantity of cysts are placed in prehydration wetting container (bucket or other suitable container) at about 25 gm/l seawater and aerated heavily for 30-60 minutes until cysts are thoroughly wet and have become spherical. Chlorine is added to hydration container in the form of chlorox or hypochlorite (25 ppm active ingredients in solution with cysts). Aeration is continued for one minute, then the cysts are poured into a collecting sieve bag (100 micron pore size) and washed thoroughly with fresh or salt water until chlorine odor is completely gone. The purpose of the chlorine bath is to decontaminate the cysts of adhering bacteria and fungi which could be transferred to the LRT's. The decontamination will not increase the percent hatch and should not be confused with decapsulation. When cysts have been washed free of chlorine, they are immediately added to hatching vessel for final hydration. A strong overhead light is added. When using a cone shaped hatching vessel with a central, bottom drain valve, it is advisable to install a central standpipe to plug the hole leading to the external plumbing. This will prevent the accumulation of cysts in dead water spaces which would prevent hatching.

Most Artemia will hatch within 24 hours of the initial hydration. The harvesting procedure consists of (a) turning off aeration and removing standpipe; (b) placing a strong light source near the surface to attract nauplii from the unhatched cysts which are settling to the bottom; (c) draining unhatched cysts after 15 minutes of settling; (d) moving the light to the bottom of the tank to attract Artemia away from the hatched cysts that have accumulated at the surface; (e) draining the hatched Artemia into a collecting bag of 69-100 micron mesh size, maintaining heavy aeration within the collecting bag; (f) rinsing the Artemia thoroughly with clean seawater; (g) and backwashing the collected Artemia into a clean graduated container. The hatching vessel is then rinsed with hot water, washed with a chlorox solution,

rinsed thoroughly with hot water to remove chlorine and prepared for next use.

The density of harvested Artemia can be counted by preparing a 1:999 dilution of concentrated harvest (a) by thoroughly mixing the concentrate to suspend all nauplii, (b) removing a 1 ml sample of the mixed concentrate with an automatic pipet, and (c) mixing the 1 ml sample with 999 ml of water (either fresh or seawater). While vigorously mixing the diluted sample, three 30 ml subsamples are removed with a Hensen-Stemple pipet or other accurate sampling device. Nauplii are counted under a dissecting microscope, the number/ml in the sample determined and multiplied by 1000 to obtain the number/ml in the concentrate.

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CHAPTER 7

I-Chiu Liao

PENAEID LARVICULTURE: TAIWANESE METHOD

7.1 INTRODUCTION

The pioneering work of Hudinaga (1942) in Japan with spawning and rearing of Penaeus japonicus (kuruma prawn) larvae laid the groundwork for modern penaeid prawn larviculture. Now there are 24 penaeid species worldwide whose cultures have been either partially or fully established (Liao 1985). While most larval rearing research has been conducted with P. japonicus, P. monodon (grass prawn or black tiger prawn), and P. vannamei (whiteleg shrimp), P. japonicus boasts the longest research history and most successful larval rearing techniques.

Propagation of P. monodon by Liao et al. (1969) paved the way for penaeid larviculture in Taiwan and established P. monodon larval rearing worldwide. Successful larviculture and mass production of high quality formulated prawn feed made possible systematic and large-scale production of P. monodon in Taiwan using intensive culture methods.

More recently, four penaeid species have reached commercial production in Taiwan, including P. monodon, P. penicillatus (redtail prawn), P. japonicus, and P. chinensis (fleshy prawn).

In 1987, Taiwan's postlarval (PL) production of P. monodon alone reached 15 billion, but dwindled to 13 billion the next year, mainly due to the infestations of monodon baculovirus (MBV) which struck prawn ponds (Liao 1989). Other factors contributing to the decline in PL production could include excessive stress during larviculture, especially use of temperatures as high as 35 to 36 C. Prawn hatchery operators believe that by using these water temperatures, the rearing period can be reduced considerably, that is, 17 days compared with 24 days that it normally takes newly-hatched nauplii to molt into PL15. Also, many hatcheries use antibiotics and other chemicals above the normal dosage to increase survival from the usual 30% to as high as 70-90%. This practice may result in PLs of inferior quality.

Landmarks of Taiwan's larviculture history includes:

- 1968 - Breakthrough in propagation techniques for P. monodon; establishment of first commercial hatchery.
- 1973 - Start of live postlarvae transport to other countries.

- 1977 - Operation of 150 commercial hatcheries; production of 100 million postlarvae.
- 1979 - International technology transfer of prawn culture techniques on a consultancy basis.
- 1983 - Prosperity generated from more than 1,200 commercial hatcheries; production of 1 billion postlarvae; widespread use of unilateral eyestalk ablation.
- 1984 - Development and commercial production of supplementary larval feed.
- 1985 - Produced 3 billion postlarvae.
- 1987 - Produced 15 billion postlarvae.
- 1988 - Postlarval production dropped to 13 billion due to disease problems.

Larval rearing techniques for different penaeid species require various modifications. With P. japonicus the community culture method with large tanks for spawning and rearing, is most suitable because it is possible to obtain numerous spawners at one time. However, P. monodon separate tank methods offer best results since the hatchery normally works with only a few spawners.

Although research on penaeid larviculture has been quite extensive, a few areas need further improvement. In Taiwan there is an inadequate supply of wild-caught P. monodon spawners, and there has been little success with quality egg production from pond reared broodstock (Liao and Body 1987). Non-gravid females have been induced to mature and spawn through unilateral eyestalk ablation, but this has resulted in low quality larvae, especially from successive spawns.

Taiwanese penaeid larviculture techniques are fairly well known and well developed (Hopkins 1986). The basic soundness of these techniques and competence of Taiwanese aquaculturists is expected to eventually offset any weaknesses in current Taiwanese penaeid larval rearing practices.

As with any discussion of larval rearing techniques, it is important to identify larval sources and handling at each developmental stage. Thus, this chapter includes a section on broodstock acquisition and maintenance. Hatcheries are also described to illustrate specialization of activities at each larval growth stage. Hatchery specialization originated in Taiwan. Finally, recommendations are made for a long-term success with penaeid prawn larviculture and hatchery business.

7.2 ACQUIRING AND MAINTAINING BROODSTOCK

We can identify three distinct phases with the history of acquiring and maintaining broodstock in Taiwan. The first phase occurred when maturation techniques were still crude and spawners were caught totally from the wild in coastal waters. Next, during 1976 to 1983 gravid females were imported from other Southeast Asian countries. During that time, there was still an unreliable supply of spawners matured in captivity. Therefore, the wild-caught ones were still preferred by prawn hatcheryists. During the current phase, unilateral eyestalk ablation was widely adopted, and non-gravid female prawns were induced to mature and spawn successively. Successful application of these methods meant that only large broodstock, not necessarily gravid females had to be imported. As a result, spawner price in Taiwan declined from a record US\$2,000 in 1977 (Liao 1984) to US\$10 for males and US\$20 for females in 1989.

A more recent broodstock development is use of artificial insemination with P. monodon (Lin and Ting 1985). This practice is most useful when combined with eyestalk ablation where fertilization rate has declined because of spermatophore depletion and/or where copulation has failed.

Another very promising approach for increasing the supply of wild spawners in Taiwan waters is the stock enhancement program. Prawns released as 30-40 g sub-adults have become gravid within two to three months. Recapture and growth rates of 15% and 30 g/mo. respectively have been achieved with P. monodon (Su and Liao 1986).

7.3 MATURATION AND SPAWNING

Successful induced maturation of penaeid prawns in captivity has been achieved in different parts of the world. Research on captive maturation and spawning before 1983 is summarized in Table 1. Various techniques have been used to induce ovarian maturation and spawning, including special diets and eyestalk ablation.

Even after achieving artificial propagation of some penaeid prawns in Taiwan, there was no assurance of a ready supply of gravid females; the supply of P. monodon spawners still depended on the capture of wild ones (Liao and Chen 1983). To solve this problem, research was conducted on induced maturation and spawning. There is still a need, however, to refine these techniques. In 1973, research was conducted using 15 mo. old laboratory-reared P. penicillatus. After one month, one of the eight females had mature ovary. Two weeks later, another prawn had mature ovary (Liao 1973). Maturation was also achieved with pond-reared P. monodon; however, no cleavage occurred following spawns.

Table 1. Summary of early research on captive maturation and spawning of penaeid prawns (from Liao and Chen 1983).

Species	Country	Treatment of eyestalk ablation*	Result			
			Maturation	Spawning	Hatching	Post-larvae
<u>Penaeus</u>	U.S.A.	+	+	?	?	?
<u>aztecus</u>	Tahiti	+	+	+	+	N/A
<u>P. californiensis</u>	U.S.A.	-	+	+	+	+
<u>P. duorarum</u>	U.S.A.	+	+	?	?	?
<u>P. japonicus</u>	Tahiti	+	+	+	?	?
	Taiwan	+	+	?	?	?
<u>P. kerathurus</u>	Italy	+	+	+	+	+
	Spain	-	+	?	?	?
<u>P. merguensis</u>	Tahiti	-	+	+	+	+
	Jepara	+	+	+	+	+
	Great Britain	-	+	+	+	+
	Fiji	-	+	+	+	+
<u>P. monodon</u>	Taiwan	-	+	+	-	-
	Great Britain	+	+	+	-	-
	Philippines	+	+	+	+	+
	Indonesia	+	+	+	-	-
	Taiwan	+	+	+	+	+
	Tahiti	+	+	+	+	+
	Great Britain	+	+	+	+	+
<u>P. chinensis</u>	Great Britain	+	+	+	-	-
<u>P. penicillatus</u>	Taiwan	+	+	+	+	+
<u>P. plebejus</u>	Australia	+	+	+	-	-
<u>P. semisulcatus</u>	Tahiti	-	+	-	-	-
<u>P. setiferus</u>	U.S.A.	+	+	-	-	-
	U.S.A.	-	+	+	-	-
	U.S.A.	+	+	+	?	?
	U.S.A.	+	+	+	+	+
<u>P. stylirostris</u>	U.S.A.	+	+	+	-	-
	Tahiti	+	+	+	+	+
	U.S.A.	+	+	+	+	+
<u>P. vannamei</u>	Tahiti	+	+	+	+	+

* + = with eyestalk ablation ; - = no eyestalk ablation

During the past few years, trials to induce the sexual maturity and spawning of P. monodon have been carried out at the Tungkang Marine Laboratory (TML) of the Taiwan Fisheries Research Institute (TFRI). Based on success elsewhere with other prawn species, and on knowledge that eyestalks of decapod crustaceans contain an X-organ that secretes

molting-inhibiting hormone (MIH) and gonad-inhibiting hormone (GIH), eyestalk ablation technique was used with P. monodon to reduce hormonal production of GIHs and to accelerate vitellogenesis (Waterman 1960; Adiyodi and Adiyodi 1970). Eyestalk ablation was performed only in females since P. monodon males mature spontaneously in captivity.

Current practice at TML to induce sexual maturity and spawning of P. monodon is unilateral eyestalk ablation where heated surgical forceps are used to sever the eyestalk at its base. Bilateral eyestalk ablation, which was originally attempted, resulted in high mortalities.

First maturation of prawns following ablation is generally observed within 1 to 2 weeks, are averaging 10 days post-ablation. Ovarian color changes are used as maturation indices, which are divided into 4 stages (Table 2). Rematuration normally occurs within 3 to 5 days after the first spawn, which repeats successively.

When ovarian development reaches Stages III or IV, females are carefully placed in 500-l circular fiberglass tanks or other suitable containers for spawning. Water temperature is maintained at 28 to 30 C and airstones are used to provide dissolved oxygen adequate aeration. Spawning usually takes place between 2100 and 2400 hr. The spawning process usually lasts about 1 min.

Spawning usually occurs during Stage IV, except in cases of regression when females experience handling stress. Maturation and spawning quality is assessed as follows: spawning or no spawning, percentage of fertilized eggs, and hatching rate. After spawning, three types of eggs can be observed under a profile projector or a microscope: unfertilized, fertilized with normal development, and fertilized with abnormal development. Percentage fertilization is determined by the number of fertilized eggs divided by total egg number in the sample multiplied by 100%. Similarly, hatching rate (H) is determined by:

$$H\% = Y/X \times 100\%$$

where: H=hatching rate, Y=total number of nauplii, and X=total number of eggs.

While induced maturation and spawning in P. monodon have been successfully achieved, other aspects still need further study, including: optimal age and size of prawns for ablation, more effective diets, improved male performance, optimum sex ratio, improved physical environment to ensure successful copulation, and optimal stocking densities.

Recently, P. penicillatus have spawned naturally in outdoor ponds. On several occasions these produced good survival rates (Liao 1988a). Penaeus semisulcatus has also spawned naturally (Liao 1988b). Other penaeids that

Table 2. Ovarian color changes as maturation indices in female prawns.
(from Liao and Chen 1983).

Species	Ovarian maturation stage			
	I Undeveloped stage	II Developing stage	III Early ripe stage	IV Ripe stage
<u>Penaeus monodon</u>	Translucent and whitish	Light yellow, yellowish brown, and yellowish green	Light green and green	Dark green
<u>P. kerathurus</u>	Slightly greyish	Greyish	Yellowish green	Bright orange-yellow
<u>P. stylirostris</u>	Whitish	Yellow and reddish	Golden brown	Greenish brown
<u>P. vannamei</u>	Whitish	Yellow and reddish	Golden brown	Greenish brown
<u>P. plebejus</u>	Translucent	Pink and brown	Orange and brown	Light orange brown

achieved ovarian maturity in captivity without eyestalk ablation are P. japonicus and P. chinensis (Liao and Chien 1990). A recent experiment on induced ovarian maturation of P. chinensis was conducted at the Tainan Branch of the TFRI using temperature manipulation and HCG injection. Three brooders spawned 12 times with 3.8 million eggs produced. Average hatch rate was 88% with 420,000 PL5 produced. Survival from egg to PL5 was 11% (Liao and Chien 1990).

In Taiwan, P. monodon hatch rate varies greatly compared with other penaeids, normally ranging from 70 to 90%. In the zoea stage, survival is lower than in any part of the production cycle, averaging between 30 and 60%. Overall survival from egg to PL averages 30%. Lately, with the practice of using high water temperatures of 35 to 36 C, survival rates of as much as 70 to 90% have been achieved through the PL stage. A recent study by Liao et al. (1989), however, has shown that water temperatures > 31 C increased the risk of MBV infection.

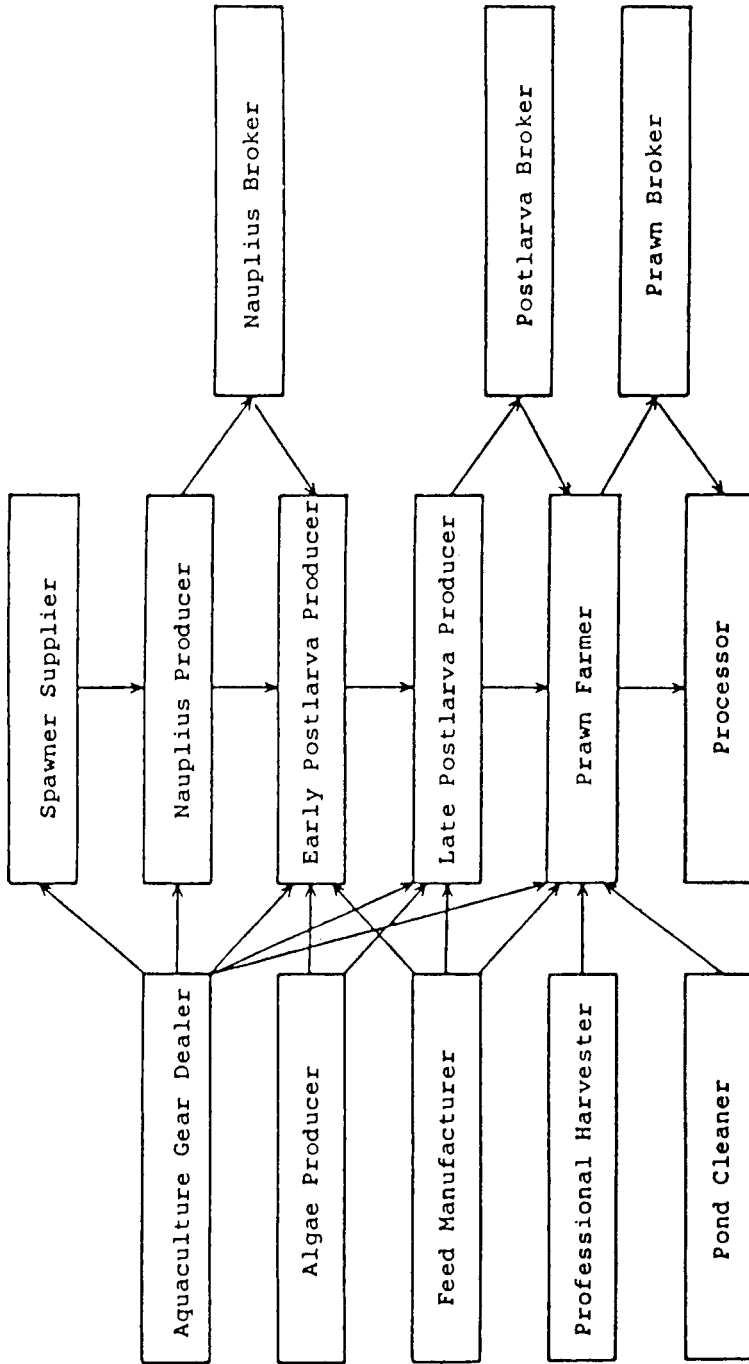


Figure 1. Specialized sub-businesses in the Taiwanese prawn culture industry (Liao and Murai 1985).

7.4 HATCHERIES

Two periods occurred in the development of Taiwan's hatcheries:

1968 - 1984: Development of hatchery techniques.

After 1984: Formation of sub-businesses and specialization in the prawn culture industry.

Taiwanese hatcheries, which have uniquely evolved into an efficient, well-organized sub-industry are characterized by specialized activities (Liao and Murai 1985). Some hatcheries produce only nauplii, while others produce PL of various stages (Fig. 1). The following are some specialized activities and inter-relationships among the sub-businesses (Body and Liao 1987):

1. Spawner suppliers procure spawners and sell them to hatcheries;
2. Hatcheries which buy the spawners, induces spawning through unilateral eyestalk ablation, hatches the eggs, and sells nauplii (N2-N5);
3. Larval nursery buys N2-N5 and grows them to postlarvae (PL10-PL14); and
4. Postlarval nursery buys from the larval nursery, rears the postlarvae and sells PL20-PL30 to the prawn farmers.

7.5 LARVAL REARING

The three commonly used hatchery types in Taiwan are categorized according to production methods that evolved over 20 years (Table 3). Feeds given at various larval stages include condensed phytoplankton at the zoea stage, brine shrimp (*Artemia salina*) nauplii at the mysis/PL stage, and microencapsulated feed. For the history and status of hatcheries, see Chapter 31.

7.5.1 General larval rearing methods

The community, or same tank method is the most appropriate method for larviculture of *P. japonicus*, *P. aztecus* (northern brown shrimp), *P. duorarum* (northern pink shrimp), and *P. setiferus* (northern white shrimp) because many spawners can be simultaneously collected, spawned, the eggs hatched, and the larvae cultured in hatchery tank of 100 tons (m³) or larger (200-2,500 tons) (Liao 1985).

The community method uses large mesh (60 to 100/mm) filters to filter seawater. Fertilizer is added directly to the tank to promote diatom growth. A food chain is thus created in the larval rearing tank where diatoms are the primary producers, which provide food for zooplankton. Both diatoms and zooplankton are consumed by larval prawns.

Ample aeration is provided. Water is not changed until after larvae metamorphose into PL, after which about 20% of the total volume is replaced

Table 3. Types of grass prawn, P. monodon, hatcheries in Taiwan (Chiang and Liao 1985)

Type	Tank size (t)	Depth of tank(m)	No. of nauplii/m ³	Feed	Stages of hatchery
"I"	Under 10	1.0-1.2	1.0 x 10 ⁴	1. Zoea stage: phyto-plankton 2. Supplement: oyster eggs 3. Mysis/PL stage: brine shrimp nauplius	(2-phase) 1. From spawner to PL11/13 2. From PL11/13 to PL20 and up
"II"	10-50	1.2-1.5	3-5 x 10 ⁴	1. Zoea stage: condensed phytoplankton 2. Supplement: artificial feed 3. Mysis/Postlarval stage: artificial feed or brine shrimp nauplius	(2-phase) 1. From spawner to PL11/13 2. From PL11/13 to PL20
"III"	10-50	1.5-1.8	5-8 x 10 ⁴	1. Zoea stage: condensed phytoplankton 2. Large quantity of artificial feed	(3-phase) 1. From spawner to nauplius 2. From nauplius to PL11/13 3. From PL11/13 to PL20

once each day (Hudinaga and Kittaka 1967). Temperature is adjusted, as necessary. When feeding Artemia, minced oyster, shellfish and clam, the application rate is adjusted daily according to the larvae's needs. Live feed applications should correspond to larval density to maintain a steady balance of supply and demand of food for the larvae. With this method, about 15,000 PL/m³ (15 PL/l) can be produced with 50% survival.

The separate tank method is better suited for P. monodon larviculture because only a few spawners are normally collected at a time, and P. monodon larvae are more sensitive to direct fertilizer applications. With eyestalk ablation to induce maturation, acquisition of multiple P. monodon spawners has become more common. Therefore, larger larviculture tanks are often used now, but live organisms are still cultured in separate tanks. Perhaps future developments will allow community culture of P. monodon.

Each larviculture method has its advantages and disadvantages (Liao 1985). The community method is relatively inexpensive, uses large tanks and normal sunlight. There is, however, high disease risks from among other things inclusion of diseased broodstock, and/or improper tank preparation. If only a few larvae are cultured, much space is wasted and production costs increase.

The separate tank method maximizes use of a limited number of spawners, isolates spawners in smaller tanks, and reduces disease risks. At the same time, production costs are relatively high and control of light is necessary. Prospects for future improvements are also limited. The community and separate tank methods are compared in Table 4.

7.5.2 Larval rearing systems and practices

Larval rearing systems differ by species and by the operator's personal preference. For instance, the Japanese or Shigueno system uses 100-ton or larger flat bottomed tanks, mainly for larval rearing of P. japonicus (Hudinaga and Kittaka 1967; Shigueno 1975). The Galveston system uses 1- to 2-ton conical tanks, which are mainly used for the rearing of P. stylirostris (Pacific blue shrimp), P. vannamei, and P. monodon (Mock and Neal 1974; Aquacop 1975; Platon 1978; Mock et al. 1980). The traditional Taiwanese system uses 0.5- to 2-ton round tanks with flat bottoms for P. monodon (Liao et al. 1969; Liao and Huang 1973; Liao 1984). Larval rearing techniques for P. penicillatus and P. japonicus in Taiwan are generally the same as those for P. monodon.

Larval rearing techniques or practices are endemic to an area. In Taiwan, P. monodon is the mainstay of the prawn industry. Larviculture practices for P. monodon are similar to most other penaeids. The nauplii are stocked in indoor or shaded outdoor concrete tanks at 40 to 60 larvae/l. Usually, the tanks are rectangular and made of concrete with an epoxy coating that is renewed before every crop. The latest trend in Taiwan is use of larger tanks, made possible by improved spawner supplies. Tanks measure 1.0 to 1.5 m deep with capacity of 20 to 50 tons. The bottom slopes gently to a corner drain. Intensive aeration is provided with one airstone for every 60 to 70 cm² of bottom area. Temperature and salinity are maintained at 28 to 31 C and 30 to 34 ppt respectively.

Water temperatures are maintained using immersion heaters. Water exchange is largely subjective and adjusted according to water quality deterioration. Water quality is judged by the amount of particulate matter in the tank, presence of foul bubbles, and culture water odor. Thermometers are used in most hatcheries, and salinity is measured with salinometers. Water pH is measured with litmus paper. Ammonia and nitrite levels are seldom determined.

Rearing P. japonicus and P. penicillatus is relatively easy compared to P. monodon, with greater average survival of the former species. Lim (1982) found average survival for P. japonicus from egg to PL5 of 23%, compared with only 11% for P. monodon. In another study, P. penicillatus had average survival from egg to PL9 of 23% (Liu and Huang 1986).

Table 4. Comparison between community culture and separate tank (monoculture) methods (Liao 1985)

	Community culture method	Separate tank method
1. Species	<u>Penaeus aztecus</u> , <u>P. duorarum</u> <u>P. japonicus</u> , <u>P. setiferus</u>	<u>P. monodon</u>
2. Size of rearing tank for spawning and hatchery	Large tank (100-200 tons)	Small tank (0.5-20 tons)
3. Number of spawners	Many	Few
4. Fertilizer	Used	Not used
5. Light intensity	Normal sunlight	Subdued light
6. Production costs	Low	High
7. Risk	High	Low
8. Prospect for future development	Promising	Limited

7.5.3 Larval feeds and feeding methods

Larval feeds are classified as either natural foods or artificial feeds (Liao 1988b). Natural, live food organisms include phytoplankton and zooplankton, as well as microorganisms. Artificial feeds come in different forms, including dried powder and microparticulate feeds. Microparticulate feeds may be either microencapsulated diet (MED), microbound diet (MBD), or microcoated diet (MCD). Some brand names include Artemia flakes, BP, Marine Sigma and Frippak Microcapsule.

Larval feeding changes throughout the 30-day period during which larvae are in the hatchery. Before 70 to 90% of the nauplii molt into the herbivorous zoea stage, a chain diatom (Skeletonema) is added to the tanks as food source at a density of 50,000 to 80,000 cells/ml. Production of this algae is usually done in fertilized outdoor tanks with a capacity of 5 to 20 tons. Since larviculture tanks are kept dark, Skeletonema is produced in well-lit outdoor tanks and then transferred to the larviculture tanks. Feeding level is usually maintained according to water color and visibility. Nutrient media for algae includes a mixture of sodium bicarbonate, potassium nitrate, sodium metasilicate, and in some cases, ferric chloride. Some hatchery operators use a variety of other mixtures for their nutrient media. A common

recipe for preparing Skeletonema media is 60 g/m³ of urea, 30 g/m³ of calcium superphosphate, 15 g/m³ of sodium silicate (Body and Liao 1987). Skeletonema is usually harvested two days after the medium is inoculated by draining the culture through a fine (150 to 220-micron) mesh nylon bag. Continuous harvests occur until algal growth declines.

Skeletonema culture is not a problem in sub-tropical Taiwan, which may have been contributed greatly to the success of prawn larval rearing here. In some other tropical Southeast Asian and South American countries, however, Skeletonema is difficult to culture. There, Tetraselmis and Chaetoceros are more commonly used.

Skeletonema is used almost exclusively for zoea and early mysis stages. Since zoea is the most difficult larviculture stage with prawn larvae, provision of high quality feed during this stage improves survival, and also results in better survival at later stages (Liao 1988b).

Late zoea, mysis and PL also require zooplankton animal protein in their diet. In Taiwan, common animal protein sources for the mysis stage are rotifers and brine shrimp nauplii. In some hatcheries, rotifers are grown in tanks which contain green algae Chlorella, while others simply harvest rotifers from a pond.

Brine shrimp (Artemia) nauplii are more commonly used, and most hatcheries depend on these nauplii as the main food source for the mysis stage. Brine shrimp feed on protozoa, microalgae, yeast, bacteria, and are omnivorous. Brine shrimp are nonselective particle filter-feeders, although they sometimes eat large particles of food by tearing them apart. They can be fed the following foods: chicken feed, rice bran, minced fish and chopped chicken dung (Liao et al. 1983). When these foods decompose, they fertilize the brine shrimp culture media and in turn produces natural food for brine shrimp, such as bacteria, yeasts, algae and different kinds of microorganisms (Tunsutapanich 1980). Culture costs of brine shrimp can therefore be quite low.

Brine shrimp eggs are imported to Taiwan since they are not produced locally. The eggs are hatched in separate tanks, and the nauplii collected and added to prawn larval rearing tanks. Prawn postlarvae are fed brine shrimp in the larval rearing tank for about two weeks after they have metamorphosed into PL. Traditionally, large amounts of ground and sieved trashfish, bivalves, snails and various dry rations were fed supplementally with brine shrimp after the PL5 stage. Recently, microencapsulated feeds were developed as replacements for these feeds. Hatchery operators usually feed larvae 4 to 6 times daily.

Feeding methods, particularly feed size and quantity, should be adjusted according to larva stage. It is not advisable to give natural feeds in large quantities because it is difficult to accurately measure the portions. Live feeds

Table 5. Composition of artificial feed used in Taiwan for grass prawn, P. monodon (Liao 1984)

Stage or body weight of prawn	Shape of Feeds	Size of Feeds	Crude protein (%)	Crude lipid (%)	Crude ash (%)	Crude cellulose (%)	Residues (%)	Moisture (%)
PL ₂₅ - 1 g	Broken granules	<φ2mm	>40.0	>3.3	<18	<3	<1	<12
1-10 g	Granules	φ2.5mm x 2.5 mm	>38.0	>3.0	<18	<3	<1	<12
> 10 g	Rods	φ3 mm x 4 mm	>35.0	>2.8	<21.5	<3	<1	<12

should be fortified with highly unsaturated fatty acids since they are often deficient in these essential nutrients.

Artificial feed preparations for larvae are available commercially and need not be prepared by the larviculturist. In Taiwan, artificial feed development has been relatively slow mainly due to the excellent climatic conditions in the area, which are suitable for mass culture of diatoms and rotifers (Liao 1984). Brine shrimp supply is not a problem, although it is imported. The more commonly used artificial feeds for P. monodon are BP and Marine Sigma which were originally formulated for P. japonicus. These are all fed to P. monodon occasionally. Compositions of P. monodon artificial feeds as adopted in Taiwan are shown in Table 5.

Production of quality artificial feeds requires attention to many factors, including nutrient composition, stability in water, and attractiveness to the larvae. The food must provide the larvae's basic nutritional requirements, and it must be bound and coated so that it will not easily dissolve in water and cause pollution.

Care is needed not to over feed. Instead, smaller quantities of feed should be fed on a staggered basis and uniformly spread over the tank. For this purpose automatic feeding machines work well. Water must be changed frequently to prevent pollution. Operators take great care so that uneaten debris cannot accumulate and affect water quality.

Artificial larval food does not at this time provide a complete diet. For that reason it is presently used as a supplement to live feed (Liao et al. 1988). Most hatcheries use a "fruit salad" approach, mixing together many commercially available larval feeds as supplements (Body and Liao 1987). Future development will hopefully soon result in improved quality such that it can serve as main food for larvae.

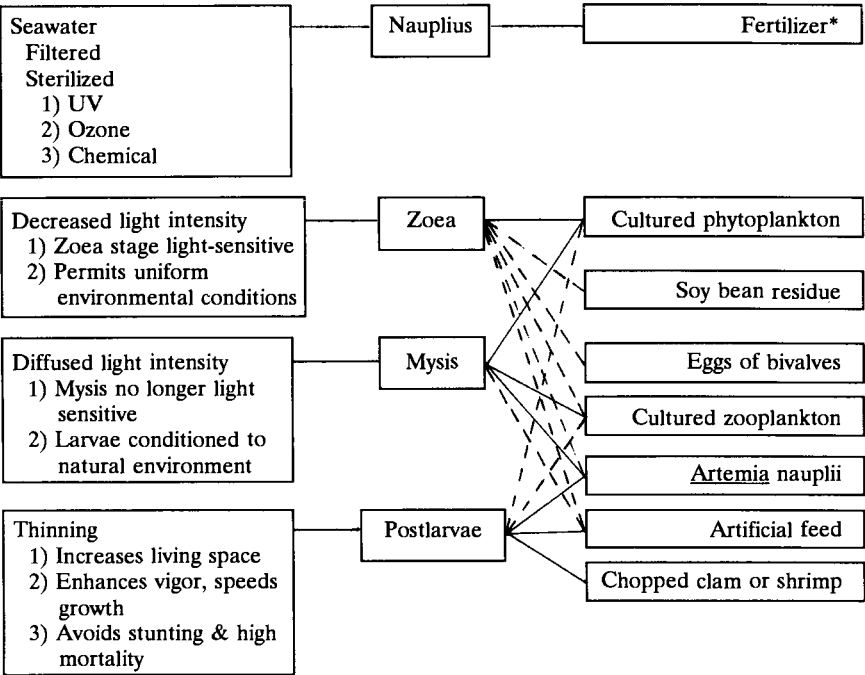


Figure 2. Schematic diagram of feeding regimes and related culture parameters for different larval stages (Liao 1985). (—, most prominent feeding regime; - - -, occasional feeding regime; *, community culture method only)

Feeding regimes and different culture parameters used for different developmental stages of penaeid prawns are shown in Figure 2.

7.5.4 Nursery phase

Before PL are stocked in growout ponds, they are first reared in nursery ponds. The nursery system in Taiwan aims to shorten time in the growout pond and to improve survival. The 15-day-old postlarvae (PL15) are transferred from the hatchery in plastic bags containing well-oxygenated seawater to outdoor nursery ponds. The shallow (0.5 to 1.0 m) nursery ponds rarely exceed 0.05 ha, generally have concrete or brick walls, and have a very clean, gravelled and a gently sloping bottom. The slope is so constructed that when the pond is fully drained, it is easy to collect the juveniles in a large filter bag at the drainage area. The water supply inlet is located at the pond side opposite the drain. Separate seawater and freshwater wells are provided. An aeration system facilitates circulation, mixing and forced oxidation of pond water.

Nursery stocking rate is about 200 to 300 PL/m². After two weeks in the nursery, the PL30 develop dark pigmentation. Nursery pond harvest is usually

done by seining or draining. The pond bottom gravel is washed to remove organic material and quicklime is used to sterilize the bottom, after which the pond is allowed to sun dry thoroughly (Hopkins 1986).

7.6 PROBLEMS IN LARVAL REARING

While penaeid larviculture in Taiwan has been fairly progressive, problems still exist.

7.6.1 Spawners

7.6.1.1 Spawning mechanism

With P. semisulcatus and P. penicillatus broodstock, the prawns are transferred to different ponds or tanks after they reach maturity. Some of the prawns will spawn spontaneously in the new pond, but it is not clear whether the prawns would spawn if they were not moved. Transfer stress may induce the spawners to release their eggs during the same night (Liao 1988b). This premature egg release results in generally poor egg quality and larval survival. The problem is therefore that of bringing forth a natural spawning when the eggs are ripe, instead of stimulating a premature release of eggs. Solution of this problem will help reduce the risk of producing poor quality eggs.

7.6.1.2 Quality of egg

The quality of the egg is very much related to such factors as spawner age, nutrition, rearing environment, and time of spawning. There are several egg quality criteria or standards for finfish, but in penaeid prawns, very little is known.

As with fish, if egg quality is deficient, larval health and performance will also be poor. Egg quality can be evaluated by observing their physical appearance under the profile projector or microscope, but better standards need to be developed.

7.6.1.3 Induced maturation

With eyestalk ablation, spawners can be induced to mature and spawn repeatedly, almost like a spawning machine. Penaeus monodon has a recorded continuous spawning of 10 cycles. Still, research on maturation and spawning induced by eyestalk ablation has not been exhaustive. Hatchery operators, however, have observed that if a spawner has spawned successively for more than three times, its health deteriorates and egg quality deteriorates with successive spawns. Unfortunately, this observation is not well documented. It is also known that prawns will mature and spawn naturally (Liao 1973). Although induced maturation without eyestalk ablation is not yet commercially viable, efforts are underway to accomplish that. Perhaps by

imitating their natural environment and feeding regimes natural spawning of prawns may be attained. Eyestalk ablation should not be used routinely, because it causes un-natural hormonal changes and poor egg quality (Liao 1984). Natural maturation and spawning are therefore preferable.

7.6.2 Larvae

7.6.2.1 Selection of healthy larvae

Unhealthy larvae should be eliminated to ensure good growth and survival of those remaining. There are some criteria for determining larvae health at different stages. Phototaxis, or swimming towards bright lit areas, is one criteria for selecting healthy nauplii. Another indicator of good health for zoea is trailing fecal strings.

Generally, the color, swimming activity and feeding behavior of the larvae at each stage can be used to determine whether they are healthy or not. Furthermore, the response of the larvae to water current, their habit of burrowing into the sand, and their tolerance to anesthetic applications can be used to judge their health. It is hoped that improved methods can be established to determine larval health more effectively and efficiently.

7.6.2.2 Nutritional requirements

Prawn larvae undergo metamorphosis very often. It is at this stage that their nutrient requirements differ the most from adults or juveniles. Knowledge of larval nutrient requirements has been applied in commercial feed production for P. japonicus. Other than with P. japonicus, few studies have been conducted on the inorganic matter requirement and on the metabolism of larvae (Liao 1988b). Further studies dealing with the relationship between enzyme activity and digestibility for the larvae are needed. Most importantly, information on nutritional requirements of other prawn species is needed.

7.6.2.3 Environmental conditions

Normally, healthy larvae are produced from naturally matured spawners. It takes about 24 days at a water temperature of 28 C for newly-hatched larvae to reach PL15. As Taiwanese prawn culture expanded rapidly, so did the demand for prawn seedstock. To meet this demand, hatchery operators increased water temperatures to as high as 35-36 C and shorten larval rearing time by as much as 7 days. This apparently reduced the larvae's immunity to diseases, which could have contributed to the recent mass mortalities in prawn production. Although the recent study by Liao et al. (1989) on P. monodon disease has already shown a close relationship between high temperatures and disease outbreak, this problem needs further study.

Most hatchery operators also aim for high PL survival rates during larviculture. To achieve this, they often overdose drugs and other chemicals, regardless of the ultimate effect on the larvae's health. This practice should be greatly reduced. Instead, good culture techniques should be used including the selection of good quality nauplii as discussed earlier (Liao 1984).

Other larviculture conditions, such as the amount and type of light need further evaluation. With P. monodon, some hatchery operators in Taiwan have adopted the dark-room hatchery method, where the larvae are reared in the dark through the PL stage. Other operators use the more common open-type hatcheries where the rearing tanks are covered only during the light-sensitive zoea stage. These two types of hatcheries differ considerably in their approach, yet they produce PL at comparable rates. It would be desirable therefore to further study optimal larval rearing requirements to establish a standard rearing method. The community method also needs further attention.

7.6.2.4 Larval diseases

Until recently, most hatchery mortality was attributed to inappropriate and insufficient food resulting in sub-standard nutrition and starvation. There were occasional non-lethal or low mortality diseases caused by protozoan infections. The recent global increase in hatchery number and larval rearing densities at the hatcheries has often been accompanied by increased occurrences of major disease problems at the hatcheries (Liao 1985). These include white-turbid midgut gland disease in P. japonicus (Shigueno 1975); lagenidium infection in all penaeid prawns (Couch 1942; Cook 1971; Lightner and Fontaine 1973; Lightner 1977; Lightner and Redman 1981; Lightner 1983); baculovirus penaei (BP) disease in P. aztecus, P. duorarum, P. setiferus, P. stylirostris and P. vannamei; and recently, the baculoviral midgut gland necrosis (BMN) in P. japonicus (Sano et al. 1981), monodon baculovirus (MBV) disease in P. monodon (Lightner and Redman 1981; Lightner 1983); and finally, the infectious hypodermal and hemperitopoietic necrosis (IHHN) in P. stylirostris and P. monodon (Lightner 1983). In the past, all these diseases were known threats to the hatchery business, except MBV whose importance was not established until recently. With mass mortalities in Taiwan's prawn ponds in the spring of 1988, it was shown that MBV can be a major pathogenic factor for fatality among prawns, especially in P. monodon (Liao 1989). The relationships between MBV outbreaks and other diseases, and use of high water temperatures in hatcheries have not yet been fully established.

Table 6. Shipping record of penaeid larvae (Liao 1985)

Shipment	Stage shipped	Destination/ Origin	Duration (hr)	Container Container	Aeration	Water (l)	Number (/bag)	Survival
1. <u>Penaeus stylirostris</u>	Nauplius	Tungkang/ Panama	35	Plastic bag in polysty- rene foam box	O ₂	10	125x10 ³	100 ^a
2. <u>P. monodon</u>	PL20-30	Rio de Janeiro/ Tungkang	30	Portable plastic tank	Air from battery pump	20	4x10 ³	20 ^b
3. <u>P. monodon</u>	PL15	Salvador, Brazil/ Tungkang	85	Plastic bag	O ₂	10	15-25x10 ²	20-30
4. <u>P. penicillatus</u>	PL ₆₋₈	Salvador, Brazil/ Tungkang	85	Plastic bag	O ₂	10	15-25x10 ²	60-70

^aTotalled 500,000 in 4 bags.

^bStopped at Tokyo for 2 days.

7.6.3 Feeds

7.6.3.1 Live feeds

Several studies have been conducted on improving the nutritional value of live feeds, but culture of these organisms in tropical settings needs further study. Aspects of these food items which need further study include their basic biology (Sudzuki 1987), culture techniques (James et al. 1983; Lubzens 1987), and reproduction (Hino and Hirano 1984; Snell and Hoff 1985).

Artemia are still one of the most important feeds in prawn larviculture, yet their full potential has not been achieved. Additional work is needed on improving their nutritional value, and on developing improved encapsulation techniques.

Maeda and Liao (1987) showed that it is possible to improve prawn larval survival and molting rate if the role of microorganisms in the ecological environment of rearing larvae can be determined. A better understanding of these relationships is needed.

7.6.3.2 Formulated feeds

Microparticulate feeds have many advantages over natural feeds, but they are not yet fully substitutable for natural feeds. Further research is needed to improve these feeds so they are a complete substitute.

7.6.4 **Rearing equipment**

Although rearing tank experience for penaeid prawn larvae is half a century old, it has not yet graduated much beyond the trial-and-error stage. Existing tank designs have yet to fully meet larval rearing requirements.

7.6.5 **Shipping methods**

There is considerable need to ship prawn larvae as nauplii, yet little work has been done on this subject. Shipping time must be kept short and completed before the nauplii molt into zoea. This is necessary to avoid mortality caused by absence of food for zoea and a high oxygen consumption during metamorphosis. Nauplii are usually shipped in PVC bags inflated with oxygen, placed in styrofoam boxes. International transport normally takes more than 30 hrs. and is expensive. At present, there is a basic lack of knowledge about naupliar and larval transport. Some such information is summarized in Table 6.

7.6.6 **Social impact**

Postlarvae oversupply in Taiwan before the 1988 crash in prawn production had an adverse social impact. Although low PL price was beneficial to pond culturists, some hatchery operators lost much of their capital investment because of the extremely low PL price, sometimes even below the break-even point.

7.7 **RECOMMENDATIONS**

Taiwanese penaeid larviculture techniques are fairly well developed, although a few aspects need further improvement. The 1988 breakdown of the Taiwanese prawn culture industry has, however, posed a major challenge to prawn hatcherists, especially in larval diseases diagnosis and prevention. A principal recommendation of the Fish Disease Preventive Working Group (Liao 1989), which was organized to investigate causes of the 1988 mass mortality, was to upgrade and normalize larval rearing methods, including avoidance of high rearing temperatures. It was further recommended to conduct studies on aquaculture vaccines and breeding of disease-resistant strains. To ensure continued development of the prawn larviculture industry in Taiwan, the following are being adopted:

1. Establish culture techniques for maintaining good quality broodstock. Existing efforts on wild stock enhancement, which have shown very promising results, need to be further strengthened.
2. Formulation of complete larval diet. Skeletonema, Tetraselmis and Chaetoceros may be abundant in one area but scarce in other locations. There is therefore a need to develop nutritionally complete, formulated larval feeds.
3. Establish measures for preventing larval diseases. Abusive use of drugs and other chemicals in preventing prawn diseases is not beneficial to the larvae. The best approach is to keep a healthy environment and to maintain quality rearing conditions in ponds.
4. Develop constructive means for producing high quality PL. Means are needed to quantify quality, and to then establish larviculture practices that produce high quality PL. Presently, quality has been sacrificed for the sake of low quality, low priced PL.
5. Licensing of hatcheries to prevent PL price collapses. Before the 1988 crisis, PL price had fallen due to overproduction. At present there are about 2,000 hatcheries operating in Taiwan which compete with each other. Hatchery licensing could avoid stiff competition for low-cost PL at the expense of quality and survival. Another solution would be to form an association of hatchery operators to promote cooperation among those in the industry.
6. Evaluation of cost-effectiveness of using modern technology in hatchery design and operation. The cost of using advanced aquaculture engineering should be weighed against effects in overall hatchery management.
7. Diversification of culture species. Species diversification may reduce the impacts of disease outbreaks.

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CHAPTER 8

Alec Forbes

PENAEID LARVICULTURE: SMALL-SCALE ASIAN HATCHERIES

8.1 INTRODUCTION

Successful, large-scale shrimp farming in Asia is relatively new. Prior to recent technological break-throughs, extensive farms existed for thousands of years where wild postlarvae (PL) were brought in with the tide. These coastal ponds were typically in mangrove swamps and rice paddies. As economic viability of shrimp farming improved, technologically more sophisticated farms developed. Semi-intensive and intensive systems with feed supplements, hatchery reared PL's and aeration devices are now common, and far out-produce extensive culture ponds. These steps toward intensive farming were natural ones, implemented by big business and Government grants.

Intensification in Asia is almost entirely dependant on hatchery reared PL for pond stocking. Wild stock PL of the right species are generally not available in sufficient quantities at the right times and places. In some cases, wild PL are simply not available at all due to climatic conditions. How then, is one to stock all the ponds with healthy postlarval shrimp? A partial response has been the development of small-scale, family operated hatcheries wherever shrimp farming has taken hold. It has become a multi-million dollar business in many Asian nations.

Basic technology transfer to these backyard operations was assisted by the crash of hundreds of small Taiwan hatcheries, starting about 1987. The cause for the demise of these Taiwan hatcheries is still a point of speculation. Whether it is temporary or not, caused by toxicant or pathogene build-up in the over-used nursery ponds and tanks, or caused by polluted source water or bad feed, the end result has been the transfer of technology by Taiwanese hatchery technicians who relocated to places like Thailand, Indonesia, Malaysia, and the Philippines. With this transfer of methods and technology, the door was opened for the growth of small-scale hatcheries whose production was, and is, booked well in advance by insatiable shrimp farms.

Hand in hand with technology transfers came the need for improvements in specialized feeds, transportation methods for gravid females and PL, pond stocking techniques, harvesting, shrimp processing and cold storage, and

marketing of the finished product. A whole new industry was born amid all the trauma of trial and error that usually accompanies such developments. At the base of this huge and complex infrastructure, the hatchery had come into its own, for without PL to support the industry, the rest comes to naught.

8.2 HATCHERY METHODS

Methods used in small-scale Asian hatcheries are very diverse. Previously, one could classify a hatchery as using the "Japanese" method, or the "Galveston" method, but not so anymore. Small hatcheries have specialized to the point where some hatcheries only spawn females and sell their nauplii to other hatcheries, who in turn raise them to PL2 (2 day old PL), or PL5. These hatcheries in turn sell PL2-PL5 to other hatcheries (or nurseries) who in turn nurse them to PL12, PL20 or even PL35, depending on what the shrimp farmer specifies. The full cycle hatchery concept, from spawning to PL20, is now becoming a rarity in small-scale operations.

Thailand is a typical example of how small-scale hatcheries operate. The successes, failures and methods of production are indicative of what is happening elsewhere. The preferred cultured species is now the giant tiger prawn (Penaeus monodon), which has overtaken the banana prawn (Penaeus merguensis). The hardy P. monodon grows quickly and is euryhaline. This omnivorous species is in demand on the export market, and with unilateral eye stalk ablation, it is fairly easy to spawn.

In 1988 there were about 300 small-scale hatcheries operating in Thailand, 16 large Government hatcheries, and 13 large private sector hatcheries. These small-scale hatcheries catered to about 45,000 ha of mostly extensive and semi-intensive shrimp farms, and do a lesser extent intensive farms. Annual production from these shrimp farms in 1988 was about 20,000 MT, or approximately the same as the 1984 shrimp culture production from Taiwan (Chiang and Liao 1985).

Thai hatcheries are mostly located around the Gulf of Thailand coast. Transportation logistics between sourcing grounds, hatcheries, farms and suppliers are best here. The eastern seaboard hatcheries from Trat and Chantaburi up to Choburi produce mostly Penaeus monodon, whilst hatcheries in the south of Thailand, towards the Malaysian border, produce a mixture of P. monodon and P. merguensis. (See Shrimp Culture Industry of Thailand, this volume).

8.3 SHRIMP/PRAWN SPECIES ALTERNATIVES

In one respect, Thailand is unique with respect to its small-scale hatchery development and history. A large number of Thailand's small-scale hatcheries

used for marine shrimp culture were originally built between the mid-1970's and mid-1980's for production of freshwater prawn (Macrobrachium rosenbergii) PL. By 1987 Thailand led the world in freshwater prawn culture with 73%, while Taiwan produced 17% of the world total (New 1988). Once P. monodon nauplii became available during the late 1980's, many of these hatcheries switched to tiger prawn PL production since prices and profits were much higher, and larval culture time is shorter. Many such hatcheries now alternate between freshwater prawn and P. monodon larviculture depending on respective PL prices and nauplii availability. This flexibility, and the low over-head nature of the operations has resulted in a very large and rapid increase in P. monodon PL production, which in turn has fueled Thailand's shrimp culture industry. Thailand's small-scale hatcheries can thus sell P. monodon PL profitably at prices below the production costs of larger hatcheries, which are less flexible and have higher over-head costs. When PL production approaches or exceeds demand, PL prices drop below breakeven price for even small-scale hatcheries at times. The long-term prognosis is not optimistic for stand alone, large-scale hatcheries that are not vertically integrated with farm operations.

8.4 ENVIRONMENTAL CONSTRAINTS

Water and soil conditions represent, to my mind, the most serious threat to the future of shrimp culture. Both are of paramount importance to shrimp farms, and therefore directly affect the hatchery business. In Thailand for example, it has long been realized that the upper Gulf of Thailand has seasonally low salinity and is polluted by industrial effluent dumped increasingly into the Gulf. The Chao phraya and other large rivers flow into the Gulf along the northern coast. Tidal exchange cannot cope with the volume of freshwater that pours into the Gulf during torrential rains. Thus, low salinity and highly polluted waters tend to backup in the upper Gulf. The demarcation line between clean ocean water and polluted Gulf water is moving further south each year. To counter this, hatcheries "import" water by large tanker trucks from points southwards, where water is cleaner and has 32 or 33 ppt salinity. Typically, once business has proven successful, a hatchery family will invest in a tanker truck and the eldest son will then make the daily or twice daily drive south to get acceptable water. This is normal practice in all the small hatcheries. Only a few have invested in more modern treatment such as ultra-violet, sand filters and ozonation.

Water problems in hatcheries and farms throughout Asia are on-going problems, and are more serious than may appear at first sight. Hundreds of entrepreneurs across Asia have built farms and hatcheries on acid-sulphate soils. Soil surveys were generally not made, perhaps with the idea that the

cost of the land was more important than its suitability for aquaculture. There are approximately five million ha of ponds in Southeast Asia, and more than fifteen million ha in the tropics that are acid sulphate. Sixty percent or more of Philippine ponds, and 90% of Malaysian mangrove swamps have these characteristics. In addition to acid soil problems, herbicides and fungicides are used regularly in the rice paddies and pineapple plantations that surround the farms and hatcheries on the coastal plains. These toxicants leech into the coastal waters through run off. Farm yields of shrimp are negatively impacted by all of these conditions, particularly when attempts are made to intensify. Hatcheries are even more sensitive to pollution than are farms.

8.5 SMALL-SCALE HATCHERY LAY-OUT

Average hatchery land area is less than 0.5 ha, partly covered in bamboo and thatch roofing (Fig. 1). Larval tanks are in the open, with a system of corrugated composite lids or covers to keep out the bright sunlight and tropical rains. Larval rearing is done in small 1,000 to 2,000 l concrete rectangular tanks in which the bottoms and corners have been somewhat rounded off with mortar or in round fiberglass tanks. Water is added via an overhead pipe running the length of the tank rows. Water is removed by siphoning, or by draining through a bung hole during tank cleaning prior to restocking. Each tank has a composite, corrugated sheet to protect it from the sun and rain as needs dictate. Seawater is pumped from a central reservoir, which may or may not have been treated with EDTA. The reservoir is kept topped up by the water tanker truck. Typical parameters are as follows: water temperature 27C to 32C; salinity 33 ppt; and pH 8.0 to 8.3. In winter, water temperatures drop alarmingly at times, and many hatcheries close down rather than heat water with immersion heaters. Hatcheries are typically equipped with a refractometer or a hydrometer, thermometers, perhaps a pH meter, and a microscope. A fair assortment of anti-biotics and medicines is also stocked.

8.6 GRAVID FEMALES/BROODSTOCK

There are two main areas off the Thai coast where gravid and non-gravid female broodstock are caught by the fishing fleet; namely off the Trat coast in the Gulf of Thailand, and in the Andaman Sea off Burma and Western Thailand. There is a thriving sub-industry to supply broodstock. Indeed, some fishing boats specialize only in broodstock procurement for sale to hatcheries. Recently, Government hatcheries have succeeded in raising broodstock in their own holding ponds. It is hoped that eventually there will

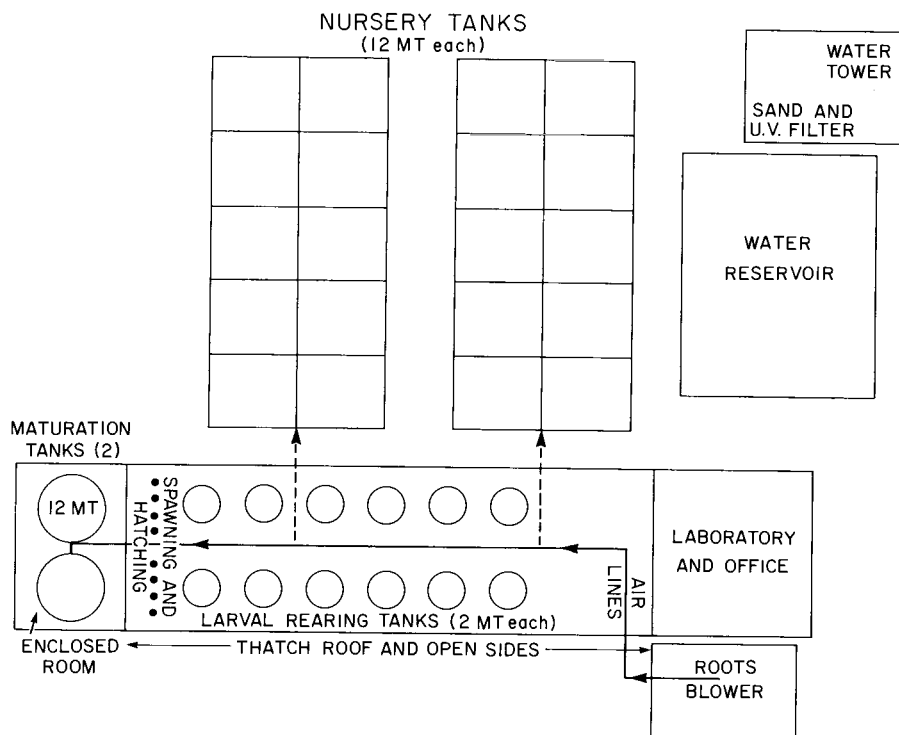


Figure 1. A typical layout for a small-scale hatchery in Thailand. Annual production capacity is 20 million PL15 from 0.5 ha. This hatchery can spawn and rear through the nursery stage.

no longer be a need to source broodstock from the wild. At present, however, the sale of wild caught broodstock is an industry in itself.

Typically, broodstock are placed in 12 tons or more circular tanks with a ratio of one female per one male, one couple per ton. The tanks are in a darkened hut or building, and are equipped with air lift pumps and constant aeration. The shrimp are allowed to rest for three or four days to recover from the stress of their journey by truck and airplane. They are then examined on a daily basis using an underwater flashlight lashed to a pole to determine ovarian maturation. Recent innovations at some hatcheries include Filipino "Disco" lights whereby the entire fiberglass bottom of the tank is lit to allow scrutiny of all animals in the tank.

When a female is considered ripe (stage IV), she is gently removed from the maturation tank, unilaterally eye stalk ablated, and placed in a spawning tank. Ablation takes many forms, including cauterization of the eye stalk with red hot forceps (a favorite Taiwan technique), ligation of the eye stalk, outright removal of the eye (my own preference), or a squash of the eye.

The shrimp is placed in a 2 ton spawning tank, and usually spawns from 500,000 to one million eggs the same night. When spawning is completed, the female is then placed back in the maturation tank and may be spawned again; although the buyer will probably insist on first or second spawn PL only, since subsequent spawn often result in stunted and weaker PL.

8.7 NAUPLII

Spawning tanks are also used for egg hatching. Only a few small hatcheries use separate egg hatching tanks. A 70% egg hatch rate is common. Nauplii are then maintained to N3 (naupliar stage 3), at which time they are likely sold to another hatchery. Thus a nauplii 'farm' typically consists of maturation tanks enclosed in a bamboo hut lined with black plastic sheeting to maintain heat and darkness; water supply; and a technician. The adult P. monodon cost about Bht.2,400 per pair (one female and one male), or about US\$96.00. The nauplii sell for Bht.10,000 per one million (US\$400.00). The nauplii hatchery is indeed a back yard operation. More and more of them are springing up, as witnessed by the myriad of signs along hatchery row; "Black Tiger Nauplius for Sale."

8.8 LARVAL REARING

As larval rearing progresses past the nauplius stage, tanks must be prepared for the hungry protozoal stage, the stage when feeding begins. Aware of serious water quality problems throughout Asia, the hatchery manager seeks water purification methods for his stock. A favorite method is to heavily chlorinate the water at 100 ppm and then vigorously aerate the tanks for three or four days to eliminate the chlorine. Then, in the really small hatcheries, rice flour is sprinkled on the water surface. This gradually sinks to the bottom where it is vacuumed away leaving the water sparkling and clear. After the water is purified, provision is made for unicellular algae. The nauplius tanks are inoculated with a preferred algae, the 'starters' being readily available from the dozens of little shops that have sprung up in every aquaculture village. In Thailand the preferred algae is Chaetoceros spp., Tetraselmis spp., and Skeletonema costatum. Hatcheries co-operate among themselves to a surprising extent, particularly in the same villages. It is not unusual for one hatchery to borrow from another, a few bags of algae to tide them over in the case of an algal bloom collapse. Japanese and Taiwanese products are readily available in the aquaculture shops throughout Asia; including a bewildering display of "guaranteed" larval feeds, booster feeds, maturation feeds, artificial plankton, medicated feeds and miracle cures which meet the eye on every shelf. A popular larval feed is Skeletonema spp., first

isolated by Matsue in 1941. His modern day counterparts all over Asia are doing the same thing today. Small-scale hatcheries are surprisingly advanced in algal culture. They use both the "same tank" system of propagating diatoms in larval rearing tanks, thus saving on cost; and the "separate tank" system of culturing single or mixed algae species in separate tanks. The task of algal culture at small hatcheries is usually allocated to the daughters of the household, or to a female employee; as is most of the laboratory work.

Once the mysis stage is reached, hatcheries then supplement algae with Artemia spp., artificial micro-encapsulated feed, and/or natural feed in the form of minced squid or mussel. The larvae are sampled and examined daily, and feed rates calculated accordingly. Feeding takes place every three hours using four natural feeds, and four artificial feeds; or every four hours using four natural feeds and two artificial feeds depending on the stage of growth. Artemia salina, a favorite mainstay of shrimp hatcheries despite its high cost, is now falling into disfavor. Invariably, all Artemia brands seem to bring with them a proliferation of zoothamnium parasites and contaminants despite chlorine decapsulation treatment. Excellent work and major advancement have been made by Sorgeloos and colleagues (Laboratory for Aquaculture and Artemia Reference Center, State University of Ghent, Belgium) in the production of suitable cysts, but Artemia used in Asia is still rife with many disadvantages.

Microencapsulated feeds, such as Frippak from the United Kingdom are becoming more and more popular in hatcheries despite their costs. I know of several hatcheries that use only Frippak or equivalent feeds during algal collapses, with great success. These feeds are clean, easy to use, and disease free.

Each Asian country has some country specific larval feed preferences. These include Skeletonema spp., for P. monodon in Thailand, duck egg custard for P. chinensis in the Peoples Republic of China, Brachionus plicatilis for many species in Taiwan, minced trash fish for the P. monodon of Indonesia and the Philippines, and ground mussels for the P. indicus on the sub-continent. The objective in every family hatchery is the same, to feed the young larvae and bring them safely to PL stage with as few mortalities as possible.

Daily observations are carried out in each tank. Larval count is maintained; and color, activity and gut content are noted. Tanks are cleaned daily by siphon prior to water exchange and morning feeding. Anti-biotic and anti-fungal treatments are common in all hatcheries. Lagenidium sp. is a common fungus thwarted constantly with formalin or treflan at a 2 ppm. Leucothrix mucor, zoothamnium, and epistylis are all treated with oxytetracycline at 100 ppm and chloramphenicol (1 to 10 ppm). Survival from nauplius to PL5 for the P. monodon is 40%. This low figure is due in all

probability to their susceptibility to bacterial infection. Nutritional diseases in Southeast Asian hatcheries are gradually being overcome, but a lot of progress remains to be made in the Peoples Republic of China.

A production rule of thumb for small-scale Asian hatcheries is about 100,000 PL/m³ (100 PL/liter) of water. A family operated small-scale hatchery will produce about two million PL/mo. A network of brokers in turn will market the products, covering farms far and wide. This eliminates the marketing responsibility from the hatchery. The ex-hatchery PL price to the farmer typically ranges from US\$8.00/1,000 PL15, up to US\$15.00/1,000 PL30. Thus strong profit incentive exists and the small-scale hatchery is there to take advantage of it. The operator will invest a great deal of his profits back into new tanks, land acquisition, education for one of his daughters at a University Marine Biological Station, or employment of skilled personnel. Nauplii producers pack 200,000 nauplii in a 5 l double plastic bag; one-third full water and two-thirds full of compressed air from a cylinder. The finished double bag looking like a large balloon. Pure oxygen is seldom used, except for long overseas trips, as it is too costly. PL "bagging" is usually a job for the sons of the household, and packing is always done at night when it is cooler and safer to harvest and transport PL. Nauplii and PL harvesting turns into quite a family gathering, with father verifying the count being made by his daughters in the plastic lined counting bowls, the sons packing the plastic bags and load the trucks, and the lady of the household handling all the financial transactions with the buyer, who is on the scene to verify the count. Prior to harvest, the buyer (farmer) will visit the hatchery to check the PL. He will also have a representative present at harvest to verify the counts.

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CHAPTER 9

Philippe Leger
and Patrick Sorgeloos

OPTIMIZED FEEDING REGIMES IN SHRIMP HATCHERIES

9.1 INTRODUCTION

A primary problem in culturing larval shrimp is food. Ideally one would feed larvae with their natural diet which consists of a wide variety and abundance of phytoplanktonic and zooplanktonic organisms. This abundance and diversity of food organisms of different sizes and biochemical composition maximizes chances for meeting all the nutritional requirements of the shrimp larvae.

Commercial success in the controlled production of shrimp postlarvae (PL) developed through trial and error which was only recently followed up by a more scientific approach. The first culture trials on a laboratory scale were carried out feeding freshly-collected wild plancton, aiming at imitating the natural habitat, free of predators. Collecting and feeding natural plancton may appear desirable, but is hardly dependable beyond laboratory scale. On an industrial scale, similarly to intensive cattle and poultry farming a readily and consistently available, practical and nutritious diet is preferred.

9.2 DIET SELECTION CRITERIA

9.2.1 Requirements of the culturist

Selection of a suitable diet is normally determined by a number of criteria based on the viewpoint of both the culturist and the cultured animal (see Fig. 1). From the practical viewpoint of the culturist, a good diet would be readily available, cost-effective, simple and versatile in application.

The consistent availability of sufficient numbers of food organisms is of utmost importance for continuous cultures. In this respect, the collection and feeding of wild plankton has proven unreliable and not practical. The only solution was the indoor production of a limited number of food organisms, such as algae (e.g. Chaetoceros and Tetraselmis produced in continuous cultures), Artemia (produced from off the shelf available dormant cysts) and in some cases rotifers and nematodes which need to be produced in continuous cultures as well.

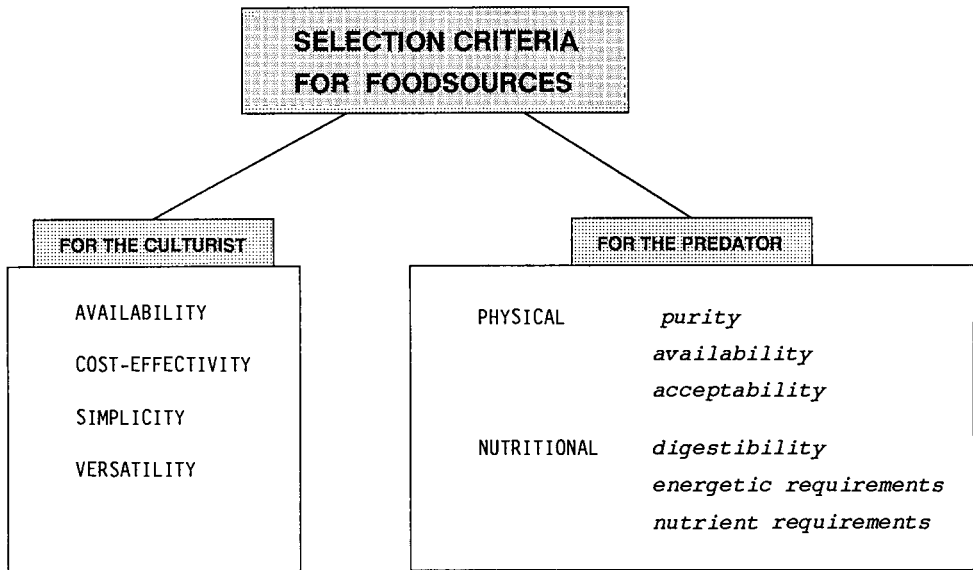


Figure 1. Selection criteria for larval food sources from the viewpoint of the culturist and the cultured larva.

A second selection criterion for larval food, from the culturist's point of view, is cost-effectiveness, i.e. the impact of cost of a particular diet on larval production cost. When the price of PL is dropping, it is imperative to save on all operational costs including diets. In this respect it is recommended 1) to reduce the cost of algae by selecting fast growing nutritious species, 2) to optimize culture procedures and protocols, and 3) to reduce the quantities needed by supplementing with cost-effective artificial diets for algae replacement. The same applies to Artemia where costs can be considerably reduced by:

- selecting cyst batches with a high hatching efficiency;
- optimizing procedures and protocols for cyst disinfection and hatching, for harvest and storage of the nauplii, and for feeding to the shrimp;
- feeding expensive high nutritional quality Artemia only for short periods and cheap, low nutritional quality but enriched Artemia afterwards;
- supplementing with cost-effective artificial diets for Artemia replacement.

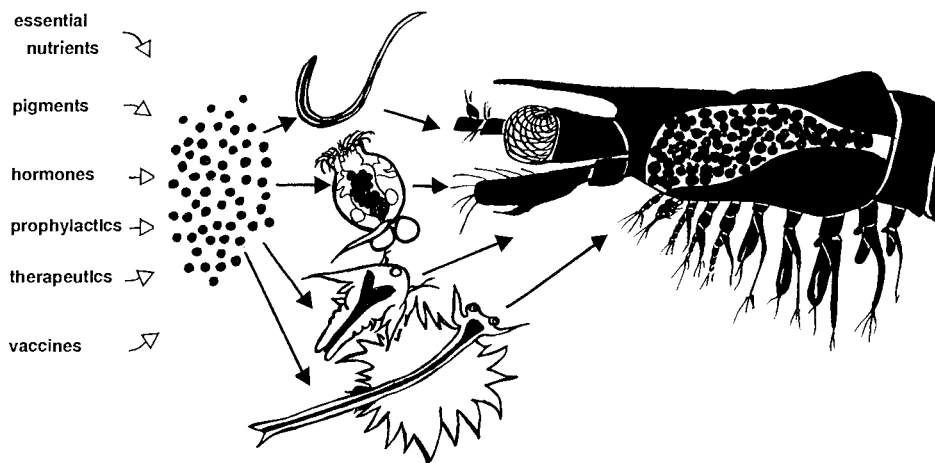


Figure 2. Schematic diagram of the use of live food sources as vectors for transfer of specific components into the cultured larva.

The next selection criterion for the culturist is simplicity of food production. Algal production is not simple at all. It requires use of complex culture media, made up with germ-free seawater treated by microfiltration and/or UV-irradiation. Algae are progressively cultured in a multi-stage upscaling system. Starting from sterile test-tubes, algae are inoculated in larger glass containers and carboys, then to bigger vessels or plastic bags and finally to large, indoor or outdoor tanks.

Producing *Artemia* is much more simple than culturing algae, as their nauplii are produced from a virtually inert, off the shelf powder, consisting of dormant, encysted embryos. The nauplii are produced by incubating the cysts for about 24 hours in seawater under optimal conditions of temperature, salinity, pH, oxygen, cyst density and illumination (Sorgeloos *et al.* 1986). These factors affect hatching success and hence the production cost of *Artemia* nauplii. Attention should be paid to select *Artemia* cysts with a high hatching efficiency, as considerable variation has been demonstrated between cysts of various origin, and even between batches from the same strain (Sorgeloos *et al.* 1986).

Culturing rotifers is relatively simple, although culture failures often occur and harvest and rinsing techniques are labour intensive (Fukusho 1989). The same applies to nematodes, especially for harvest and rinsing (Fontaine *et al.* 1982).

The last selection criterion for larval food, from the viewpoint of the culturist, is their versatility. Food organisms should be tolerant of changing salinity and temperature and of handling. This criterion is met by algae and *Artemia* which can withstand environmental stress and handling so well that they may be pumped from their culture tanks into the larval rearing tanks. A single diet is either too small (algae) or too large (*Artemia*) to be fed during all the larval stages of penaeid shrimp. The possible use of different sizes of one foodsource contributes to its versatility. In this respect *Artemia* can be offered at different sizes. Its smallest form, a decapsulated cyst of about 200 μm , was shown to be a suitable diet for the Zoea II - Zoea III stages of shrimp (Wilkenfeld *et al.* 1984). However, in view of the high sinking rate of the non-moving decapsulated cysts, their use is limited in commercial operations. *Artemia* nauplii measure about 420 μm to 520 μm and are readily accepted by the mysid and postlarval stages. PL accept larger *Artemia* metanauplii and juveniles. Adult brine shrimp can be successfully used for nursery and broodstock feeding (Browdy *et al.* 1986, Flores Tom 1987, Salgado 1988). *Artemia* may be cultured in indoor intensive systems, collected from natural sources (e.g. salt lakes and salt ponds), or pond-cultured in fertilized brines of 100 to 200 ppt salinity (Sorgeloos *et al.* 1986).

A last aspect of the versatility of some food-organisms involves their use as a carrier for various dietary components (Fig. 2). Essential nutrients, pigments, hormones, prophylactics, therapeutics or vaccines may be injected by the live prey, e.g. *Artemia* (nauplii as well as adults), rotifers and nematodes, which in turn are consumed by the larvae. Some components, such as the essential fatty acids 10:5w3 and 22:6w3 are not only carried in the gut of the prey but are accumulated in its tissue, which leads to very high doses in the prey organisms (Fig.3). Essential fatty acid enrichment is common practice in marine fish hatcheries and is catching on very fast in larval shrimp culture (Sorgeloos *et al.* 1987). Like fatty acids, other components such as drugs may be introduced into the predator larva via the prey. A recent experiment with *Artemia* nauplii showed a high accumulation of the antibiotic mixture Trimethoprim - Sulfamethoxazole formulated as an emulsion in a commercial product (SUPER SELCO, Artemia Systems S.A., Ghent, Belgium). Concentrations up to 1500 ppm (dry weight basis) were achieved. This demonstrates the efficiency of this procedure (see Fig. 4; Leger *et al.* unpublished data). Figure 5 shows how quickly high levels (3-4 ppm) of the antibiotic chloramphenicol (which was used as a model in this

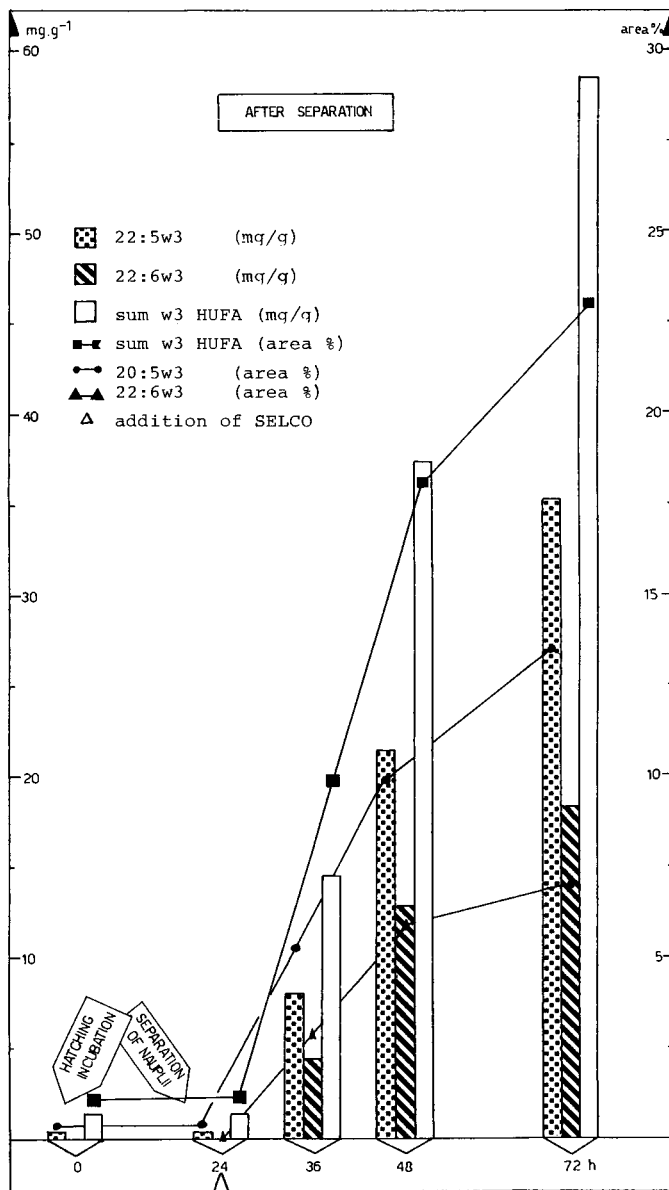


Figure 3. Accumulation of w3-HUFA, especially 20:5w3 and 22:6w3, in *Artemia* nauplii after enrichment with an emulsified enrichment diet (from Leger et al. 1987).

study) build up in the caudal muscle tissue of fish larvae which received only one ration of chloramphenicol fortified *Artemia* nauplii. Nauplii were enriched with a commercial enrichment emulsion (SELCO, Artemia Systems

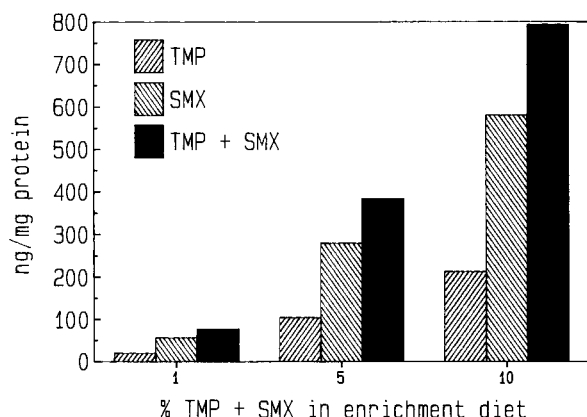


Figure 4. Accumulation of Trimethoprim (TMP) and Sulfamethoxazole (SMX) from a medicated emulsion in *Artemia* nauplii after 24 h enrichment.

S.A., Ghent, Belgium) fortified with 10% Chloramphenicol. Tissue concentrations above the therapeutic levels remained constant for at least 8 h.

9.2.2 Requirements of the larva

Once all criteria are fulfilled from the viewpoint of the culturist, food-organisms must meet a number of requirements for the shrimp larvae (see Fig. 1). Physical as well as nutritional criteria are important. Food purity is a prerequisite, as contamination by debris and pathogens may indeed be transferred via the live food into the larval culture tank. Since contamination can hardly be removed from algae suspensions, we recommend use of only pure cultures. *Artemis* cyst shells may be loaded with bacteria and fungi. These may be effectively removed by disinfection using bleach. A minimum treatment consists of a 30 min. soak of the cysts in a 200 ppm hypochlorite solution (fresh- or seawater) prior to incubation for hatching. This treatment may not kill microbes present in the alveolar and cortical layer of the chorion. In order to cure this problem, many commercial hatcheries use decapsulated cysts. These are sterile because their chorion is completely dissolved at high pH and hypochlorite levels. A detailed outline of the decapsulation procedure can be found in Sorgeloos *et al.* 1986.

9.2.2.1 Physical requirements

After hatching, but prior to feeding them to the shrimp larvae, *Artemia* nauplii should be thoroughly rinsed with freshwater, preferably in submerged filters to prevent physical damage to the nauplii. This can be done most effectively with a special type of *Artemia* concentrator/rinser, the filter of which is made of stainless steel, welded, wedge material. Using this new

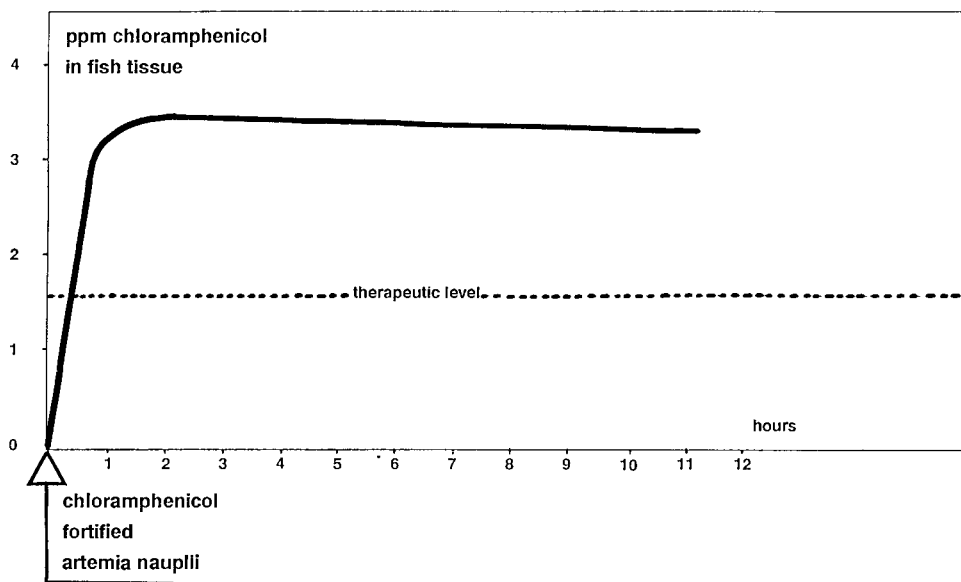


Figure 5. Chloramphenicol levels in caudal tissue of fish larvae, *Cichlasoma nigrofasciatum*, fed a single ration of 24 h-chloramphenicol-enriched *Artemia* nauplii (Nin et al. unpublished).

filter, commercial hatcheries report production of *Artemia* of increased purity with less labour and time for harvesting and rinsing. Using tapwater for rinsing nauplii instead of seawater appears to be more effective in removing bacteria from the *Artemia* suspension (Gidon Minkof, Tina Menor SA Spain, pers. comm.).

A second physical restriction for good larval food is its continuous availability for ingestion. Contrary to many artificial diets, most live food organisms remain readily available in the water column because of their swimming activity. If a prey is available, it should then be tested for physical acceptability to the larvae, before nutritional parameters are considered. Prey acceptability is conditioned by several factors. First, it has to be easily perceived by the predator. Perceptibility is affected by colour, contrast with the environment and movement. It is obvious that the perceptibility of a prey is only critical for shrimp from the later Zoea stages onward when visual hunting occurs.

After being perceived by shrimp larvae, a good prey needs to be easily caught. Prey catchability is determined by its swimming speed and escape response, which are very slow in *Artemia* nauplii. Once caught a prey will only be ingested if it has an acceptable taste and appropriate size. Prey size will indeed determine the time of earliest possible administration. The smaller it is, the earlier it may be fed in development. From an energetic

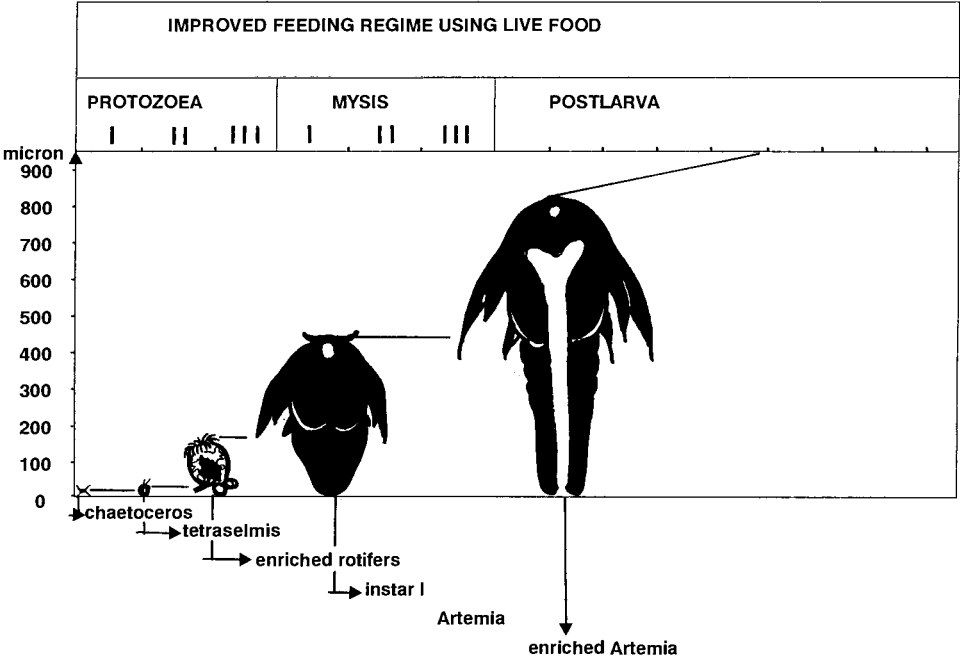


Figure 6. Schematic diagram of an optimized feeding regime for penaeid shrimp larvae using different types of available live food (note size differences of live prey items).

point of view, a prey should be as large as possible in order to maximize the energy intake by the predator per hunting effort. Common feeding practice for shrimp larvae is to use only two prey sizes; first, algae measuring less than 20 μm , followed by *Artemia* nauplii of about 500 μm . For energetic benefits, it is recommended that the size gap between algae and *Artemia* be minimized by feeding rotifers, nematodes or decapsulated *Artemia* cysts to Zoea II and III-stages, then switch to freshly hatched, and finally to enriched and ongrown *Artemia* for the postlarval stages (Fig. 6).

9.2.2.2 Nutritional requirements

Although fulfilling the physical requirements, a prey can only contribute to good growth and survival when it meets the nutritional needs of its predator. Once ingested, a foodsource has to be digested before the predator can profit from its nutritional components. In this regard, live food organisms provide an advantage over artificial diets because their proteolytic enzymes will contribute to their auto-digestion. The energetic content of an individual food particle may be maximized by feeding the largest allowable prey-size in its highest energetic form. We recommend that one starts in Zoea-I with

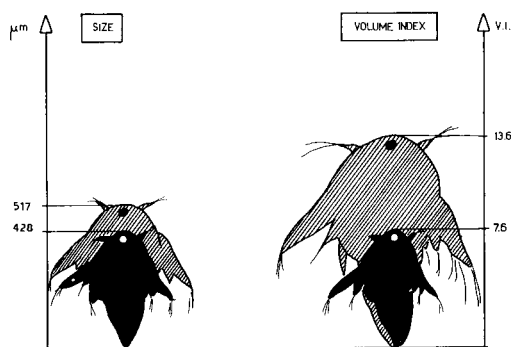


Figure 7. Schematic diagram of the biometrical variation in freshly hatched instar I *Artemia* nauplii from different geographical origin (size=nauplius length; volume index=Coulter Counter

small *Skeletonema* or *Chaetoceros* and switches in Zoea-II to larger cells such as *Tetraselmis*. Algae display their highest nutritional value when harvested in their exponential growth phase.

With *Artemia*, considerable differences have been reported between strains both in biometrics and energy content (Figs. 7 and 8). Furthermore, first instar nauplii provide better nutrition than starved, second instar metanauplii which are less visible. Instar II *Artemia* are larger and swim faster than first instars, as a result of which they are less acceptable as prey. Furthermore they contain lower amounts of free amino acids, so they are less digestible and their lower individual organic dry weight and energy content will reduce the energy uptake by the larva per hunting effort. All this will be reflected in a reduced growth of the larvae (Fig. 9), and an increased expenditure on *Artemia* cysts because 20 to 30 % more cysts need to be hatched to feed the same weight of starved metanauplii).

Molting of the *Artemia* nauplii to the second instar stage may be avoided, and their energy metabolism greatly reduced, by storing the freshly hatched nauplii at a temperature below 10 °C in densities of up to 8 million nauplii per liter, for periods up to 24 hrs (Leger *et al.* 1983). Slight aeration is needed in order to prevent the nauplii from accumulating at the bottom of the tank and suffocating. With 24 hrs cold storage using styrofoam insulated tanks and blue ice packs for cooling, commercial hatcheries reduce their *Artemia* cyst hatching efforts (e.g. fewer tanks, bigger volumes, maximum one hatching and harvest per day). Furthermore cold storage facilitates increased frequency of *Artemia* feeding, thereby reducing naupliar retention time in the shrimp tanks. The shrimp benefit from a more nutritious food. When applying several distributions of cold stored *Artemia* nauplii per day, shrimp farmers report improved ingestion of the initially slow-swimming prey. This

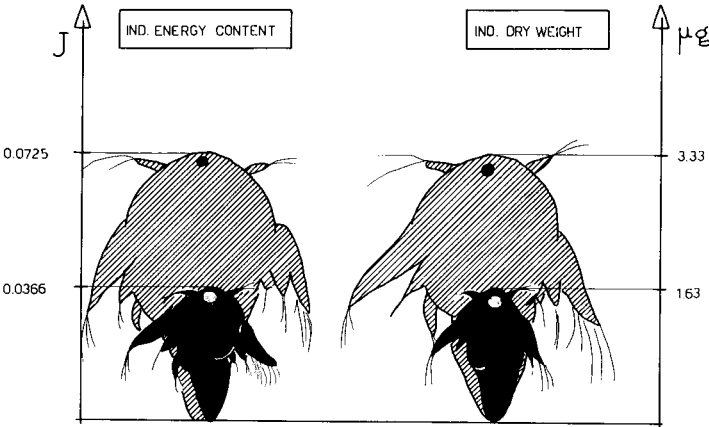


Figure 8. Schematic diagram of the variation in individual energy content and dry weight of frshly hatched instar I Artemia nauplii from different geographical origin (data from Vanhaecke and Sorgeloos 1980).

is especially true of Penaeus monodon which is a poor hunter as compared to many other species. As a consequence, fewer maturing Artemia occur in the shrimp tanks.

The most concentrated energy form of Artemia is the decapsulated cyst containing up to 50% more energy than first instar nauplii (Fig. 10).

Even when a food-source meets all the requirements discussed sofar, undesirable symptoms may still appear in the larvae, such as reduced appetite, stunted growth, slow movement, abnormal pigmentation, lack of coordination, molting and metamorphosis problems, abnormal larval development, deformities and mortality. All these symptoms may be an expression of either toxic contamination or a nutrient deficiency. Recent studies have proven that

Table 1. Dietary protein requirements (in % of dry diet) for different Penaeus species. (data from Tacon 1987)

<u>P. setiferus</u>	28 - 32
<u>P. vannamei</u>	30 - 35
<u>P. stylirostris</u>	30 - 44
<u>P. indicus</u>	30 - 43
<u>P. monodon</u>	34 - 55
<u>P. aztecus</u>	40 - 51
<u>P. merguensis</u>	42 - 55
<u>P. japonicus</u>	52 - 57

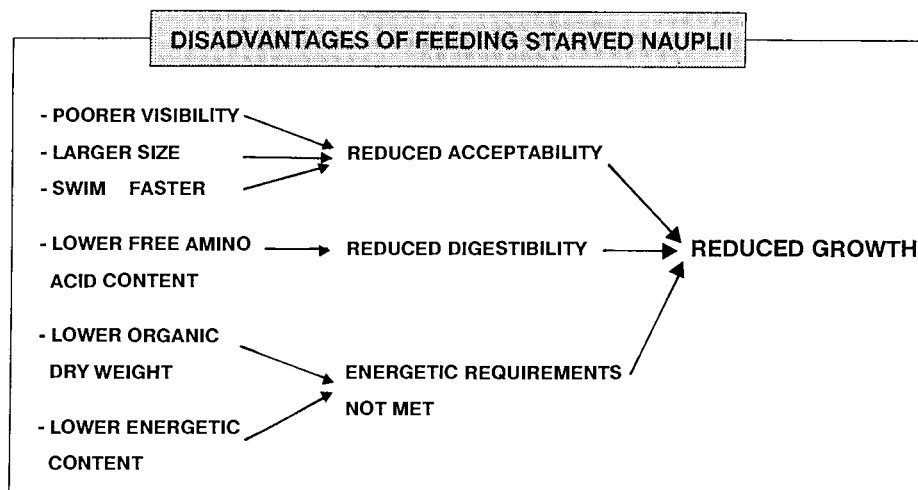


Figure 9. Effects of feeding starved instar II and III *Artemia* nauplii to larval shrimp.

nutrient deficiencies have much more impact than the contamination levels which have been found so far in live prey organisms (Leger *et al* 1985; Leger *et al* 1986; Leger *et al* 1987 a,b).

Dietary protein requirements are apparently met by most live feeds used for *Penaeus* larvae (Table 1 and 2). In terms of amino acid composition, major deficiencies have not been reported to cause abnormal symptoms during larval development. Low levels of the sulfur amino acids, such as methionine, do exist in all zooplankton prey species, including *Artemia* and rotifers.

During the last decade much research has been devoted to better understanding the role and importance of lipids, particularly the fatty acids. It has been demonstrated that the most important essential fatty acids for brackishwater and marine crustaceans, fish and molluscs are the ω 3-highly unsaturated fatty acids (ω 3-HUFA's), especially eicosapentaenoic acid (20:5 ω 3) and docosahexaenoic acid (22:6 ω 3). These are essential compounds required for membrane formation, osmoregulation, synthesis of prostaglandins. Also, they appear to have an activating role in the immune system. Marine fish and shrimp larvae cannot synthesize these ω 3-HUFA's rapidly enough to fulfill their physiological requirements. As a result they need to acquire these vital components through their diet. Analyses of essential fatty acids in the live food organisms used in shrimp larviculture (Table 3) revealed that 20:5 ω 3 is low in all, except for *Chaetoceros*, and that in no case is 22:6 ω 3 present in significant amounts. Furthermore it has recently been demonstrated that for both algae and *Artemia* ω 3-HUFA contents vary much within the same species or strain depending on their culture conditions *e.g.* 20:5 ω 3 levels in

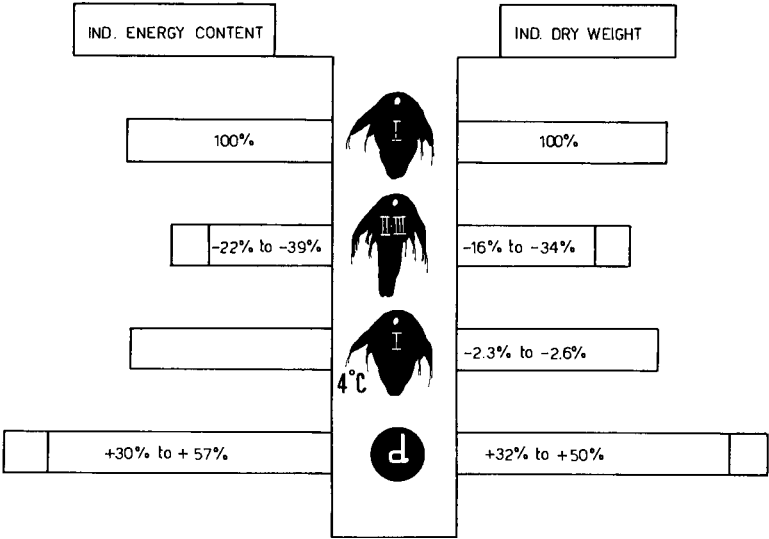


Figure 10. Change in energy content and dry weight of *Artemia* after hatching. Freshly hatched instar I larvae are equated to 100% and are compared to instars II-III, cold-stored instar I and decapsulated cysts (from Leger et al. 1987a).

different cyst harvests of *Artemia* from the San Francisco Bay salterns (CA-USA) can vary from less than 1 to over 10 mg/g nauplius dry weight (Leger et al. 1986).

Table 3. Concentrations of highly unsaturated fatty acids (in % of total fatty acids) in live foods used in *Penaeus* larviculture (- = < 0.1%)

Foodsource		Fatty Acids		
		20:5w3	22:6w3	Σw3HUFA
Algae	<i>Chaetoceros</i>	13.6	-	16.4
	<i>Tetraselmis</i>	4.7	-	5.2
Nematodes	<i>Panagrellus</i> (cultured on "machica")	0.1	-	0.3
Rotifers	<i>Brachionus</i> (cultured on baker's yeast and algae)	2.5	-	3.1
<i>Artemia</i>	nauplii (freshly hatched, UT-USA strain)	2.8	-	3.7

Table 2. Typical protein content (in % of dry weight) of different live feeds used in Penaeus larviculture.

Food Type	Genus or Stage	% Protein Content
Algae	<u>Chaetoceros</u>	24.4
	<u>Tetraselmis</u>	49.8
	<u>Skeletonema</u>	37.0
	<u>Phaeodactylum</u>	33.0
	<u>Isochrysis</u>	37.0
Nematodes	<u>Panagrellus</u>	62.0
Rotifers	<u>Brachionus</u>	52.0
<u>Artemia</u>	nauplii	55.0
	adults	62.0

Variability in 20:5w3 contents as well as the absence of significant levels of 22:6w3 in the traditional live feeds used in shrimp larviculture has stimulated research on the commercial development of w3_HUFA rich algal substitutes/supplements (e.g. microcapsules, w3-enriched yeast products, microparticulate diets), w3_HUFA enrichment products for zooplankton organisms (e.g. microcapsules, emulsions, microparticulate diets), as well as formulated feeds as supplement/substitute for the zooplankters. Using w3-yeast (TOPAL, Artemia Systems S.A., Ghent, Belgium) as an algal substitute/ supplement and the w3-HUFA enriched (SELCO) Artemia, clear improvements have been demonstrated (Figures 11 and 12). Survival and growth rates increase significantly when w3-HUFA supplementation is applied in the zoea-stages. Further improvements are noticed when extra w3-HUFA enrichment is provided in the mysis and postlarval stages, though data were not statistically significant. Hatchery operators feeding w3-HUFA-fortified diets observe more consistent results and production of more robust PL, (e.g. "PL-5 as big as PL-10 which were fed a non-enriched Artemia diet", D. Borlogan, in Sorgeloos 1988; Chamberlain 1988). Improved nutrition in early larval stages affects not only hatchery outputs but also survival and growth in later postlarval stages. This is clearly illustrated in a simulated nursery-test with P. vannamei larvae (PL-8), which were previously fed under different w3-HUFA regimes, but all switched to the same commercial nursery diet afterwards (Fig. 13).

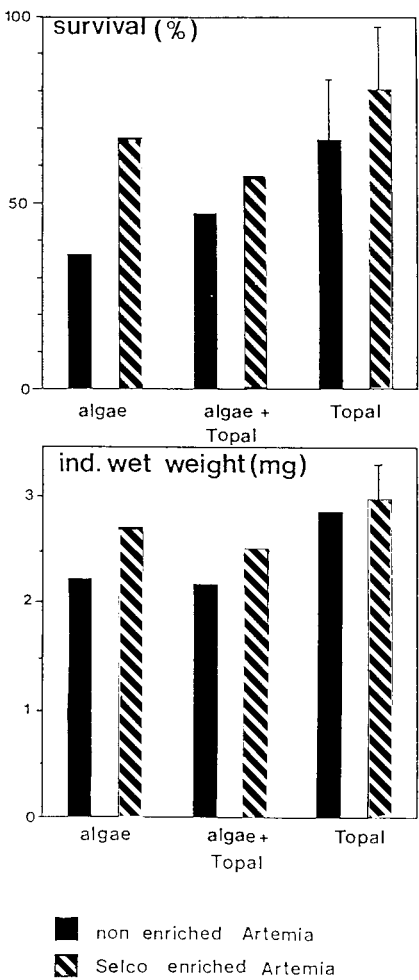


Figure 11. Survival and weight of *P. vannamei* PL8 fed only algae, a mixture of algae and TOPAL or TOPAL only up to M2. Each treatment was split at M3 into groups fed fresh *Artemia* or SELCO enriched *Artemia*.

9.3 PHYSIOLOGICAL EVALUATION

A way to evaluate the physiological status of PL is to submit them to a stress-test (Tackaert *et al.* 1989). *P. monodon* PL-10 transferred from 35 ppt to 7 ppt for 30 and 60 minutes (Fig. 14) showed a significant difference in survival as a function of their PL and larval diet. The best performance was recorded for those larvae that received the diet with highest w3-HUFA levels. Variable physiological condition of shrimp PL may result in

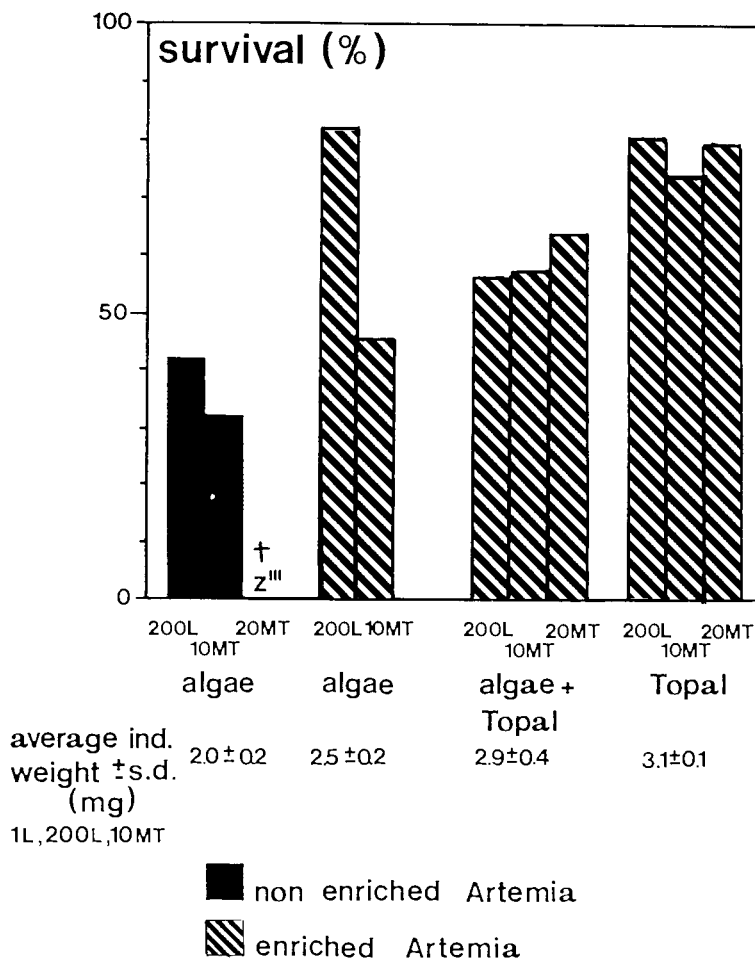


Figure 12. Comparison of survival results in *P. vannamei* at PL8 when reared in large culture systems following the same feeding regimes as in Fig. 13 (after Leger et al. 1987b).

differential performance under growout conditions. Furthermore, the better stress resistance of PL fed enriched *Artemia* might also result in better resistance to diseases. The role of dietary unsaturated fatty acids in immunoresistance is well documented for many organisms (Di Luzio 1972).

Stress-test procedures are now applied by commercial hatcheries in South America and Southeast Asia for evaluating the quality and determining the price of their PL. In several operations in Ecuador, transfer of PL's from the hatchery to the growout ponds is no longer performed at a particular PL-stage. Instead PL are submitted to a 1 h combined temperature-salinity shock (20 °C, 10 ppt) and when survival is over 60% they are considered to be ready for stocking. When survival is lower, PL are cultured for a few days

after which time they are re-evaluated with the stress test (J. Broome, in Sorgeloos 1989).

9.4 RECOMMENDED FEEDING REGIMES

Because we expect different requirements for the w3-HUFA's 20:5w3 and 22:6w3 among Penaeus species (as is well documented for different marine

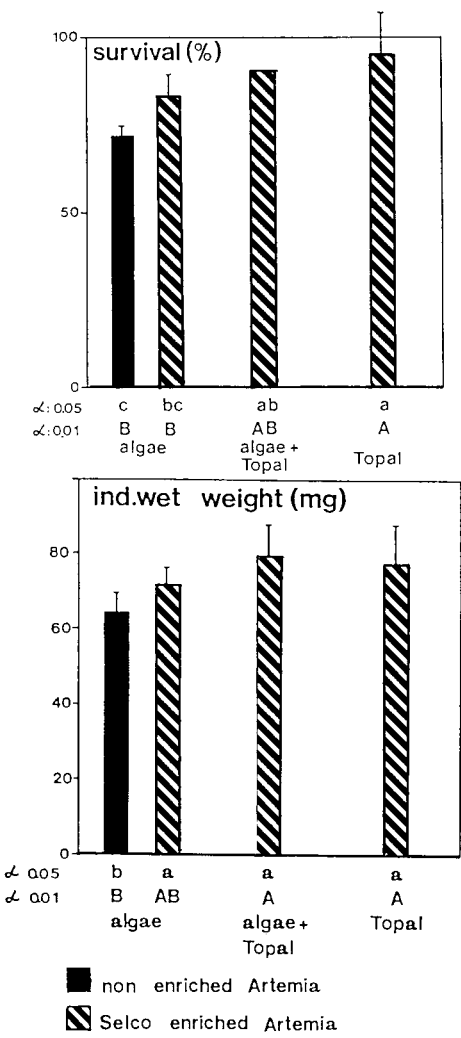


Figure 13. Effect of pre-PL8 feeding regimes (as in Figure 13) on survival and growth of PL9 to PL21 fed a commercial nursery diet (after Leger et al. 1987b).

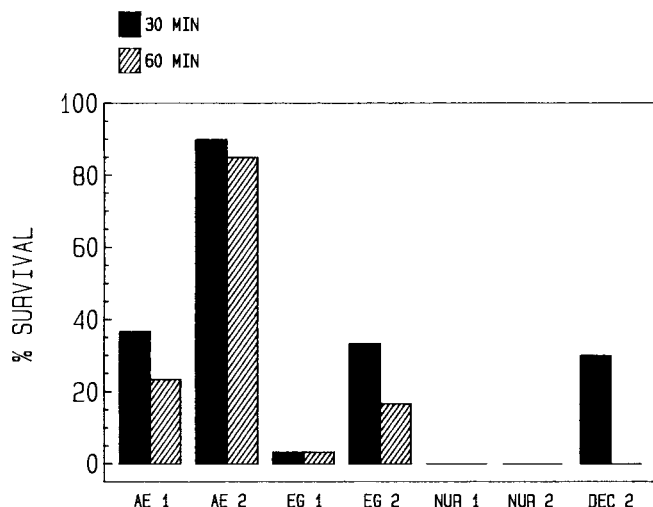


Figure 14. Survival at 7ppt of *P. monodon* PL10 from 35ppt fed several diets (1= algae+*Artemia*; 2= algae+TOPAL+ZM; AE= SELCO-enriched *Artemia*; EG= *Artemia*; NUR= commercial nursery; DEC= decapsulated cysts).

fish species, Sorgeloos *et al.* 1988) the following is recommended to optimize hatchery feeding regimes (Fig. 15):

- use pure cultures of nutritious algal species (e.g. *Chaetoceros*, *Skeletonema* sp.) supplemented with w3-yeast or artificial diets (microcapsules or microparticulate diet);

- introduce freshly hatched *Artemia* from a selected batch of *Artemia* cysts rich in 20:5w3 (containing > 5 mg w3-HUFA/g) and of a small size (450 μ m total length) at zoea III-mysis I (*P. vannamei*) or mysis I-II (*P. monodon*);

- as prey size permits gradually switch to 12-h and later 24-h w3-HUFA enriched *Artemia*, e.g. in *P. vannamei* M-3 up to PL-2 12-h enriched, as of PL-3 24 h enriched *Artemia*. For this purpose w3-HUFA deficient *Artemia* may be used, e.g. of Great Salt Lake, Utah, USA origin (for enrichment procedures consult Leger *et al.* 1985; Leger *et al.* 1987).

- for reasons of cost and nutrition (size, composition) apply artificial diets for partial live food replacement. For best results, appropriate particle sizes should be used (for example, first zoea stages: <10 μ m; later zoea-early mysis: <30 μ m; later mysis early PL: <100 μ m, later PL: >100 μ m).

The new feeding regimes outlined above have proven very effective with different *Penaeus* species, yielding over 60% survival at PL-10 in commercial hatcheries producing more than 5 million PL's per month.

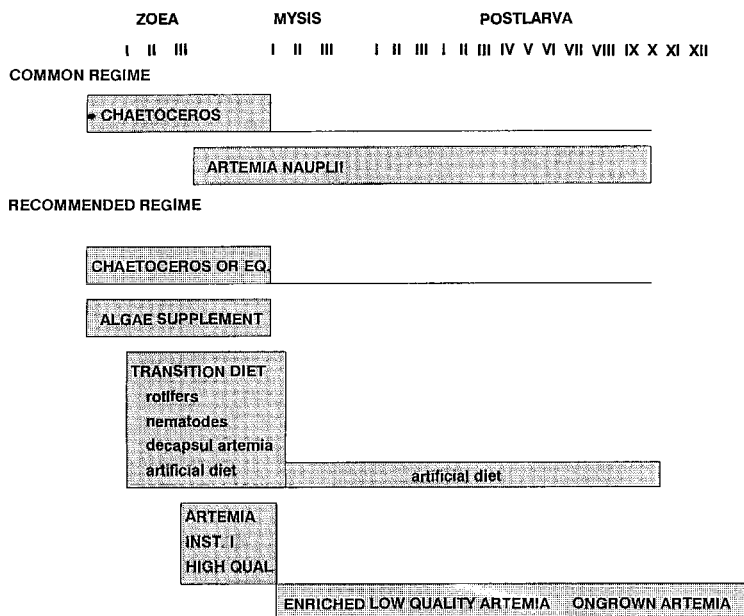


Figure 15. Comparison of the common and recommended feeding regimes for larviculture of penaeid shrimp.

Artificial diets will certainly gain in popularity in the future as they greatly reduce some problems and risks involved in the production of live food. Furthermore, they could better meet the food size requirements of the predator and be more energetically effective. Their nutritional composition and physical performance, especially regarding suspension in the water column and leaching, need to be further perfected before they can completely replace live food.

Finally, it is the cost-effectiveness of the different feeding strategies that will determine the preferential use of artificial diets and/or live food organisms. It is likely that this might differ much from region to region, and between industrial and backyard hatcheries.

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CHAPTER 10

John Colt and John Huguenin

SHRIMP HATCHERY DESIGN: ENGINEERING CONSIDERATIONS

10.1 INTRODUCTION

Modern, intensive shrimp farming started with Motosaku Fujinaga's first commercial shrimp farm during the mid-1960's on Japan's Inland Sea. The industry was founded on Fujinaga's 30 years of pioneering research with shrimp hatchery techniques. The advantages of hatchery produced post-larvae (PLs) were sufficient to support a viable industry in Japan. Hatchery methods were further refined for large scale commercial use (JMPPMA 1973; Shigueno 1975), and extended to other penaeid species elsewhere (Yang 1975).

While captive maturation of non-gravid female shrimp was known, it was not consistent and reliable enough for large scale production until recently. Recent progress in closing the life cycle and removing dependence on wild gravid females has considerably increased the value of commercial hatcheries. While hatcheries are only a part of shrimp farming, without a steady reliable source of PLs, there can not be any marketable shrimp. In short, the hatchery is critical and if it fails, the total operation may fail.

While there is a large and varied scientific literature dealing with shrimp larviculture, there is little published information on commercial hatchery physical plants and operating procedures. Research results are only marginally useful for design and scale-up procedures required for production operations. While all hatcheries are based on the same biological principles, equipment and procedures vary. Some of these variations result from environment, site, species, or economic differences. Other differences are due to personal preferences, sociopolitical conditions, and factors which are harder to identify.

Even with current state-of-the-art, all production hatcheries have problems and crises. The difference between successful and unsuccessful hatcheries is often the number and severity of the crises. Successful hatcheries maintain production, more or less on schedule, in spite of problems. Some problems are readily identifiable, while in other cases the causes are subtle and indirect. Occasionally, the root causes are either unknown or highly speculative, even after extensive investigations. In many ways, hatchery production today is an art rather than a precise science. Skill, judgment, and intuition of key personnel are very important and not easily taught. There is

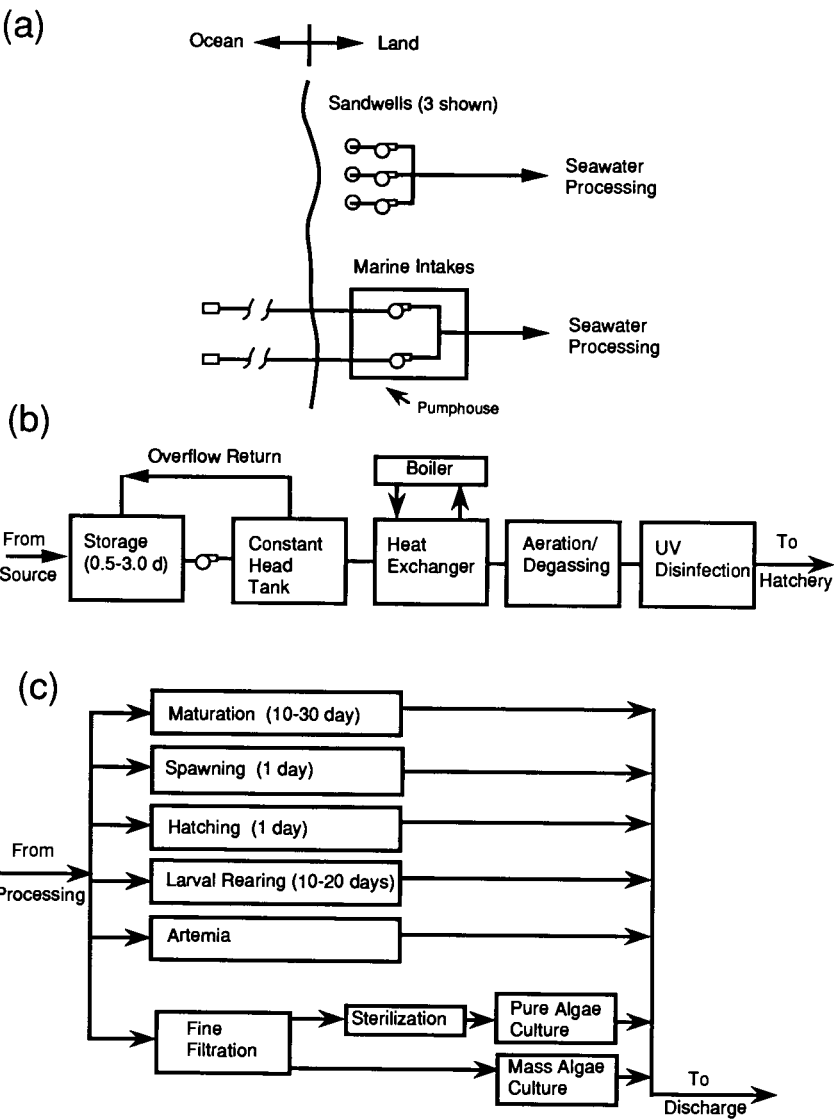


Figure 1. Generic process flowsheet for shrimp hatchery seawater system: a) seawater sources, b) seawater processing, and c) hatchery functions.

no design or operations "manual" that can be used with complete confidence. Commercial shrimp hatcheries are more or less divided into two approaches. One is the "large tank" Japanese method. This involves very large larval tanks, typically 30 to 200 tonnes (30-200 m³ water volume). These tanks are used to culture phytoplankton in situ along with larval shrimp at low

densities; PL-10 to PL-20 shrimp are produced for stocking in nursery or growout ponds. The other approach is the "Galveston method" which uses smaller 1 to 2 tonnes (1-2 m³) tanks. With the Galveston method, larval densities and water exchanges are greater, and phytoplankton and zooplankton are provided from external cultures; there is great process control and shrimp are moved to larger tanks, at PL-1 to PL-5, before transfer to nursery or growout ponds. In practice, there are many options between these two methods. Many commercial hatcheries have 10-15 tonne larval tanks which produce $\geq$ PL-10 shrimp using a blend of the two hatchery methods.

Since the mainstay of any hatchery is its seawater system and water quality, this chapter will concentrate on these aspects. Hatchery procedures are discussed as they relate to physical equipment and their limitations. The intent is to explore types of equipment, seawater system problems, and possible solutions. Many of these considerations are common to other seawater culture systems, and for hatcheries for non-shrimp species; these considerations are well covered in a previous work (Huguenin and Colt 1989) and will not be repeated here. This chapter will focus on those aspects specific to penaeid shrimp hatcheries. The reader should bare in mind, however, that there are species specific and situation specific considerations for some applications. This chapter should be used with some caution as it does not apply to any specific penaeid species, hatchery, or set of conditions, but it is generally representative of all.

10.2 GENERAL REQUIREMENTS

Penaeid shrimp production cycles typically consist of adult maturation, spawning, hatching, larval rearing, nursery, and grow out. Each of these life stages has its own set of requirements and durations.

A process flowsheet for marine shrimp hatchery seawater systems is shown in Figure 1. Water source is either from an ocean intake or from wells driven into the beach or higher ground. Water can be pumped into storage reservoirs for "aging" or emergency use, and EDTA (Ethylenediamine-tetraacetate) may be added to the reservoir water. With ocean intakes, water should be filtered one or more times to remove debris, predators, parasites, competitors, sand, and silt. Coarse screening, followed by slow or rapid sand filters are commonly used. A constant head tank is usually present to control and maintain water flow rates within the hatchery. Depending on specific use, water may be disinfected, degassed, and temperature regulated. Size and cost of seawater processing equipment will be strongly effected by flow rates, raw water conditions, and performance specifications. The consequences for either over and under specification of seawater processing requirements can be

Table 1. Shrimp density and water flow criteria for penaeid shrimp under hatcheries conditions.

Activity	g/m ³	#/m ³	g/m ²	#/m ²	Water Exchange (volumes/day)
Adult Acclimation	120-220	3-4	200-360	5-6	1-3
Spawning/ Hatching	80-120	1-2	200-300	2-3	0
Larval Rearing					0.2-0.3
"small tank"		1-2 x 10 ⁵		0.5-1 x 10 ⁵	
"large tank"		2-4 x 10 ⁴		1-3 x 10 ⁴	

costly. Depending on specific location and conditions, not all the functional units in Figure 1 may be required for a given hatchery, and there are many possible variations.

10.3 PROCESS CRITERIA

Hatchery system design is based on process criteria. The most important process criteria are density, water flowrates, and water quality.

10.3.1 Density and Water Flowrate

Shrimp density may be specified on a volumetric or areal basis. Shrimp density and water flowrate criteria for the shrimp culture stages are summarized in Table 1.

10.3.2 Water Quality

Appropriate water quality criteria are important for hatchery site selection and for hatcheries with water reuse systems. Because water quality is so important to hatchery success, and because of the relatively low flow rates, very conservative water quality criteria should be used in the hatchery. Suggested water quality criteria for penaeid shrimp under hatchery conditions are presented in Table 2. Important parameters such as dissolved oxygen, carbon dioxide, and total gas pressure must be measured on-site and special techniques must be used to preserve samples for total sulfides and heavy metal analysis.

Water quality criteria are primarily based on single-factor laboratory experiments with selected life stages and species. Therefore, these criteria

Table 2. Suggested water quality criteria for penaeid shrimp hatcheries.

Parameter	Criteria					Reference
	Nauplii	Zoea	Mysis	PL	Juvenile	
Ammonia($\mu\text{g/l NH}_3\text{-N}$)	10	17	48	100	100	Chin and Chen 1987 Wickins 1976
Nitrite($\text{mg/l NO}_2\text{-N}$)	0.11	0.29	0.45	1.36	-	Chen and Chin 1988a
Nitrate ($\text{mg/l NO}_3\text{-N}$)	-	-	-	-	<200	Wickins 1976
Carbon dioxide(mg/l)	<1 ^a	----->				Wickins 1984
Dissolved oxygen (%)	>95 ^a	----->				
Gas supersaturation (δP , mm Hg)	<20 ^a	----->				Lightner et al. 1974
Hydrogen sulfide ($\mu\text{g/l @ H}_2\text{S}$)	<2 ^a	----->				Oseid and Smith 1974 USEPA 1976
Chlorine residual ($\mu\text{g/l}$)	<10 ^a	----->				USEPA 1976
pH	7.9-8.2	----->				
Temperature (C)	25-28	(optimum is species dependent)				
Suspended solids(mg/l)	<1 ^a	----->				
Salinity (g/kg)	26-34	(optimum is stage dependent)				
Metals (total)						USEPA 1976
Cadmium ($\mu\text{g/l}$)	<5.0	----->				
Chromium ($\mu\text{g/l}$)	<25	----->				
Copper ($\mu\text{g/l}$)	<3	----->				
Iron ($\mu\text{g/l}$)	<300	----->				
Mercury ($\mu\text{g/l}$)	<0.1	----->				
Manganese ($\mu\text{g/l}$)	<50	----->				
Nickel ($\mu\text{g/l}$)	<50	----->				
Lead ($\mu\text{g/l}$)	<50	----->				
Zinc ($\mu\text{g/l}$)	<50	----->				

^a Estimate based on related species or ability to maintain parameters under hatchery conditions; additional information can be found in listed references

may under-estimate biological effects under production conditions where shrimp are exposed to a number of compounds simultaneously (Chen and Chin 1988b).

Metals criteria are based on total metals (particulate + dissolved forms), as the toxic mode of iron and manganese may be physical blocking of the gills by particulate matter (Chen et al. 1985). The addition of 1 - 10 mg/l of EDTA can significantly reduce the toxicity of heavy metals (Castille and Lawrence 1981; Lawrence et al. 1981; Licop 1988). In areas where heavy metal concentrations exceed the criteria in Table 2, it may be prudent to conduct pilot-scale rearing trials before finalizing hatchery design or starting construction.

In general, water quality criteria for larvae are more stringent than for juveniles and adults. For example, Wickins (1976) suggested an un-ionized ammonia criteria of 100 $\mu\text{g/l}$ $\text{NH}_3\text{-N}$ based on a 1% reduction of growth for five species of penaeid shrimp. Chin and Chen (1987) estimated the "safe" level for nauplii was only 10 $\mu\text{g/l}$.

10.4 SITE CONSIDERATIONS

Ideally, the final hatchery site should be selected through a thorough site reconnaissance and selection process. There are many important and potentially critical site selection parameters including water quality, soil characteristics, weather, economics, and social, legal, logistical, and political factors. Many of these have been discussed by Webber (1971) and Huguenin and Colt (1989). We will concentrate our discussion on physical and technical considerations. Unfortunately, in many projects there is no site selection process since the site is often fixed for various reasons. A common reason is that the site is already owned or controlled by the project's owners, family or friends, or by the governmental agency sponsoring the project. Construction and operation on unsuitable sites is the most common reason for poor hatchery performance and failure.

10.4.1 Marine conditions

Prior to the detailed design, basic information is needed on marine conditions at the site. This includes tidal, beach profile, ocean exposure, and water quality.

10.4.1.1 Tidal data

Hatchery design requires detailed data on tidal conditions during both normal and extreme events. Data on high and low tide extremes are often difficult to acquire. Methods for estimating the highest and lowest 1% are given by Huguenin and Colt (1989). Extreme tidal values are required to design against flooding and breaking waves, but other aspects of system design may be based on less severe tidal conditions. Extreme high water levels commonly result when predicted high tides coincide with strong inshore winds and/or with major (low pressure) storms. These events occur randomly; the fact that a severe tidal event has not occurred in the last 20, 30, or 40 years does not mean that serious floods will not occur twice in the next two years. It is important to remember that abnormally low tides can also cause problems, especially for seawater intakes.

10.4.1.2 Beach profile

The beach profile should be measured from the potential site to 2 m below extreme low water. This is critical especially if marine intakes and discharges are required. Ideally, the beach profile should be determined at least 4 times over the year, as significant seasonal beach profile differences may exist. If large seasonal differences exist, multi-year data would be even better. Average slope of the off-shore bottom can usually be estimated from published charts.

10.4.1.3 Ocean exposure

Historic long term data on normal and abnormal weather for the site are critical but may be unavailable. Wind directions for common and rare events combined with charts showing site exposure and water depths can be used to estimate normal and extreme wave characteristics at the site. From these calculations, the wave run-up, the limits of the surf zone (breaking waves), and the risk of wave damage can be estimated (see Huguenin and Colt 1989; USACE 1975).

10.4.1.4 Water Quality

Water quality is critical and by necessity one of the prime site selection criteria. Minimum and maximum acceptable water quality parameters are discussed elsewhere. Problems can develop in applying the given criteria. Water quality parameters can vary considerably on a seasonal basis, particularly salinity and temperature. Some local recreational, industrial, or agricultural activities of potential concern may be very seasonal in nature. Water quality measurements should be taken throughout the year. If the potential hatchery site is near rivers, the impact of runoff on salinity must be carefully assessed. Runoff can carry agricultural and industrial contaminants. Contamination discharges may not be visible for parts of the year. If the site is located close to present or prior industrial and agricultural activities, heavy metals and pesticide analysis may be required. Water quality conditions within the hatchery system can also change due to seasonal weather factors. Dry winds and elevated temperatures can produce high evaporation rates, particularly in outdoor maturation and nursery ponds. Incoming seawater salinity is likely to be highest under these conditions and may exceed acceptable limits. Many potential sites with good marine water quality have been rejected because of the unavailability of freshwater needed for salinity control during the dry season. Larval shrimp bioassays can help detect unforeseen water quality problems.

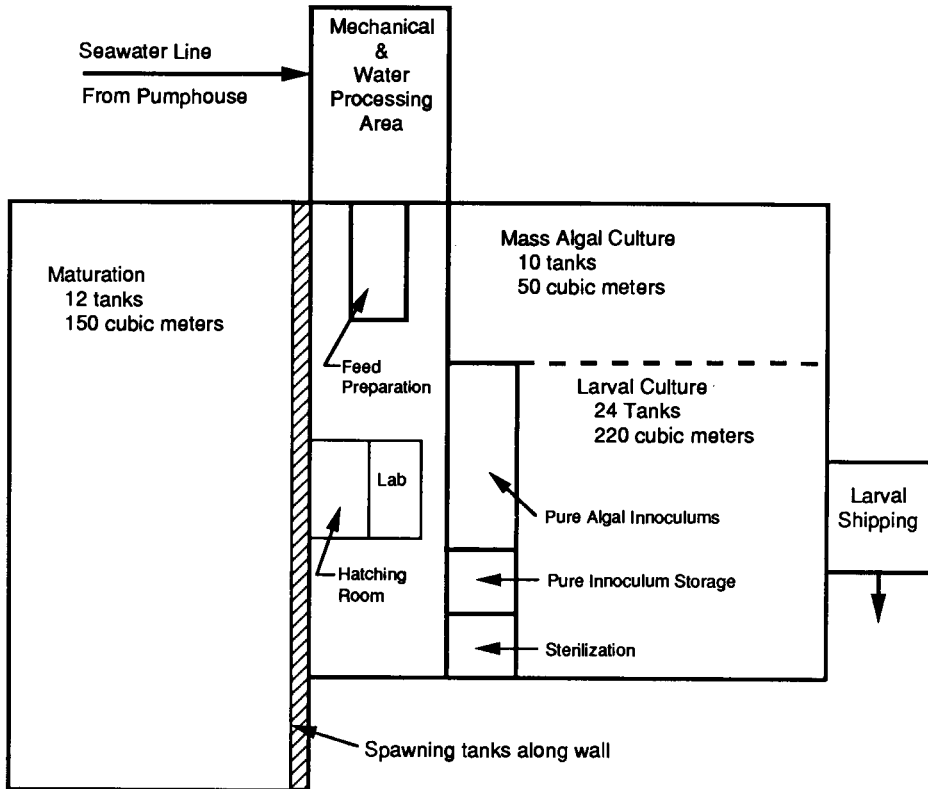


Figure 2. Layout of a one million PL-20 per month hatchery using a design combining the large tank and Galveston method.

10.4.2 Terrestrial Conditions

Information on terrestrial conditions is needed prior to preparation of detailed designs. The property should be surveyed; all corners and sidelines clearly marked and the topography recorded. It may also be prudent to establish permanent corner markers with concrete and steel. Unless the hatchery site is clearly within the property boundaries, use registered surveyors to establish a legal basis for any property disputes. It is also desirable to bring in a vertical datum from the nearest benchmark. At sites where it is prohibitively expensive to bring in a vertical datum, comparison of observed and predicted tides may allow a rough estimate of mean sea level. A permanent vertical benchmark based on mean sea level can then be established near the hatchery. In addition, soil types on the site to a depth of at least 2 m should be established. If the site has relatively uniform soils, such as all sand, this might be very simple. If the soils are variable or of low

bearing strength, detailed soil testing may be required. Extensive filling and compacting can significantly increase the cost of site development.

10.5 LAYOUT

Layout of various hatchery components significantly impacts hatchery efficiency and economy.

10.5.1 Space

Adequate space must be available for the hatchery building, parking, roads, small ponds if required, and other logistic activities. Generally, at least 2-3 ha are needed for a production hatchery. Approximately 30-40 m of open space should be left around the main hatchery building for future expansion and security. In many locations, a chain-link fence and nighttime security guards are needed.

10.5.2 Layout of the Hatchery

Functional layout of the hatchery buildings should integrate the biological production steps. Generally, water processing and standby power equipment are placed on the ocean side of the hatchery with direct access doors to the outside. The maturation room should also have outside access doors for rapid transfer of wild-caught or pond-reared adults. Spawning containers can be placed along the wall of the maturation room, or in a small separate room between the maturation and larval rearing rooms. If hatching is not done in the spawning tanks, then hatching tanks may be located in a separate room adjacent to the larval rearing room. Brine shrimp, algae, and laboratory rooms can be located on another side of the larval rearing room.

Space requirements for three hatcheries are presented in Table 3. The layout for a 1 million PL-20/month hatchery using a hybrid of the large tank and Galveston method (hatchery # 1 in Table 3) is presented in Figure 2. The movement of animals is from left (maturation) to right (larval collection). The layout for a 2 million PL-5/month using the Galveston method (Treece 1985; hatchery # 3 in Table 3) is presented in Figure 3. Space must be provided between individual rearing units for access. Generally, 1.0-1.5 m between maturation units and 1.0-2.0 m between larval rearing units is sufficient.

10.5.3 Distribution of Services

Influent water and discharge piping, electric power, and compressed air lines are generally set either in the concrete floor in covered culverts, or hung from the ceiling. Often a combination is used for different areas of the hatchery. The overhead method is usually preferable since the supply lines are

Table 3. Floor areas assigned to various functions in three hatcheries. The areas do not necessarily add up to the total hatchery areas as the spaces for some minor functions may not have been specified.

Parameter	Hatchery 1	Hatchery 2	Hatchery 3
Output			
PL/month	1 x 10 ⁶	5 x 10 ⁶	2 x 10 ⁶
Final stage	PL-20	PL-10	PL-5
Area (m ²)			
Maturation	675	650	125
Larval	380	1175 includes <u>Artemia</u> & PL packing	127
Spawning	included in maturation	not given	26
Hatching	21	not given	same as above
Intensive Algae	72	not given	included with value below
Mass Algae	207	170	23
Zooplankton/ Artemia	18	included in larval	20
Laboratory	33	50	40
Shop/Mechanical	80	55	22
PL packing	36	included in larval	not given
Offices & Misc	198	50	29
Total	1725	2150	418
Reference	Huguenin, unpublished	Simon, 1981; 1982	Treece, 1985

relatively well protected from accidental damage, provide minimal restrictions for ground level access, movement and operations, and can be readily accessed if needed. The disadvantage of this method is that the drainage system must be run separately at ground level or below, thus losing the advantage of a single distribution system for all supplies and discharges. In either case, electrical wiring must be contained in PVC or hardwall conduit. Groundfault interrupters should be installed on all electrical receptacles to prevent electrical shock. Electrical receptacles should be located either overhead or at least 1 m above the floor to reduce exposure to splashing. Electrical hazards with seawater should not be taken lightly.

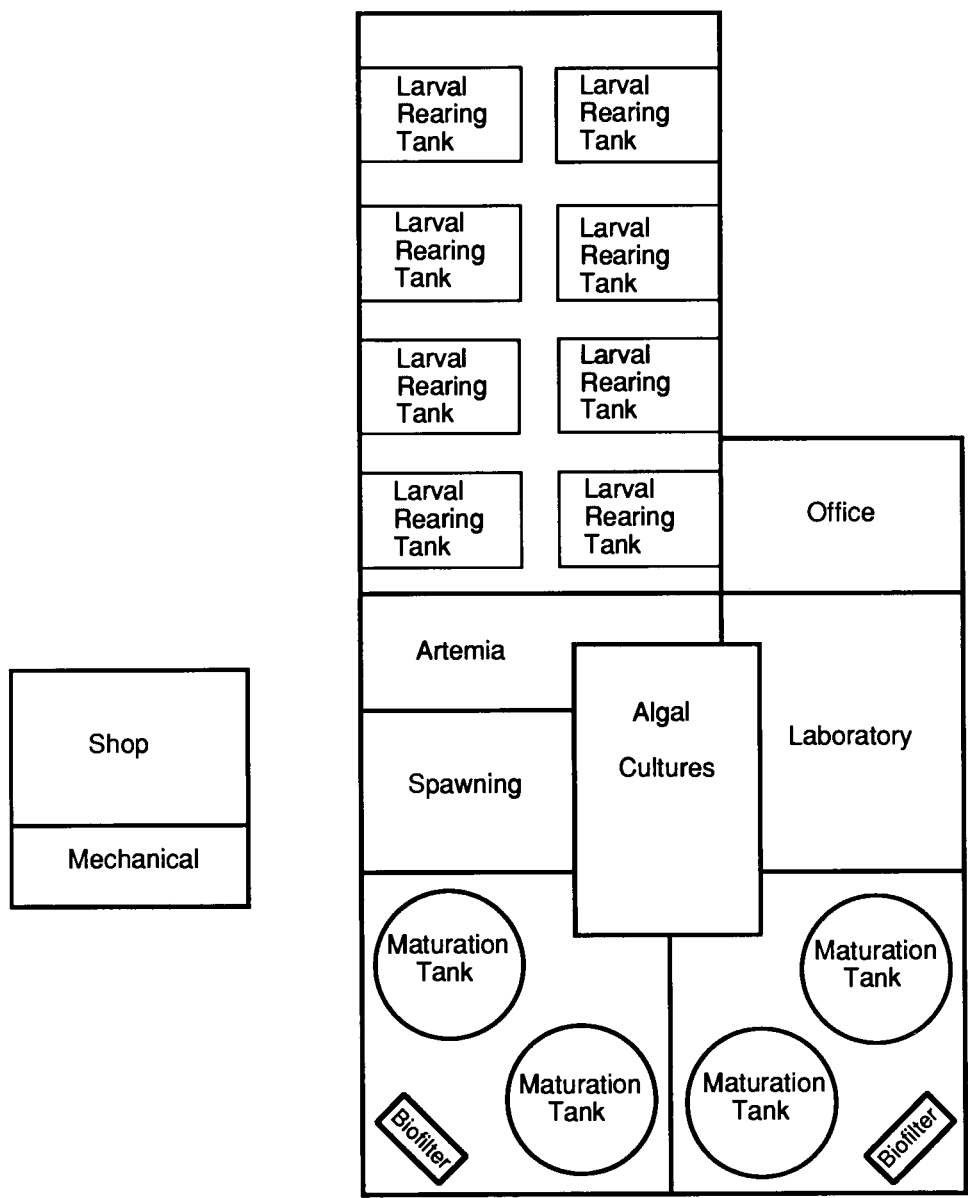


Figure 3. Layout of a 2 million PL-5 per month hatchery using the Galveston method (Treece 1985).

10.6 DESIGN OF WATER SUPPLY SYSTEMS

A penaeid hatchery requires a continuous supply of high quality seawater and freshwater. A poorly sited hatchery or inadequately designed water supply system can easily doom a hatchery to economic failure.

10.6.1 Seawater Wells

Seawater wells can be drilled or jetted through beach sand, below the static water level. With small tidal ranges, pumps can be installed at beach or pier level. If the tidal range is large, costly submersible pumps or an open ocean intake will be needed. Water from even shallow seawater wells does not normally require additional filtration and has a small yearly temperature variation (Cansdale 1975). With the exception of iron and manganese, heavy metal concentrations from seawater wells are generally lower than the open ocean (Chen et al. 1985; Scholes 1980). In a reducing environment such as often exists in groundwater, high concentrations of reduced manganese and iron may be present. Exposure of these compounds to oxygen in the hatchery results in their oxidation and formation of particulate solids that can block the gills of shrimp larvae. When high levels of dissolved manganese and iron are present in well water, it may be necessary to aerate the water and settle out the particulate solids prior to hatchery use. Salinity and pH from seawater wells are typically lower than the open ocean.

Wells may not produce seawater of the proper salinity, or they may have undesirable water quality properties such as low dissolved oxygen and high hydrogen sulfide, iron, and manganese concentrations (Cansdale 1981). Where geology permits, shallow seawater wells are very attractive, however, the permeability of many coastal beaches is insufficient to provide anything but modest flows.

10.6.2 Ocean Intakes

Direct ocean intake is the most common seawater source. If designed properly, an ocean intake can provide a reliable source of quality seawater. A poorly designed ocean intake may result in operational problems, high operating costs, and marginal (or unacceptable) water quality.

10.6.2.1 Pumping schedule

Continuous pumping capability is the most desirable but requires an intake below the extreme low tide level (Fig. 4a). Since the pumps are or can be operated continuously, operations are simplified.

At locations with high tidal ranges, it may not be practical to pump continuously (Fig. 4b). The intake for a system using a discontinuous pumping schedule can be placed above the low tide level, but requires larger pumps,

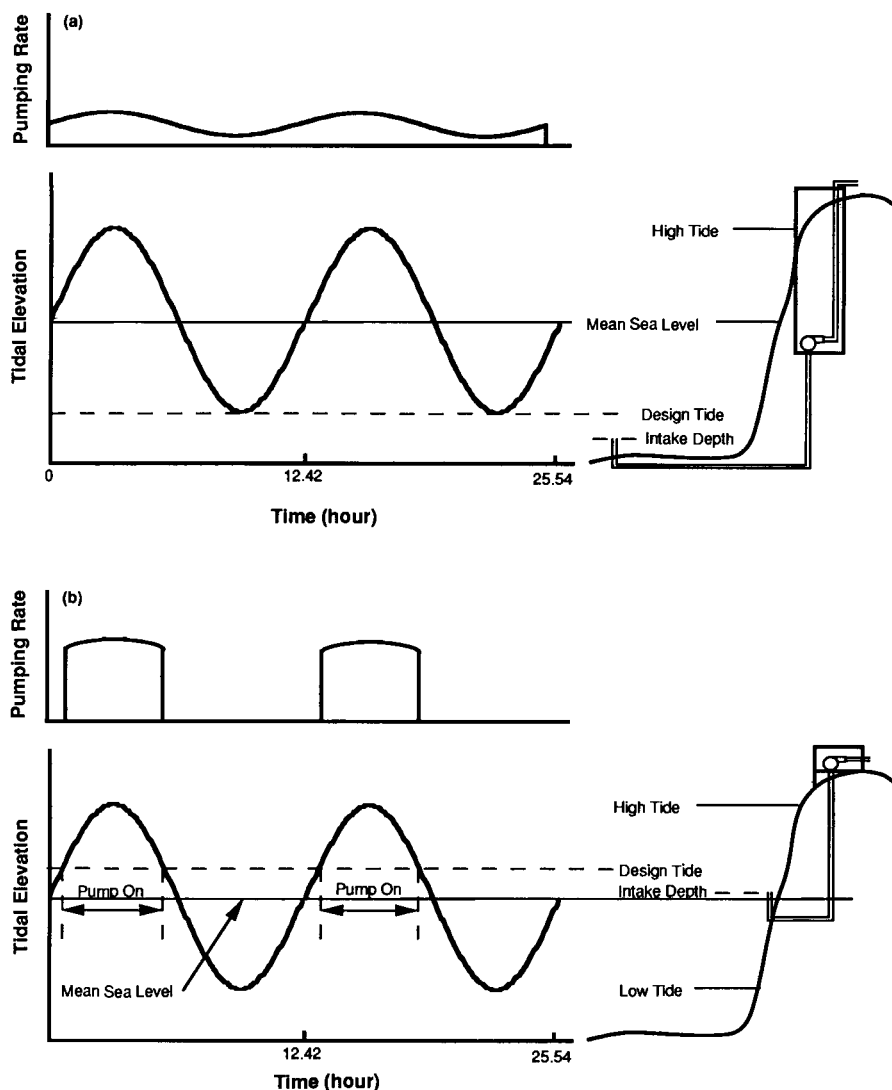


Figure 4. Pumping schedule a) continuous, b) intermittent.

motors, and piping to deliver the same water volume per day. Typically, the pumps are operated during the upper quarter of the tidal cycle (6.20 hours/day). With this pumping schedule, pumps must be started and stopped at specific times. If the pumps are allowed to operate below the design low tide, the pump may cavitate and lose prime. This can result in damage to the impeller, seals, or packing. Level sensors and automatic controls can be installed, but most hatcheries of this type operate the pumps manually. This

type of system can also be designed to pump the required daily water requirement during a single high tide. This allows starting and stopping of pumps during daylight hours and has a large safety factor if additional water is needed.

10.6.2.2 Depth and location of intake

Intake depth depends on pumping schedule, wave characteristics, sediment type, and pipe velocity (Huguenin and Colt 1989). Typically, ocean intake systems are designed for the 99 % low tide (i.e., only 1% of the low tides will be lower than this tide). Reduced water flow during extreme tidal events can be provided for by reserve storage. At some sites, intakes may have to be located 100-500 m offshore since nearshore water quality may at times be unacceptable due to freshwater runoff, turbidity, or sediment concentration.

10.6.2.3 Location and height of pumphouse

The pumphouse must be located far enough from the ocean to reduce flooding or wave erosion risks. In exposed locations, rip-rap may be needed.

Pumphouse height, or more correctly the pump impeller centerline height is probably the single most critical parameter in the design of seawater systems. There is a strong tendency to build the pumphouse at grade or at higher elevations to reduce flooding potential and construction costs. Two important parameters limiting pump impeller height above the design tide are (1) net positive suction head available ($NPSH_a$), and (2) repriming suction lift.

Net positive suction head required ($NPSH_r$) is published by manufacturers for each specific pump and represents the point where pump efficiency has already started to decrease due to cavitation. $NPSH_a$ must be greater than $NPSH_r$ to prevent impeller cavitation damage and reduced efficiency.

The $NPSH_a$ depends on the (1) difference between the centerline of the pump impeller and the minimum design tidal elevation (suction lift), (2) head losses in the suction piping and fittings, (3) barometric pressure, and (4) water vapor pressure. Of these four parameters, only the suction lift and suction side head losses can be controlled. Suction lift can be reduced by either increasing the minimum operating tidal level or lowering the pump station height. Head losses on the suction side can be reduced by increasing the pipe size and providing regular maintenance.

Self-priming pumps are useful for both types of pumping schedules. Self-priming pumps may be able to self-prime over only part of the tidal cycle. A small vacuum pump can be used to prime pumps when the water level is too low for self-priming.

10.6.2.4 Pump selection

Self-priming, centrifugal pumps with water lubricated mechanical seals are preferred for primary seawater pumps. Cast-iron or fiberglass pumps are most common. "Trash" pumps that allow impeller access without disconnecting the piping may be preferred at some sites. Pumps should have a thermal overload sensor for motor shutdown if the pump runs dry. Typically, two complete intake, pump, and motor systems will be required. Electrical service and discharge piping should be sized to accommodate simultaneous operation of both systems.

Pump flowrate should be computed hourly over the entire pumping cycle. Minimum and maximum flows must lie within the normal operating envelope for the pump. Motor sizes must be large enough to handle the current load required during extreme high water. Pumps and piping systems are highly interrelated; changes to one may have major effects on the other.

10.6.2.5 Piping

High density polyethylene pipe is the preferred material for suction piping; but, PVC is commonly used due to its availability. Biofouling is one of most serious problems associated with open ocean intakes. Mussels, barnacles, and sea squirts can turn a 20 cm pipe into a 10 cm pipe within months. Intake screens are particularly vulnerable to biofouling. As noted above, most hatcheries are built with two complete intake systems (Huguenin and Colt 1989). Typically, one system supplies the water required, and the other system acts as a backup. Alternate use at 2-3 week intervals will result in anaerobic conditions in the unused system that can kill but not remove attached organisms.

10.6.3 Freshwater Supply

Freshwater is needed for cleaning and salinity adjustment. At some sites, freshwater must be imported or produced on-site by reverse osmosis.

10.7 DESIGN OF SEAWATER PROCESSING EQUIPMENT

There are many seawater conditioning processes, most of which have been used at some time or other in shrimp culture (Huguenin and Colt 1989). The most commonly used seawater processing in shrimp hatcheries is discussed below but many variations exist.

10.7.1 Chemical Addition

EDTA (Ethylenediaminetetraacetate) and chlorine are two chemicals commonly added to hatchery water. Residual chlorine decays in the storage tanks or is chemically removed. EDTA is a chelating agent that improves

larval shrimp survival and growth, although its specific modes of action are not completely understood (Castille and Lawrence 1981; Lawrence et al. 1981; Licop 1988). EDTA is commonly added at 1 to 10mg/l to the source water after the main pump. A flow sensor, controller, and proportional pump are needed when the flow varies significantly over the pumping cycle. Chlorine is often added as a disinfectant to influent water in a batch process at 0.5 to 1.0 mg/l. Reactions between EDTA and chlorine may potentially produce toxic compounds.

10.7.2 Storage

Commonly, water storage for 0.5 to 3.0 days usage is provided. This storage may be needed for those rare tidal conditions when the pumps can not supply enough water or in the event of mechanical failure. This storage may also function as a head tanks or for seawater "aging". Ideally, several tanks each of about one day's supply each are used. This arrangement allows water to be drawn from an "aged" tank, while another tank is being filled. Tanks are often constructed from reinforced concrete, although pre-fabricated coated steel tanks may be economic under some conditions.

10.7.3 Filtration

A number of different filtration systems have been used in shrimp hatcheries, each with individual performance and operating characteristics. Different filtration systems may be used at various places in a shrimp hatchery (see Huguenin and Colt 1989).

Coarse screening with 1.5 - 4 cm hole dimensions may be placed around the main intake to remove large objects that could clog or damage the pump impellers. Fine saran or nylon netting can be fabricated into a "sock" and placed over the discharge into the storage reservoir to filter out finer materials. These "socks" are designed on a loading rate of about 80 liters/m² and can be cleaned by simply inverting and flushing. Sock filters can remove debris, fish eggs, and larvae down to a size of approximately 0.5 mm.

Water settling for 24 hours removes most of the large suspended solids; but, sand filtration may be necessary to remove fine suspended solids below 20 µm. Sand filters may be located between the storage reservoir and the hatchery or between the storage reservoir and the constant head tank (if present).

Conventional sand filters must be backwashed when the filter clogs. If the filter run times are less than 1 to 2 days (quite common), then it may be necessary to have personnel available on a 24 hour basis or to increase the number of filters. While automatic backflushing filters are available, their control circuits and valves are complex, prone to failure in a hot salty environment, and close to impossible to repair by hatchery or local personnel.

Continuous backwash sand filters (Weinschrott and Tchobanoglous 1986), have a higher initial cost than conventional sand filters under some conditions; but, they offer improved operational reliability, lower head losses, and lower operating costs. In addition, the continuous backwash filters have a constant low head loss of about 0.6 m; this greatly simplifies their design, operation, and control. In contrast, the head losses through conventional filters may vary from 4 to over 9 m, and may continually change over the filter run.

Water for algal and brine shrimp rearing typically requires filtration down to 1 μm using diatomaceous earth (DE) or cartridge filtration. The diatomaceous filter requires more labor; but, it has much lower operating costs than the cartridge filters, especially at higher flow rates. In addition, diatomaceous earth is readily available from local swimming pooling suppliers. If cartridge filters are imported, a 6-18 month inventory must be maintained to prevent normal problems (currency restrictions, shipping strikes, general strikes, etc.) from disrupting production.

10.7.4 Constant Head Tank

Depending on site topography, storage reservoirs may also serve as a constant head tank (header tank). In other cases, water is pumped from the reservoir into the constant head tank by separate recirculation pumps. A standpipe overflow drain returns excess water to the storage reservoirs. The purpose of the constant head tank is to maintain a constant water pressure and flowrate into the hatchery. In addition, the constant head tank supplies water to the hatchery during pump or power failure. Piping between the constant head tank and individual valves in the hatchery must be over-sized to minimize head losses. Without a constant head tank, water pressure will vary significantly during the day in response to reservoir level, filter losses, and water demand. Water pressure changes will result in water flow changes during the day; this can cause many problems. In order to maintain constant flow at the use point, it may be necessary to constantly adjust the individual valves, or to size the recirculation pumps and filters to provide the required flow when the reservoir is nearly empty and/or head losses in the filters are close to the backwash values. When head losses in the recirculation loop are less than the maximum value, water flow will be greater than required. Therefore, the water requirement may have to be increased by 20 - 30 % to cover these flow variations. This will require larger intakes, pumps, and motors. More importantly, the ultraviolet radiation (UV), boiler(s), heat exchanger, and any other on-line water processing equipment must be sized for maximum flow; this may considerably increase their size and cost.

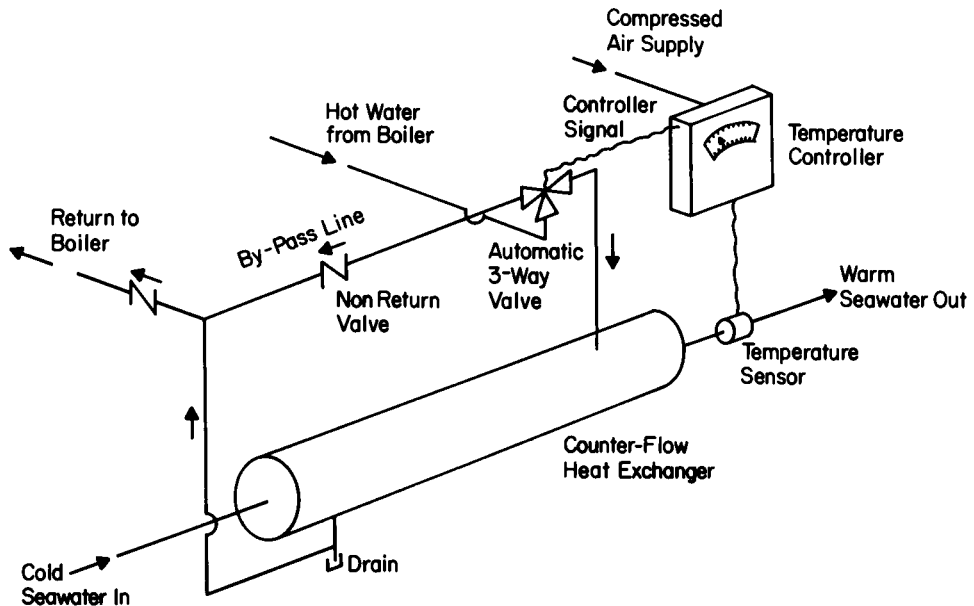


Figure 5. Typical temperature control system using a hot water heat source (Huguenin and Colt 1989).

10.7.5 Ultraviolet Radiation

Ultraviolet radiation (UV) is a very common in-line method used to disinfect the process water. Conventional UV systems are designed to deliver $35,000 \mu\text{W}\cdot\text{s}/\text{cm}^2$. The applicability of this radiation level for marine shrimp larviculture is unknown. Suspended solids or high turbidity seriously reduce UV performance. In new UV systems, water passes through the unit inside Teflon pipes (transparent to UV radiation), and the UV bulbs are simply mounted in air. In older units, the UV bulbs were mounted inside quartz sleeves that isolated the bulbs from the water. Fouling of the quartz sleeves and water leakage around the sleeve seals can be serious problems with older units. UV effectiveness must be continuously monitored, as performance drops off with age. UV bulbs must be replaced on a regular basis.

10.7.6 Heating

Optimum temperature for larval penaeid shrimp is near 28°C , maintaining this temperature may require heating 2-5 months/year. The most common type of heating system includes a natural gas, propane, or fuel oil fired hot water boiler, a heat exchanger, and a temperature control system (Figure 5). The boiler sensor will work to maintain a constant water temperature leaving

the boiler. Since the water flow and heat requirement may vary significantly during the day, maintenance of a constant water temperature will require a temperature sensor and proportional control valve to adjust the amount of hot water passing through the heat exchanger loop. Seawater is highly corrosive; therefore, titanium or carbon heat exchangers are preferred, although other materials can be satisfactory under some conditions (Huguenin 1976). Head losses through the heat exchanger may be an important design consideration in many systems. Thermal shock may occur due to temperature control failure, or following power or water outage. Restarting of the boiler following a power or water outage requires careful planning and precise execution of the required start-up procedure. It is highly desirable to have a backup boiler as this unit is critical and may be difficult to repair or replace quickly.

10.8 DESIGN OF HATCHERY SUPPORT SYSTEMS

10.8.1 Water Distribution System

Generally, water flows by gravity from the constant head tank through the water processing equipment and into the hatchery. The water distribution system should be over-sized to allow rapid filling of tanks. PVC plastic pipe is most commonly used.

10.8.2 Drains

Drains should be designed to accommodate at least 10 times the average water flow. Open channel drains, covered with grating allow easy access, cleaning, and servicing.

10.8.3 Effluent Treatment and Discharge

Discharges of antibiotics and chemicals from penaeid shrimp hatcheries is largely unregulated at this time. Continuous prophylactic use of antibiotics in shrimp culture may lead to the development of resistant strains of both shrimp and human pathogens (Brown 1989). Treatment and disinfection of hatchery discharges may be required in the future. Since chlorine or other toxic chemical are used in the hatchery, hatchery discharges should be at least 500 m "downstream" from the main intakes.

10.8.4 Air System

Hatchery air requirements range from 1-3 m³/minute per million PLs/month. Since only low pressure air (15-20 kPa) is needed, regenerative blowers are most commonly used. These units are oil-free and relatively trouble-free. At least 1 unit plus a backup are needed. If standby power is not provided, the backup blower should be engine driven. If oil lubricated

compressors are used, special filters must be installed to remove oil contamination. Since heat is produced by the blowers, the first 10 m of the main distribution piping should be steel; PVC pipe is typically used for the remainder of the distribution system. Air velocities should be less than 6-9 m/s (20-30 ft/s), with typical pipe sizes of

Main Distribution Lines:	10-15 cm	(4-6 inches)
Primary Feeder Lines:	5-8 cm	(2-3 inches)
Secondary Feeder Lines:	3-5 cm	(1-2 inches)

10.8.5 Electrical Power Supply

Electrical power demand depends strongly on pumping requirements and operational procedures. Main pumps and other heavy loads are best operated with 3 phase power at 220 or 440 V.

A backup, propane or diesel fueled, motor-generator is prudent. The most common type of switching system is a manual transfer switch. When power failure occurs, the transfer switch is manually moved to the standby side, and the motor-generator started. Systems connected to standby power may include: emergency interior lighting, blowers, and seawater pumps. During standby generator operation, electrical loads must be brought on-line in a specific, pre-determined order. In areas where frequent power outages occur, continuous duty motor-generators should be used.

10.9 DESIGN OF HATCHERY PRODUCTION SUB-SYSTEMS

Design of hatchery production sub-systems are based on process criteria. The most important process design parameters are water flowrate, rearing volume (or area), and the size and number of individual rearing units.

10.9.1 Specific Process Requirements

Process design parameters are presented below for each hatchery sub-system, based on existing practice. Significant differences may occur between different locations and hatchery managers. Production from similar hatcheries may vary by a factor of 2 due to these differences. "Art" is still important in larval shrimp rearing. Generally, the design process starts with the selection of the overall production objectives in terms of million PLs/month and the process is worked backwards to compute the required numbers of adults needed for the maturation process.

10.9.1.1 Maturation systems

Wild-caught or pond-reared broodstock are held in shallow (40-70 cm water depth) circular or elongated tanks (3-5 m in diameter). The sides are

Table 4. Process and design criteria for penaeid shrimp maturation.

<u>Process Definition</u>			
Starting point	adult female from wild sources or maturation ponds		
Ending point	ripe, mated female		
Production objectives	NumRipeFemale; number of ripe, mated females/month		
Production safety factor	SF _m ; expressed as a ratio (typically in the range of 2-7)		
<u>Process Criteria</u>			
<u>Parameter</u>	<u>Symbol</u>	<u>Unit</u>	<u>Range</u>
Average size of adult females	W _{af}	g	40-60
Average size of adult males	W _{am}	g	40-60
Male/female ratio	M/F	---	0.5:1-1:1
Maturation success	MatSuc	%	70-90
Spawns/cycle	NumSpawn	#	1-6
Length of cycle	Length _m	d	40-60
Areal stocking density	ASD _m	#/m ²	3-8
Feeding rate	Feeding _m	%/d	3-5
Water depth	WD _m	cm	40-75
Tank depth	TD _m	cm	100-120
Tank area	TA _m	m ²	4-10
Water turnover rate	WTR _m	tank volumes/d	1-3
<u>Design Parameters</u>			
<u>Parameter</u>	<u>Symbol</u>	<u>Unit</u>	
Number of females	NumFemale	#/month	
Total tank area	Area _m	m ²	
Volume/tank	Vol _m	m ³	
Number of tanks	NumTank _m	#	
Water flow/tank	Q _m	lpm	
Total water requirement	TWR _m	lpd	

dark colored to reduce collisions with the sides. Light levels should be dim (0.5 $\mu\text{E}/\text{m}^2\cdot\text{s}$; Chamberlain 1985). Photoperiod can vary from 13-14 hours/day (Chamberlain 1985; Simon 1982) to 24 hours/day. Maturation tanks should be located away from the standby power system, and other sources of vibration and noise. Some hatcheries use a sand substrate for species such as P. monodon (AQUACOP 1983a), while others do not (Simon 1982). Sand substrate significantly increases problems with hygiene and water quality. Shrimp are fed 3-5% of body weight per day of formulated diet, squid, oysters, and polychaete worms (Brown et al. 1980; Chamberlain 1985). Food type can have a significant impact on maturation success. Typically, unilateral

eyestalk ablation of the females is used to induce reproduction. The females are inspected for ovarian development daily and removed to spawning facilities when ripe. A single female may spawn 1-6 times (AQUACOP 1983a). Percent fertilization, hatch, or nauplii-protocozoa transformation are monitored to assess broodstock performance (Simon 1982). When performance in a maturation tank drops below an acceptable value, the broodstock are replaced with new animals (typically every 6-8 weeks).

Process and design criteria for maturation are listed in Table 4. Design parameters can be computed as follows:

$$\text{NumFemale} = \frac{3.3(\text{Length}_m)(\text{NumRipeFemale})(\text{SF}_m)}{(\text{MatSuc})(\text{NumSpawn})} \quad (1)$$

$$\text{Area}_m = \frac{(\text{NumFemale})(1 + M/F)}{\text{ASD}_m} \quad (2)$$

$$\text{Vol}_m = \frac{(\text{Area}_m)(\text{WD}_m)}{100} \quad (3)$$

$$\text{NumTank}_m = \frac{\text{Area}_m}{\text{TA}_m} \quad (4)$$

$$Q_m = \frac{(\text{WTR}_m)(\text{Vol}_m)}{1.44} \quad (5)$$

$$\text{TWR}_m = 1440(\text{NumTank}_m)(Q_m) \quad (6)$$

10.9.1.2 Spawning systems

Gravid, mated females are removed from the maturation tanks and placed in individual circular spawning tanks (typically 40-50 cm in diameter, and 60-70 cm deep). Gentle aeration is provided. Typically, the females spawn during the first night. In the morning, spawning tanks are checked for fertilized eggs. Fertilized eggs may be recovered using a 120 μm screen and transferred to the hatching tanks, or left in place to hatch. Spawned females are returned to the maturation tanks. Egg collectors can be used to remove eggs from spawns in the maturation tanks (Simon 1982).

Table 5. Process and design criteria for penaeid shrimp spawning.

<u>Process Definition</u>			
Starting point	ripe, mated female		
Ending point	release of eggs		
Production objectives	NumSpawn; number of spawns/month		
Production safety factor	SF _s ; expressed as a ratio (typically in the range of 1.5-3.0)		
<u>Process Criteria</u>			
<u>Parameter</u>	<u>Symbol</u>	<u>Unit</u>	<u>Range</u>
Average size of adult female	W _{af}	g	40-60
Time to spawn	t _s	d	1
Spawning success	SpawnSuc	%	80-90
Stocking density	SD _s	#/tank	1
Feeding rate	--	--	zero
Water depth	WD _s	cm	60-70
Tank depth	TD _s	cm	90-100
Tank area	TA _s	m ²	0.5-0.8
Water turnover rate	--	--	zero
<u>Design Parameters</u>			
<u>Parameter</u>	<u>Symbol</u>	<u>Unit</u>	
Number of ripe females	NumRipeFemale	#/month	
Volume/tank	Vol _s	m ³	
Number of tanks	NumTank _s	#	
Total water requirement	TWR _s	lpd	

A number of variations in the spawning process have been used. Large communal spawning tanks (15 m³) for 15-20 females have been used in Central America (Chamberlain 1985). In the large-tank larval rearing systems (JMPPMA 1973), gravid females are sometimes placed within a net enclosure in the rearing tank.

Process and design criteria for spawning are listed in Table 5. Design parameters can be computed as follows:

$$\text{NumRipeFemale} = \frac{100(\text{NumSpawn})(\text{SF}_s)}{(\text{SpawnSuc})} \quad (7)$$

$$\text{Vol}_s = \frac{(\text{TA}_s)(\text{WD}_s)}{100}$$

(8)

$$\text{NumTank}_s = \text{NumRipeFemale}/30$$

(9)

$$\text{TWR}_s = 1000(\text{NumTank}_s)(\text{Vol}_s)$$

(10)

10.9.1.3 Hatching systems

Fertilized eggs from the spawning tanks are placed in individual circular or rectangular hatching tanks. Gentle aeration is provided. Nauplii are photopositive; they can be concentrated with light and removed by siphoning. Both the number of eggs/female (Egg/F) and hatching success (HatchSuc) are very species-specific (AQUACOP 1983a,b; Liao and Chao 1983).

Table 6. Process and design criteria for penaeid shrimp hatching.

<u>Process Definition</u>			
Starting point	fertilized eggs		
Ending point	nauplii		
Production objectives	NumNaup; number of nauplii/month		
Production Safety factor	SF _h ; expressed as a ratio (typically in the range of 1.1-1.4)		
<u>Process Criteria</u>			
<u>Parameter</u>	<u>Symbol</u>	<u>Unit</u>	<u>Range</u>
Average size of eggs	Size _{egg}	μm	280
Eggs/female	Egg/F _♀	#	60,000-600,000
Time to hatch	t _h	d	0.6-0.8
Hatching success	HatchSuc	%	10-80
Average size of nauplii	Size _{nau}	μm	500
Feeding rate	--	--	zero
Water depth	WD _h	cm	40-60
Tank depth	TD _h	cm	50-70
Tank area	TA _h	m ²	0.4-0.8
Water turnover rate	--	--	zero
<u>Design Parameters</u>			
<u>Parameter</u>	<u>Symbol</u>	<u>Unit</u>	
Number of spawns	NumSpawn	#/month	
Volume/tank	Vol _h	m ³	
Number of tanks	NumTank _h	#	
Total water requirement	TWR _h	lpd	

Process and design criteria for hatching are listed in Table 6. Design parameters can be computed as follows:

$$\text{NumSpawn} = \frac{100(\text{NumNaup})(\text{SF}_h)}{(\text{HatchSuc})} \quad (11)$$

$$\text{Vol}_h = \frac{(\text{TA}_h)(\text{WD}_h)}{100} \quad (12)$$

$$\text{NumTank}_h = \text{NumSpawn}/30 \quad (13)$$

$$\text{TWR}_h = 1000(\text{NumTank}_h)(\text{Vol}_h) \quad (14)$$

10.9.1.4 Larval systems

Larval rearing tanks range from 1 - 2800 m³ (JMPPMA 1973; McVey and Fox 1983; Shigueno 1975; Simon 1981; Yang 1975). Large larval tanks are built from coated concrete, while fiberglass or plastic are used for smaller tanks. Concrete tanks must be filled with seawater and aged for at least 50-60 days before use (Yang 1975). Larval tanks must be designed to allow rapid and complete draining. Most larval rearing tanks are in-doors. Large tank systems are usually enclosed in greenhouse structures or buildings with translucent fiberglass panels (JMPPMA 1973; Yang 1975). Larvae should be protected from freshwater inflow, direct sunlight, and dust.

Aeration is by diffused aerators or airlift pumps. In the large tank method, the air requirement is about 36 lpm/m³ with one diffuser every 3-10 m² (Yang 1975). In a 2000 liter conical Galveston type larval rearing tank, 3 airlift pumps and 12 diffusers were used (McVey and Fox 1983). In a 10 m³ raceway tank, 14 airlift pumps were used (Simon 1981). Depending on larval stage, they are fed phytoplankton, Artemia, or a prepared diet (Treece 1985). Recently, much progress has been made in replacement of Artemia with a dry larval diet. Commonly, chloramphenicol, erythromycin, furazolidone, furanace, or tetracycline are added prophylactically (Brown 1989; Mock et al. 1980; Simon 1981).

Closed system larval rearing systems have been developed (Mock et al. 1973; 1977). These systems are not widely used in production hatcheries.

Process and design criteria for larval rearing are listed in Table 7. Design parameters can be computed as follows:

NumNaup

=

$$\frac{100(\text{NumPL})(\text{SF}_l)}{(\text{LarvalSur})}$$

(15)

Vol_l

=

$$\frac{(\text{TA}_l)(\text{WD}_l)}{100}$$

(16)

NumTank_l

=

$$\frac{30\text{NumNaup}}{(\text{Vol}_l)(\text{VSD}_l)(t_l)}$$

(17)

Table 7. Process and design criteria for penaeid larval rearing.

Process Definition			
Starting point	nauplii		
Ending point	post-larvae (PL)		
Production objectives	NumPL; number of PLs/month		
Production safety factor	SF _l ; expressed as a ratio (typically in the range of 1.5-2.0)		
Process Criteria			
Parameter	Symbol	Unit	Range
Average size of nauplii	Size _l	μm	500
Time in larval rearing	t _l	d	15-30
Volumetric stocking density of nauplii	VSD _l	#/m ³	20,000-40,000 (L.T.) 100,000-200,000 (S.T.)
Larval survival (nauplii to PL)	LarvalSur	%	15-70
Average size of post-larvae	Size _{pl}	mm	4.2-5.0
Volumetric stocking density of PLs	VSD _{pl}	#/m ³	10,000-150,000
Areal stocking density of PLs	ASD _{pl}	#/m ²	10,000-150,000
Feeding concentration	Feeding _l	#/ml	variable
Water depth	WD _l	cm	100-200
Tank depth	TD _l	cm	150-250
Tank area	TA _l	m ²	1-200
Water turnover rate	WTR _l	tank volumes/d	0.2-0.3
Design Parameters			
Parameter	Symbol	Unit	
Number of nauplii	NumNaup	#/month	
Volume/tank	Vol _l	m ³	
Number of tanks	NumTank _l	#	
Water flow/tank	Q _l	lpm	
Total water requirement	TWR _l	lpd	

$$Q_i = \frac{(WTR_i)(Vol_i)}{1.44} \quad (18)$$

$$TWR_i = 1440(NumTank_i)(Q_i) \quad (19)$$

10.9.1.5 Algal systems

Algae are fed to larval shrimp during the protozoa, mysis, and early post-larval stages. Many algal species are used (AQUACOP 1983c; Fox 1983; Treece 1985). Cell concentrations of 80,000 to 100,000 cells/ml are typically maintained in the larval system. The three common sizes of algal culture are presented in Table 8. The 5 million PL-10/month larval culture system described by Simon (1981) used 36-1,000 liter tanks for mass algal rearing.

10.9.1.6 Brine shrimp systems

Newly hatched brine shrimp nauplii are fed to late protozoa, mysis, and early post-larval stages. The brine shrimp density is increased from 0.25 to 8 Artemia/ml during the rearing period (Treece 1985). Brine shrimp cysts are often de-capsulated with sodium hypochlorite (Sorgeloos et al. 1983). Brine shrimp cysts hatch in about 1 day (Sorgeloos et al. 1983). While many types of hatching containers are used, 20 l units are common (Simon 1981). Separate hatching containers are used for each larval rearing tank.

10.9.2 Overall Hatchery Water Requirements

Overall water requirements for a hatchery with a one million PL-20/month capacity are shown in Table 9. Maturation and larval rearing account for 94% of total water use in the hatchery. Maximum water requirement is 465,420 lpd, with the maximum peak usage of 871 lpm. It is unlikely that all the secondary flows will be turned on at the same time. If only the two largest secondary flows are on at the same time (83 + 50 lpm), then the maximum peak requirement is reduced to 748 lpm:

Total Water Requirement	=	465,420 lpd
Maximum Water Flow	=	751 lpm
Minimum Water Flow	=	138 lpm

Water losses from filter backflushing increase the total by 5%. Therefore, total pumping capacity must be 490,000 lpd.

It is important to note that maximum peak flow is 2.3 times the average flow. Therefore, the boiler, heat-exchanger, and UV systems must be sized for

Table 8. Characteristics of the three types of algal culture used in shrimp culture.

Type	Culture Size
Pure cultures	20 ml
Pure inoculum cultures	2-10 l
Mass culture	1,000 to 35,000 l

the maximum peak flow. If these systems are not designed for maximum flow, excessive time will be needed to fill spawning, hatching, and larval rearing tanks. For hatcheries with a large peak demand, a second treated water, constant-head tank can be used to reduce peak flows.

10.10 OPERATIONAL PHILOSOPHY AND POLICIES

10.10.1 Operating Procedures

Hatchery design should accommodate anticipated operating procedures. These procedures include batch vs. continuous operations within the hatchery; seasonality in demand or performance; scale and duration of each culture phase; water conditioning needs; and possible operating changes. Will brood stock maturation be required, or will gravid females be used? Will large tank, Galveston, or some hybrid culture method be used? What are the normal,

Table 9. Component water flows for a hatchery producing 1 million PL-20s per month (based on hatchery #1 in Table 3).

Activity	Total (lpd)	Average (lpm)	Maximum (lpm)
Maturation	198,000	138	138
Larval Rearing	240,000	167	480
Subtotal	438,000	305	618
Algae - intensive	3,000	-	50
Algae - mass	10,000	-	83
Artemia	6,000	-	50
Spawning	6,020	-	50
Hatching	2,400	-	20
Subtotal	27,420	19	253
TOTAL	465,420	324	871

emergency, and disaster procedures? For example, decontamination and start-up procedures after disease incidence can influence selection of tank materials, access requirements, shapes, and sizes. Hatchery physical plant design and capabilities will depend on the answers to these, and other questions. If procedures later change, the hatchery may be incompatible or inadequate to support the new procedures. This may require major system modifications, or simply accepting inefficient operating methods. Operating procedures can change in many ways. If additional service needs becomes apparent after the design is completed, problems can result if these needs were not anticipated. Examples include needs for chlorination and dechlorination of culture water, EDTA addition and water "aging", additional filtration, greater water quantities, more aeration, or greater water temperature control capabilities. Often these needs were anticipated during the design phase but dropped for cost reasons and because their inclusion was not compelling at the time. A thoughtful designer will leave floor space and easy access to piping for later retrofits.

Operating procedures tend to reflect individual preferences, especially with details and organization of tasks. This is inevitable, since hatchery operations are still largely an art. This does not make one set of procedures right and the other wrong, they are just different. Some design decisions are often based on preferences and values of key individuals, including the potential hatchery manager. If these key personnel change, incompatibilities and inefficiencies can occur between the physical plant and the "new" operating procedures.

The primary purpose of commercial shrimp hatcheries is production not research; however, most commercial hatcheries conduct considerable testing to solve operating problems. In addition, they may have in-house research projects with long-term objectives for improving process efficiency. If these activities are not anticipated during the design phase, problems can result. One result is that tests are carried out using production equipment. This is doubly unfortunate since the scale is usually too large for precise research measurements, and the control required for research purposes and yields for commercial production are reduced.

10.10.2 Assignment of Responsibilities

Hatchery operations are usually divided into separate functions such as algal culture, maturation, larval rearing, etc.. Man-power requirements are shown in Table 10 for one large commercial hatchery. Each functional area is usually under the direction of one individual who has considerable prior experience. Individual workers are assigned to specific functional areas. In addition, larval and PL tanks are often assigned by number to individual technicians to assure continuity and responsibility. All of these areas and

Table 10. Labor requirements of a commercial shrimp hatchery based on a 5 million PL-10/month commercial shrimp hatchery (Simon, 1981).

Function	Number of Workers
Broodstock Acquisition & Maintenance	5
Maturation, Spawning, & Hatching	6
Phytoplankton Culture & Zoeal Feeding	3
Larval & PL Rearing	6
Physical Plant Operations & Maintenance	2
Management & Administrative	3
Total	25

organizations are critical and essential for PL production. The hatchery manager is the most critical person in a hatchery as he/she must assure that all aspects are functional. Problems anywhere along the line can quickly threaten PL production. Data and record maintenance are important for efficient hatchery operation, which can be facilitated by the use of large, carefully maintained chalkboards with fixed formats listing each tank or unit in each area. This approach has proven effective in managing complex, commercial hatchery operations (Simon 1981).

While the chain of command for hatchery production functions is usually clear, this is often not the case for the servicing, maintenance, and repair activities. Problems in these areas can be as critical to PL production as any of the biological functions. There may not be a clearly identifiable individual responsible for these services, and if he exists, he is unlikely to have the same status as the other area leaders. If service personnel are not directly supervised by the hatchery manager (or assistant), problems can develop. Area leaders will continually try to improve their respective operations, and they will task the service personnel accordingly. This may result in suboptimization of the overall hatchery production by expending valuable time and resources on non-critical, non-limiting activities. It is essential that the service function be accountable only to one person; usually, the hatchery manager. In this way, the correct priorities can be assigned and long-term, but critical aspects, such as preventive maintenance, scheduled overhauls, and an adequate spare parts inventory can be maintained. With all the problems that routinely occur in hatchery operations, these important operational activities are often ignored until they become critical, usually as a result of equipment failure. The hatchery manager is, however, often preoccupied with other matters and generally can not give the service area the attention required.

10.10.3 Spares and Redundancy

During the design phase, considerable thought should be given to system reliability and the need for redundant equipment which is ready for use in the event of equipment failure. Decisions and trade-offs for backup equipment costs versus reliability and dependability must be carefully made. Redundancies can include spare pumps, blowers, intakes, boilers, and backup power sources. Redundant equipment gives time to make repairs without loss of service. Prolonged loss of services usually means economic loss.

What often happens in practice is that increased demands for production results in backup equipment being brought on-line. The backup equipment is then no longer redundant, but primary. Thus, the probability of a critical failure is now probably twice as much. With the increased demand for services, the consequences of a failure when it occurs will also be much more severe. The hatchery manager should strenuously resist increasing available services by use of standby equipment. If the backup equipment is needed for a short term emergency in a critical area, it will obviously be used. Once so used, the equipment may now be considered available for routine service. If there is no alternative, additional backup equipment must be immediately purchased and installed. If it can not be actually installed due to space limitations, it should be purchased and assembled so that it can be installed rapidly. Unfortunately, convincing management to purchase expensive equipment when there is no immediate problem or crisis is often very difficult. The problem also exists with replacing or improving temporary jury-rigged systems that are momentarily satisfactory. The best argument is to clearly emphasize to management (or who ever pays the bills) the time that will be required to purchase, deliver, and install essential equipment and restore required services after a failure. Lost production, especially at remote sites, will often be unacceptable to management, but they still may delay a decision as long as possible.

The spare parts problem has several other aspects. One is the availability of spare parts. If spare parts are readily and quickly available, then a minimum of on-hand spare parts is needed. If spare parts are difficult and time consuming to get, then a large inventory is required. Usually some spare parts are ordered with the basic equipment. As these are used, they should be immediately replaced as these are the ones most likely to be needed again. This can easily be put off in the presence of more immediate problems. At remote sites, absence of parts can close down production for prolonged periods. Service loss and resultant mass larval mortality will, as a minimum, result in a loss of one production cycle even if the parts are quickly available. It will be much longer if parts are not available.

10.10.4 Preventive Maintenance

Much of the philosophy relating to spares and redundancy also applies to preventive maintenance. Equipment failure that can not be quickly accommodated for can lead to unacceptable consequences. Equipment that is not properly maintained will fail. Even if properly maintained, with extended service parts will wear out. Wear prone parts are replaced in major overhauls. These overhauls should occur when the probability of failure becomes sufficiently high due to wear. Both routine maintenance and equipment overhaul should occur while the equipment is operating normally, without immediate problems. All these activities require personnel time, resources, and sometimes appreciable money. In the presence of immediate crises and tight budgets, maintenance activities are usually put off, and the potentially disastrous consequences of failure are forgotten. In practice, it is very difficult to give priority to maintenance activities dictated by long-term economics.

10.10.5 Monitoring and Control

Monitoring and control are critical hatchery activities, although this engineering terminology is rarely used. It is one's capability to know at any time what is happening in the hatchery, and one's capability to alter or influence this. If something is going wrong and you do not know it, you obviously can not do anything about it. If you know something is going wrong but do not have the capability to effect it in a timely manner, you are no better off. With experience, monitoring and control functions are usually accomplished but often without the realization of what they are. Greatly increased capabilities can result from more conscious attention. This does not necessarily mean more monitoring/alarm systems and automated equipment, although these can be helpful.

One of the most valuable hatchery monitoring signals are sounds, or rather changes in sounds. These sounds may be from flowing water or mechanical equipment. An experienced person will react to even minor sound changes and promptly investigate. An inexperienced person may feel uneasy, without knowing why, especially if the sound change is not dramatic. Timely action can often prevent serious damage. Visual and sound checks by hatchery personnel during normal daily activities, and the reporting of anything unusual, provides substantial monitoring capability. Problems arise when equipment is remote, rarely visited, or during periods of greatly reduced personnel activity, such as at night. Under these conditions, if something goes wrong, it may not be discovered for a long time or until it produces serious effects elsewhere. Automatic monitoring and alarm systems are most valuable under these conditions.

It is important not only to know something is wrong, but to also inform someone who can act quickly. In an emergency, actions may require the sacrifice of some activities to save others. Obviously, the overall hatchery priorities should rule rather than individual areas priorities. While the normal chain of command for such decision making is usually clear, problems can develop during the hatchery manager's absence (like at 3 am on a Sunday morning). There must be an identifiable individual and a backup person available at all times who are responsible for reacting to emergencies. These people must be provided with decision making guidelines by the hatchery manager and access to technical information, communications, and keys/codes that may be required. They also must be familiar with the equipment and its operation. A common solution to this problem is to provide on-site housing for the hatchery manager and a few of the senior operating personnel. In their absence, emergencies may force relatively junior hatchery personnel to make critical decisions. Under these conditions, a do nothing or deferred decision may be worse than a wrong decision. Problems should be anticipated before they occur.

10.11 OPERATIONAL PROBLEM AREAS

Operational problems tend to arise from two sources. One set of problems is the result of design errors or inadequate operating procedures. These include problems arising from materials, chlorine use, gas supersaturation, biofouling, and monitoring and control limitations. The second set of operational problems is the result of the climate and environment, such as flooding, earthquakes, winds, and waves. The most common types and causes of such failure are listed in Table 11. Some of these problems can be anticipated during site selection, but others occur at even the best sites. Generally, good design, followed by good operating procedures and routine maintenance can reduce these problems. Good design can reduce the impact of some problems, although cost concerns may eliminate many items that are cost-effective in the long run.

10.11.1 Materials

Materials selection for hatchery equipment and supplies is a critical area with no easy answers. Larval and PL shrimp are extraordinarily sensitive to many chemicals at very low concentrations. Chronic toxicity of many chemicals to marine shrimp is not well known. Guidelines for materials selection are at best incomplete and crude (Huguenin and Colt 1989). Some common plastics are initially toxic and must be leached in running seawater for about 2 weeks before use. Some synthetic materials have persistent toxicity, and they can not be used even after extended leaching. In addition, plastics formulation can

Table 11. Common types of equipment failures in shrimp hatcheries.

Component	Cause
Intake Structures	Biofouling of intake Clogging of intake structure resulting from debris Damage to intake structure resulting from rocks or floating debris Intake screen collapse resulting from clogging and pressure difference Wave damage Scouring (undermining) or deposition resulting from water currents Collision (anchors, boats, fishing gear) damage
Piping	Clogging resulting from biofouling Collision damage Inadequate burial and being run over by a moving vehicle Gunshot damage Erosion resulting from entrainment of abrasive particles in water Ground movement, earthquake, or earth slides Storm waves and currents depositing intake piping on beach
Pumps and Motors	Gunshot damage Loss of electrical power or loss of one leg in 3 phase power Poor regulation of frequency or voltage Power transients Poor alignment of the motors, shafts, and pumps Debris lodged in impeller or against the shaft Cavitation resulting from blockage of suction lines Shorting of controls/motors resulting from splashing or water leaks Inadequate lubrication or maintenance Corrosion Over speeding of motor resulting from pump being run dry Over heating resulting from pump being run against a closed valve
Air Blowers	Flooding with water when shut down Surging and bearing damage resulting from excessive pressure
Electrical Supply	Tree or animal damage to power lines Flooding of conduit and shorting of lines Wind or storm damage to power lines Failure of standby electrical power during emergency
Culture systems	Fouling of valves, drains, or pipes resulting from biofouling or silt Excessive freshwater or waste water inflow Earthquake damage Direct storm wave or wind damage to hatchery Excessive high water resulting from storms and flooding Clogging of filters and other equipment from storm related turbidity Loss of temperature control resulting from storm effects or power loss

vary from batch to batch. It is highly desirable to bioassay each batch of material using shrimp larvae. It is also important to test sealants, paints/coatings, piping, and tubing that are exposed to seawater, as well as materials for the hatchery building itself (wood treatments, insulation, etc).

Volatile components not in direct seawater contact with may be absorbed into the water from the air, or condensate may drip into the water. Mortalities or reduced growth resulting from materials toxicity have the same symptoms as those from many other sources. These may be very difficult to identify as a materials problems. By trial and error, it is sometimes possible to identify the problem. As an example, one of the authors experienced sudden, high mortalities in a fish hatchery that was ultimately traced to a specific brand of silicon tank sealant. The brand of sealant had been used for a long time without any problems. The formulation apparently was changed without notice. Such problems can doom a project, if the source of the problem is not identified.

10.11.2 Chlorine Toxicity

Chlorine in various forms is commonly used in shrimp hatcheries to disinfect seawater, usually as a batch process. This may cause toxicity problems. The chemistry of chlorine in seawater is complex and not completely understood (Sugam and Helz 1980). Chlorine residuals in the range of 10 to 20 μ g/l may have significant chronic effects on larval and PL shrimp. Wet chemical analysis for chlorine residual have a detection level of about 10-40 μ g/l. Many of the commercially available chloride test kits are designed for swimming pool applications, and are not accurate below 100-200 μ g/l. Residual chlorine can be allowed to decay in the storage tanks or it can be chemically removed. The chlorine residual decay rate can vary widely depending on exposure to sunlight and water chemistry. Without the ability to monitor low-level concentrations of chlorine residual, it is impossible to determine the water aging time for non-toxic concentrations. Empirically determined storage time can be site specific. Chlorine residual can be removed by passing the water through activated carbon, or by addition of sulfur dioxide, sodium sulfite, or sodium thiosulfate. In freshwater, activated carbon treatment can remove 80-90% of the chlorine residual, but the effluent may still contain 50-70 μ g/l of residual chlorine. Typically, a reducing agent must be added at 1:3 to 1:6 molar excess to remove the remaining chlorine residual (Giles and Danell 1983; Seegert and Brooks 1978). Sodium thiosulfate is toxic to penaeid shrimp at concentrations above 0.5 mg/l (Johnson and Cichra 1985). Under freshwater conditions, sodium sulfite is less toxic than sodium thiosulfate (Seegert and Brooks 1978). While dechlorination compounds have some toxicity, these compounds are significantly less toxic than chlorine. Without effective dechlorination and monitoring, chlorination of source water should be avoided.

10.11.3 Gas Supersaturation

Excess dissolved gases can produce gas bubble trauma or gas bubble disease, characterized by gas bubble formation in the tissues and vascular system. Gas supersaturation is described in terms of δP , the difference between total dissolved gas pressure and the local atmospheric pressure (Colt 1986). Dissolved oxygen is not a good measure of gas supersaturation, although supersaturated oxygen may suggest gas supersaturation.

In larval brown shrimp (*Penaeus aztecus*) a $\delta P = 110$ mm Hg resulted in increased mortality (Lightner et al. 1974). Information on the chronic effects of gas supersaturation to larval shrimp is not available at this time, and a criteria of $\delta P = 20$ mm Hg is suggested (Table 2).

Three common ways to create gas supersaturation are: air entrainment on the suction side of pumps (Brisson 1985; Hughes 1968), water heating (Lightner et al. 1974), and photosynthesis (Supplee and Lightner 1976). Seawater may be naturally supersaturated, especially in the spring or following storms (Colt 1986).

Shrimp at greatest risk to gas supersaturation in a penaeid shrimp hatchery are the adults, because of high water flowrates, low water depths, and minimal aeration. Since gas supersaturation may depend on randomly occurring events, degassing of process water may be prudent (Colt and Bouck 1984). Dissolved gas concentrations in larval rearing tanks depends more on the type of aeration and on photosynthesis, rather than on the gas concentrations of the influent water. After filling a larval tank with fresh seawater, the aeration system should be operated for 4-6 hours prior to stocking larval shrimp.

10.11.4 Biofouling

One of the most important factors effecting seawater system performance is marine biofouling. Biofouling control is also one of the most troublesome problem that occurs. The problem depends on season and location. Different sites can differ greatly in biofouling rates, even between nearby sites. Biofouling roughens pipe and equipment surfaces, and reduces effective pipe diameter. If unattended, it will reduce flow areas, increase pipe velocity, reduce flow capacity, and increase energy consumption. This not only greatly reduces system performance, but also leads to total system failure resulting from pump cavitation or operation outside of recommended limits. As a consequence, considerable effort is often devoted to biofouling control. Biofouling control is much easier if control options are considered during the design phase, rather than during operation. If biofouling proceeds until flowrates are significantly reduced, the hatchery may be shut-down for prolonged periods (days to months) to fix the problem. Cleaning methods for heavily fouled lines may seriously damage plastic or fiberglass pipes and

fittings, especially in turns. In some cases, it may be quicker and cheaper to completely replace heavily fouled pipes and fittings. Biofouling can be a major threat to hatchery production goals and delays in performing routine biofouling maintenance can have severe repercussions.

Many methods have been used to control biofouling in seawater systems, and each method has its advantages and disadvantages (Huguenin and Colt 1989). In a complex system, several methods may be used in different parts of the system. It is good practice to consider at least two options for each part of the system. Many of the control options require consideration during design and construction.

10.12 SUMMARY COMMANDMENTS FOR HATCHERY SEAWATER SYSTEMS

The following "Commandments" are guidelines and rules for maximizing the probability of success with seawater culture systems (Huguenin and Colt 1989). The consequences of mistakes are particularly severe for commercial production hatcheries. Many of these commandments were learned the hard way from direct experience with a number of shrimp hatcheries.

- * Take great care in quantifying the requirements, as they will greatly effect system complexity and cost.
- * Consider long-term as well as short-term requirements, even though they are more difficult to quantify.
- * Major cost underestimates are more likely to result from necessary but uncounted components and services or increased requirements, rather than from errors with specific items.
- * Consider operating approaches and procedures before the design is fixed. Significant input from operational personnel is needed in the design and construction phases.
- * Demands for services (flow rate, compresses air, etc.) usually increase in quantity and quality with time. If possible, provide extra floor space, access to piping, access to drains, and provisions for electrical power for potential future retrofits.
- * Remember that the key to low risk and high performance systems is large amounts of high quality seawater. In short, keep very conservative biomass loading relative to the available water quality and quantity. Increasing the biomass will increase the risks.
- * Anticipate probable failures and plan accordingly to minimize the consequences.

- * Provide redundant equipment to back up critical functions in emergencies. Resist the temptation to use backup equipment in normal operations just because it is available.
- * Responsibilities and decision-making procedures for emergencies should be decided before a crisis occurs, remembering that they rarely occur at convenient times.
- * Do not forget to routinely maintain and inventory necessary spare parts when operations are going well. They are twice as important when things are not going well.
- * Be extremely careful in selecting all materials and supplies used in and around seawater systems, because your organisms may be very sensitive and seawater is very corrosive. Do not forget to include the surrounding building and paints, sprays, cleaners, sealers, and solvents used near culture organisms.
- * Leach all materials in running seawater for at least two weeks before use.
- * Take great care with all fittings, pipe, and equipment on the suction side of pumps to avoid even the most minute air leak. Supersaturation can easily kill.
- * Make the suction-side lines as large in diameter and as short as possible to minimize suction-side frictional losses.
- * Place pressure gauges on both the suction and discharge side of pumps to monitor the condition of the lines and the performance of the pumps. Watch for biofouling, especially on the suction side. Service regularly.
- * Adequately pitch all floors in wet-lab areas towards the drains remembering that concrete may shrink on drying.
- * Greatly over-size drains to take high transient flows. Drains can never be too large. Even the largest drains will occasionally clog if not maintained.
- * Expect very high suspended solids content in incoming seawater from shallow water intakes during storms or heavy waves.
- * Anticipate the need to remove sediment and debris from any parts of the system that have low flow velocities.
- * Bury or otherwise make inaccessible as little of the system as possible. The inaccessible parts are inevitably the parts you will want to get at later.
- * Place all electrical outlets up high, above any un-intentional water input.
- * Use ground fault interrupters on all indoor and outdoor electrical outlets. Do not underestimate the electrical hazards associated with seawater.
- * Inspect and service intake screens regularly.
- * Be careful in locating the intakes. They should not be situated where they will pick up debris, recycle drain water, or ever experience breaking waves. Do not underestimate the forces of the sea on intakes and other exposed structures.

- * Remember that the piping/processing system and the pumps are highly interactive. Changes in either area will effect the other.
- * In wet-lab and mechanical areas, use "X" fittings with blanked faces where "L"s and "T"s are needed. This maximizes accessibility for cleaning and future modifications.
- * Do not place on automatic alarm any functions or events that can wait until normal working hours.
- * In a field with so much misleading or incomplete information, data voids, "experts", and variations in conditions, it is worth remembering when dealing with the unknown or uncertain that one test, under actual conditions, may be worth 1,000 expert opinions.

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CHAPTER 11

**USE OF ONE-LITER IMHOFF CONES
IN LARVICULTURE PRODUCTION**

11.1 INTRODUCTION

Important aspects of shrimp larviculture research and development are replicability, both within and among laboratories; and reliable scale-up of small-scale experiments to large-scale applications. Small-scale trials have an advantage over large-scale trials in that maintenance and start-up costs are reduced, stocking and experimental parameters are more controlled, replication is practical, and use of valuable resources is minimized. The latter is particularly important at commercial operations that wish to conduct in-house experimentation without jeopardizing production capacity and risking millions of larvae in mass culture. Perhaps the greatest application of a small-scale, in-house research will be the evaluation of new products (eg. feeds, chemicals), evaluation of seawater quality, and monitoring of performance (quality) of offspring spawned from specific maturation broodstock (eg. in relation to maturation dietary regimes, age or source of stock).

The need for a standardized experimental approach has long been recognized. Wilkenfeld et al. (1983) cited early attempts to standardize experimentation with penaeid larvae, including use of various sizes of glass beakers, carboys and tanks ranging in volume from 250 ml to 200,000 liters. None of these systems gained wide acceptance, either because they were difficult to manage and the volume was too great to allow for accurate total population counts, or the volume was too small to simulate large-scale applications. In addition, small container shape often did not allow effective mixing of food particles, or small containers were easily broken; while space and cost of maintaining large cultures made replication difficult. Physical difference between experimented systems, as well as variations in environmental conditions, water quality, water exchange rates, stocking densities and feeding regimes, have all contributed to equivocal performance and interpretation of larviculture experiments.

In an effort to standardize methods, Wilkenfeld et al. (1983) developed a small scale, experiment approach which uses a series of 1-liter, plastic

Table 1. Survival and mean weight of larvae fed control (algae+ Artemia) feeding regimes.

Species	Control Diet (cells/ml x 1000) + <u>Artemia</u> ^a	% Survival	Mean Dry Wt/PL (ug)	Age	Reference
<u>P. aztecus</u>	100 <u>S. costatum</u> +	89 ± 5	100 ± 3	PL1	1
	40 <u>T. fluviatilis</u>	93 ± 3	121 ± 3	PL1	1
	70 <u>S. costatum</u> +	91 ± 7	110 ± 5 ^b	PL1	2
	70 <u>C. gracile</u>	93 ± 4	110 ± 1 ^c	PL1	2
	100 <u>Isochrysis</u> +	88 ± 2	107	PL2	3
	50 <u>T. chuii</u>	74 ± 12	74	PL2	3
		64 ± 13	69	PL2	
<u>P. schmitti</u>	100 <u>C. gracile</u> + 30 <u>T. chuii</u>	97 ± 2	98 ± 2 ^d	PL1	4
<u>P. semisulcatus</u>	100 <u>C. gracile</u> +	84 ± 8	197 ± 6	PL1	5
	40 <u>T. chuii</u>	96 ± 2	171 ± 7	PL1	5
		86 ± 4	148 ± 10	PL1	5
		92 ± 3	158 ± 4	PL1	5
		88 ± 4	142 ± 3	PL1	5
		91 ± 7	138 ± 8	PL1	6
		86 ± 10	155 ± 3	PL1	6
		83 ± 6	155 ± 5	PL1	6
		85 ± 2	145 ± 5	PL1	6
		54 ± 12	154 ± 8	PL1	6
		43 ± 6	194 ± 13	PL1	6
		62 ± 8	183 ± 5	PL1	7
		76 ± 8	138 ± 5	PL1	7
	200 <u>C. gracile</u> +	68 ± 2	117 ± 11	PL1	8
	80 <u>T. chuii</u>	54 ± 20	156 ± 13	PL1	8
		69 ± 8	139 ± 3	PL1	8
		82 ± 3	152 ± 8	PL1	8
		62 ± 5	196 ± 12	PL1	8
		51 ± 7	217 ± 16	PL1	8
	200 <u>C. gracile</u> +	90 ± 5	93 ± 18	PL1	8
	250 <u>Isochrysis</u>	43 ± 10	175 ± 13	PL1	8
	500 <u>Isochrysis</u>	48 ± 7	195 ± 12	PL1	8
		69 ± 13	124 ± 12	PL1	8
		86 ± 23	74 ± 17	PL1	8
<u>P. setiferus</u>	100 <u>S. costatum</u> +	96 ± 3	138 ± 1	PL1	1
	40 <u>C. gracile</u>	97 ± 5	140 ± 3	PL1	1
	70 <u>S. costatum</u> +	94 ± 3	109 ± 4 ^e	PL1	2
	70 <u>C. gracile</u>	92 ± 4	109 ± 1 ^f	PL1	2

Table 1. Continued

Species	Control Diet (cells/ml x 1000) + <i>Artemia</i> ^a	% Survival	Mean Dry Wt/PL (ug)	Age	Reference
<u>P.</u> <u>setiferus</u>	100 <u>Isochrysis</u> +	52 ± 14	111	PL3	3
	50 <u>T. chuii</u>	45 ± 4	112	PL3	3
<u>P.</u> <u>stylirostris</u>	100 <u>S. costatum</u> +	99 ± 1	118 ± 2 ^b	PL1	1
	40 <u>C. gracile</u>	99 ± 2	124 ± 5	PL1	1
	100 <u>C. gracile</u> +	88 ± 6	127 ± 2	PL1	6
	30 <u>T. chuii</u>	89 ± 5	152 ± 9	PL1	6
		86 ± 7	147 ± 16 ^b	PL1	13
<u>P.</u> <u>vannamei</u>	100 <u>S. costatum</u> +	91 ± 4	118 ± 7 ^b	PL1	1
	40 <u>C. gracile</u>	95 ± 5	128 ± 0 ^b	PL1	1
	100 <u>C. gracile</u> +	84 ± 4	136 ± 7	PL1	9
	30 <u>T. chuii</u>	80 ± 4	127 ± 13	PL1	9
		77 ± 7	118 ± 13	PL1	9
		80 ± 8	113 ± 3	PL1	9
		81 ± 8	137 ± 6	PL1	9
		77 ± 10	103 ± 6	PL1	10
		85 ± 9	139 ± 10	PL1	10
		98 ± 2	115 ± 1 ^b	PL1	15
		98 ± 1	110 ± 5	PL1	6
		84 ± 6	120 ± 10	PL1	6
		90 ± 4	153 ± 12	PL1	6
		82 ± 9	105 ± 10	PL1	11,12
		86 ± 10	131 ± 6	PL1	16
		85 ± 5	132 ± 4	PL1	16
		73 ± 13	132 ± 15 ^b	PL1	13
		93 ± 7	178 ± 6	PL1	14
		79 ± 8	227 ± 16	PL5	11
		72 ± 11	290 ± 32	PL5	11
		94 ± 4	272 ± 14	PL5	11
		62 ± 19	236 ± 15	PL5	12
		87 ± 5	265 ± 13	PL5	12

^a *Artemia* feeding levels varied among experiments.

^b Weight based on samples containing 90 - 98% PL.

References: 1, Kuban et al. 1985; 2, Wilkenfeld et al. 1984; 3, Kuban et al. 1983; 4, Smith et al. 1986; 5, Samocha et al. 1989; 6, Samocha 1984; 7, Samocha 1985; 8, Samocha 1983; 9, Biedenbach et al. 1989; 10, Biedenbach et al. 1990; 11, Smith and Lawrence 1988a; 12, Smith and Lawrence 1988b; 13, Thomsen et al. 1987; 14, Villamar and Lawrence 1989; 15, Smith et al. 1986; 16, Talley et al. 1988.

Imhoff cones, individually supplied with aeration. The 1-liter volume is large enough to be representative of scaled-up conditions, yet small enough to conduct multiple replicates for each set of test conditions. The cone shape prohibits settling of food and larvae. Variability is further reduced by the use of artificial seawater and a standard feeding regime as a control. Finally, the system is constructed of durable materials which are widely available.

Since its initial description, the Imhoff cone approach has undergone improvements, and is currently used internationally by research and industrial concerns. This method has been used successfully in research with *Penaeus aztecus*, *P. marginatus*, *P. monodon*, *P. schmitti*, *P. semisulcatus*, *P. setiferus*, *P. stylirostris*, and *P. vannamei*. It should prove suitable for other penaeid species.

Tables 1 and 2 summarize survival and mean weight for several penaeid species cultured in cones under control feeding trials. These trials included either algae plus *Artemia*, or algae alone. Depending on shrimp source, penaeids species, and feeding regime, survival ranged from 40 to 100%, but is normally above 85%. Mean weight per PL1 fed a diet including *Artemia* was generally between 100 and 150 ug, whereas PL fed only algae were significantly smaller (30 to 70 ug). Further size reduction was seen in PL5 denied an animal food source.

Imhoff cone experimental methodology has been used to investigate larval performance for a variety of topics, including genetics, nutrition and toxicity. For example, Lester (1988) used the cone system to follow the performance of larvae from individual spawns. The contribution of live animal feeds (Kuban et al. 1983; Wilkenfeld et al. 1984; Thomsen et al. 1987; Biedenbach et al. 1988, 1989; Samocha et al. 1989), live algae (Wilkenfeld et al. 1984; Kuban et al. 1985) and non-living feed particles, such as dried algae (Biedenbach et al. 1990) chicken egg yolk (Fuze et al. 1985), and dry feed formulations (Smith and Lawrence 1987; Stuck et al. 1988; Stuck and Barrett 1989; Villamar and Lawrence 1989) have been investigated using this system. Protein (Smith and Lawrence 1988a) and fatty acid requirements (Yates et al. 1987; Smith and Lawrence 1988b) have also been examined.

Cone methodology has also been used to examine environmental influences, such as quality of artificial seawater (Talley et al. 1988), light intensity (Olin and Fast 1988), and methods of pH and salinity acclimation (Olin 1987). Smith et al. (1986) modified the system to examine both the chronic and sublethal effects of exposures to sodium hypochlorite and sodium thiosulfate. One advantage of the Imhoff cone system is that most individual components can be used repeatedly without replacement. Caution must be exercised in choosing chemicals that will not bind with the plastic of the cone, thus making the cone unusable for subsequent research. A new innovation

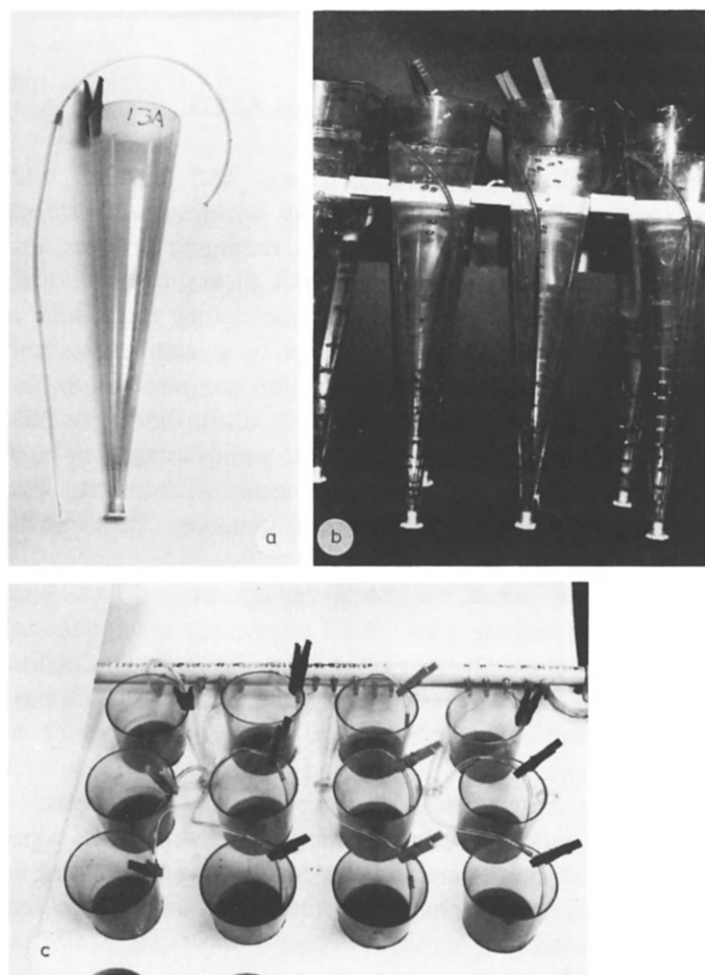


Figure 1a. Unassembled Imhoff cone fitted with teflon wrapped push-plug. Aeration to cones is supplied from an air manifold through a feeder airline of variable length connected to a 30-cm extension airline and glass pipet (both shown in photo).

1b. Assembled cones. Side view through table; note pipet placement in cone tip and air bubble pattern.

1c. Top view of Imhoff cones arranged on table showing manifold and PVC clips holding feeder lines on table.

using a disposable cone is being tested for examination of chemically reactive substances (Thomsen 1990).

11.2 DESCRIPTION OF CONE CULTURE APPARATUS

Test vessels consist of one-liter plastic Imhoff cones (45.5 cm high, 10.5 cm top diameter), fitted with either plastic push-plugs wrapped with teflon tape or plastic screw caps (Fig. 1). Individual cones, arranged in rows, are supported in 9 cm diameter holes cut into a 20 mm thick plywood board table top. The table top is sealed with a waterproof white epoxy paint and is supported on the lip of a fiberglass tank, held in place by plastic screws and bolts. The tank acts as a water bath to maintain seawater temperature in the cones. Temperature within the tank is thermostatically controlled with 200-watt heaters; circulation is maintained by a submersible pump located at each end of the tank, with airstones suspended toward the center of the tank. The tank and table top can be constructed of any desired dimension. Between 10 and 20 replicate cones are used per treatment.

Aeration is supplied via an air manifold system constructed of PVC pipe and chrome-plated brass pipe valves (3/8" NPT, specially designed for threading into PVC pipe), with one valve per cone (Fig. 2). A feeder airline (5 mm O.D.), held under plastic clips affixed to the table, connects each pipe valve to a 30 cm extension air tubing which is fitted with a glass pipet (1 ml in 1/10 volume). Extension airlines are connected to feeder airlines with plastic or glass adapters. The only parts of the air system which come in direct and continuous contact with the seawater medium are the glass pipet and the extension airline. Glass pipets are sterilized after use by soaking in 1-N nitric acid for a few minutes, and should be changed daily before salt crystals form in the pipet tip restricting air flow. Prior to first use, new glass pipets must be soaked in 12-N nitric acid and scrubbed to remove the markings. Feeder airlines are used for several consecutive experiments, whereas extension airlines are disposed after each experiment. The extension airline is secured to the side of the cone by a clothes pin, or maintained stationary in the center of the cone by one of several methods (Fig. 3a-d). Whichever method is chosen, the glass pipet must be secured in the apex of the cone so that larvae do not become trapped in the apex under the stream of air bubbles. A slow trickle of air bubbles is adequate to maintain a uniform distribution of larvae and food particles, and adequate dissolved oxygen concentrations. For disease or toxicity studies, plastic lids are used to prohibit airborne contamination of chemicals. Continuous overhead illumination is provided by 40 watt cool white bulbs.

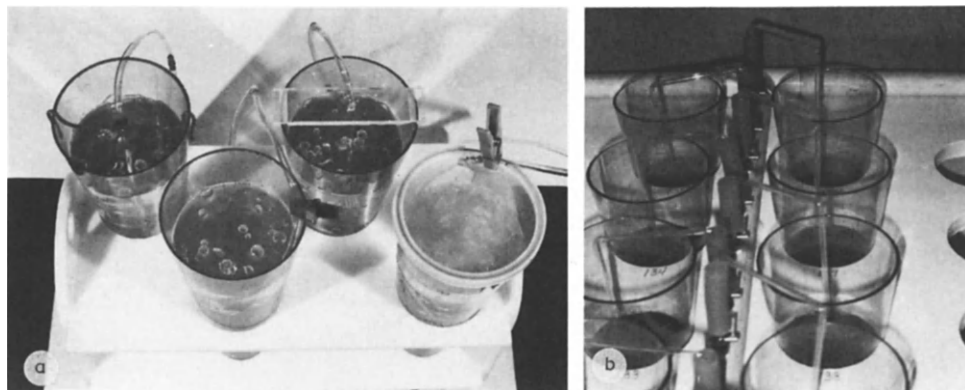


Figure 2. a) Examples of methods for securing pipet and extension airline in a cone (clockwise from top left): wire loop, plexiglass bar, plastic clothes pin and plastic lid, plastic clothes pin only. b) Replacement of the extension airline by a bent pipet connected to the pipet in the cone by a piece of airline tubing.

11.3 METHODOLOGY FOR CONE CULTURE

11.3.1 Seawater Preparation

The experimental design will determine the most suitable seawater source. Either source seawater or artificial seawater may be used. Artificial seawater is recommended for applications where the influence of local source water is considered an undesirable variable. Comparable growth of *P. vannamei* larvae has been demonstrated in hW Marinemix + Bio-Elements, Tropic Marin, Sera and Ocean 50 artificial sea salt brands (Talley et al. 1988). Artificial seawater is mixed 24 hrs in advance of daily use and kept constantly and vigorously aerated. One batch of seawater is mixed with deionized water and 10 mg/l EDTA in sufficient quantity to satisfy all seawater requirements for the day. On the day of use, the pH, salinity and temperature of the batch seawater are adjusted to 8.0-8.3, 30 ppt and 29 ± 1 C, respectively, and the seawater filtered through 1 micron mesh to remove suspended solids.

11.3.2 Acclimation and Stocking Procedures

Except in special cases, nauplii are acclimated to artificial seawater as a single population (ideally composed of subsamples of three or more spawns to better represent the species), by slowly exchanging the original seawater over a period of 60 minutes. Once acclimation is complete, nauplii are transferred to a holding container and density is diluted to 100 nauplii/l. Temperature is maintained during acclimation with 200 watt submersion



Figure 3. Procedures for daily seawater medium exchange (a, b, c) and final cone termination (a, b, d). See text for details.

heaters or water baths. Larvae remain in the holding container until they metamorphose into the substage desired for the tests.

Prior to counting and stocking, the apparatus is assembled; cones are scrubbed with a biodegradable detergent, rinsed and plugged (a strip of teflon tape wrapped around the push-plugs will assure a tight fit), extension airlines are attached to clean pipets (wetting the end of the pipet with freshwater facilitates attachment and subsequent removal), and cones are filled with seawater medium. Pipets are held flush to the cone bottom, and aeration is adjusted after all cones have been filled with medium.

Consideration must be given to the experimental objectives in order to determine the most suitable larval substage for stocking. For example, if an objective is to evaluate larvae variability from maturation broodstock treatments, cones should be stocked with nauplii shortly after acclimation, since transition from nauplius to protozoa-one is a key indicator. If, however, survival after transition from nauplius to protozoa is not a factor in the experimental design, nauplii can remain in the acclimation container until they become protozoa-one. In the latter case, algae must be added to the seawater medium after naupliar acclimation because protozoa require phytoplankton as soon as metamorphosis is complete. If the purpose of the experiment is to evaluate replacements for *Artemia*, such as dry prepared feeds or other live animal foods, cones can be stocked as late as the protozoa-two or protozoa-three substage.

The cones are stocked by counting 100 larvae from the acclimation chamber individually into a 30 ml beaker, and the contents poured into a cone. If constructed carefully, there will be no variability among cones across the table induced by differences in light or temperature. Thus, treatments are grouped by rows rather than as individual random cones, thereby reducing the chance for mistakes during stocking and during subsequent feedings. Larvae are stocked across all treatment rows in a continuous back-and-forth pattern to eliminate possible variability due to the time when a cone, or an entire treatment was stocked.

11.3.3 Daily Maintenance

Daily maintenance involves assembling materials, rinsing soaked glass pipets, filtering and adding algae to the seawater medium, exchanging seawater medium in the cones, counting or estimating survival and rate of larval metamorphosis in each cone or in a randomly selected cone from each treatment, adding feeds to the cones, and preparing artificial seawater for use the following day. Water exchange is made at 24 hour intervals, taking care to avoid changing seawater during the active molt period. The seawater medium and food in each cone is replaced by first pouring the entire cone contents through a sieve which collects the larvae (Fig. 5a). Larvae are kept

Table 2. Survival and mean weight of larvae fed control (algae only) feeding regimes.

Species	Control Diet (cells/ml x 1000)	% Survival	Mean Dry Wt/PL (ug)	Age	Reference
<u>P. aztecus</u>	100 <u>Skeletonema costatum</u> +				
	40 <u>Tetraselmis fluviatilis</u>	93 $\pm$ 4	72 $\pm$ 0	PL1	1
	70 <u>Skeletonema costatum</u> +				
	70 <u>Chaetoceros gracile</u>	86 $\pm$ 14	72 $\pm$ 3 ^a	PL1	2
	100 <u>Isochrysis</u> sp. +				
	50 <u>Tetraselmis chuii</u>	55 $\pm$ 12	44	PL2	3
<u>P. semisulcatus</u>	100 <u>Chaetoceros gracile</u> +				
	40 <u>Tetraselmis chuii</u>	69 $\pm$ 13	105 $\pm$ 10	PL1	4
		74 $\pm$ 7	101 $\pm$ 10	PL1	4
		78 $\pm$ 5	97 $\pm$ 7	PL1	5
	200 <u>Chaetoceros gracile</u>	94 $\pm$ 10	76 $\pm$ 6	PL1	6
	500 <u>Isochrysis</u> sp.	93 $\pm$ 8	64 $\pm$ 6	PL1	6
<u>P. setiferus</u>	100 <u>Skeletonema costatum</u> +				
	40 <u>Chaetoceros gracile</u>	98 $\pm$ 1	72 $\pm$ 3	PL1	1
	70 <u>Skeletonema costatum</u> +				
	70 <u>Chaetoceros gracile</u>	92 $\pm$ 4	59 $\pm$ 7 ^b	PL1	2
<u>P. stylirostris</u>	100 <u>Skeletonema costatum</u> +				
	40 <u>Chaetoceros gracile</u>	99 $\pm$ 3	68 $\pm$ 0	PL1	1
	100 <u>Chaetoceros gracile</u> +				
	30 <u>Tetraselmis chuii</u>	91 $\pm$ 3	47 $\pm$ 3	PL1	7
		93 $\pm$ 6	73 $\pm$ 4	PL1	7
		82 $\pm$ 7	54 $\pm$ 6 ^c	PL1	8
<u>P. vannamei</u>	100 <u>Chaetoceros gracile</u> +				
	30 <u>Tetraselmis chuii</u>	74 $\pm$ 12	57 $\pm$ 5	PL1	9
		76 $\pm$ 2	50 $\pm$ 1	PL1	9
		72 $\pm$ 8	43 $\pm$ 7	PL1	9
		85 $\pm$ 7	46 $\pm$ 2	PL1	9

continuously submerged by holding the sieve in a petri dish during the exchange procedure. Sieve mesh sizes are 102 micron for nauplii and protozoa-one, 202 micron for protozoa-two and three, 355 micron for mysis and 355-500 for postlarvae. The filtrate from the cone is collected in a small container, and is used to rinse the cone to retrieve any stranded larvae. The cone is then; refilled with approximately 700 ml of new seawater medium, the extension airline wiped clean, the glass pipet replaced, and the extension airline secured in place. At this point, larvae are examined under a binocular microscope for condition and dead animals, while excess food particles are

Table 2. continued

Species	Control Diet (cells/ml x 1000)	% Survival	Mean Dry Wt/PL (ug)	Age	Reference
<u>P. vannamei</u>	100 <u>Chaetoceros gracile</u> + 30 <u>Tetraselmis chuii</u>	68 $\pm$ 12	64 $\pm$ 10	PL1	9
		84 $\pm$ 6	51 $\pm$ 3	PL1	10
		82 $\pm$ 8	51 $\pm$ 7	PL1	10
		90 $\pm$ 4	51 $\pm$ 4	PL1	7
		73 $\pm$ 8	51 $\pm$ 3	PL1	7
		84 $\pm$ 6	57 $\pm$ 5	PL1	7
		84 $\pm$ 6	45 $\pm$ 2	PL1	11,12
		76 $\pm$ 16	50 $\pm$ 6 ^d	PL1	8
		32 $\pm$ 10	45 $\pm$ 13	PL5	12
		29 $\pm$ 12	29 $\pm$ 7	PL5	12
		83 $\pm$ 8	36 $\pm$ 3	PL5	11
		37 $\pm$ 17	31 $\pm$ 7	PL5	11
		38 $\pm$ 11	34 $\pm$ 7	PL5	11

^a Mean weight per larva; 91 $\pm$ 4% PL at termination.

^b Mean weight per larva; 90 $\pm$ 4% PL at termination.

^c Mean weight per larva; 94 $\pm$ 5% PL at termination.

^d Mean weight per larva; 90 $\pm$ 12% PL at termination.

References: 1, Kuban et al. 1985; 2, Wilkenfeld et al. 1984; 3, Kuban et al. 1983; 4, Samocha 1983; 5, Samocha 1985; 6, Samocha 1984; 7, Smith and Lawrence 1987; 8, Thomsen et al. 1987; 9, Biedenbach et al. 1989; 10, Biedenbach et al. 1990; 11, Smith and Lawrence 1988a; 12, Smith and Lawrence 1988b.

removed. The remaining 300 ml of new seawater medium is used to backwash the larvae from the collecting sieve into the cone (Fig. 5b). Before disposal, the collected filtrate is examined macroscopically for larvae which may have overflowed the sieve due to sloppy pouring technique, or escaped through unnoticed tears in the mesh.

11.3.4 Feeding

Experimental objectives will determine the most suitable feeding regime. For example, the control regime recommended for non-dietary experiments with Penaeus vannamei consists of live algae (100,000 cells/ml Chaetoceros gracile Schutt, clonal designation WTAX1; and 30,000 cells/ml Tetraselmis chuii Butcher, clonal designation UW474), fed from nauplius-five through postlarva and freshly hatched instar-I Artemia (1.5/ml during P-3, 3.0/ml during M-1, 4.0/ml during M-2, 5.5/ml during M-3, 7.5/ml during M-3/PL transition, 10.0/ml during PL-1, 14.0/ml during PL-2, 22.0/ml during PL-3, and 32.0/ml during PL-4). Artemia feeding levels for P. stylirostris can be based on Thomsen et al. (1987). Both algae and Artemia are added in single

feedings per day. In dietary experiments, such as those which examine Artemia replacements or use dry feeds to study basic nutritional concepts, the objective of the study will determine whether or not a basal algal regime is fed during the mysis and PL substages, since the presence of algae can mask or enhance the nutritional contribution of the experimental feed. An additional control, consisting of only algae, is used in dietary experiments to interpret whether or not the Artemia replacement diet actually enhances larval growth.

To eliminate density fluctuations among cones within a treatment, live algae is added to the filtered batch seawater medium, rather than to individual cones. Hemacytometer counts of the batch medium confirm final density. Warming the algae to the temperature of the seawater before addition eliminates temperature fluctuations.

The first aliquot of dry feed or live animal food is added directly to the cone immediately after the seawater exchange, taking care with live animal feeds not to change the final volume upon addition.

11.3.5 Termination of Trials and Data Collection

The experiment is terminated when at least 90% of the larvae in any single treatment metamorphose into the desired final stage. Metamorphic rates of all other treatments are compared relative to this one. The usual termination stage is the first postlarva (PL-1). In some studies, however, such as those which examine replacements for Artemia, the trial may continue into the early postlarval stages. Postlarvae can be successfully held at a density of 100/l until the PL-5 stage without loss due to jumping. For longer trials, we recommend that densities be reduced to 25-50/l.

Cones are terminated in the same pattern in which they were stocked. Cone contents are poured onto a sieve and the cone is rinsed with up to 1,000 ml of filtered seawater until all larvae are removed. Sieve contents are transferred to a labeled petri dish (25 mm x 100 mm), using filtered seawater from a squeeze bottle, and filled to half volume. Petri dishes are transferred to a freezer and the larvae are chilled until immobilized, but not dead. Petri dishes are then transferred to a refrigerator where they can remain for several hours. Larvae in each petri dish are counted and staged for metamorphosis. Postlarvae are removed from the petri dish, counted, and concentrated in a 30 ml beaker. Postlarvae are then poured onto a screen, rinsed with deionized water and lumped onto a drying screen or into small receptacle suitable for drying. Larvae can either be oven-dried at 60 C or freeze-dried; the latter is preferred if tissues are to be analyzed for biochemical composition. Dried postlarvae are group weighed, and individual weight, reported in micrograms, is determined based on the total number weighed.

After termination, extension airlines are disposed and the entire table top, including feeder airlines, is rinsed. Chlorine is added to the water bath for sterilization and water volume adjusted, if necessary. Cones and plugs are soaked in a detergent to facilitate later scrubbing. Extended soaking in chlorine should be avoided as the plastic material will become brittle over time. Glass pipets with broken tips are disposed, and the remainder are soaked in acid.

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CHAPTER 12

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PENAEID PL HARVEST, TRANSPORT, ACCLIMATION AND STOCKING

12.1 INTRODUCTION

Postlarval (PL) harvest at the hatchery, transport from the hatchery to the farm, acclimation and pond stocking are important aspects of marine shrimp culture requiring careful planning and attention to detail. The overriding concern during these operations is to avoid stress which could cause mortality or otherwise compromise PL survival. Failure to maintain optimum conditions during each step can result in low survival and low crop yield. Appropriate techniques will contribute to high survival, good crop inventory control, and optimal profitability for a given culture system.

There is a scarcity of documented information on penaeid PL harvest, transportation, and acclimation. At the same time, however, shrimp culturists possess a wealth of information concerning successful techniques established through experience. Some of these empirical approaches have proven to be highly reliable and efficient. In this chapter, we will review some of the more reliable techniques and present some previously unpublished data from experimental trials.

12.2 PL HARVEST AT THE HATCHERY

12.2.1 PL Quality

PL quality is crucial to growout success. Good quality PLs will easily withstand the rigors of harvest and transport, and readily adapt to a wide range of pond conditions.

PL quality assessment requires knowledge of culture conditions during the larval cycle, and microscopic examination of the PLs. Inadequate nutrition, or exposure to extreme salinity or temperature during larviculture can easily compromise PL hardiness and their ability to withstand the transition from hatchery to pond. The consequences of such stresses are not always apparent through microscopic examination, but can be manifested by subsequent mortality due to reduced resistance to pond conditions. Therefore, strict adherence to optimal larviculture practices is an important requirement for production of high quality PL.

Table 1. Good quality 1 to 20 day old PL *Penaeus vannamei* and *P. monodon* will tolerate an abrupt reduction from 30 ‰ with less than 15% mortality if the salinity reduction is less than the value listed in this table. (Data from Olin in prep.)

<i>Penaeus vannamei</i>	<i>Penaeus monodon</i>
PL1 --- 15 ‰	PL1 --- 10 ‰
PL5 --- 15 ‰	PL5 --- 15 ‰
PL10 -- 25 ‰	PL10 -- 15 ‰
PL20 -- >25 ‰	PL20 -- 20 ‰

Visual assessment of PL quality includes observation of their activity, size, coloration, and swimming behavior. PL are generally planktonic for 5 to 7 days following metamorphosis (PL5 to PL7). During this time they should swim actively using their pleopods with occasional abrupt movements from vigorous tail flicks. Erratic behavior such as irregular, zig-zag or spiraling swimming are abnormal and may indicate physical deformities or other problems. PL should not be lethargic nor should they appear to bounce off the bottom of an observation container. PL become benthic at about PL5-7, orienting to the bottom and walls of rearing tanks. Their behavior should be similar to earlier stages described above although general orientation is towards tank surfaces rather than the water column. Under microscopic examination, PL should appear slightly translucent without an opaque, cloudy or whitish appearance. Abdominal musculature should fill the area between the intestine and ventral body surface, particularly in the last abdominal segment. Muscle should be translucent, and not have an opaque, grainy or striated appearance. Chromatophores should be well defined and localized along the mid-ventral axis. The hepatopancrease and anterior gut should be full and well developed. All appendages should be intact and without gross deformities or bent setae. Protozoans and long filamentous bacteria are absent from the exoskeleton of healthy PL. Setae and gill chambers should be clear of debris or bacteria. If PL do not possess these qualities, efforts should be made to improve larviculture practices.

PL quality can be further assessed using various stress tests. These tests evaluate PL survival when challenged with abrupt changes in temperature, salinity, or a combination of both. Table 1 illustrates the maximum salinity change that good quality PL should be able to withstand without compromising survival (Olin, in prep.). These data agree with those of Charmantier (1988) who documented increased salinity tolerance for 10 days following PL metamorphosis. This tolerance continued to increase at a slower rate for an additional 10 days. Although stress tests can provide information on PL condition, they are not often used. Instead, most commercial hatcheries

rely on visual inspections, as described above, and on larval performance to evaluate PL quality.

12.2.2 Harvest Equipment

Harvest equipment are those used to concentrate PL into a smaller container, sample and compute population estimates, and to maintain good water quality. The overriding priority during these operations is to avoid stressful conditions and unnecessary handling which might injure PL.

One commonly used harvest chamber consists of a fine mesh capture bag suspended in a tank of water such that the PL are captured in the bag during drain harvest of the culture tank. Drain water flows through the capture bag and overflows the container, thus preventing a crush of PL against the mesh as might occur if the container had only small screened openings. Total PL weight is obtained by simply lifting the capture bag from the container and attaching it to a spring scale, or by immersing the bag in a previously weighed container of water placed on a scale.

Another harvesting device uses two containers. The inner harvest chamber retains PL, with screen covered ports to allow outward passage of water and prevent overflow (Fig.1). The larger outside container provides a water bath for the inner harvest chamber. The outside chamber has an external standpipe to maintain a water level above the screened ports and below the top of the inner harvesting chamber. This system prevents PL from being forcefully pressed against the outflow screen. Screened ports should have the largest mesh size which will retain PL, but allow debris or small organisms to pass. Nitex, or similar screen of 500 μm mesh is adequate for most PL, although larger mesh should be used for late PL and juveniles. Harvest chambers should be sized such that maximum density does not exceed about 2,000 PL/l.

Prior to draining the culture tank its water volume must be reduced using a screened siphon. This is done to facilitate harvest and reduce stress during harvest. Screened siphons are generally of two types. One type consists of a length of PVC pipe with numerous screen covered holes. One end is closed while the other is fitted with a nipple for attachment to a siphon hose. Another type of siphon, sometimes called a "banjo", consists of a 4 to 6 cm wide section of 15 to 20 cm dia. PVC pipe with screen mesh attached. A siphon hose is attached to a nipple drilled and tapped into the pipe. As an alternate, if the larval rearing tank is fitted with a standpipe, the standpipe can be replaced with another which has mesh covered holes similar to the first siphon described above. The screen surface area must be large enough so that water flow does not impinge PL nor clog the screen. After most of the water has been removed from the larval rearing tank, the remainder is drained into the harvesting chamber.



Figure 1. PL harvesting device.

A device to efficiently mix the harvest chamber is necessary for accurate population estimates. Small harvest chambers can be mixed well using hands in a circular motion, upwelling, and randomly mixing the water. Larger chambers require a slotted paddle. These can be easily fabricated from a longitudinal section of PVC pipe with numerous holes or slits in the paddle end (Fig. 2).

PL sampling is done using small cups, beakers, or a device such as a Hensen-Stemple pipette (Hardin et al. 1985). Sample water volume must be accurately measured in a graduated cylinder, and PL subsequently counted. Counting chambers can be made from a 40 cm length of 4.4 cm dia. PVC pipe with end caps cemented to each end (Fig. 2). These closed tubes are then cut in half longitudinally to form two open troughs in which PL subsamples are rapidly counted from one end of the trough to another.

It is important to maintain saturated dissolved oxygen (DO) concentrations in the harvest chamber. This requires a compressed oxygen cylinder, airstones, and airline tubing. Silica bead airstones are recommended because of their durability and smaller bubbles which transfer oxygen efficiently.

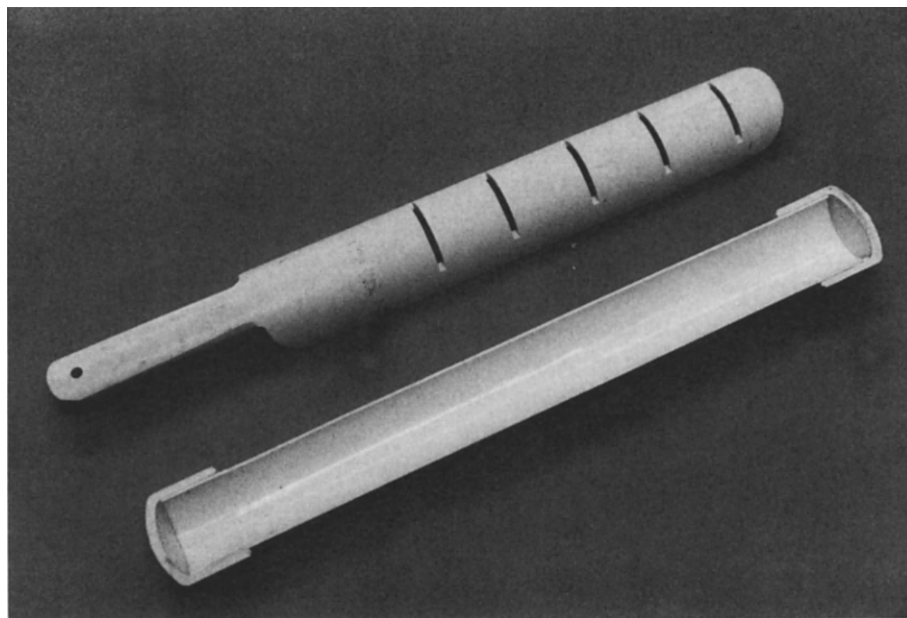


Figure 2. A slotted paddle used to mix PL harvest chambers and a PL counting chamber.

12.2.3 Harvesting Techniques

One of the most important considerations in harvesting PL is maintenance of good water quality. Harvest chambers should be aerated at all times. A slow trickle of oxygen is recommended to insure that DO levels remain at or above saturation. Harvests should be scheduled to minimize transport and acclimation time. Harvest times will vary based on distances and modes of transport, but are typically in early morning or late afternoon to avoid elevated temperatures during mid-day, both at the hatchery and pond site.

In preparation for harvest, the larval rearing tank should be well flushed with clean water and partially drained as described above. The remaining water and PL are then drained into a harvest chamber via flexible tubing or fixed PVC pipe. If the larval tank bottom is too flat for efficient draining, PL can be moved towards the drain using low pressure water from a hose, or using a plastic watering can. Clean seawater of similar pH, salinity and temperature should be used to flush the harvest chamber thoroughly after harvest.

12.2.4 PL Population Estimates

A variety of techniques are used to estimate PL population size. The best technique for a particular location is that which is accomplished quickly and accurately using readily available equipment. There are two basic techniques used commercially which rely on either visual estimation (Apud et al. 1983) or on volumetric sampling (Mock and Murphy 1970; Hardin et al. 1985; Wen-Young Tseng 1987). For older PL and juveniles, or when small numbers of shrimp are present, hand counting is often most convenient and accurate (Apud et al. 1983).

The visual inspection technique involves hand counting approximately 5,000 PL and placing them in a white plastic basin. Other basins with the same water volume are placed around this reference basin and PL are added to each until the density appears equal.

Volumetric sampling is used in many commercial facilities. This technique uses small containers (0.1 to 1.0-l) to take replicate samples from a thoroughly mixed harvest chamber. Water volume and PL number are measured for each sample and the density is calculated. PL densities (#/ml), multiplied by harvest chamber volume provide replicate population estimates. With three replicate samples, properly done, the population estimate is typically within $\pm 10\%$ of the actual number. Correct technique requires a thoroughly mixed harvest chamber, rapid scooping of the sample from the chamber, and adequate sample size. A rule of thumb is that each sample be large enough to contain 100 to 200 PL. During sampling, the containers should be quickly scooped at the water surface and not submerged, or filled and pushed through the water. A full or submerged container pushed through the water generates a pressure wave which causes PL avoidance.

Water temperature and PL age or size effect sampling accuracy (Hardin et al. 1985). Hardin and co-workers evaluated volumetric count estimates using 4, 6 and 10 mm P. stylirostris PL at 18, 22, 26 and 30 C. They found significant underestimation of PL population sizes when sampling from 500 ml of water using a 10 ml Hensen-Stempel pipette, with all but the smallest PL. Accuracy increased with decreasing temperature and/or size. Densities were underestimated from 16 to 18% with 6 and 10 mm PL at 18 C, and up to 43% with 10 mm PL at 30 C. They recommended using an experimentally derived correction factor to compute corrected population estimates.

The effects of water temperature and PL size on population estimates for other penaeid species have not been reported, but would be expected to effect estimates. Olin (unpublished data) using PL5 P. vannamei in larger harvest chambers at 28 C obtained estimates within 10% of the actual value, which indicates that sampling methods and species are also important factors effecting accuracy.

While PL chilling can increase accuracy, it also induces stress and is inconvenient. If PL will be chilled prior to shipping however, it is advisable to perform volumetric sampling after chilling.

12.3 PL TRANSPORT TO FARMS

12.3.1 General Considerations

During PL transport from hatchery to growout locations, shipping time should be minimized to reduce stress. High PL density in sealed containers promotes cannibalism. Metabolic wastes such as carbon dioxide and ammonia can reach potentially lethal concentrations. For these reasons, every attempt should be made to rapidly transport PL, use appropriate packaging materials, and employ sound shipping techniques.

There are a number of publications concerning packaging and transport of penaeid PL (Imai 1971; Terazaki et al. 1974; Hamid and Mardjono 1979; Apud et al. 1983; Smith and Ribelin 1984; Tenedero and Villaluz 1985; Maugle 1987; Tseng 1987). These describe several successful techniques, and collectively emphasize the need to maintain appropriate PL density, water quality and shipping conditions to insure high PL survival. Shrimp transport techniques are well founded on extensive earlier experience with fish (see review by Berka 1986). In this section, we will present strategies described in these publications, along with some unpublished techniques used by commercial hatcheries. In all cases, the objective is delivery of healthy PL at pond side for acclimation and stocking.

PL may be shipped in open containers or in sealed plastic bags. The former are most commonly used for short distance transport where a truck can easily be driven from the hatchery to the pond site, and where less sophisticated methods are generally used. Plastic bag transport greatly reduces shipping weight and facilitates acclimation and handling. In this section we will concentrate our discussions on PL transport from the hatchery to the farm in plastic bags. Much of the discussion on transport conditions also applies to transport in open containers and transport from ocean collection sites to farms.

12.3.2 Water Quality

PL metabolism results in dissolved oxygen (DO) consumption, and release of carbon dioxide (CO₂) and ammonia (NH₃). The CO₂ and NH₃ can adversely effect crustacean health with effects ranging from minor irritation to sublethal or acute toxicity (Pope et al. 1981). Carbon dioxide also lowers water pH, which reduces ammonia toxicity. It is important to maintain high DO and reduce build up of NH₃. Additional considerations for penaeid PL

transport include bacterial proliferation, cannibalism, temperature, salinity, and suspended solids.

Ammonia exists in water as either un-ionized (NH_3) or ionized (NH_4^+) forms. The un-ionized form is far more toxic and exists in greater proportion at higher pH (Meade 1985). Ammonia toxicity is inversely related to DO levels (Thurston et al. 1981) and is influenced by temperature, although to a much lesser degree than pH (Colt and Tchobanoglous 1976). Steps should be taken to reduce ammonia production and toxicity during PL transport.

Control of ammonia production is more thoroughly studied in fish than shrimp, and for fish includes fasting (withholding feed), use of anesthetics, and temperature reduction (Amend et al. 1982). While fasting works well with fish it is not recommended with penaeid PL since it increases the risk of cannibalism. Unlike with fish, provision of feed during shipment may even increase PL survival. Maugle (1987) reported increased PL survival in Ecuador when Artemia nauplii were added to PL transport water at 2 to 5 nauplii/ml. Anesthetics are not commonly used in shrimp transport, and their use are not recommended (Johnson 1974). Temperature reduction, on the other hand is widely used with success. Temperature reduction lowers PL metabolic rates, thereby reducing DO consumption, and production of NH_3 and CO_2 . Lowered temperatures also reduce cannibalism.

Once produced, ammonia toxicity can be reduced by lowering water pH such that the relatively non-toxic ionized ammonia form predominates. In sealed containers, respiratory CO_2 production reduces water pH. Carbon dioxide release at the gill/water interface may also cause localized pH reduction at the gill surfaces, further ameliorating ammonia toxicity to sensitive gill tissue (Meade 1985).

While water pH can be stabilized within a narrow range by using buffers during transport, this does not appear advantageous and is not recommended. Robertson et al. (1987) found that penaeid broodstock treated with Trisma 8.3 buffer at 0, 4, 8 and 12 g/l had survivals of 100, 92, 25 and 25% respectively. Water pH was 6.1 in the control (0 g/l buffer), compared with 8.0 in the treated groups. Decreased broodstock survival in the treated groups may have been due to buffer toxicity and/or increased ammonia toxicity at the higher pH. In any event, buffer use is not recommended during shrimp transport. Short-term exposures (24 to 30 hrs) of shrimp PL and broodstock to lowered pH or elevated CO_2 does not appear to seriously effect survival under most conditions (Kim Page, pers. commun.).

Nitrifying bacteria in "biofilters" can effectively oxidize toxic ammonia to non-toxic nitrate. Biofilter use during PL transport has been limited due to the need for large substrate surface areas with established Nitrosomonas and Nitrobacter bacteria populations. Addition of substrate with nitrifying bacteria effectively reduced ammonia concentrations by 90 to 95% during

transportation of marine fishes (Turner and Bower 1981). Bacteria biofilters have potential application for shrimp PL transport, but further research and development is needed.

Phytoplankton addition to PL transport water can effectively reduce total ammonia concentrations, while consuming CO₂. The diatoms *Chaetoceros* and *Isochrysis* have been used successfully at about 100 cells/ml, depending on PL density and type of diatom (Maugle 1987). Higher phytoplankton densities may give even better results, although caution is advised. Possible negative effects of algal additions include; higher water pH values with a resultant increase in toxic unionized ammonia, increased oxygen consumption due to algal respiration, and a complex of potential problems if the algae become moribund and/or lyse. Addition of excess algal nutrients should also be avoided because of their potentially toxic effects.

In summary, ammonia toxicity during PL shipment can be mitigated by decreased water temperature, short shipping time, and phytoplankton addition to transport water. These procedures cause minimal PL stress while reducing ammonia excretion, concentration and toxicity.

Adequate DO is perhaps the most important water quality parameter during PL transport. Reduced oxygen consumption and pure O₂ use in shipping containers is essential for good PL survival and health. Many publications describe shipping trials using pure oxygen (Imai 1971; Hamid and Mardjono 1979; Smith and Ribelin 1984; Maugle 1987); while other reports document general procedures (Apud et al. 1983; Chamberlain et al. 1985; Tenedero and Villaluz 1985; Tseng 1987). They recommend an oxygen gas to water volume ratio of 1:1 or greater, and indicate no adverse impact of oxygen supersaturation on PL or adult shrimp.

Temperature reduction is one of the most effective and economical methods for improved PL survival during transport. This causes a reduction in metabolic rate and oxygen consumption. In addition to improving water quality by reducing metabolism, cooler temperatures also reduce aggressive interactions. These interactions include cannibalism and appendage loss. Appendage loss and other injuries are prone to bacterial infection in pond environments. PL are less likely to molt in cooler water, which also improves survival.

Typically, PL shipping temperatures range from 18 to 20 C. The lower temperature is recommended for longer shipments, while 22 to 24 C is better for short duration transport. For shipments exceeding 24 hrs, temperatures as low as 14 to 15 C have been used, although caution is recommended since PL become immobile, cramp and die at about 13.5 C. Acclimation to cool temperatures should be undertaken gradually, not greater than 1 C/15 min. While PL can survive abrupt temperature changes of 8 C or more, this is not recommended as it creates stress.

Other water quality parameters of concern include bacteria, suspended solids, dissolved organics and metals. Bacterial and suspended solids control is easily accomplished by thoroughly rinsing and shipping PL in clean, filtered seawater. While antibiotic use with fish transport is accepted practice (McCraven and Millard 1978), it is not necessary for penaeid transport if proper shipping techniques are used. Dissolved organics can be reduced by using clean seawater, and by placing activated charcoal in a screen bag at 1 g charcoal/l of shipping water. Transport water should be free of pesticides and excessive metal concentrations, although the use of EDTA may temper their adverse effects. EDTA has been successfully used at levels of 10 ‰ for PL and broodstock shipments from 24 to 30 hrs (Kim Page, pers. commun.). A final consideration is to avoid excessive levels of adult Artemia in penaeid PL transport water by reducing Artemia in the larval culture tanks prior to harvest. Adult Artemia can be eliminated through starvation by removing phytoplankton from larval culture tanks 3 to 5 days prior to PL harvest.

12.3.3 PL Shipping Density

PL shipping density is a function of temperature, PL age, PL size, shipping conditions and shipment duration. Many published reports document conditions used for different sized PL (Table 2). Density is also limited by water quality and aggressive interactions. Survival during transportation should exceed 90%, provided that PL health is good and appropriate procedures are used.

Shipping procedures reported by different authors are given in Table 2. Some of these data are approximations, and when a range of values is given, lower densities apply to larger, older PL and/or longer shipping times.

Penaeus vannamei are typically shipped as PL5 to PL10 or when total length from tip of rostrum to telson is 5 to 9 mm. Wet weights for this size PL are from 1 to 2 mg, while shipping densities range from 1,000 to 5,000 PL/l. The lower density is more appropriate for PL10 up to 30 hrs, while the higher density is recommended only for smaller PL5 to PL8 shrimp during transport of 2 hrs or less. In both cases, water should be chilled to 18 to 24 C, with the cooler temperatures for longer transport time.

Penaeus monodon are generally nursed to PL15 to PL20 at the hatchery site. These larger PL are then transported to farms at 250 to 2,500 PL/l. As with P. vannamei, the lower densities are for larger PL and long transport times, and so on. In Central Java, Indonesia, the Yayasan Dian-Desa hatchery found optimal shipping densities for PL18 to PL20 of 750/l over 2 hrs, and 500/liter for 6 hr shipments at 24 C (Edwin Sudjarwo, pers. commun.). This hatchery also ships nauplii at 50,000/l up to 8 hrs at 24 C. Cooler temperatures may allow even greater densities (Hamid and Mardjono 1979).

Table 2. Recommended or observed conditions for transport of penaeid postlarvae (PLs).

SPECIES	PL AGE (days)	DENSITY (PL/l)	WATER VOLUME (l)	ICE ³ (kg)	TIME (# hrs)	SURVIVAL (%)	TEMP (C)
<i>P. vannamei</i> ¹	5	1,500-3,000	10	0.5	30		24
<i>P. vannamei</i> ¹	10	1,000-1,500	10	0.5	30		24
<i>P. vannamei</i> ²	36	83-167	12		18		18
<i>P. vannamei</i>	6-8	2,000-4,000	14		2-5		22-24
<i>P. vannamei</i>	6	4,000-5,000	14			80	20-23
<i>P. vannamei</i>	6	2,100	14			94	20-23
<i>P. monodon</i>	15-20	600-800	6-8	0.5	6		20-24
<i>P. monodon</i>	30	250-650	6-8	0.5	6		20-24
<i>P. monodon</i>	15-20	1,250-2,500	6-8	0.5	6		20-24
<i>P. monodon</i>	10-20	250-588	17-20	2.0	10		24
<i>P. monodon</i>	10	500	10		24	95	24-28
<i>P. monodon</i>	10	600	10		20	95	16-18
<i>P. monodon</i>	10	500-2,000	5-10	0.5	6		20-24
<i>P. monodon</i>	18-20	750	10	yes	2		24
<i>P. monodon</i>	18-20	500	10	yes	5-6		24
<i>P. monodon</i>	30	200	10	yes	5-6		24
<i>P. monodon</i>	8	1,250	10	yes	12	88	24
<i>P. monodon</i>	15-18	833	6		4		28
<i>P. japonicus</i>		650	6-8		18	95	14-18
<i>P. japonicus</i>		584	6-8		18.5	95	12-19
<i>P. japonicus</i>		500-800	6		24		14-17
<i>P. merguensis</i>	20-25	200	5		8	95	28-29
<i>P. merguensis</i>	20-25	200	5		12	82	28-29
<i>P. merguensis</i>	20-25	400	5		8	91	28-29
<i>P. merguensis</i>	20-25	400	5		12	52	28-29
penaeid	PL	1,000	10	yes			18
penaeid	nauplii	10,000	10	yes			18
<i>P. monodon</i>	nauplii	50,000	12	yes	8		24
<i>P. monodon</i>	juvenile	50-400	5-10	0.5	6		20-24

1. EDTA used in transport water at 10 ppm.

2. Animals fasted for 24 hrs prior to transport.

3. Ice is placed outside transport bags.

Sources of information: Imai 1979; Hamid 1979; Apud 1983; Smith 1984; Treece 1985; Tenedero 1985; Maugle 1987; Tseng 1987; personal communications, Sudjarwo 1989, Wang 1989, Cantrell 1990, Page 1990.

Tseng (1987) reported use of malachite green (3 to 50 ppm) and methylene blue or furanace (50 ppm) as effective chemicals for *P. japonicus* transport. Caution is advised when chemically treating small water volumes as a high degree of accuracy is essential. Recommended doses for malachite

green are 5 ppb to 5 ppm, methylene blue 1 to 2 ppm, and furanace (prefuran) 0.5 to 10 mg/l (Lightner 1983; Brock 1988). One difference with P. japonicus transport is their tolerance of temperatures down to 10 C, while with P. monodon and P. vannamei 14 C should be viewed as minimum.

12.3.4 Packaging PL

As mentioned earlier, PL shrimp are typically transported in large (1 to 2 m³) live haul tanks mounted on trucks, or in small plastic bags. Temperature, DO, and PL density requirements are similar for both methods.

Live haul tanks should have a drain suitable for gravity flow when stocking PL into nursery or growout ponds. They should also have internal baffles to prevent violent water movement within the tank which can damage sensitive PL or even cause vehicle overturn. Tanks should contain an aeration and/or oxygenation system and they should be insulated to maintain desired water temperatures.

Polyethylene transport bag capacity typically ranges from 10 to 40-l, with dimensions of 50x50 cm (Tseng 1987); 50x40 cm (Imai 1971); 50x90 cm (Tenedero and Villaluz 1985); 40x40 cm (Hamid and Mardjono 1979; and 40.5x71 cm (Kim Page pers. commun.). Hamid and Mardjono (1979) found that use of smaller bags increased survival. During 12 hr shipments at 300 PL/l, survival was 88% in 1-l bags compared with 73% in 10-l bags. Chilled water in the larger bags increased survival to 97% with higher densities (6,000/l) and longer shipping time (20 hrs). They also found that bags larger than 10-l were more easily damaged.

Plastic bags should be positioned during transport to maximize bottom surface area. This minimizes dense concentrations of animals and increases water surface for gaseous exchange. High localized PL densities can increase cannibalism causing damage and reduced survival. Sharp corners should be rounded with securely bound rubber bands to prevent PL from becoming trapped. The plastic should have a minimum thickness of 5 to 6 mils (0.005 to 0.006 inch), and plasticizer concentrations should be at non-toxic levels. If bags are suspected to contain toxic compounds, soaking in flowing water for a few days is usually adequate to leach out toxicants.

In preparation for harvesting and packaging, all necessary equipment should be on hand, travel arrangements made, and advance preparations completed. PL should be packaged in double plastic bags, with one bag inserted into another prior to filling. Estimates of population size and shipping density will determine how many bags to prepare. Each bag should be aerated with an air stone, and contain 1 or 2-l of clean filtered seawater at the same temperature and salinity as the shipping water. This water prevents PL injury during transfer.

If shrimp are to be chilled prior to shipping, it is advisable to chill them in the harvesting chamber as this will reduce aggressive interactions while increasing accuracy of population estimates (Hardin et al. 1985). Freshwater ice added at an ice:water ratio of 1:100 will reduce water temperature about 1 C and salinity by 1%. If no salinity reduction is desired, brine ice can be used or freshwater ice can be placed in a separate plastic bag. After chilling, an appropriate water volume containing the desired number of PL is transferred to each bag. The bag is then filled with clean water to the desired volume, the airstone is removed, and excess air is deflated from the bag. An oxygen line is then placed in the bag well below the water surface and the top of the bag is clamped securely around the line. Oxygen is slowly bubbled into the water for 1 to 2 min until the bag is inflated. The bag top is then twisted, folded over on itself and securely fastened with a #73 rubber band (about 1x10 cm). Leave room to fasten the outer bag in the same manner.

The water:oxygen ratio should be between 1:1 and 1:2. Tseng (1987) reports an oxygen requirement of 4 to 5 cc/PL during a 24 hr shipment of P. japonicus at 14 to 17 C. This may represent the high end of oxygen requirements as many successful shipments are made with 1.5 cc O₂/PL. In any event, it is prudent to provide excess oxygen in case of unscheduled delays.

Plastic bags are typically carried in un-insulated "Pandan" woven bags (Tenedero and Villaluz 1985), or in cardboard boxes lined with styrofoam insulation 1.2 to 2.5 cm thick. Uninsulated transport containers are recommended only for short durations (<4 hrs). Ice or frozen gel packs can be used to maintain cool temperatures. Ice:water ratios range from 1:10 (Hamid and Mardjono 1979; Tseng 1987) to 1:30 (Tenedero and Villaluz 1985). The ice or gel packs should not contact water through the polyethylene bag as this may critically reduce water temperatures. Ice or gel packs should be insulated with newspaper, or contact only the oxygen filled portion of the bags.

12.3.5 Transport Modes

For best results, transport should be by airplane or in air conditioned vehicles during the morning or evening to avoid mid-day heat. Boxes and bags should be covered to prevent direct sunlight exposure. Ideally, an oxygen bottle should accompany shipments for re-oxygenation in case of unanticipated delays. Macrobrachium PL transport time has been successfully increased from 30 to 60 hrs by such re-oxygenation (Ludovic de Parseval, pers. commun.). With commercial air transportation, advanced reservations should be made and confirmed prior to packaging. Insure that the size, packing method and package weights are acceptable to the carrier. Make sure that all required export/import documents, and required health certification

are provided. It is advisable to verify that shipments are airborne following flight departure. Any indication of moisture or leaks is sufficient cause for an airline to refuse shipment, sometimes without immediate notification. Routing should be confirmed and the receiving party informed in order to alert cargo handlers at the destination. Provision of a shipping number will often allow recipients to check progress of the shipment, or to help locate missing packages.

12.4 ACCLIMATION

12.4.1 General Considerations

Acclimation is a complex process involving behavioral and physiological responses to changing environmental conditions. These reversible changes aid organisms' adjustment to fluctuating conditions such as temperature and salinity. In their natural environment and in hatcheries, shrimp experience a very stable environment as larvae and early PL. This ceases to be the case when shrimp migrate inshore to estuarine nursery areas, or are stocked into growout ponds. In their new environment, shrimp are exposed to a wide variety of fluctuating variables. A gradual transition into this new environment is important to insure maximum survival. Appropriate acclimation procedures will minimize PL stress during this transition.

12.4.2 Abiotic Factors

Normally, the two most important environmental variables PL must acclimate to during pond stocking are temperature and salinity. Pond temperatures undergo relatively predictable diurnal and seasonal cyclic fluctuations. Salinity may also follow a seasonal cycle with occasional changes due to heavy rainfall or droughts. Other parameters which can differ considerably from hatchery conditions include oxygen, pH, light, substrate and pollutants. All of these parameters are potentially stressful, and their individual or cumulative stressors may compromise survival. To minimize this possibility, potential stress should be reduced or eliminated when possible. While PL can tolerate a wide temperature range, absolute temperature, rate of change, and magnitude of change all influence shrimp behavior and physiology (Zein-Eldin and Aldrich 1965; Hughes 1969; Pantastico and Oliveros 1980).

PL P. aztecus have survived temperatures as low as 11 C, although their growth increased markedly with temperature, particularly between 17.5 and 25 C (Zein-Eldin and Aldrich 1966). There was decreased tolerance to low salinities below 15 C. Lethal minimum temperatures for the tropical species P. monodon and P. vannamei are about 13.5 C. Weisepape et al. (1972) report lethal maximum temperatures for P. aztecus PL in the range of 36 to

40 C, with increased upper lethal limit based on prior acclimation to warmer water.

Higher temperatures also cause increased oxygen consumption, although this increase is not significant in P. monodon (PL5 to PL28). Increased oxygen consumption at higher temperatures becomes significant by PL35-38 or older (Licop 1984).

Temperature extremes may compromise survival by reducing PL activity and increasing predation risks. Serious predation on P. japonicus PL by the gastropod Niotha livescens occurred at 35 C when PL activity was reduced while feeding behavior in the gastropod remained normal (Kurata 1981). It is therefore important to protect PL from rapid changes as well as extreme temperatures. Pond stocking should be timed to avoid these situations.

Salinity is another variable which strongly influences PL metabolism, physiology, behavior and distribution (Gunter et al. 1964; Hughes 1969; Lei et al. 1989). Although PL shrimp are remarkably euryhaline, during acclimation and stocking every attempt should be made to minimize exposure to salinity extremes, and to gradually introduce PL to different salinities.

Penaeid PL ability to survive direct transfer over a wide range of salinities is well documented (Venkataramiah 1974; Pantastico 1979; Mair 1980; Pantastico and Oliveros 1980). Shrimp can effectively use their antennal gland, gills, integument and digestive tract to maintain osmotic and ionic balance (Kamemoto 1976). Nevertheless, the consequences of transferring PL into salinity extremes are equivocal and not recommended. With P. monodon, Pantastico (1979) and Pantastico and Oliveros (1980) reported good survival and growth when PL were transferred into freshwater, while Cawthorne et al. (1983) observed 100% PL mortality within 4 hrs of freshwater transfer. Freshwater transfers and growout with P. vannamei are reported from commercial growers in Ecuador with good survival and growth (Nick Carpenter and Yuan Wang pers. comm. 1989).

Age significantly influences the acclimation capabilities of PL penaeids. Ontogeny of osmoregulatory capabilities with larval and PL P. japonicus was recently described by Charmantier et al. (1988). They found decreasing osmoregulatory capability from nauplii through metamorphosis to PL. Osmoregulatory ability then increased rapidly for the next 10 days and more slowly the following 10 days. These results agree with unpublished data from our lab, where we found increasing salinity tolerance up to PL20 for P. monodon and to PL15 for P. vannamei (Fig. 3). If salinity tolerance is a general indicator of PL hardiness, this may explain the common practice of stocking P. monodon at PL18 to PL20 (about 12 mm length), while P. vannamei are commonly stocked at PL7 to PL10 (7 to 9 mm).

In production ponds, DO should always be maintained at levels above 2 mg/l, and above 4 mg/l for any extended period. While 2 mg/l DO will not

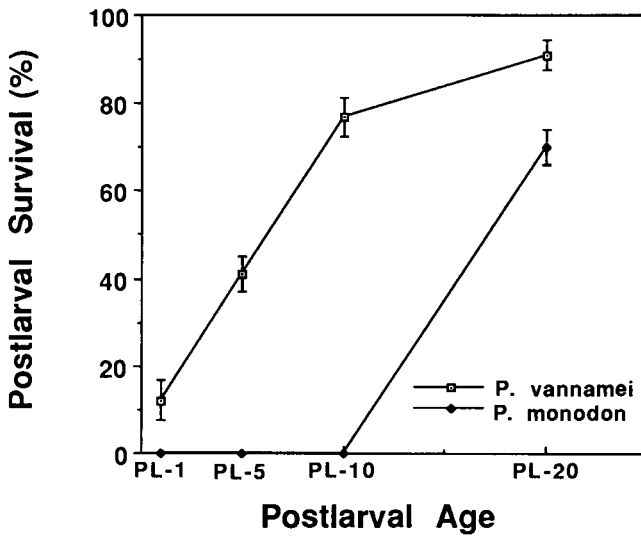


Figure 3. Changes in PL survival during salinity acclimation as PL age increases for *P. vannamei* and *P. monodon*. Data represent cumulative survival of PL exposed to abrupt salinity of 5, 10, 15, 20, 25 and 30 ppt.

cause immediate mortality, it can cause chronic stress which will predispose shrimp PL to disease and reduce growth.

Other factors influencing PL include pH, light and pollutants. Production pond pH should remain above 7.0 to avoid alteration in the cuticular mineral composition, which could adversely impact growth and molting. Light intensity alone does not seem to have much impact on PL survival, but high light intensity during mid-day is associated with high temperature and pH. For this reason, early morning or evening stocking times are recommended. Ponds should be free of any organic or inorganic pollutants which may compromise survival. Pond preparation is important to insure a healthy, dynamic plankton community. It will also help avoid reduced organic materials and toxicants at the sediment/water interface; a preferred habitat of the shrimp.

12.4.3 Biotic Factors

Biotic factors influencing PL acclimation and survival are disease, physical deformities, predation and diet. Suffice it to say that PL should be free of disease and deformities associated with cannibalism or molting difficulties prior to acclimation and stocking. If there is uncertainty about PL quality, they should be further cultured in tanks or held in nursery ponds before

release in growout ponds. Incoming water should also be screened to prevent entry of predators into the pond.

PL experience an almost complete diet change when moved from the hatchery and stocked in ponds, with little or no apparent adverse effect. This abrupt transition is generally avoided with most cultured species, but low PL biomass and their omnivorous nature apparently allows them to easily adapt to pond environments.

12.4.4 Acclimation Techniques

The principle objective during penaeid PL stocking into nursery or growout ponds is to acclimate them as quickly as possible to new conditions without compromising survival. Acclimation can be done either at the hatchery or pond site. Ideally, PL should be gradually acclimated at the hatchery beginning with PL1 by slowly adjusting salinity to that of the ponds by the time the PL are ready to harvest and transport. This allows for a gradual rate of change. Alternately, PL can be acclimated at the pond site, if a hatchery is without freshwater, unaware of pond salinities, or is shipping PL to a number of sites with a wide range of salinities. Acclimation guidelines were developed in Ecuador and Panama for P. vannamei, which serve as good guidelines for all penaeid species (Table 3).

Different authors propose a variety of procedures for PL acclimation and stocking. Apud et al. (1983) recommend stocking in the evening or when the sky is cloudy and pond temperatures are below 26 C. They suggested floating bags in the pond for 30 min to equalize temperature, and then release the PL if the salinity is within 5 ‰. If salinity differences are >5 ‰, they recommended slowly adding pond water to the bags until the water volume is 2 to 4 times the original. In Indonesia, farmers typically allow 2 to 3 hrs for acclimation with a salinity difference of 2 to 8 ‰ (Edwin Sudjarwo, pers. commun.). Other farmers suggest changing the salinity 1 ‰ every 30 min but not more than 1 ‰ every 15 min.

Freshwater acclimation requires considerably more attention to detail than with the 5 to 15 ‰ difference normally encountered between hatchery and farm. Pantastico and Oliveros (1980) achieved greater than 90% survival when acclimating PL20, PL35 and PL90 P. monodon to 6 ‰ salinity from 16 ‰ over 15 hrs. These PL had survivals of 60, 80 and 27% respectively when acclimated from 16 ‰ to freshwater over 24 hrs. Acclimation to freshwater over three days resulted in survivals of 72, 88 and 52% respectively. In contrast, Cawthorne et al. (1983) found 100% mortality with P. monodon PL within 4 hrs exposure to freshwater. There was no mortality when <PL40 were acclimated to 1.7 ‰ from 30 ‰ over 6 hrs. Older PL, from PL10 to PL55 required an acclimation period of 24 hrs to assure <10% mortality when acclimated to 1.7 ‰.

Table 3. Recommended temperature and salinity acclimation times for penaeid postlarvae (Maugle 1987).

Water Temperature Differences (C)	Acclimation Time (min.)	Water Salinity Differences (‰)
14	140	7
12	120	6
10	100	5
6	60	3
4	40	2
2	20	1
0	4-6	0

Acclimation procedures for *P. vannamei* destined for freshwater ponds in Ecuador are as follows (Yuan Wang, pers. commun.). One m³ acclimation tanks at the farm site are used to hold PL during acclimation. These tanks are filled with water similar to that at the hatchery. Caution is advised against the use of rock salt to raise salinity as this can result in 100% mortality of PL. PL are stocked into the tanks and water from freshwater ponds is pumped into the tanks at a rate that will drop salinity from 30 to 20 ‰ over 5 to 8 hrs. Reduction from 20 to 10 ‰ should occur over 10 to 15 hrs, while the final decrease from 10 ‰ to freshwater should take 24 hrs. Total acclimation time thus ranges from 39 to 47 hrs. Survival up to 90% is reported using this technique, with good growth and survival during subsequent growout.

It is essential to quantify pond stocking success. Survival bucket use allows for computation of survival 24 and 48 hrs after stocking, or at some other desired time. These buckets are easily fabricated from 20-l plastic pails with foam flotation collars to keep the top of the buckets 10 or 20 cm above water. Openings 8 to 10 cm square are cut in the bucket walls below the water line and covered with 500 µm screen which allows water and food organisms to flow through the bucket. These buckets are typically stocked with 100 PL at the same time the pond is stocked. The PL are typically counted 1 and 2 days after stocking to determine initial survival. If there was substantial mortality, the cause should be determined and corrected, and additional PL should be stocked in the pond to replace mortalities.

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CHAPTER 13 **Leslie N. Sturmer, Tzachi M. Samocha
and Addison L. Lawrence**

**INTENSIFICATION OF PENAEID
NURSERY SYSTEMS**

13.1 INTRODUCTION

The present technology for pond production of shrimp is adequate for commercial operation in areas having a year-round growing season. Improved technology for the growout phase could be beneficial, as most of the capital and production costs are associated with cultivation of marketable shrimp from postlarvae. This is particularly true in temperate regions where multiple crops per year are difficult using presently available technology.

Incorporation of a nursery phase into the production cycle is a significant management strategy and has been implemented by many progressive shrimp farmers. Six percent of the shrimp farmers in Ecuador produce 20% of the crop using this two phase pond system (Hirono 1983). Two phase growout is standard technology for semi-intensive and intensive shrimp farming in the United States (Lawrence and Huner 1985, Lawrence et al. 1985) and the world (Lawrence 1985, New and Rabanal 1985). Although research efforts have evaluated the use of three phase systems which include an intermediate phase (Parker et al. 1974), the two phase system prevails. Handling and harvesting of larger shrimp from the intermediate phase in the former system can be stressful, whereas transfer of juveniles (0.5-1.5 g) from nursery systems can be accomplished with minimal losses. Additionally, three phase systems require greater organization and management, as shrimp are stocked at higher densities to maximize the carrying capacity of the system (Duenas et al. 1983).

Advantages of nursery rearing have been acknowledged for crustacean aquaculture and include increased control, efficiency, predictability and profit in both phases of production (Hirono 1983, Pretto 1983, Aquacop 1985a). Aquacop (1985b) cited the need for a nursery phase between the hatchery and final production pond to provide a better assessment of stocked shrimp. Stocking juvenile shrimp, as opposed to direct stocking of PL, enables managers to more accurately predict survival, standing crop, feeding rates and production levels in growout ponds. Nursery systems with water conditions similar to the hatchery eliminate predators, provide greater water quality control, and increase feeding efficiency during critical initial life stages (Pretto

1983). This allows for larger and hardier shrimp at stocking into the growout pond. Use of nursery ponds reduces culture time in the growout ponds and increases production by increasing the number of crops per year (Clifford 1985). Additionally, juvenile shrimp can be maintained in small, earthen nursery ponds at very high densities for up to six months (Duenas et al. 1983); thus serving as seed-holding areas to protect against PL shortages.

In spite of the acknowledged importance of nurseries, little information is available concerning the production of juvenile shrimp in nursery ponds. A summary of nursery pond management practices and production results compiled from selected references reflects this paucity of information (Table 1). Further, little work has been initiated on the intensification of nursery techniques in small earthen ponds. The general procedure is to rear 5 to 10-day old PL in ponds of 0.1-1.0 hectare at densities of 50 to 200/m² for 30 to 60 days. An average survival of 70 to 80% is obtained, producing 0.5 to 1.0 g juveniles (Escobar 1985). Research efforts were initiated in 1986 by the Texas A&M University (TAMU) Shrimp Mariculture Project, to support development of nursery systems for Penaeus vannamei PL. Objectives included evaluation of stocking densities and improving pond management practices. These studies will be reviewed and related to present nursery pond technology.

13.2 INTENSIFICATION OF NURSERY PONDS

13.2.1 Pond Management Practices

Nursery pond management includes a combination of fertilization and feeding regimes, water exchange, circulation and supplemental aeration. The first priority in preparing earthen ponds, however, is the quality or condition of the pond bottom prior to filling. Daniels and Stern (1990) evaluated several pond bottom treatments commonly used in Ecuador to reduce the organic matter content in the soil. At TAMU, pond bottoms are dried, and the upper 2-4 cm of substrate tilled to allow for further oxidation and mineralization. If ponds are not allowed to dry completely, puddles of standing water are treated with lime. Clifford (1985) described other chemical treatments (rotenone, saponin) for the removal of predators from remaining pools of water. Additionally, pond inlets at TAMU are screened with a series of two fine mesh (0.5 mm) filter bags or socks to eliminate predators from entering the pond during filling and water exchanges. The filters are checked daily to prevent clogging and tearing. Where gate structures are used for filling instead of pipes, screens of 0.75 mm are usually placed at the entrance to filter incoming water (Pretto 1983).

An optimal fertilization regime for nursery ponds combines inorganic fertilizers to stimulate phytoplankton or primary production, and organic

Table 1. Summary of selected references regarding nursery pond management practices and production variables.

Reference	Pond Size (ha)	Stock Rate (#/m ²)	Culture Period (days)	Feed (daily)	Fertilization (kg/ha)	Harvest Size (g)	Survival (%)
Parker et al. (1974) ¹	.05	200	32	2.2 kg	200, (45-0-0)	-	84
Apud et al. (1979) ²	.02-.05	150	25	20-100 %BW ⁴	500, (18-46-0)	-	55
Duenas et al. (1983) ¹	.98-1.91	150-200	30-45	14 kg/ha	none	.25-1	-
Pretto (1983) ¹	-	150-200	45-60	25 %BW	2000, (organic)	.50-1	-
Hirono (1983) ¹	.50-4.0	-	-	-	-	-	70
Aquacop (1984) ¹	.25-1.0	50-200	30-60	2-10 %BW	-	1-2	>60
TAMU unpublished ¹	.15	166	45	10 kg/ha	77,(urea) 1300, (organic)	1.6	-
Issar et al. (1987) ³	.035	28	38	20-10 %BW	-	3.5	>65
Seidman & Issar (1988) ³	.035	109-194	45-69	20-10 %BW	-	1.5-5.3	55-85

¹ Penaeus vannamei² P. monodon³ P. semisulcatus⁴ %BW = percent body weight

fertilizers to encourage growth of larger microorganisms or secondary production (Geiger 1983). Guidelines are presented in Chapter 22 for developing fertilization programs. Boyd (1979, 1989) cautioned that it would be unreasonable to assume that a single management strategy would be effective for all conditions. Ponds differ greatly in morphometry, hydrology, soil chemistry, and water quality, so their responses to a given program vary greatly.

At TAMU, ponds are filled slowly or "puddled" approximately 14 days prior to stocking PL. This period is generally sufficient to allow adequate primary and secondary production. At approximately 50% of total pond volume, an initial application of granular urea (46-0-0) and liquid phosphoric acid (0-54-0) is made at calculated levels of 3.0 mg/l-N and 1.0 mg/l-P₂O₅, respectively, based on total pond volume. This equates to an application rate of 50 kg/ha of urea and 15 kg/ha of phosphoric acid, with a nitrogen to phosphorus ratio of 6:1. Fertilization of saltwater ponds to increase algal abundance requires a fertilizer with relatively more nitrogen (Daniels et al. 1987). In addition, this and higher N:P ratios promote growth of diatoms, which are considered favorable in shrimp ponds (Wyban et al. 1988). Water is added to maintain chlorophyll *a* concentrations between 20 and 60 ug/l and Secchi disc visibility readings between 25-50 cm. Subsequent applications of inorganic fertilizer are made after phytoplankton abundance drops below 20 ug/l chlorophyll *a* or Secchi readings are greater than 50 cm. Fertilizer rates at one-half to one-fourth the initial rate are applied on an "as needed" basis. In addition, each TAMU nursery pond is fertilized during the course of filling with an organic source. Normally 450 kg/ha of cottonseed meal or 900 kg/ha of cow manure are used, depending upon availability. Other manures, e.g. poultry and swine, are used by some nursery pond managers, but at higher initial dosages (Pretto 1983). Disadvantages of organic fertilizers include low nutrient content and high oxygen demand (Boyd 1989).

Another management tool used at TAMU for regulating phytoplankton composition in ponds is the herbicide simazine, which is effective in selective control of blue-green algae. This is particularly important when water temperatures exceed 28 °C and mat-forming algae predominate. Benthic algal control in nursery pond systems was cited as a priority for research by Aquacop (1985a). Blooms of certain blue-green algae have been associated with a disease syndrome characterized by acute hemocytic enteritis in penaeid shrimp (Lightner et al. 1978). A preflooding application of 4 kg/ha simazine, sprayed as a solution on the pond bottom, promotes growth of favorable algal species. Tucker and Boyd (1978) cautioned, however, that due to the prolonged persistence of this algicide, a decrease in overall phytoplankton abundance may result, and pond preparation may require a longer time period. This was not observed at TAMU, possibly due to the age of the ponds. Instead, dense diatom blooms were achieved within 4-7 days of initial fertilization.

Information regarding feeding rates and nutritional requirements of juvenile shrimp, particularly *P. vannamei*, are limited and consists largely of "trial and error" results. Feeding rates used for juvenile shrimp have been estimated from expected growth, assumed feed conversion, and rates used for other species and ages of shrimp. No specific studies have been conducted

to determine optimum feeding rates for shrimp from PL to juveniles in a pond environment. Even studies concerning the nutritional requirements of juvenile shrimp are few, with only two published evaluations of protein requirements for *P. vannamei* (Colvin and Brand 1977, Dokken and Lawrence 1987).

The need to supplement natural forage promoted by fertilizers with a formulated feed ration is accepted for most nursery systems (Apud et al. 1979, Rubright et al. 1981, Aquacop 1984, Clifford 1985, Boyd 1989). At TAMU, a high protein diet is provided one week after stocking PL in nursery ponds. The feeding regime consists of using a fine crumble (0.6-1.0 mm) during the second week at rates of 50-80% of estimated shrimp biomass per day. During the third week, a medium-sized crumble (1.0-1.4 mm) is fed at half the previous rate. Feeding rates of 5-15% of estimated shrimp weight are applied during the remaining weeks. A large crumble (1.4-1.7 mm) is fed after the fourth week. The daily feed ration is divided into several feedings, and broadcast over the pond surface if water quality parameters are within acceptable limits. Feeding is discontinued whenever early morning dissolved oxygen falls below 2 mg/l or exceeds 100% saturation during late afternoon. Although this feeding protocol is similar to those reported by Pretto (1983) and Clifford (1985), the back-calculated feed rates used in the nursery pond studies at TAMU are higher. Higher stocking densities, resulting in larger shrimp standing crops, lead to a more rapid depletion of natural productivity in the ponds and increase dependence on supplemental feed.

Water exchange is initiated in the nursery ponds after the second week and is an important management practice in maintaining adequate water quality. Exchange rates vary from 5-20% of the total pond volume per day, according to phytoplankton densities and oxygen dynamics in the pond. The addition of new water into a pond also causes some circulation. Benefits of artificial circulation have been documented in prawn production ponds (Fast et al. 1983) and in fingerling fish rearing ponds (Geiger 1983), but have not been evaluated in shrimp nursery ponds. Continuous circulation is included in TAMU's intensive nursery pond management practices. Modified, 10-cm airlift pumps (40/ha), driven by blowers (10 hp/ha), provide pumping rates of 1-7 l/sec and pond turnover rates of 1-2 times per day. This reduces diurnal oxygen fluctuations and improves distribution of nutrients in the pond.

13.2.2 Stocking Density, Growth, and Survival

Densities of PL stocked into earthen nursery ponds range from 50 to 200 PL/m² of bottom area, as reported in the literature (Table 1). Sturmer and Lawrence (1987a) evaluated three stocking densities and two nursery rearing

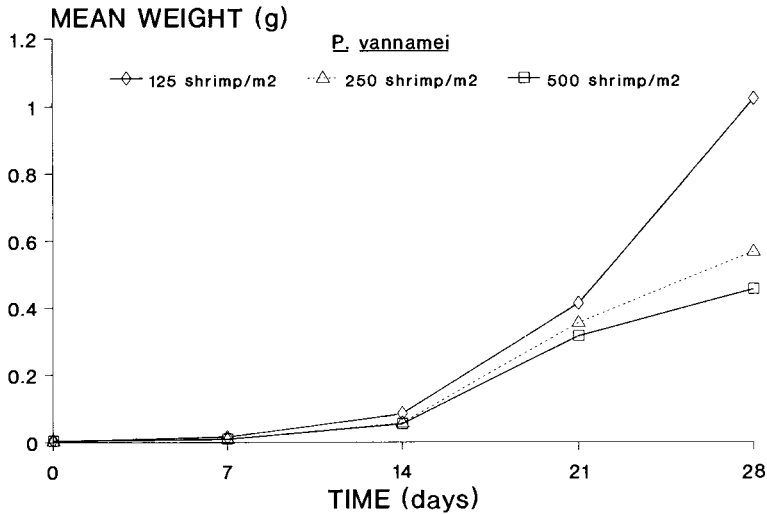


Figure 1. Growth of *P. vannamei* stocked at 125, 250, and 500 PL per m², and nursed for 28 days in intensively managed ponds (Sturmer and Lawrence 1987a).

periods to determine if commercially acceptable growth and survival could be achieved at rates of 125, 250, and 500 PL/m² through improved pond management strategies. Each density treatment was replicated in four 0.1-ha ponds. Ten to twelve-day PL, obtained from a commercial hatchery, were acclimated to pond conditions by pumping pond water into holding tanks. Acclimation procedures followed those recommended by Olin and Fast (1989, Chapter 12) for penaeid PL. Shrimp were sampled by seines and cast nets during the culture period, to assess condition and growth, and to adjust feeding rates. However, these sampling procedures did not allow for reliable estimates of survival of shrimp in nursery ponds. Growth of *P. vannamei* PL stocked at these three densities for 28 days is shown in Figure 1. Growth was independent of density until the final week when significant differences were apparent among treatments. Harvest weights were 1.0, 0.6 and 0.4 g for the low, medium, and high stocking rates, respectively. Growth of *P. vannamei* PL stocked at the lower two densities for 42 days resembled those of the previous study during the first two weeks (Fig. 2). Differences between stocking densities were detected after 21 days and growth reduction was evident after 35 days. Final weights of 2.1 and 1.3 g, and yields of 170 and 230 g/m² were achieved, for the low and medium density treatments, respectively. In an unpublished study at TAMU, similar results (0.5 g harvest weight, 88% survival and 110 g/m² harvest biomass) were obtained for *P. stylirostris* nursed at 250 PL/m² for 28 days using the pond management procedures described herein.

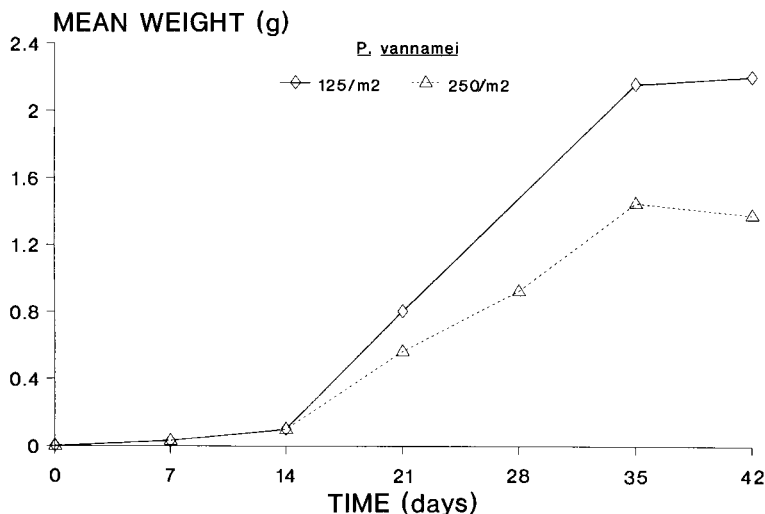


Figure 2. Growth of *P. vannamei* stocked at 125 and 250 PL per m², and nursed for 42 days in intensively managed ponds (Sturmer and Lawrence 1987a).

In properly managed nursery ponds, survival of PL is usually high because control over predation and adequate nutrition are achieved. Survival in the TAMU density studies was excellent. Mean survival did not differ significantly between treatments, ranging from 85 to 95% in the 28-day nursery study, and 75 to 78% in the longer nursery study. Survival exceeded 100% in two replicate ponds, confirming the problem of accurately estimating the number of PL at stocking. Trimble (1980) underestimated a count by over 100% for *P. vannamei* PL despite the use of eleven 400-ml aliquots. Using a spring operated pipette, Chamberlain et al. (1981) underestimated stocking rates of *P. vannamei* PL by 40%. Nonetheless, the common practice in estimating PL populations for stocking ponds is volumetric subsampling (Hardin et al. 1985). This procedure can lead to considerable undercounting, and, if not recognized, result in overstocking with concomitant underfeeding and depressed growth. Some pond managers minimize the inaccuracies associated with counting PL by deducting an arbitrary percentage in the final tabulation from the population estimate. Techniques used to sample shrimp from nursery ponds for management decisions provide unreliable estimates of survival in ponds (Hutchins et al. 1980). A technique to more accurately determine shrimp population sizes in ponds is needed.

13.3 INTENSIVE NURSERY RACEWAYS

The continuing development of semi-intensive and intensive shrimp culture in temperate areas creates a need for indoor or enclosed nursery systems (Lawrence et al. 1985, Sandifer et al. 1988). Most areas of the continental United States do not have climatic conditions necessary for year-round shrimp cultivation. For example, in Texas and South Carolina, temperatures are adequate for one crop per year, but the growing season is too short for two crops, if PL are stocked directly into growout ponds. Intensive nursery systems have recently been developed that allow shrimp farmers to "headstart" seed shrimp in greenhouses before stocking growout ponds (Sturmer and Lawrence 1987b, Sturmer and Lawrence 1988, Samocha et al. 1990). Using "headstart" systems not only incorporates advantages of two-phase production systems but also allows initiation of growout earlier in the year. This effectively increases the growout period by one to two months and permits production of two crops per year.

"Headstarting" requires intensification of nursery culture techniques in raceways or tanks. This technology, for extending the growing season in temperate climates, was first used for freshwater shrimp culture (Sandifer and Smith 1977). It was later used in greenhouse raceways for intensive culture of penaeid shrimp (Mahler et al. 1974). The latter research was continued through collaboration between the University of Sonora and University of Arizona (Salser et al. 1978), and used in commercial production at a Hawaiian site (Lawrence and Huner 1985). Detailed information regarding culture practices and the production of juveniles in this system has not been made public. Concurrent efforts by Mock et al. (1973,1977) dealt specifically with closed system raceway design and construction techniques. Kneale et al. (1981) used a similar system of raceways under greenhouses for the growout of penaeids, with limited success.

A culture technique for intensive nursery rearing of penaeids was developed by Aquacop (1985a). This technique relied on the development of a bacterial medium using strong aeration, no water exchange and no external filter or artificial substrates. Penaeus vannamei PL grew to 0.1 g in up to one month, in 10-100 m³ tanks, at densities of 1 to 10 PL/l, with daily growth rates of 30% (Aquacop 1985b).

13.3.1 Studies at IOLR

The climatic limitations to culturing shrimp in the United States are similar to those in Israel. Research initiated in 1984 at the National Center for Mariculture of the Israel Oceanographic and Limnological Research (IOLR) in Eilat, focused on developing intensive shrimp nursery technology (IOLR Annual Report 1984, 1985, Issar et al. 1987). Use of water circulation

via airlift pumps to improve waste removal was first mentioned by Mock et al. (1973), for growing shrimp in a small recirculating system. Employing this concept, preliminary nursery experiments with P. semisulcatus PL at IOLR provided encouraging results. PL1 stocked in a 6 m³ circular tank at a density of 27 PL/l reached an average weight of 31 mg after 31 days, with survival of 77%.

Subsequent experiments during 1984-1988 were conducted to study the role of algae in an intensive nursery system. Shallow (0.8 to 1.0 m deep), circular tanks, ranging in size from 3 to 20 m², were equipped with central drain and airlift pumps. Postlarval stocking densities varied between 2 and 70 per liter, with survival ranging from 41-100%, depending on age, size, and culture period. Experimentation during 1987-1988 focused on developing a small-scale system to further evaluate the effect of selected parameters on growth and survival of PL. Water exchange rate, algal species and density were controlled by header tanks and flow meters in temperature-controlled rectangular tanks, each 130 liters. In most experiments, better survival and improved growth were achieved when PL were nursed in the presence of algae (Tetraselmis, Chaetoceros, and Isochrysis spp.) as compared to "clear water" media. A summary of selected nursery experiments from 1984 to 1988 is presented in Table 2.

13.3.2 Studies at TAMU

At TAMU, research efforts to develop suitable production technology for intensive nursery systems in the United States were initiated in 1985. The following describes studies of major parameters affecting growth and survival of juvenile P. vannamei and water quality using intensive culture methods in raceways.

13.3.2.1 System Design

The intensive nursery rearing facility of TAMU, located in Corpus Christi, Texas, consists of six, 50 MT raceways enclosed in a 1,014 m² greenhouse. Each raceway is 30.48 m long (bottom length 28.04 m), 3.38 m wide (bottom width 2.44 m), with a mean depth of 0.58 m. Raceways were constructed by excavating trenches, reinforcing sides with gunnite, and lining sides and bottom with polyethylene (Fig. 3).

Each raceway has an outlet equipped with an internal standpipe, nested within a larger diameter pipe fitted with a filter screen (Fig. 4). Artificial habitats, constructed of seine netting vertically suspended, are installed in each raceway to provide additional substrate area. Rope pulleys, attached to the habitat framing, facilitate removal of the netting during maintenance procedures and harvesting.

Table 2. Summary of selected nursery experiments with Penaeus semisulcatus PL from 1984 to 1988 at the National Center for Mariculture in Eilat, Israel.

Initial Age (days)	Initial Density (PL/l)	Size (mg)	Culture Medium*	Duration (days)	Temp. (°C)	Harvest Size (mg)	Survival (%)	Source
PL 1	27	1	CG/TET	31	26-31	31	77	a
PL 1	34	1	ISO	28	18-22	6	50	b
PL 1	70	1	ISO	12	18-24	2	76	b
PL 6	29	2	ISO	12	23-26	6	72	b
PL 20	6	8	ISO	14	23-28	24	87	b
PL 33	2	14	ISO	24	22-29	150	96	b
PL 46	3	91	ISO	20	25-30	374	78	b
PL 57	8	150	ISO	10	23-25	217	60	b
PL 10	20	8	CSW	10	24-26	20	95	c
PL 10	20	8	ISO	10	22-29	22	65	c
PL 10	20	8	CG	10	22-28	25	91	c
PL 10	20	7	CG	17	23-26	23	100	d
PL 35	5	19	CG	25	18-26	101	53	e
PL 35	5	19	CSW	25	18-26	118	41	e

* Culture Media: CSW - Clear seawater, no algae were added; TET - Seawater and Tetraselmis suecica (up to 100,000 cells/ml); ISO - Seawater and Isochrysis galbana (up to 500,000 cells/ml); CG - Seawater and Chaetoceros gracilis (up to 200,000 cells/ml).

Sources: a - 1984 IOLR Annual Report (In Hebrew); b - 1985 IOLR Annual Report (In Hebrew); c - 1986 IOLR Annual Report (In Hebrew); d - 1987 IOLR Annual Report (In Hebrew); e - 1988 IOLR Annual Report (In Hebrew).

Raceways are covered by a quonset-style, greenhouse structure with translucent fiberglass roofing to allow natural light penetration. The inflatable, polyethylene sidewalls can be detached during warm weather usage. Less costly options for greenhouse enclosures are available and should be considered for commercial applications.

13.3.2.2 Raceway Management Practices

Requirements for proper water exchange levels, aeration rates, appropriate phytoplankton species and concentrations, feeding regimes and feed quality have been examined during the past five years. The following management practices have resulted (Sturmer & Lawrence 1987b, 1988). An open or semi-open system is employed, with water exchange dependent upon water quality and estimated shrimp biomass. Water is pumped from a settling pond into each raceway through a pressurized sand filter at 100 l/min. During 1985-1987, average daily water exchanges increased from 10-20% of the total raceway volume in the first week to 30-40% during the second week. In the third and fourth weeks, exchange rates averaged 80% and 160% per day,

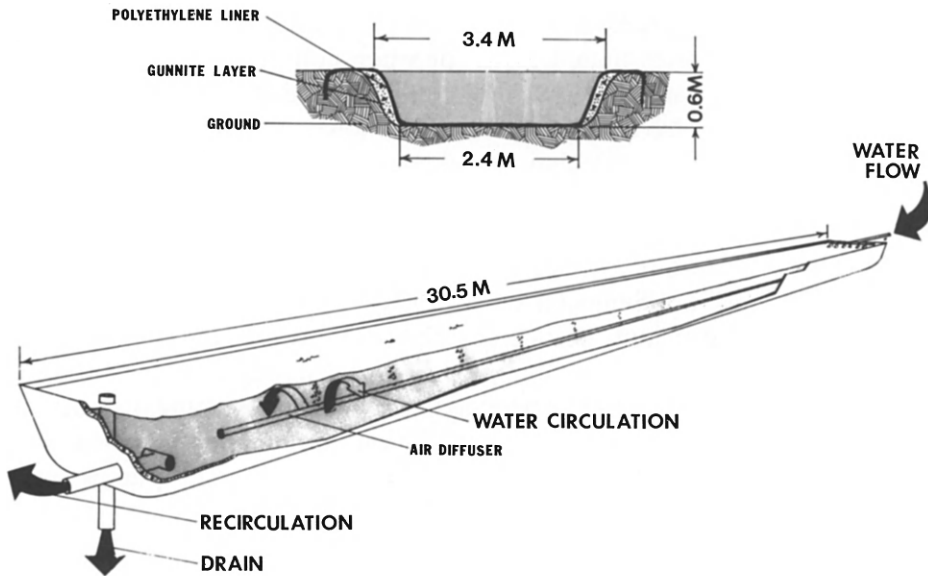


Figure 3. Diagram of raceway configuration and construction detail.



Figure 4. A 50 MT raceway at the intensive nursery rearing facility operated by the TAMU Shrimp Mariculture Project. Note the nested standpipe, air diffuser and artificial habitats.

respectively. Maximum exchange rates of 280% per day were usually required when biomass was greater than 1 kg/m² or when culture exceeded 28 days. Continuous aeration was provided by longitudinal air diffusers (microporous polyethylene tubing), driven by regenerative blowers (1 hp per raceway), which created an upwelling circulation in the raceway. Accumulation of fecal matter and uneaten feed on raceway bottoms was removed through the use of flexible impeller pumps.

In 1989, modifications in design and water management were tested to improve waste removal (Samocha et al. 1990). All raceway outlets were modified to allow efficient particulate removal during water exchange. Raceways were flushed daily by pulling the internal standpipes. In addition, settled particulate matter was resuspended twice weekly by stirring the bottom during water exchange. An "active circulation" treatment, in which two raceways were provided with six banks of three 5-cm airlift pumps, was evaluated. Airlift placement created a counterclockwise current around a central fiberglass wall, which aided in suspending particulate matter and facilitating waste removal (Fig. 5). As a result of this design, waste removal was found to be more efficient and less labor intensive in the raceways with active water circulation. Daily water exchange rates in these raceways were lower in the latter weeks (30% and 80% for the third and fourth weeks, respectively), as less water was needed to maintain water quality. The harvest weights, survival, yield, and feed conversion values obtained in an evaluation of this system are presented in Table 3.

Fertilization of raceways prior to stocking PL is included in the TAMU management practices for two reasons. First, natural productivity can significantly contribute to the nutritional requirements of shrimp in raceways. Secondly, algal populations can reduce ammonia levels which tend to rise in the presence of high shrimp biomass (Krom et al. 1985, Wajsbrodt et al. 1989). Preliminary results obtained from the Israeli nursery studies also suggest better survival and, in most cases, improved growth in the presence of algae instead of a "clear water" media. Further, the ability to transfer monocultures of algae from small-scale laboratory to large-scale open air conditions has been successfully accomplished by inoculating with pure cultures of algae concomitant to fertilization (Witt et al. 1981). A high nitrogen to phosphorus ratio (10:1), provided by applications of urea and phosphoric acid, supplementation of silicate levels (1.5 mg/l-Si), and inoculations of Chaetoceros gracilis cultures, promoted diatom blooms in the TAMU raceways. The presence of these algal blooms (>100 ug/l chlorophyll a, b, and c) at stocking conditions the water during a period of limited water exchange. In spite of higher exchange rates required during the latter part of the nursery period to manage water quality, total chlorophyll (a, b, and c) values are still maintained above approximately 30 ug/l. Samocha et al. (1990)

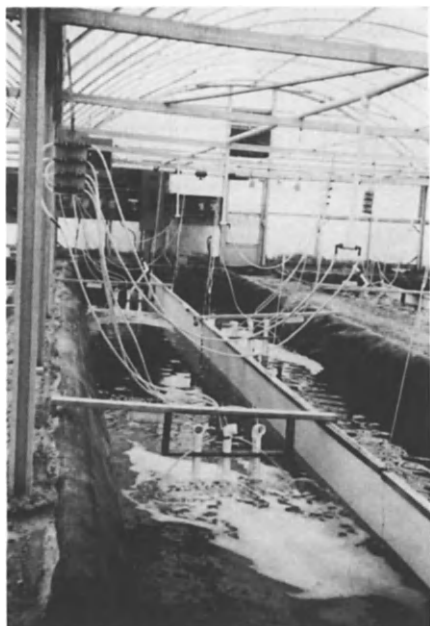


Figure 5. Modified TAMU raceway, depicting arrangement of airlift pumps and central partition, designed for efficient waste removal.

demonstrated that it is possible to promote diatom blooms simply by using a high N:P fertilization regime. However, as algal species composition in natural seawater may vary from one season to another, site location and seasonal changes should be considered when choosing the appropriate method. Additional studies are needed to evaluate the effect of different algal species on juvenile shrimp production, and their role on secondary productivity.

Artificial habitats, constructed of seine netting suspended vertically, provided 114 m² of additional substrate area in the TAMU raceways. Sandifer et al. (1987) found that added substrate in experimental nursery tanks, improved survival (82% versus 58%) but not growth. Results of earlier feeding studies at TAMU suggested that "fouling" communities associated with artificial habitats contributed to low feed conversion ratios (Sturmer and Lawrence 1988). More recently, no beneficial effects were observed by Samocha et al. (1990), when the area of vertical netting was increased 67% in two raceways (Table 3). Furthermore, nursing PL without added substrate did not reduce growth or survival.

Proper feeds, at the required rate and number of feedings per day are not only important in providing necessary nutrients to postlarval and juvenile

Table 3. Summary of 1989 nursery raceway experiment conducted at TAMU Shrimp Mariculture Project with P. vannamei PL. Initial mean weight: 1.58 mg; stocking density: 3,100 to 3,300 PL/m²; duration: 35 days. (Samocho et al. 1990)

Raceway #	Treatment	Average Weight (g)	Survival (%)	Yield (kg/m ²)	FCR
2	Double netting	.481 ± .024*	96.6	1.46	.97
4	Double netting	.767 ± .034	68.2	1.66	1.12
3	Single netting	.688 ± .024	76.9	1.61	1.12
1	Single netting	.601 ± .028	77.7	1.52	1.12
5	Active circulation	.590 ± .031	99.1	1.89	.98
6	Active circulation	.478 ± .028	90.5	1.42	1.02

* Standard error of mean

shrimp, but also improper feeding regimes with low quality feeds have the potential to degrade water quality in intensive culture systems. A high quality commercial ration containing 50% protein, 8% fat, less than 3% fiber, and vitamin and mineral supplements is used in three crumble sizes. The feeding regime consists of using a fine crumble (0.6-1.0 mm) during the first week, a medium-sized (1.0-1.4 mm) crumble during the next two weeks, and a large crumble (1.4-1.7) for the remaining weeks. Shrimp are routinely collected with dipnets twice weekly to determine growth, and to adjust daily feed amounts. Average feeding rates, back-calculated from the 1986-1987 nursery studies, decreased from 100-150% of the estimated shrimp biomass in the first week to 40-60% the second week, and 25-30% in the third week. During the fourth through sixth weeks, the feeding level was maintained at 10-20% of estimated shrimp weight. In 1989, feeding levels were reduced to 10, 15, 20, 15 and 10% of the total estimated biomass during the first through fifth weeks, respectively. Daily rations were adjusted according to observations of postlarval consumption, using an underwater viewing apparatus. The feed ration is distributed over the entire raceway surface, four to six times daily. In one nursery study, the effects of continuous feeding versus periodic feeding on shrimp growth and survival were compared (Sturmer and Lawrence 1988). Six automatic feeders were installed per raceway. No differences in performance under the two feeding regimes, coupled with low feed conversion ratios (means of 0.9:1 - 1.1:1), implied utilization of the high natural productivity in the raceways. Labor requirements, however, were reduced by 50% using automation. In addition to the dry diet, newly hatched Artemia nauplii are fed for the first week after stocking. Frozen or live adult Artemia are provided two to three times a week, after the second week, at a rate of 2-5% of the estimated shrimp biomass. Artemia feeding promotes molting of PL shrimp which precludes exoskeleton fouling.

13.3.2.3 Water Quality Parameters

Physico-chemical parameters of raceway water are maintained within acceptable ranges for PL by utilizing the described management practices. The dense algal blooms (up to approximately 11×10^6 cells/ml) obtained during the first two weeks, generally result in pH values as high as 9.7. As shrimp biomass exceeds 1 kg/m^2 during the later weeks, pH values below 7.0 can be expected. No adverse effect upon growth and survival of the PL were observed within this pH range. Total unionized ammonia and nitrite concentrations in the raceways are low in spite of high feeding rates, and, in most cases, lower than the range of tolerance determined by Wickins (1976). Dissolved oxygen may approach critical levels, when shrimp biomass reaches 1.5 kg/m^2 in a raceway. Compressed pure oxygen was injected into the air manifold to maintain values above 2.5 mg/l during the final culture days in some of the early nursery studies. To avoid stress due to oxygen depletion and ultimately to increase stocking rates and subsequent production, raceways were equipped with an on-line oxygen injection system in 1990.

Perhaps the most critical water quality parameter for growth of postlarvae in the nursery phase is temperature. The presence of a greenhouse enclosure proved to be a major factor influencing raceway water temperatures. For example, from March through April of 1987, water temperature in the raceways averaged 25°C , resulting in a mean differential of 5°C over ambient outdoor pond temperatures. A daily minimum of 18°C was maintained in the raceways during early spring using only a passive heat source, while the corresponding pond temperature was 10°C . Even in May and June, a mean differential of 2°C was provided, with raceway temperatures averaging 28°C . Salinities were maintained between 30 and 40 ppt for all nursery studies.

13.3.2.4 Stocking Density, Growth, and Survival

In 1986, stocking densities ranging from 550 to 4,400 *P. vannamei* PL per m^2 were tested during nursery periods of 28 to 42 days (Sturmer and Lawrence 1987b). Each density was replicated in three raceways. Results were obtained on growth, survival, yield, and feed conversion. Growth rates were markedly density dependent (Fig. 6). Mean weights of 1.7 and 1.3 g were reached at stocking rates of 550 and 1,100 PL/ m^2 , respectively, in 42 days. Respective harvest weights of 0.9 and 0.7 g were obtained in 28 days at stocking densities of 1,100 and 2,200 PL/ m^2 . Stocking rates of 2,200 and 4,400 PL/ m^2 resulted in 1.7 and 1.3 g juveniles after a nursery period of 42 days. Yield was also influenced by density. At stocking densities of 550 and 1,100/ m^2 , yields were 0.5 and 0.8 kg/m^2 , respectively. Whereas, at stocking densities of 2,200 and 4,400 PL/ m^2 , yield averaged 1.5 and 2.0 kg/m^2 .

Within the range tested, survival was not significantly influenced by stocking rates. Overall means for each density study were 68, 60, and 70%.

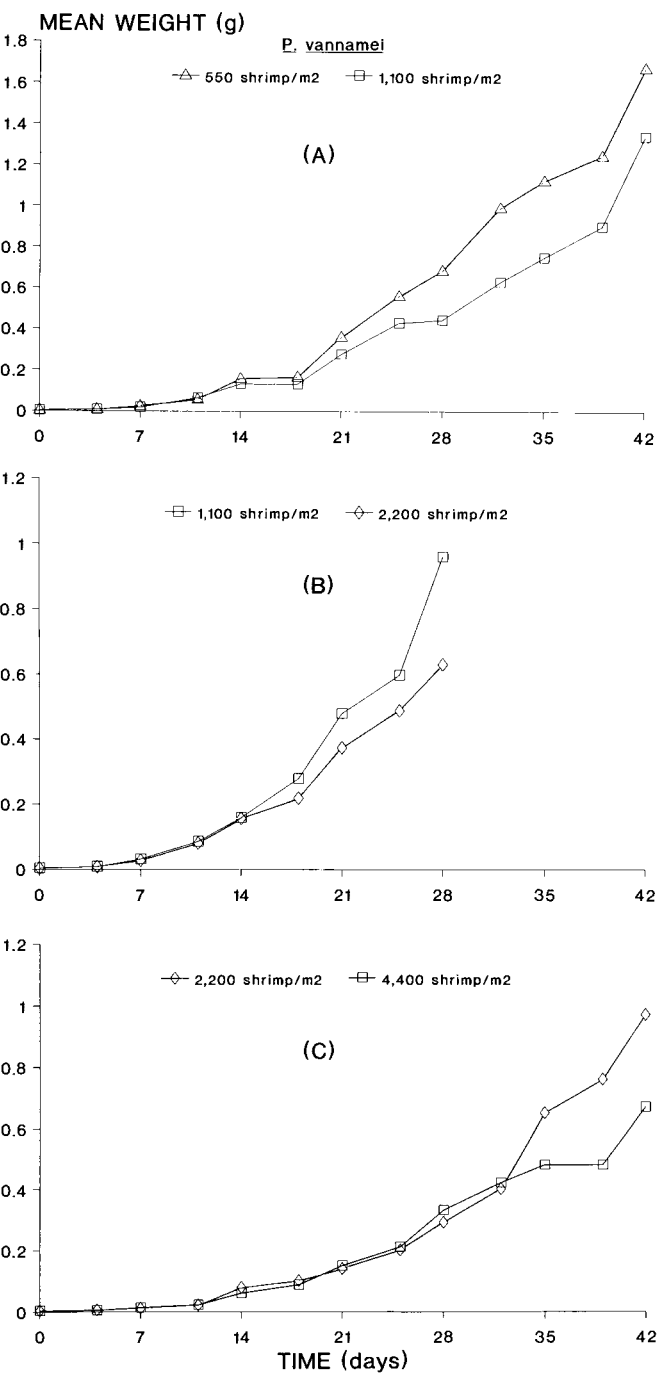


Figure 6. Growth of *P. vannamei* in raceways stocked at A) 550 and 1,100 PL/m² for 42 days; B) 1,100 and 2,200 for 28 days; and C) 2,200 and 4,400 for 42 days.

Survival may be higher at lower stocking densities (for example, 250 to 500 PL/m²), but such densities are unlikely to be economically attractive where enclosed nurseries must be employed. In a recent nursery trial conducted by TAMU during the spring of 1990, survivals of over 92% were obtained at stocking densities of 7,800 *P. vannamei* PL/m². Furthermore, no stunting effect was observed and a growth rate of 2 g/week was achieved in subsequent growout trials at stocking densities of 30 juveniles/m².

Penaeus stylirostris PL were also nursed at TAMU using intensive management practices. After 42 days, 1.9 and 1.2 g juveniles were harvested at densities of 280 and 680 PL/m², respectively. This penaeid species appears to be amenable to high density rearing, with production of over 5 kg/m² of marketable shrimp reported from intensive raceway systems in Mexico (Salser et al. 1978).

13.3.2.5 Other Studies and Applications

Concurrent with TAMU's raceway studies, tank and pond rearing studies were conducted in South Carolina to assess the potential for intensive culture of *P. vannamei* (Sandifer et al. 1987). PL stocked in 4.5 m³ circular tanks at 500/m² reached a mean harvest weight of 1.3 g in 68 days. The data generated from both investigations indicated commercially promising results. As a consequence, adaptation of intensive nursery systems has been made by the emerging shrimp industry in the United States. A concept of stock manipulation which would produce the same yield as a one crop system, while producing an additional smaller crop in two out of every three ponds, was initiated at a commercial farm site in Texas (Cook et al. 1988). *P. vannamei* PL for the first crop were "headstarted" by covering a portion of the water distribution canal, thus eliminating construction of a separate nursery. Greenhouse-enclosed raceways, each holding approximately 150 MT of water, were used in South Carolina to nurse *P. vannamei* PL stocked at 1,600 to 1,800 per m² (D. Fuze, Pers. comm. 1988). High density nursery trials in a 330 m² circular, earthen pond were conducted at the Oceanic Institute, Hawaii (McSweeney et al. 1988). PL were stocked at 1,000 per m² and 1.0-gram *P. vannamei* juveniles were produced in approximately one month.

13.4 SUMMARY AND ECONOMIC REVIEW

The potential for commercial production of juvenile shrimp from intensified nursery pond or intensive nursery systems, such as raceways, has been demonstrated. Need of either system depends on the management strategy used for the growout phase. In some circumstances, the nursery phase may be unjustified. Direct stocking of PL may be a practical alternative in growout ponds of less than 1.0 ha in size, or in tanks which are intensively

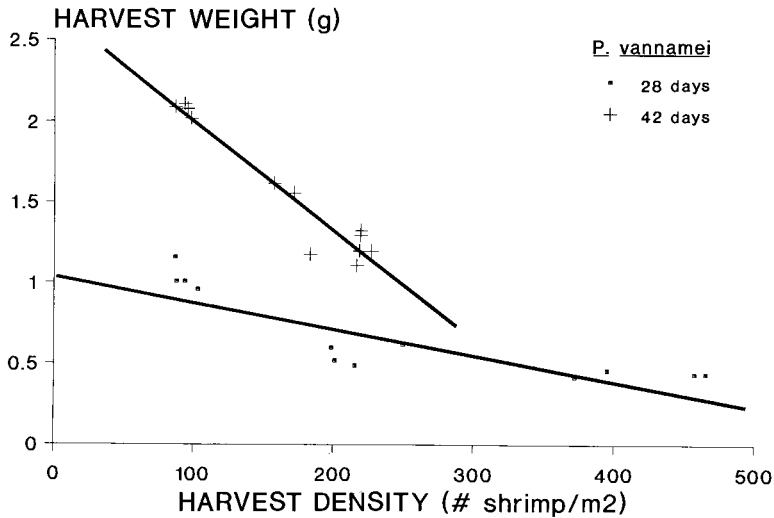


Figure 7. Relationship between final weight and harvest density of *P. vannamei* juveniles in small earthen ponds after nursery periods of 28 and 42 days (Sturmer and Lawrence 1987a).

managed. However, to achieve maximum yields of higher value shrimp, nursery systems must be employed in conjunction with intensive growout. Sandifer et al. (1988) observed no differences in survival when juvenile, rather than postlarval shrimp were stocked, but substantial differences in mean weight at harvest were obtained. In comparing production figures from the latter study with that from intensive round pond systems (6,700 kg/ha versus 32,272 kg/ha), Wyban et al. (1988) concluded that differences in management accounted for differences in shrimp growth rate. Nursed juveniles were used in round pond trials, while direct postlarval stocking was used in the South Carolina study. Clifford (1985) recommended the use of nursery ponds for maximum annual production in semi-intensive growout ponds of 10-20 ha. In ponds larger than 20 ha, where the required management of water is impractical, stocking larger shrimp is necessary to minimize mortalities and maximize profits. Aquacop (1985a) noted that yields from traditional extensive ponds may be increased by greater control of seed size and quality.

The use of ponds versus raceways for the nursery phase of a two phase production system is dependent on both biological, site and economic considerations. Figures 7 and 8 summarize the relationship between harvest density and final weight of shrimp reared in nursery ponds and raceways. In 28 culture days, 1.0 g *P. vannamei* juveniles were obtained from ponds with a harvest density of 46 juveniles/m², whereas the shrimp weighed only 0.5 g when harvested at a density of 355 juveniles/m² (Sturmer and Lawrence 1987a). A 1.0 g juvenile can be obtained in a longer pond nursery period of 42 days at a harvest density of approximately 250 juveniles/m².

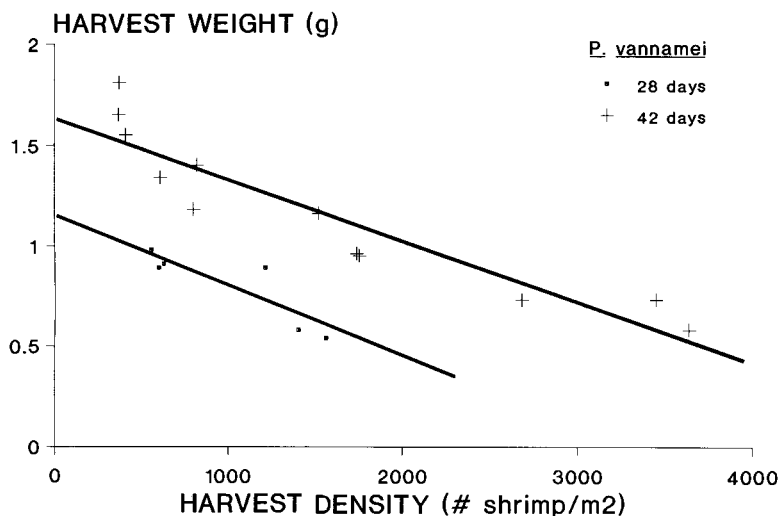


Figure 8. Relationship between final weight and harvest density of *P. vannamei* juveniles in intensively managed raceways after nursery periods of 28 and 42 days (Sturmer and Lawrence 1987b).

Comparatively, during a 28-day nursery period in raceways, *P. vannamei* juveniles of 1.0 g were produced at a harvest density of 456 juveniles/m², whereas smaller juveniles of 0.5 g were produced at a harvest density of about 1,870 juveniles/m² (Sturmer and Lawrence 1987b). In 42 days, 0.5 g and 1.0 g juveniles can be produced at harvest densities of approximately 3,500 and 2,000 juveniles/m², respectively. According to the TAMU results, raceway technology can produce eight to ten times as many kg/m² of 1.0 g juveniles as a nursery pond, regardless of culture period, and an increase of five times more than pond production of 0.5 g juveniles. The coefficient of variation of shrimp size at harvest was significantly reduced in the raceway nursery systems.

Factors influencing growth of *P. vannamei* in nursery systems were evaluated by Ogle (1991) over a five year period. Unreplicated studies were conducted at various densities, using several types of culture tanks. Among the systems studied, an outdoor pond produced the best growth. Conversely, replicated nursery studies at TAMU revealed that larger juveniles could be harvested from raceways as opposed to ponds, when comparing *P. vannamei* growth curves for stocking densities of approximately 500 PL/m² (see Figs. 1 and 6A). The use of raceways instead of ponds allows greater control and efficiency. Further, Aquacop (1984) stated that the nursery phase is the most difficult part of shrimp culture, and that use of intensive nursery rearing techniques should give more predictable production. However, intensive

nurseries require more highly skilled labor to manage the systems, and therefore increase operational costs.

Much of the economic information necessary for appraising the costs of intensive nursery systems is not yet available. Sandifer et al. (1983) indicated that a two phase system, using nursery ponds, increases the profitability of Macrobrachium rosenbergii culture in tropical areas, and probably be required in temperate areas for the same reason. In a later study, Smith et al. (1983) showed that there were economic benefits to stocking juvenile freshwater shrimp from intensive nursery systems instead of smaller postlarval shrimp into growout ponds. Analysis by Pardy et al. (1983) of pond stocking strategies for penaeid shrimp culture in Texas indicated that two crops per year yield smaller economic returns than one crop per year without "headstarting" in raceways under greenhouses. Johns et al. (1983) also concluded that two crops per year yield less net revenue above selected costs than one crop per year, since length of the growout period determines size of shrimp produced. Further, Sadeh et al. (1986) stated that the growing season in Texas is adequate for more than one crop per year, but too short for two crops per year if PL are stocked directly into growout ponds.

Production costs of rearing P. vannamei juveniles in an intensive nursery system were analyzed by Juan et al. (1988). For three types of greenhouse enclosures and three types of raceway construction, costs ranged from \$7.00 to \$9.00 per one thousand 1.0 g juveniles produced. Based on the assumptions of that study, the intensive nursery system was less profitable than direct stocking in Texas. Enclosed nurseries could be more profitable, if less expensive greenhouses and raceway designs were employed. Optimum nutrition and management practices for intensive nursery systems still need to be developed for conditions of high stocking density, high survival, high growth rate, and low operational costs.

13.5 ACKNOWLEDGEMENTS

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CHAPTER 14

Arlo W. Fast

PENAEID GROWOUT SYSTEMS: AN OVERVIEW

14.1 INTRODUCTION

Marine shrimp have been cultured in earthen ponds for many centuries, usually as incidental entrants along with fish. This practice dates back several thousand years in the Mediterranean area, where Roman's practiced brackishwater pond culture (Brown 1983). The Romans undoubtedly learned their pond culture practices from earlier civilizations. Egyptian artworks also depict pond culture.

Asia also has a long history of pond culture for fish and other species, perhaps older than all other civilizations. The earliest written descriptions of pond culture are from China during the 12th century B.C. (Atkinson 1983). These earliest activities were with freshwater carps. By the 15th century A.D., milkfish (*Chanos chanos*) and other species, including marine shrimp were commonly cultured on a large scale in Indonesian brackishwater ponds (Ling 1977). These practices continue today, in some cases not much changed from earlier times.

Until very recently, marine shrimp were almost always co-cultured with fish in extensive pond systems that were simple, unsophisticated, and low yield. Modern shrimp culture has changed that. Now, in addition to the extensive production systems, shrimp can be monocultured at very high densities in complicated, sophisticated systems that produce high yields. These options were made possible by a combination of seed availability, suitable biological characteristics of many penaeid species, high market demand and prices, and limited availability of wild caught shrimp from the world's oceans. These strong driving forces have led to a very rapid expansion of shrimp culture technology.

In this chapter, I will give a general overview of some broad categories of pond culture systems. In following chapters, I will describe these systems in more detail with specific examples.

Shrimp culture systems form a continuum in terms of complexity and yield, ranging from low yield, extensive systems mentioned above, to very high yielding, ultra-intensive systems than can produce 150,000 kg/ha/yr or more of shrimp (Table 1). While the culture systems are a continuum, it is

Table 1. Characteristics of Marine Shrimp Culture Systems (modified from Fast, in press; and Apud et al. 1983).

Characteristics	Production Type			
	Extensive	Semi-Intensive	Intensive	Ultra-Intensive
Production (MT/ha/yr)	<0.1 to 0.3	0.5 to 2.5	5 to 15	30 to 150
Stocking Rate (#/m ² /crop)	0.1 to 1.0	3 to 10	15 to 40	> 100
Seed Source	wild	wild & hatchery (? nursery)	hatchery (nursery)	hatchery (nursery)
Maximum Standing Crop (g/m ²)	< 25	25 - 150	250 - 1,000	1,500 - 4,500
Feed	Natural (no supplement)	Natural + Supplement (incomplete)	Formulated (complete or nearly complete)	Formulated (complete)
Feed Conversion (kg feed/kg shrimp)	0	< 1.0 - 1.5	1.5 - 2.0	> 2.0
Nuisance Species	Abundant	Common	Rare	Rare
Polyculture	Common	Occasional	Rare	Rare
Water Exchange Rate (%/day)	< 5%	< 5 to 20%	10 to 20%	> 100%
Water Exchange Mode	Tidal or pump	Pump	Pump	Pump
Aeration & aerators	natural water exchange	water exchange	aerators & O ₂ injection	aerators & water exchange
Pond size (in ha)	> 5	1 to 20	0.25 to 2	< 0.25
Pond shape	irregular	more regular	uniform square or rectangular	uniform tank or raceway
Water Depth (m)	0.4 to 1.0	0.7 to 1.5	1.5 to 2.0	variable
Survival (%)	<60	60 to 80	80 to 90	80 to 90
Dike Construction	earthen	earthen	earthen or concrete	concrete
Crops/yr	1-2	2-3	2.5-3	> 3
Potential energy requirement (hp/ha)	0-2	2-5	15-20	> 25
Labor needs (persons/ha)	< 0.15	0.10 - 0.25	0.5 - 1.0	> 1
Management	minimal attention	continuous skilled	continuous skilled	continuous highly skilled
Disease Problems	minimal	usually not a problem	can be serious	can be very serious
Potential Profit (per kg shrimp)	moderate	high	low	very low
Potential Profit	very low	moderate	high	very high (per ha)

convenient to conceptually divide the continuum into categories based on yield potentials and operating characteristics. Most pond culture authorities recognize these categories, although since we are considering a continuum, there may be differences between classifications by various people. For convenience then, we will view the range of shrimp culture as following into four categories of intensity; extensive, semi-intensive, intensive, and ultra-intensive.

Before discussing some of the respective characteristics of these four categories, one additional point is worth mentioning. That is, the art and science of pond culture has largely evolved to its present form through the individual efforts of farmers and commercial companies. The governmental scientific community has played a minor role in this evolution. There are three main reasons for this situation. First, postlarval availability was the principal impediment to large scale shrimp culture until very recently. Consequently, most government research efforts concentrated on solving this problem rather than on pond research. Secondly, basic pond research can be expensive. It often requires large pond complexes which are expensive to construct and operate. Lastly, the most economically viable pond growout systems for a given location will depend on a host of economic, climatic, historical, sociological, and biological factors. Growout systems appropriate for Ecuador might be totally inappropriate for Taiwan. Growout, more than any other aspect of shrimp culture has many site specific consideration. Furthermore, these conditions can change rapidly with time making existing systems obsolete.

The dynamics of shrimp pond growout systems, therefore, have made government funded research on pond growout difficult. Governments tend to move slowly; too slowly to respond to the rapidly changing needs of the industry. Given these constraints, and good progress by the private sector in pond culture innovations, public domain pond research has lagged. Until now, trial and error progress has served the industry well. Perhaps that situation will soon change as captive production of marine shrimp increases the supply faster than market demand. This will result in shrimp price decreases and greater emphasis on production efficiencies.

While the private sector can and will continue to contribute to advances in shrimp pond culture, many problems can best be solved by public sector research. I believe we will see increased interest and contributions from university and governmental institutions during the next few years. These will provide a solid basis for pond culture of shrimp and fish, and thereby lead to a more "principled" pond culture technology.

Let us now consider some of the characteristics of existing marine shrimp pond culture systems.

14.2 PRODUCTION LEVEL

Extensive systems are characterized by very low yields, often less than 50 kg/ha/yr from one or two crops per year (Table 1). Even with well managed extensive systems, yield seldom exceeds 300 kg/ha/yr. Yields from extensive ponds can often be increased to semi-intensive levels through various management actions. Yields from semi-intensive ponds range from 500 to 2,500 kg/ha/yr. The next level of intensity, intensive ponds typically produce yields of 5,000 to 15,000 kg/ha/yr. It is usually not possible to upgrade less intensive ponds to intensive levels without major renovations. Intensive and ultra-intensive cultures systems most often require custom designs specific to location, shrimp species cultured, and production level. Ultra-intensive culture can produce more than 150,000 kg/ha/yr of shrimp.

Except for shrimp culture practices that involve multiple stocking and selective harvest of individual ponds (Hirasawa 1985; Chapter 30), annual yield is a product of maximum standing crop and number of crops per year. Maximum standing crop typically ranges from $<25 \text{ g/m}^2$ for extensive systems to $4,500 \text{ g/m}^2$ or more for ultra-intensive (Fig. 1); while crops range from 1 to more than 3 per year (Table 1).

14.3 STOCKING

Extensive ponds typically have stocking densities of 1.0 PL or juvenile / m^2 /crop or less. This seed is normally carried into the pond during flooding and water exchanges. This often results in the introduction of undesirable species as well, including shrimp, fish, crabs, and other species. Polyculture with desirable fish species, intentionally stocked is common with extensive culture. Stocking densities with semi-intensive ponds range from 3 to 10 seed/ m^2 /crop. Seed may enter the pond with influent water, but more commonly it is stocked at desired densities from shrimp produced in hatcheries, or captured elsewhere and then brought to the pond. Polyculture with fish is common, especially at lower production levels of semi-intensive culture. Nuisance species are more easily controlled by screens and piscicides in smaller semi-intensive ponds, but control of unwanted intruders are difficult or impossible in large ponds. With intensive culture systems, shrimp stocking rates range from 15 to 40 seed/ m^2 /crop or more. Virtually all seed for intensive culture comes from hatcheries where shrimp species and size are controlled. Fish and other intruders are controlled by screens and selective toxicants such as rotenone and teaseed cake (Minsalan and Chiu 1986). Ultra-intensive systems have stocking densities of 100 to 500 seed/ m^2 /crop. As with intensive culture, shrimp is monocultured and intruders are strictly controlled.

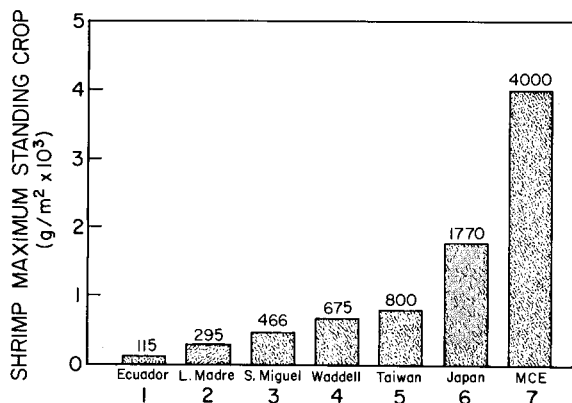


Figure 1. Maximum standing crops at harvest (g/m^2) for marine shrimp production systems ranging from extensive (Ecuador) to ultra-intensive (MCE).

Sources: 1. Craig Emberson (1986), 2. Craig Emberson (1986), 3. Liu and Mancebo (1983); Veloso (1984), 4. Sandifer, et al. (1986), 5. Fast et al. (1989); Chiang and Liao (1985), 6. Shigueno (1985), 7. Chris Brand (1984); Colvin (1985).

14.4 FEED

With extensive culture, virtually all feed for shrimp comes from natural pond production, supplemented with organic manures and wastes (Wickens 1976, Clifford 1985). These manures and wastes are consumed by the shrimp to some extent, while at the same time they provide nutrients for plant growth and organic matter for detritivores. With semi-intensive culture, shrimp rely on natural pond productivity during early growth, but typically require supplemental, formulated feeds during final growout. These feeds are low cost formulations that do not contain all the necessary nutrients for shrimp in adequate amounts. They are adequate, however, to achieve desired shrimp yields when consumed in addition to natural food items in the pond. Shrimp in intensive culture ponds still consume some natural foods produced by the pond, but the amount is small and probably accounts for 5% or less of their total nutritional needs. Formulated feeds for intensive culture are high quality and costly. Feeds for ultra-intensive culture are nutritionally "complete". That is, they typically provide the sole source of nutrition for shrimp in these growout systems. Feed conversions ratios (FCR), kg of formulated feed applied per kg of shrimp produced, are, of course, 0.0 for extensive ponds to about 3 for ultra-intensive culture systems. Feed cost is the major operating expense for higher intensity culture systems, and can account for 40% or more of these costs.

14.5 WATER

Most extensive ponds without mechanical pumping rely on tidal water exchange twice monthly. While the percentage daily water exchange is high on those days when water is exchanged, it is zero on other days. The average daily water exchange for most extensive ponds is about 5% or less. Semi-intensive ponds, especially those patterned after the Panama and Ecuador designs can have high daily water exchange of 20% or more. These ponds do not use mechanical aeration, but use water exchange as the principal means for regulating water quality. Water may be exchanged at 50% per day or more in some cases. In Asian semi-intensive ponds with mechanical aeration, lower water exchange rates are used. Intensive culture ponds have little or no water exchange early in the crop cycle, but increase to 20% or more during final growout. Ultra-intensive culture ponds exchange well over 100% per day. Intensive and ultra-intensive culture systems use mechanical pumps for water exchange, while most semi-intensive systems use pumps also.

14.6 POND SIZE

Extensive ponds are typically large, with irregular shapes. Average water depths are normally less than 1 m to accommodate tidal water exchange. Ponds of 10 ha or larger are common. With intensification and increased management attention, pond size decreases. Ultra-intensive systems are typically less than 0.25 ha, use concrete construction, and have special design features.

14.7 AERATION

Extensive ponds do not use mechanical aeration, but instead rely on balanced biological physical processes to assure adequate oxygen concentrations for shrimp. As intensification increases, mechanical aeration becomes more necessary; and with ultra-intensive systems pure oxygen may be used to assure adequate oxygen concentrations. Aeration principles and practices are described more fully in Chapter 22.

14.8 POND DEPTH

Extensive ponds, as noted above, are shallow to allow for tidal water exchange on a regular basis. Deep ponds in areas with limited tidal range, may not completely drain or fill at times. Ponds that use pumps for water exchange are freed from this depth limitation. There is a trend for increased

water depth in semi-intensive ponds to 1.0 - 1.5 m, and in intensive ponds to 1.5 - 2.0 m. Ultra-intensive ponds tend to be shallower, however, with average depths of 1 m or less.

14.9 SURVIVAL

Shrimp survival is lowest in extensive ponds, 60% or less. This is due to several factors, including the high incidence of unwanted predators and competitors that come in with source waters. Localized water quality problems, and incomplete harvest are also sources of shrimp loss in large, extensive ponds. Survival in the more intensive growout systems ranges from 80 to 90%.

14.10 ENERGY

Energy use in pond growout is mostly for water pumping and water aeration. In extensive ponds, with tidal exchange and no mechanical aeration, energy use may be zero. Energy capacity increases greatly with intensification ranging from 2 to 5, 15 to 20, and more than 25 hp/ha for semi-intensive, intensive and ultra-intensive systems, respectively.

14.11 MANAGEMENT AND LABOR

Extensive ponds require the least amount of management and labor. Manpower needs are mostly restricted to initial flooding and seeding, water exchange during growout, and harvest. Average manpower expenditures are less than 0.15 people/ha with extensive systems. The needs for total manpower, as well as skill level increase with intensification. Greater skills and labor are needed for such things as monitoring, feeding, equipment operation, and harvesting. With semi-intensive and greater intensity culture systems, continuous attention is generally needed by people and/or electronic monitoring devices.

14.12 DISEASE

Disease is not considered to be much of a problem with extensive and semi-intensive systems which use relatively low shrimp densities and wild seed. Disease is a serious potential problem with intensive and ultra-intensive systems due to high shrimp densities and hatchery produced seed. Seed may be infected at a hatchery with the effects manifested after pond stocking.

14.13 PROFITS

Potential profits per kg of production are greatest with semi-intensive culture, and lowest with ultra-intensive culture (Hirasawa 1985). Potential profits per ha, on the other hand, are greatest with ultra-intensive culture and lowest with extensive culture. The emphasis here is on potential, since actual profitability will depend on many factors, not the least of which is price/kg to the farmer.

Examples of the four categories of pond growout systems are presented in the next four chapters. Some of the features of shrimp culture discussed in this chapter, such as aeration, water supply, monitoring, pond design, feeds, and economics are discussed at much greater length elsewhere in this volume.

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CHAPTER 15

Arlo W. Fast

PENAEID EXTENSIVE GROWOUT SYSTEMS

15.1 INTRODUCTION

Extensive pond culture was historically the first to evolve, and is the least sophisticated. Extensive ponds are much like natural ecosystems with respect to nutrient inputs, nutrient cycling, species diversity, oxygen dynamics, and level of human intervention. Extensive ponds are also still the most common. Although their yield per ha is small, they require little attention or operational cost; and the owners realize continued net income year after year (Nailon 1985). In some cases, individual extensive ponds have been in operation for centuries.

In their least complicated form, extensive ponds are built by constructing dikes around a low lying land area within the intertidal zone. Water exchange is accomplished through tidal action. Mangrove areas in estuaries have been prime candidates for such pond construction since they typically have gentle slopes, adequate tidal range, abundant wild shrimp seed, and land ownership vested with government. Such land was usually easy to use and inexpensive. Until very recently, there was little concern about conversion of mangrove forests into aquaculture ponds with resultant loss of other potential or known resources. Resource managers are now generally concerned about loss of mangroves. This awareness, and resultant regulations now make it difficult to build in these locations.

Mangrove areas are not without problems for shrimp culture. Much of the soil in these areas, especially in Asia, is acidic. Exposure of this soil during dike construction and between crops can lead to acidification of pond soils and waters. The pond dikes are particularly vulnerable since their upper portion is always exposed to air and acidification. Following long dry periods, rain can wash lethal amounts of acid into the ponds. If properly managed over time, these problems decrease due to sedimentation, leaching and loss of acid from dikes. Reconstruction of these ponds, however, can expose acid soil and renew the problem.

Mangroves areas also have extensive trees and other roots that should be removed. It is not possible to remove all roots from the soils, but the larger stumps and roots can be removed by a variety of means (Fig.'s 1 and 2).

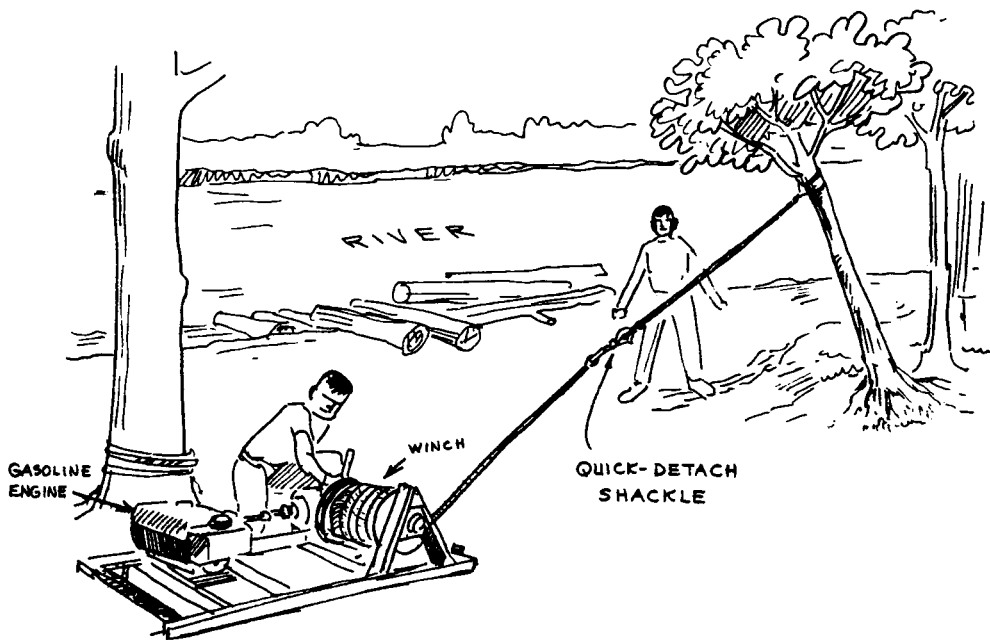


Figure 1. A mechanical, power driven tree puller used to clear pond areas. Figure from Jamandre and Rabanal (1966).

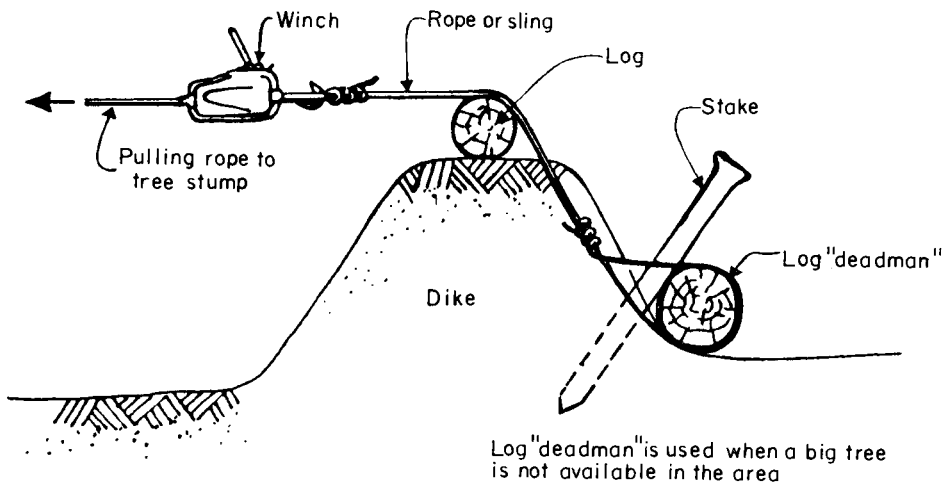


Figure 2. A mechanical, hand winch used with "deadman" and dike to remove tree stumps from pond areas. Figure from Hechanova and Tiansongrusmee (1980).

Roots and other vegetation in acid soils do not decompose readily because most bacteria and other decomposers are not very effective at low pH.

15.2 WATER EXCHANGE

The tidal pattern, range and wetted area at each tidal stage are particularly important when siting and constructing extensive ponds. dela Cruz (1983) discusses these and other considerations when locating farms dependent on tidal water exchange. At a prospective site in the Philippines, with a maximum tidal range of -0.6 m mean sea level (MSL) to +2.2 m MSL, the most ideal elevation for the ponds are between elevations 0.0 and 1.4 m MSL (Fig. 3). Ponds built within this range can be filled and drained twice monthly since water can enter the pond during ordinary high tides, and the ponds can also be drained completely during ordinary low tides. Ponds with bottoms above +1.8 m MSL will normally require mechanical pumping to fill, while those with bottoms below -0.3 m MSL will require pumping to fully drain. Neither situation is desirable if the objective is to rely solely on tidal action for water exchange. Using pumps to drain a pond is highly undesirable in almost all situations.

As discussed more fully in a later chapter (see Chapter 22), water exchange by mechanical pumping, especially with semi-intensive or more intensive culture is more economical than water exchange by tidal action (Gedrey et al. 1983). With mechanical pumping, ponds can also be located at higher elevations behind the mangroves. This not only preserves this resource and perhaps avoids some acid soil problems, but it also allows water exchange at any time. It is easier to intensify culture in ponds with pumps than in tidal exchange ponds.

dela Cruz (1983) gives another example of a possible Malaysian pond site where tidal exchange could be used (Fig. 4). At that site, the tidal range was from +0.1 to +2.9 m MSL, while the average range during spring tides was from +0.5 to +2.7 m MSL. He recommended an optimum pond bottom elevation of +1.4 m MSL, while the outermost dikes should be built to +3.5 m MSL. Perimeter dikes must have ample freeboard and strength to withstand storm waves, storm surges, and the highest expected tides. Inner secondary and tertiary dikes can be lower since they are protected by the perimeter dikes and primary gates.

Normal daily tidal ranges in Indonesia, Malaysia, Philippines, Singapore and Thailand range from 0.4 to 3.6 m, with an average of 1.5 m at 34 sites considered (dela Cruz 1983). The range in absolute annual tidal extent was 1.0 to 5.5 m, with an average of 2.6 m. Tidal ranges tend to be smaller in tropical areas than at higher latitudes.

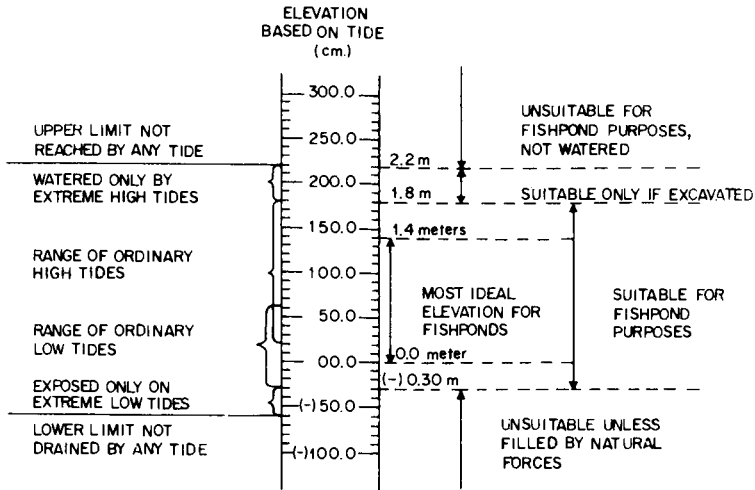


Figure 3. An example of pond elevation suitabilities relative to ordinary and extreme tide conditions at a prospective site. Figure from Jamandre and Rabanal (1975).

15.3 CONTROL GATES

The most primitive extensive ponds did not have gates to control water exchange between the pond and the water source. Instead, the dike was simply breached at high tide to flood the pond, the breach was closed, the "crop" grew in the pond for some time, and then the dike was again breached at low tide to harvest. This simple system did not easily allow for screening of the water, nor routine water exchange during the crop cycle. Yields from these primitive extensive ponds were low and unpredictable. This system is not widely used today.

Water gates, or sluice gates allow for greater control over pond stocking, pond productivity, and harvest. Wooden sluice gates were the first used (Fig. 5). They are still commonly used on small ponds, or for small harvest structures on large ponds. More recently, concrete and ferro-cement sluice gates became widely used (Fig. 6). These structures are strong, long lasting, multi-purpose and easy to construct. They can serve very large ponds. Average size of extensive ponds is greater than 5 ha, but can exceed 100 ha for a single pond.

Typical operation of extensive ponds with gates include flooding the pond at the beginning of the crop cycle, exchanging water twice monthly during spring tides, and draining fully at harvest. Flooding and initiation of the crop are often timed to coincide with seed abundance in the source water. This is often dictated by monsoon conditions, and varies locally. Fish as well as

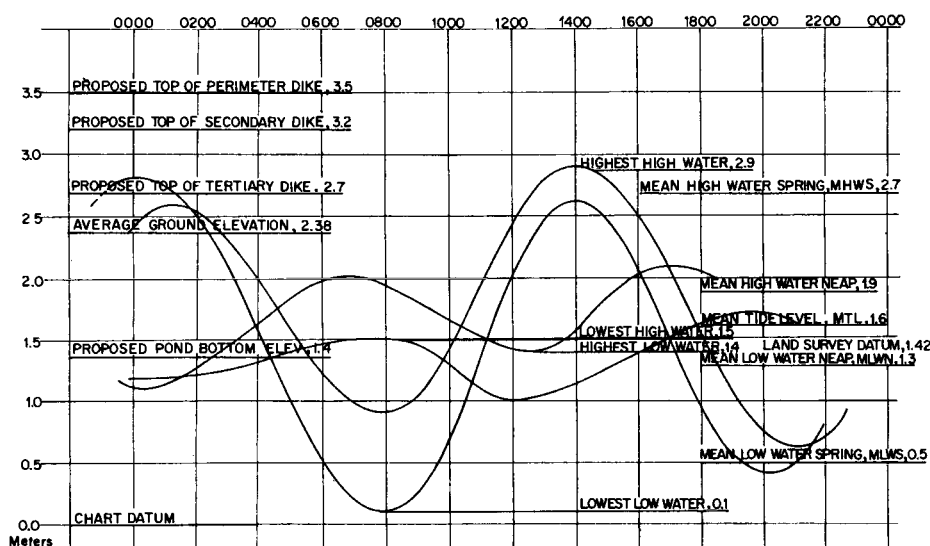


Figure 4. Proposed elevations of primary, secondary and tertiary dikes at a site in Malaysia relative to tidal conditions. The semi-diurnal tidal patterns are shown, as is the optimal pond bottom at 1.4 m MSL (Hechanova and Tiensoongrusmee 1980).

shrimp are introduced during flooding. Additional fish and/or shrimp are sometimes stocked with those that come in with the flood waters. Water exchange during the crop cycle increases productivity by nutrient additions, and perhaps other means. Water exchange is typically possible for 3 or 4 days twice a month, on the highest tides during the new and full moons. Additional seed may come in with these water exchanges. In some very large ponds built at low tide elevation, which are therefore difficult to drain fully, shrimp and fish are partially harvested during each water exchange. Smaller ponds, properly sited are normally drained fully at harvest time, and the crop harvested in nets at the sluice gate (see Chapter 19).

15.4 TAIWANESE EXTENSIVE PONDS

The earliest ponds in Taiwan date back more than 300 years. These extensive ponds were used to polyculture fish and shrimp, had irregular shapes with mud dikes, and in most cases no permanent inlet/outlet gates (Liao 1986). Their uneven bottoms were often littered with tree roots, rocks and other obstacles (Fig. 7). "The production of prawns depended on many uncontrollable environmental factors and people believed it was luck which determined the harvest" (Liao 1987). These primitive extensive ponds were

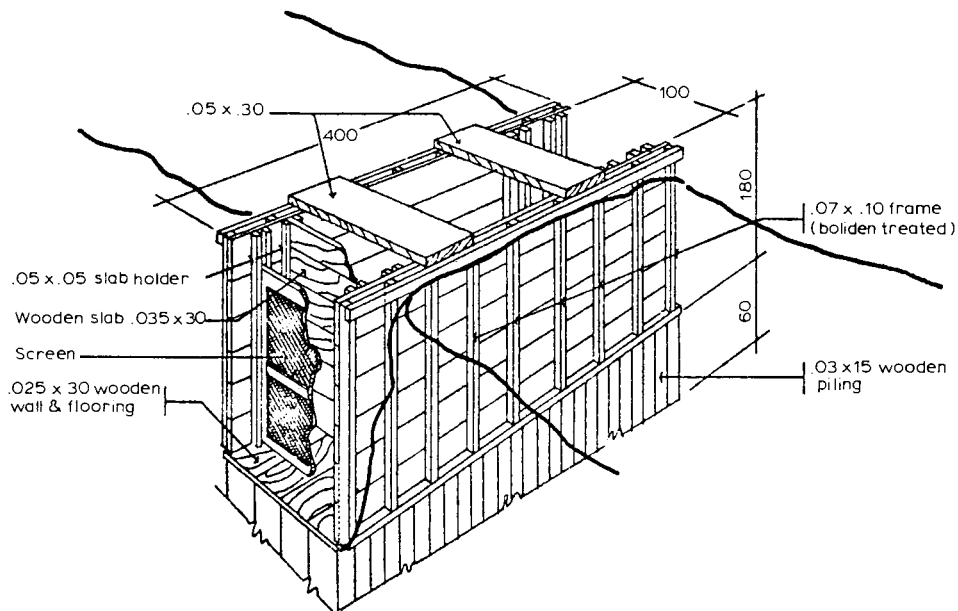


Figure 5. A secondary wooden sluice gate showing screens, control boards, and pilings. Figure from Jamandre and Rabanal (1979).

later upgraded by reducing pond area to about 3 ha, constructing more regular shapes with dikes surfaced on the inside by brick or concrete, and installation of one inlet/outlet gate (Fig. 8). Water exchange was by tidal action. Milkfish was the principal crop in these ponds, with shrimp as a secondary crop at less than 200 kg/ha/yr (Huang 1969, Liao 1981, Liao and Huang 1983).

15.5 PHILIPPINE AND INDONESIAN EXTENSIVE PONDS

The Philippines and Indonesia have perhaps the largest extensive brackishwater pond systems in the world, and perhaps the oldest large scale culture systems. Each country now has well over 200,000 ha of brackishwater ponds, most of which are still operated extensively. These ponds were built primarily for milkfish culture where shallow water is needed to promote the growth of benthic algal mats, the natural food of choice for milkfish in these ponds. Water depths range from 0.4 to 1.0 m. Ponds deeper than 0.5 m are less suitable because less light reaches the bottom resulting in less growth of benthic algae. These extensive ponds were traditionally served by tidal water exchange, and shrimp seed entered the ponds during flooding and water exchange. Most milkfish fry were stocked. Shrimp were the secondary crop

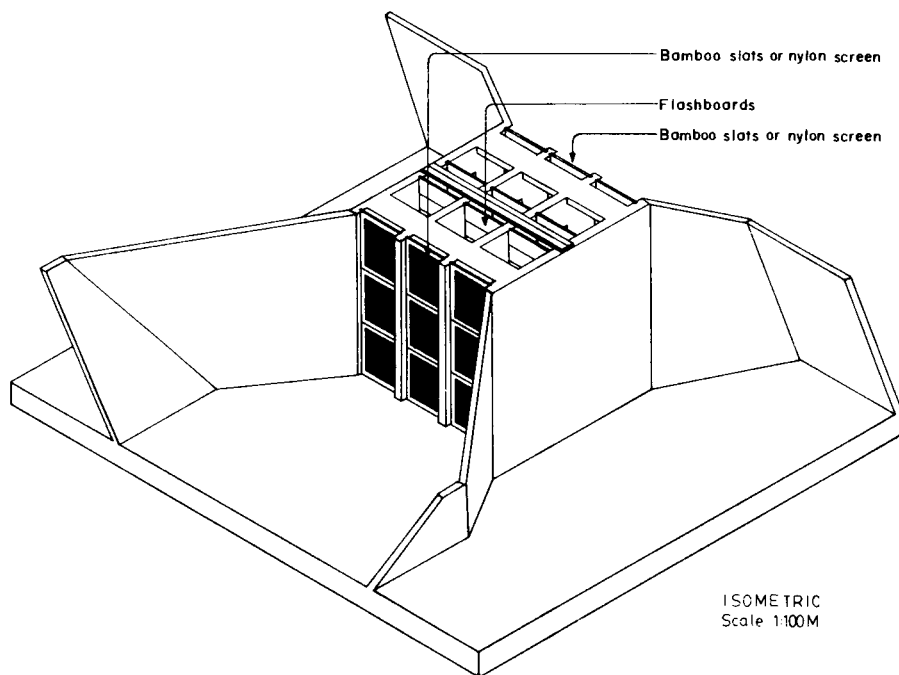


Figure 6. A concrete main gate with three openings. These gates would be placed on the primary or periferal dike and control water exchange between the entire farm and water source (dela Cruz 1983).

with yields of about 50 kg/ha/yr. As greater interest and profits developed from shrimp culture, many of these farms supplemented natural shrimp seed with seed from hatcheries and from wild seed collectors. Penaeus monodon is favored, and many farms intensified shrimp production for this species. Milkfish are now stocked in these ponds primarily to control excessive plant growth, which is considered harmful to the shrimp (U.S. Department of Commerce 1988).

Philippine extensive ponds, whether used for milkfish/shrimp polyculture or monoculture of shrimp only at low densities, typically have a single inlet/outlet from a single water source (Apud et al. 1983, Fig. 9). Ponds may have a harvest basin as shown, or simply use nets attached to the sluice gate for harvest. Ponds used for shrimp tend to be slightly deeper than milkfish ponds, to perhaps 1.0 m.

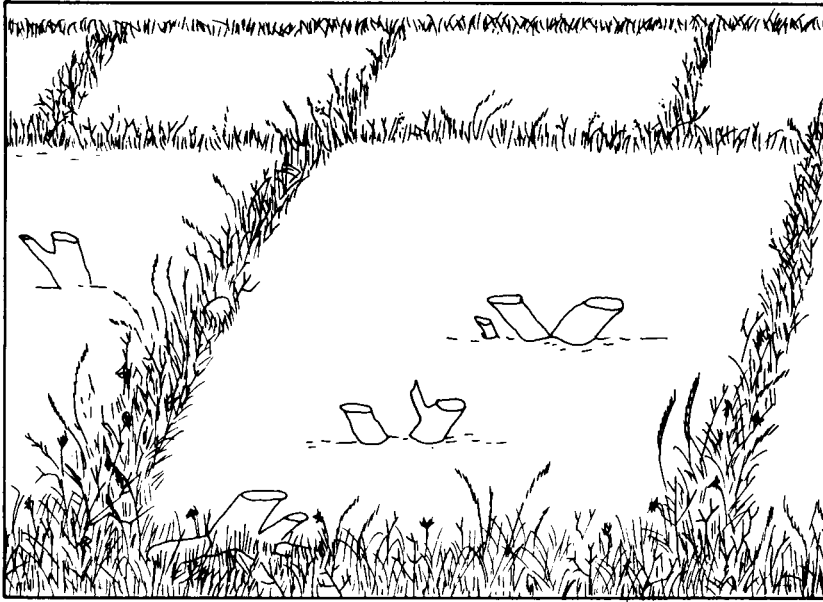


Figure 7. Primitive growout pond used for low intensity shrimp and fish culture in Taiwan. Note the lack of a gate and the obstacles on the pond bottom. (Liao 1986)

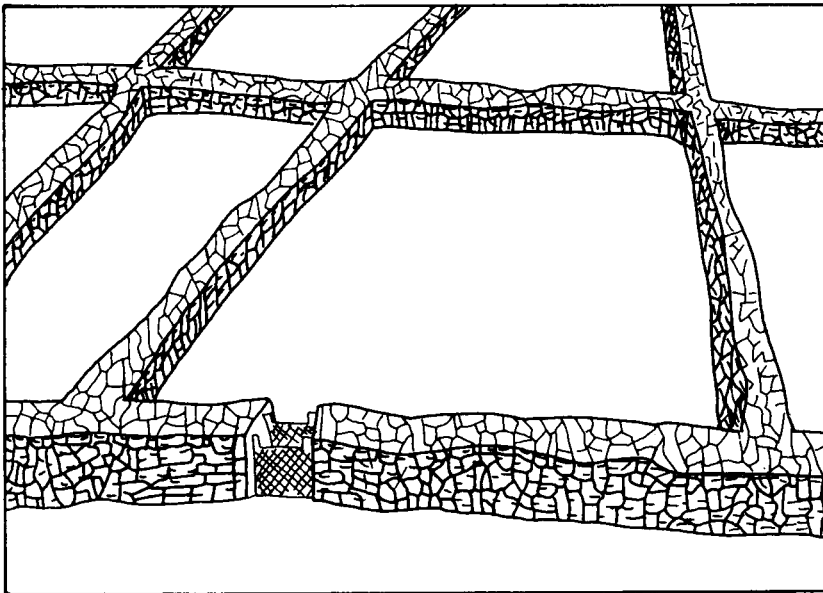


Figure 8. Improved shrimp or milkfish pond typically used in Taiwan before 1960. Note the gate, well maintained, dike and lack of obstacles. (from Liao 1986)

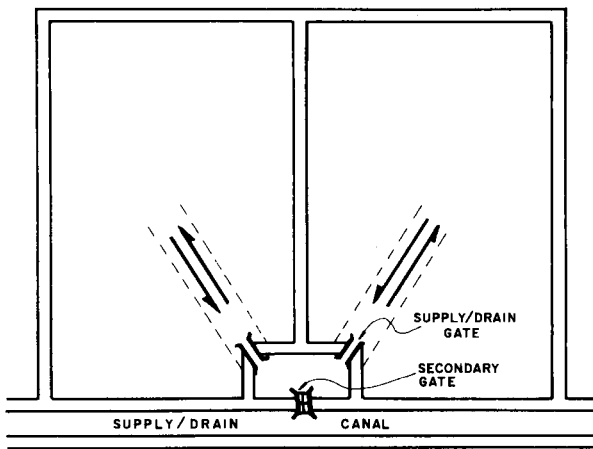


Figure 9. Traditional shrimp and fish pond used in the Philippines. The ponds share a catch pond and a supply/drainage canal. (from Apud et al. 1983)

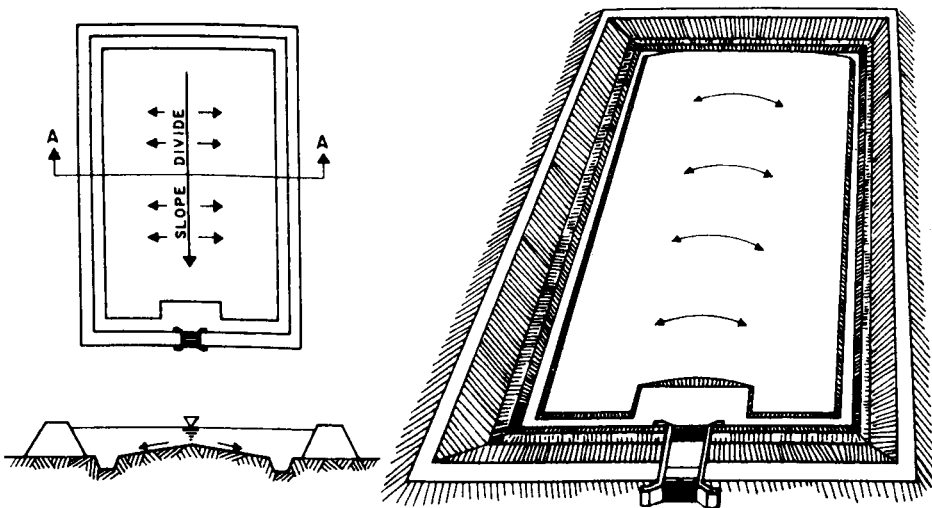


Figure 10. A peripheral ditch shrimp pond of the type used in Thailand for extensive shrimp culture (dela Cruz 1983).

15.6 THAI EXTENSIVE PONDS

Many extensive marine shrimp ponds in Thailand were converted from rice paddies or salt production ponds. These ponds typically have raised central platforms surrounded by a peripheral canal next to the dike (Kunguankij et al. 1986; Fig. 10). The peripheral canal provides material for the dike. Canal depth is 0.9 to 1.0 m, while the central platform depth is only 0.4 m. Shrimp stay in the cooler, darker canal during the day, and forage for food on the platform at night. The shallow platform depth encourages benthic algal mat growth, as with milkfish/shrimp ponds in the Philippines and Indonesia. In large, extensive Thai ponds, a submerged dike is sometimes placed at the periphery of the central platform to reduce wave action and dike erosion (Fig. 11). Thai ponds may have a peripheral canal only, or peripheral and central canals (Fig.'s 10 and 12).

These canals not only provide refuge for the shrimp during the day, but they also facilitate drain harvesting as well. During the initial stages of draining, water velocities are low and shrimp will generally move with the water into the canals, if they are not there already. Once the central platform is exposed, and water volume is reduced to the canals only, water velocity increases. This increased velocity more effectively carries shrimp to the outlet where they are captured (Apud 1985). Shrimp stranding is thus reduced, and those that do remain in the pond after complete draining are more easily retrieved from the smaller area of the canals.

Most extensive ponds have irregular shapes, not like those illustrated so far. Some more typical Indonesian extensive ponds are shown in Figure 13. These ponds were used for milkfish only, or polyculture of milkfish with shrimp.

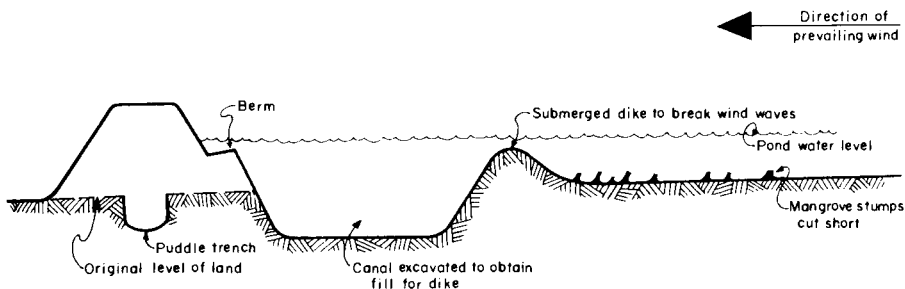


Figure 11. Cross-section view of dike-canal style shrimp pond of Thai construction. A submerged dike is also provided to reduce wave action, and to protect the dike. (dela Cruz, as modified from Cook 1976).

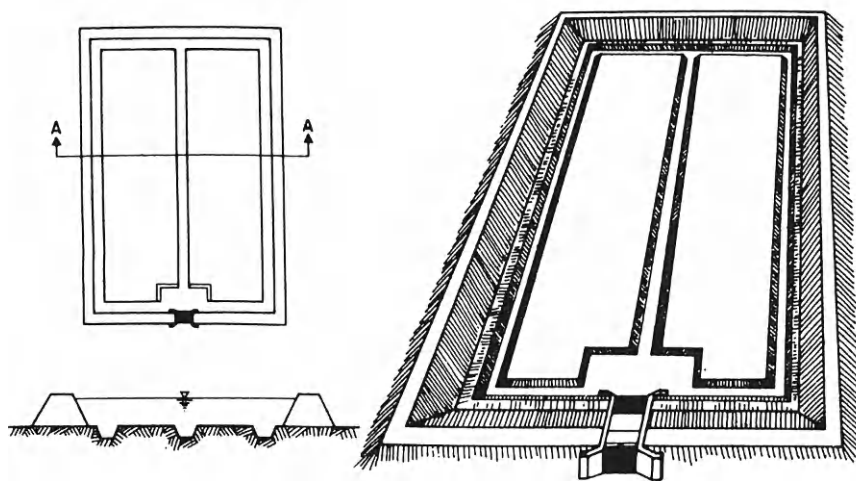


Figure 12. A peripheral ditch style shrimp pond of the type used in Thailand, with a central ditch in addition to the peripheral ditch (de la Cruz 1983).

15.7 BANGLADESHI AND INDIAN EXTENSIVE PONDS

In Bangladesh and India, 20,000 ha of low-lying rice fields near the ocean are flooded annually during the dry season (Nov. - March) for extensive production of shrimp and fish (Tang 1981, Shang 1983). Coastal dikes are breached and these areas are flooded, passively stocking the fields with shrimp, fish and other aquatic organisms. After flooding, the dikes are sealed and the crop allowed to grow for 4 to 5 months until harvest at the end of the dry season. Rice is then planted during March, at the beginning of the wet season. Shrimp yields are about 50 kg/ha/yr from these systems. In Bangladesh, shrimp are commonly grown in salt evaporation ponds during the wet season, with salt production during the dry season. Shrimp stocking and production in a salt-shrimp rotation, as with rice-shrimp, is left to chance with virtually no attention to water exchange, fertilization, feeding, or other pond

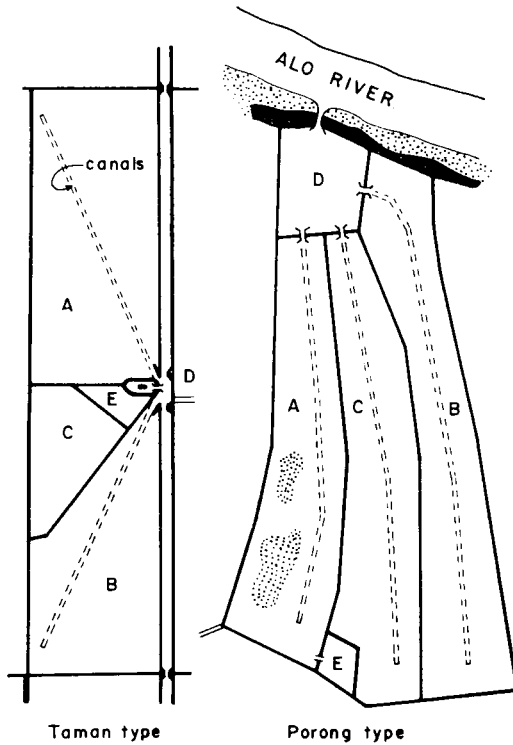


Figure 13. Two types of extensive milkfish and shrimp pond used in Indonesia (Djajadiredja and Daulay 1982).

management activities. Bangladeshi shrimp yields with salt-shrimp rotation are about 60 kg/ha/yr from about 6,000 ha.

15.8 ECUADOREAN EXTENSIVE PONDS

In Ecuador, one of the world's largest producer of cultured marine shrimp, the industry got its start in 1962 by what could be termed, "accidental extensive" pond culture. According to most accounts, impetus for the industry began after an unusually high tide breached a coastal dike intended to protect a banana plantation. The resultant flooding carried in shrimp seed which grew to a large size and were subsequently harvested months later when the area dried (U.S. Dept. Commerce 1988).

15.9 SUMMARY

Extensive pond culture of marine shrimp can be quite profitable. Feed, seed, energy, and labor costs are all low. The principal potential costs are land, construction, and maintenance. Large, vacant land areas, available at low cost for new farms are now in short supply. For many existing extensive farms, however, land and construction costs are fully depreciated, and they can operate profitably even with depressed shrimp prices (Hirasawa 1985). Furthermore, many extensive ponds lend themselves to intensification, at least to semi-intensive levels. There will likely be more land devoted to extensive marine shrimp culture, but total resource considerations and rising land costs are likely to limit this expansion. Extensive ponds, even an expanded amount, will not be able to meet the future market needs for marine shrimp. These needs may be met most profitably through more intensive culture systems, particularly through semi-intensive culture (Hirasawa 1985). Thus we can reasonably expect continued upgrading of many extensive ponds.

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CHAPTER 16

Arlo W. Fast

PENAEID SEMI-INTENSIVE GROWOUT SYSTEMS

16.1 INTRODUCTION

Semi-intensive shrimp ponds are relatively recent. Most development has occurred during the past 10 to 15 years. They are efficient and profitable to operate, but depend on a reliable seed supply, and greater management intervention in the pond's operation than with extensive ponds. Most seed for semi-intensive culture come from hatcheries, or from seed collectors who capture wild seed and sell them to the farms. Management is needed to affect satisfactory dissolved oxygen content, timely water exchange, nursery operations, appropriate feeding, and control of unwanted intruders. Skilled labor needs per unit land area increase greatly for semi-intensive ponds relative to extensive ponds, although there is a corresponding increase in shrimp production.

Semi-intensive pond systems in Latin America evolved quite differently from those in Asia. Latin American farms rely almost exclusively on high water exchange rates by diesel driven pumps to maintain water quality. Electric or diesel driven aerators are rare in Latin America. In Asia, electric aerators and electric water pumps are far more common. Much less water is exchanged in semi-intensive Asian shrimp ponds. Perhaps the main reason for the differences had to do with low fuel prices in some Latin American countries, particularly Ecuador. In most Asian countries, fuel is expensive and electrical service is the system of choice.

16.2 ECUADOREAN SEMI-INTENSIVE PONDS

In Ecuador, semi-intensive shrimp growout ponds are large, with many ranging from 20 to 40 ha. Farms are also large. In 1982, 50% of Ecuador's shrimp farms were 50 ha or larger, and 10% were larger than 200 ha (Hirono 1983; Chapter 38). A typical semi-intensive shrimp farm in Ecuador consists of a large central canal that delivers water to the individual ponds (Fig.'s 1, 2 and 3). Water is pumped into the canal from a turbid estuary. The pumps are very high volume and are normally operated only during certain tidal stages to take advantage of desirable salinities (Fig.'s 4 and 5). Once in the

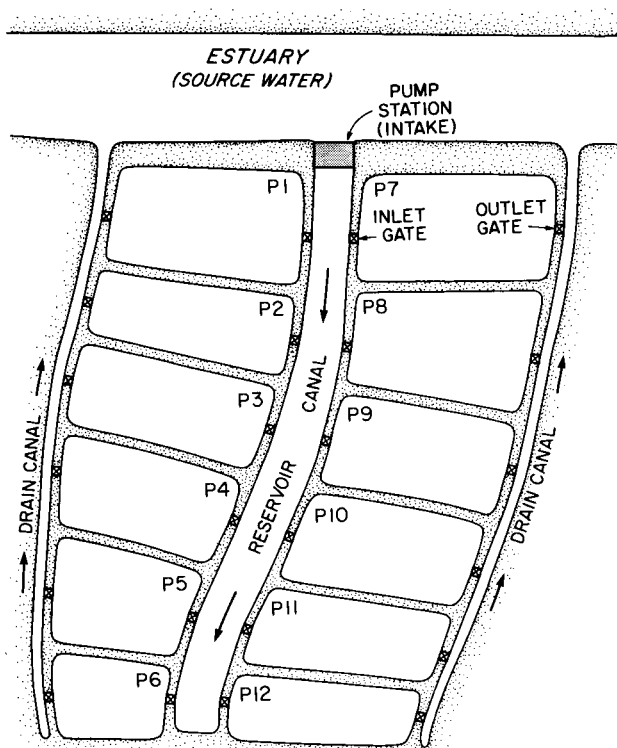


Figure 1. A typical semi-intensive farm in Ecuador. The farm has one water intake structure, a reservoir canal feeding the ponds, and drainage canals that return waste water to the water source. (Fast in press).

central canal, suspended solids settle out before reaching the ponds. It is easier, more economical, and less disruptive of crop cycles to remove sediment from the canal than from the ponds. Diesel-powered water pumps with 60 to 90 cm diameter intake/discharge pipes and 100 m³/minute or greater capacities are commonplace. On average, 10% of farm pond water volume is exchanged daily, although water exchange in a given pond may range from 0 to more than 50% per day. Some large farms employ several biologists whose main task is to monitor water quality. Water quality, especially dissolved oxygen, algae densities and algae health are closely monitored and are the main criteria used to determine water exchange.

This form of semi-intensive culture evolved in large part due to the large supply of low cost diesel fuel in Ecuador. Ecuador is a petroleum exporting country, and during 1987 diesel fuel price was \$0.08/l. The basic concepts for



Figure 2. Aerial view of semi-intensive farm in Ecuador. A reservoir/canal delivers water from the pump station (upper right) to nursery and growout ponds. A drainage ditch at the opposite end of each pond returns effluent water to the source.



Figure 3. Aerial view of semi-intensive farm in Ecuador. A triple reservoir canal delivers water from the pump station (upper left) to nursery and growout ponds. Three-phase nursery/growout ponds are shown below the reservoir canals.



Figure 4. A large, primary pump station on a semi-intensive shrimp farm of more than 800 ha in Ecuador. Ten diesel driven pumps delivered water from the source estuary to the reservoir canal.

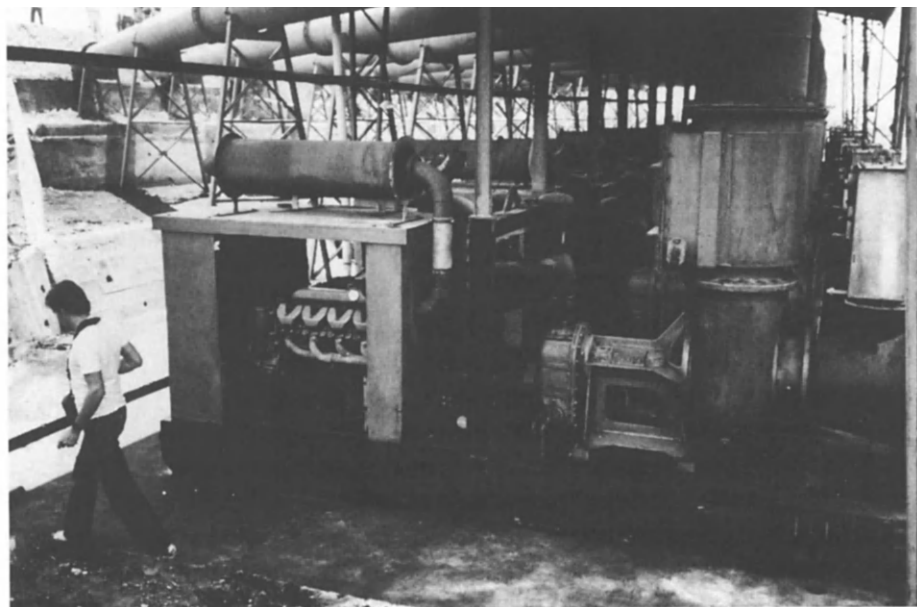


Figure 5. Diesel driven pumps at the primary pump station in Figure 4.

semi-intensive shrimp culture systems in Ecuador are an extension of earlier strategies in Panama, although Ecuador has developed them more fully. Perhaps the next logical development in Ecuador farm operation is use of diesel-powered aerators, which should result in less water use, greater overall energy conservation, and greater yields per ha. Hirono and Leslie (see Chapter 38) describe Ecuadorian shrimp culture in more detail.

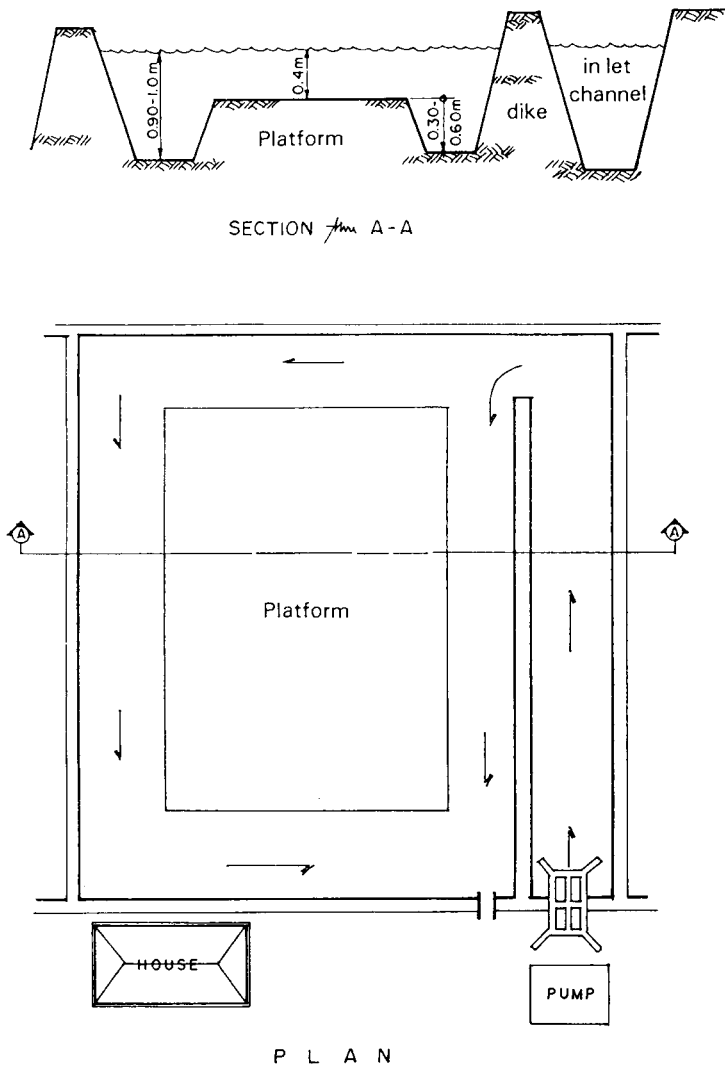


Figure 6. An extensive shrimp pond in Thailand. Water inflow may be with from pump or tidal. One water source is used for supply and drainage. A cross-section of the pond is shown above (Kungvankij et al. 1986).

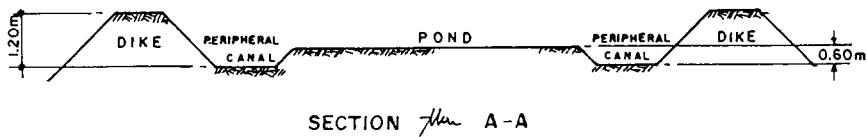
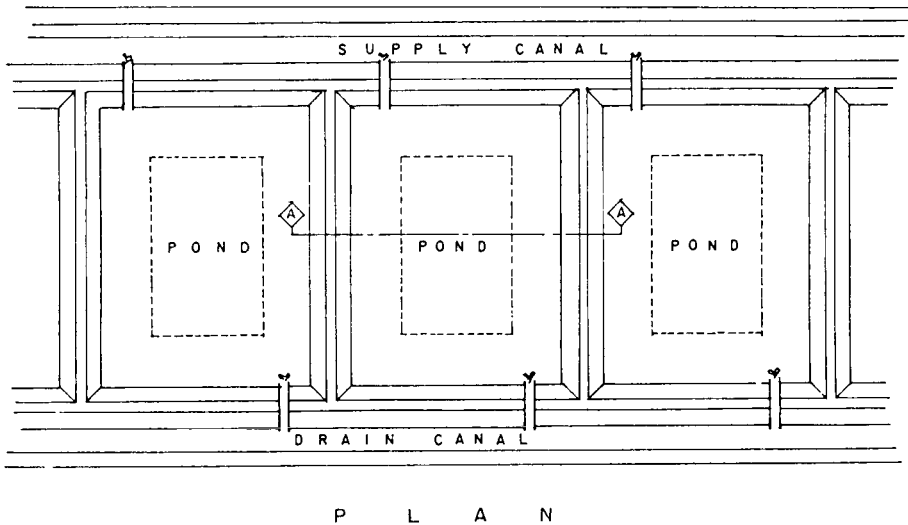


Figure 7. Semi-intensive, dike-canal style shrimp ponds used in Thailand. One gate is for supply water, the second for drain water. Water may be exchanged by tidal action, or by water pumps (Kungvankij et al. 1986).

16.3 THAI SEMI-INTENSIVE PONDS

In Thailand, semi-intensive shrimp ponds typically have a pump station on each pond, with either an outlet on the same water supply (Fig. 6), or an outlet on a separate canal (Fig. 7). They usually use the same central platform described earlier for extensive ponds.

16.4 PHILIPPINE SEMI-INTENSIVE PONDS

In the Philippines, semi-intensive ponds are typically converted from extensive ponds by either raising the dikes, thus increasing water depth, or by provision of a diagonal canal (Fig. 8). The canal has a water depth of 0.8 to 1.0 m, and the shallow platforms are about 0.4 m deep. These diagonal canal ponds are analogous to Thai peripheral canal ponds. In former mangrove

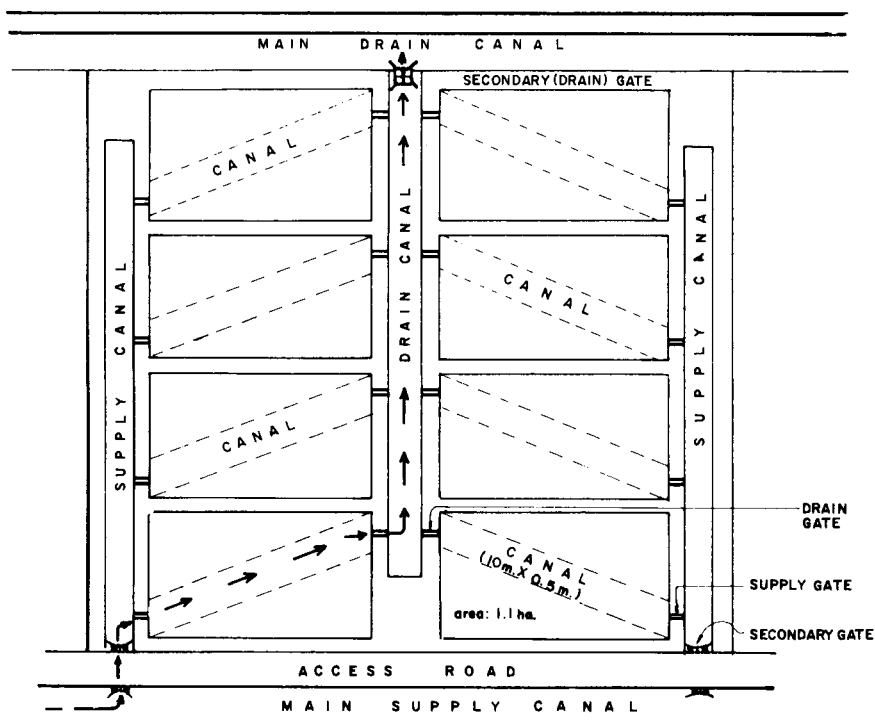


Figure 8. Semi-intensive shrimp ponds in the Philippines with diagonal canal between the pond inlets and outlets. Each pond has two gates, one for supply and one for drain water (Apud et al. 1983).

areas with acid soils, care must be taken when deepening ponds or excavating canals so as not to recreate acidic conditions.

16.5 INTENSIFICATION OF EXTENSIVE TO SEMI-INTENSIVE CULTURE

Semi-intensive culture ponds may be created through intensification of existing extensive ponds. This may include such things as clearing and leveling the pond bottom; increasing water depth by raising the dikes, deepening the bottom, and/or digging canals in the pond bottom; converting from tidal water exchange to pumped water exchange; provision of mechanical aeration; conversion to multiphasic growout with nursery phases; control of stocking density; greater use of fertilizers; use of fish toxicants to control fish intruders; and provision of feed.

Table 1. Comparison between operational characteristics, costs and income per hectare from traditional extensive shrimp farm, and semi-intensive shrimp farm in The Philippines. Modified from Kungvankij et al. (1986).

Item	Farm Type	
	Extensive	Semi-intensive
Pond size	more than 3 hectares	5000 m ² -2 ha
Pond shape	Irregular	rectangular or square
Depth	30-40 cm	80-100 cm
Water gate	One	2 gates, inlet and outlet
Central ditch	None	5-10 m wide, 50 cm deep
Pond preparation		
draining	Yes	Yes
drying	Yes	Yes
eradication of predator	Yes	Yes
liming	Yes	Yes
fertilization	Prior to stocking only	Throughout culture period
Stocking (PL)	3000-8000/ha	20,000/ha
Supplementary feed	None	Two months after stocking
Water management	Tidal	Tidal
Total yield (kg)	400	900
INCOME	\$1,700	\$3,800
FIXED COSTS	767	1,128
OPERATING COSTS	490	1,389
TOTAL COSTS	1,257	2,517
NET INCOME	\$443	\$1,283

Kungvankij et al. (1986) conducted a hypothetical comparison between an extensive milkfish/shrimp pond in the Philippines converted to semi-intensive shrimp culture. The conversion included reducing the pond size; adding a water gate (separate inlet/outlet gates); increasing water depths from 0.3 to 0.4 m, to 0.8 to 1.0 m; and feeding after 2 months in the semi-intensive case (Table 1). Tidal water exchange was used in both cases.

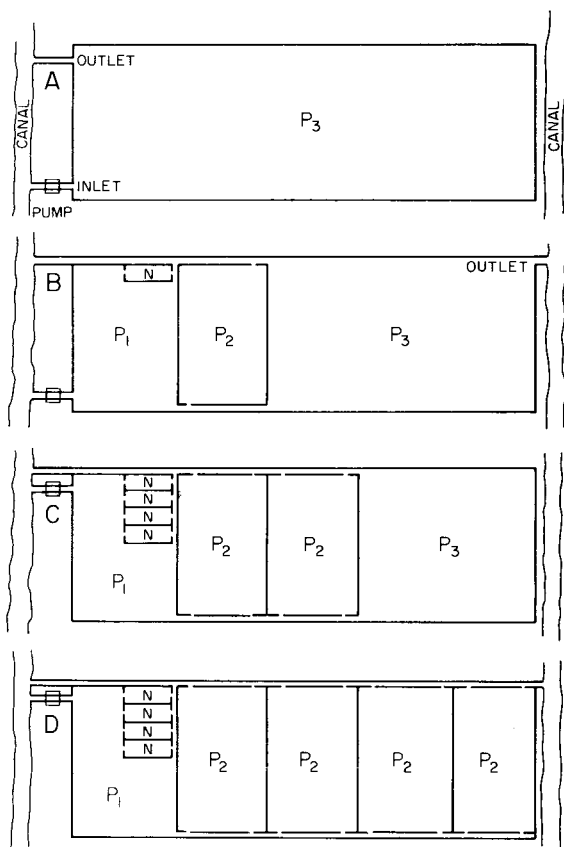


Figure 9. Intensification of traditional Thai shrimp ponds. Pond A is unimproved; D is upgraded to semi- intensive. N, nursery; P_1 , PL capture pond; P_2 , semi- intensive pond; P_3 , traditional pond (Menasveta and Higuchi 1983).

Black tiger prawn (*Penaeus monodon*) were stocked in both cases, but at more than 2 to 6 times the density with semi-intensive culture. Total yield increased from 400 kg/ha of fish and shrimp with the extensive case, to 900 kg/ha of mostly shrimp with the semi-intensive case. Net incomes were \$443 and \$1,283 respectively.

Menasveta and Higuchi (1983) describe a similar staged intensification of a Thai extension shrimp farm to semi-intensive culture. This simulation was conducted as part of an Asian Development Bank planning study. The original farm consisted of a single 4.8 ha pond with inlet and outlet on the same canal (Fig. 9A), while the fully intensified case consisted of a sedimentation and PL collection pond, four nursery ponds and three growout ponds with inlet and outlet on separate canals (Fig. 9D). Shrimp production was about 150 kg/ha/yr with the original configuration, but was expected to

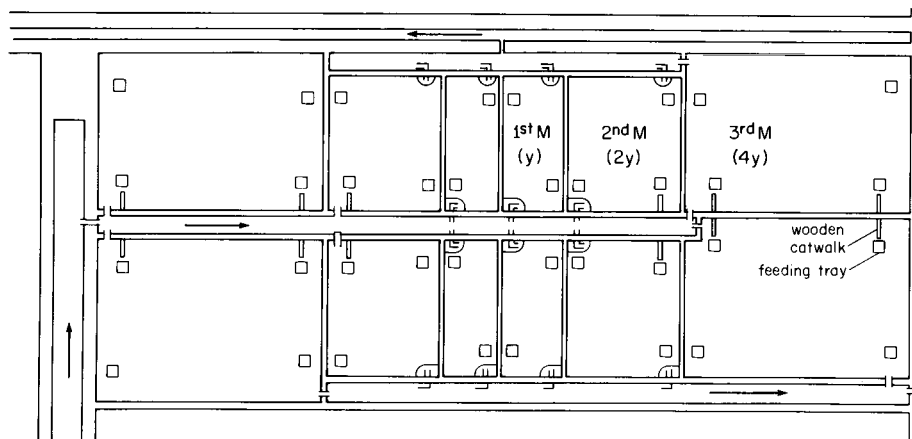


Figure 10. Pond layout for contiguous multiphasic growout system using two nursery ponds and one growout pond per set (Pudjiatno and Baliao 1987).

be 450 to 600 kg/ha/yr or more after intensification due to better use of space, better intruder control, less inoperable time for sediment removal, and higher water quality.

Nursery ponds are commonly used in semi-intensive and more intensive culture, whether the PL are wild caught or hatchery reared. By first placing the PL in nursery ponds for 30 to 60 days before stocking in the growout ponds, better use is made of a given land area. More crops can be reared in the growout pond per year, and overall yield per ha is increased. During transfer from nursery to growout ponds, an accurate shrimp count can be made, resulting in better inventory assessment and more accurate feeding rates. If properly managed, a greater portion of the shrimp's feed needs can be provided by food chain sources with multiphasic growout in semi-intensive culture. In addition, it is easier and more effective to eliminate fish intruders from nursery ponds, due to the smaller size of these ponds.

Pudjiatno and Baliao (1987) propose a semi-intensive pond layout for Philippine conditions that includes two nursery ponds and a final growout pond (Fig. 10). There is a doubling in pond area with each stage. The growout pond contains four times the area of the first nursery pond. Each pond has inlet and outlet gates on separate canals. Although the nursery and growout ponds are contiguous, shrimp can be transferred between any two ponds. In some contiguous nursery/growout configurations, gravity transfer is normally used only between ponds in a given series.

The International Finance Corp. (1987), an affiliate of the World Bank conducted a study of marine shrimp farming, and prepared a guide to feasibility study preparation. Their "ideal" example for a profitable shrimp

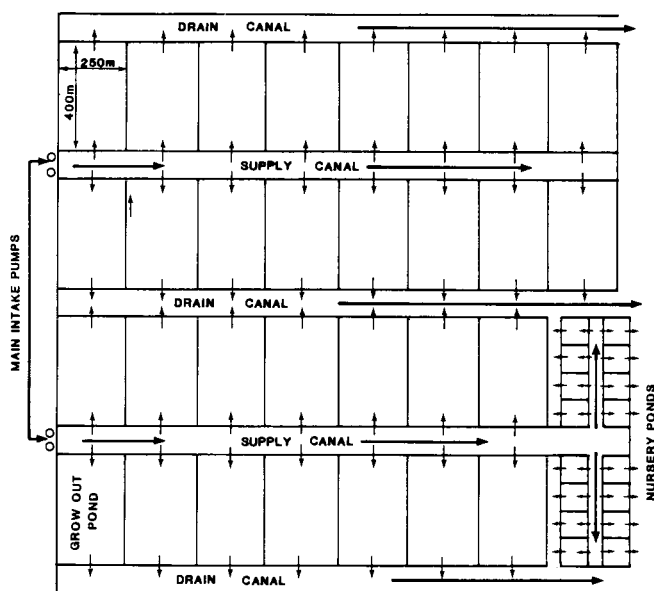


Figure 11. Proposed semi-intensive farm layout: 300 ha, 30-10 ha growout ponds, and 16-1 ha nursery ponds. The production of any nursery pond could be stocked into any growout pond (International Finance Corp. 1987).

farm was a 300 ha, semi-intensive farm including thirty 10 ha growout ponds, and sixteen 1 ha nursery ponds (Fig. 11). Each pond had its own water supply canal and gate, and a separate drain canal and gate. Two pump stations provided water for the entire farm. The nursery ponds were independent of each other and of the growout ponds, and nursed shrimp could be moved from any nursery pond into any growout pond, thus offering maximum operational flexibility. In this example, only one nursery stage was used.

With or without nursery ponds, semi-intensive shrimp culture has the greatest profit per kg of production (Hirasawa 1985). This means that semi-intensive farms can remain profitable during times of falling shrimp prices when extensive, intensive and ultra-intensive farms are all operating at a loss. If world shrimp prices follow an expected downward trend due to over supply, or if prices fluctuate widely as during 1989, then efficient, semi-intensive culture of shrimp should prevail.

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CHAPTER 17

Arlo W. Fast

PENAEID INTENSIVE GROWOUT SYSTEMS

17.1 INTRODUCTION

Like semi-intensive shrimp culture, intensive marine shrimp culture is a recent development which has taken place over the last 20 years. Like ultra-intensive shrimp culture, intensive culture is only practiced where seed to stock the ponds are available when needed, in adequate amounts, and of the preferred species. For the most part, this means use of hatchery produced PL which have been nursed 20 to 60 days.

17.2 TAIWANESE INTENSIVE PONDS

Although intensive culture systems first developed in Japan with Penaeus japonicus (Hirasawa 1985), intensive culture is now most associated with Penaeus monodon culture in Taiwan; and is often referred to as the Taiwanese intensive shrimp culture system. This technology evolved in southern Taiwan, mostly in the Kaohsiung area as a result of maturation and larviculture developments by Dr. I-Chiu Liao and others at the Tungking Marine Laboratory near Kaohsiung (Liao 1984, Liao and Chao 1983). This area is blessed with warmer weather than northern Taiwan, ample freshwater, a fishing fleet, suitable pond soils, and well developed industrial and community support infrastructure. Taiwan also has a long tradition of pond culture for many marine species.

Csavas (1988), describing the relevance of Taiwanese intensive shrimp culture, concluded that; "Future developments notwithstanding, Taiwan will always be quoted by historians of aquaculture as the forerunner of shrimp culture development, whose example, techniques and technicians shaped events on a global scale. Whether this example was clearly understood in other countries, whether these techniques are applicable under different geographic and socioeconomic conditions, is and will be disputed for a long while." Several authors describe these practices in detail (Liao 1984, Chiang and Liao 1985, Liu and Mancebo 1983, Hirasawa 1985, Fast et al. 1989). Here, I will give a brief overview.

Unlike extensive and semi-intensive culture where food chain production of shrimp forage is important, almost all of the shrimp's nutrition in intensive systems comes from costly formulated diets (Table 1). These feeds during

Table 1. Comparison between pond culture systems for marine shrimp in Ecuador (Hirono 1983) and Taiwan (Fast, in press).

	Ecuador	Taiwan
1. Growout Intensity	Semi-intensive	Intensive
2. Business Form	Corporation	Family business
3. Farm Size (ha)	50-500	4
4. Pond Size (ha)	10-40	0.5
5. Shrimp Species	<u>P. vannamei</u> <u>P. stylirostris</u>	<u>P. monodon</u>
6. Water Source	Surface waters	Wells
7. Salinity Control	Very little	Good, blend fresh and salt water
8. Principal Power Source	Diesel engines	Electric service
9. Power Cost (diesel fuel vs. electricity)	\$0.08/liter	\$0.048/kw-hr
10. Land Costs	Low	Very high
11. Pond Construction	Earthen	Concrete wall
12. Water Depth (m)	1	2
13. Aeration	None	Paddlewheel
14. Seed Source	Wild & hatchery	Hatchery/nursery
15. Nursery	Some	Most
16. Seed Cost	\$3-\$6/1,000 PL5-10	\$3-\$5/1,000 PL5 \$40/1,000 PL20-40
17. Stocking Densities (PL/m ²)	5 to 12	30-40
18. Crops/yr	2.4	2+
19. Survival	75%	75%
20. Feed Conversion	2.6	1.7
21. Feed cost/kg	\$0.28 to \$0.40	\$0.88
22. Harvest size (g) (whole shrimp)	16 - 24	30 - 35
23. Yield (kg/ha/crop) (kg/ha/yr)	800 to 1,500 1,900 to 3,600	5,000 11,500
24. Labor Costs	Low	Low
25. Water Exchange	High	High

1985 cost \$0.88/kg in Taiwan, compared with \$0.26 to \$0.40/kg for semi-intensive diets in Ecuador. High quality feed for intensive culture is necessary because of dense stocking rates of 20 to 40 PL or juvenile shrimp/m², and ultimate standing crops at harvest 5 to 10 times greater with intensive than semi-intensive culture, or more than 40 times greater than with extensive culture. Intensive shrimp culture is to extensive shrimp culture as cattle feed lots are to cattle on range land. In both cases, the comparison is between the crops (shrimp and cattle) obtaining sustenance from natural

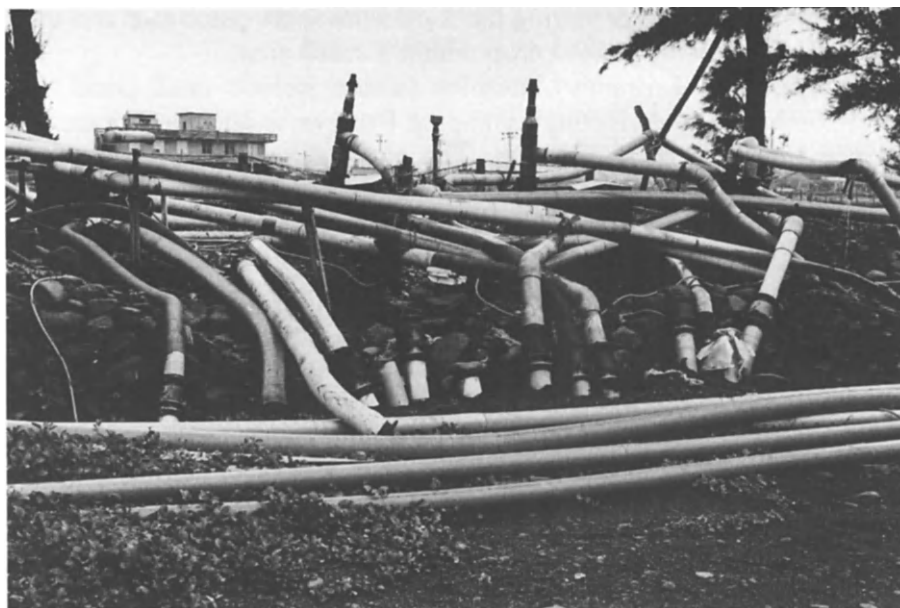


Figure 1. Seawater supply pipes in Taiwan leading from wells near the ocean to many farms inland. Pipe diameter are typically 11 cm (4 to 5 inches). Photograph from Fast et al. (1989).



Figure 2. Old style concrete pond wall in Taiwan with double water supply canal on top. Photograph from Fast et al. (1989).

productivity as opposed to gathering the food from some place else and then applying it to the densely packed crop within a small area.

Other aspects of Taiwanese intensive culture include small pond size, high water exchange rates through pumping from wells and the ocean, and dependence on mechanical aeration. The small pond size resulted from several conditions. First, land costs in Taiwan are very expensive, which not only favors production systems that produce large amounts of crop per unit land area, but also small farms as well. Taiwanese intensive shrimp ponds average 0.5 ha or smaller, and average farm size is only 4 ha (Table 1). This is the size that a family can conveniently operate. Average pond and farm sizes for semi-intensive Ecuadorian systems are 10 to 40 ha, and 50 to 500 ha respectively. These large Ecuadorian farms are normally vertically integrated corporations, often including a hatchery, feed mill, and processing plant. In Taiwan, vertical integration is rare, with each aspect of shrimp culture conducted by independent business people. Secondly, small pond sizes resulted in less risk and more constant cash flow. The loss of crop from any one pond would have relatively little impact on overall income with a farm consisting of many small ponds compared with the other extreme; a farm consisting of one large pond. Many ponds also means that crops are harvested and restocked more often, thus a more constant cash flow.



Figure 3. New style reinforced concrete pond wall under construction in Taiwan. Photograph from Fast et al. (1989).

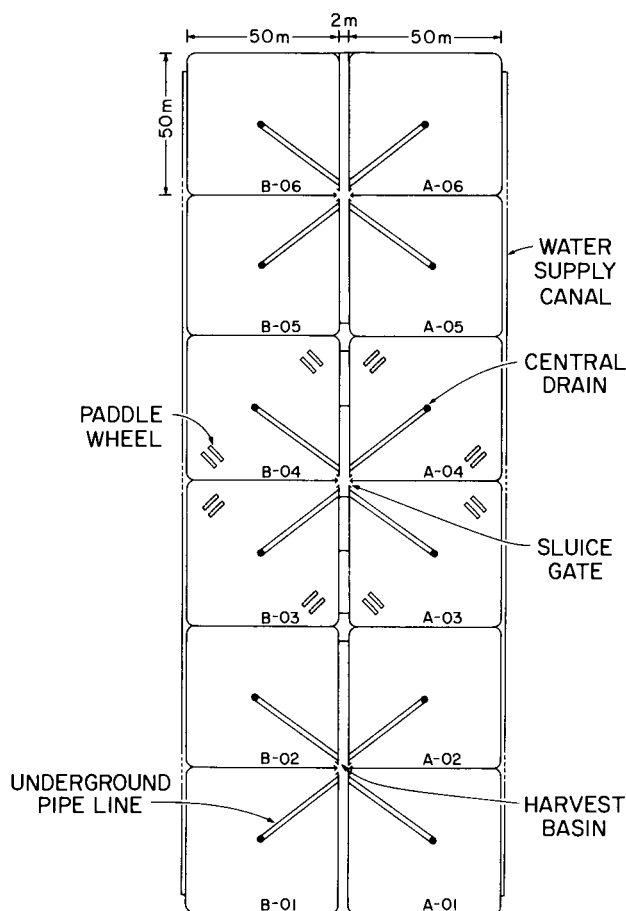


Figure 4. Twelve concrete walled shrimp ponds of Taiwanese design with center drains and paddlewheels (Liu and Mancebo 1983).

Average water exchange rates in Taiwanese intensive culture ponds ranges from only a few percent per day at the beginning of the crop cycle, to 20% or more per day just before harvest. Average water exchange per crop cycle is about 10%/day (Fast et al. 1989). The preferred methodology is to blend seawater (30 ‰) with freshwater to achieve pond salinities in the range 15 to 20 ‰. This necessitates two wells, or water sources. In those areas with many farms, PVC plastic pipes stretched several kilometers inland from the ocean to the farms (Fig. 1). The fresh groundwater in some of these areas has also suffered severe overdraft, with resultant land subsidence, saltwater intrusion into the groundwater, and greatly lowered ground water tables.

Mechanical aeration is mostly accomplished by paddle wheel aerators (see Chapter 22). On the average, 10 hp or more of these aerators are required per ha to maintain adequate oxygen concentrations.

Concrete pond walls are another unique characteristic of Taiwanese intensive shrimp culture (Fig. 2 and 3). Although these walls are expensive to construct, they allow more productive use of a given land area. This is particularly important when the land parcel is small (and expensive), and when many ponds are built on the parcel. When the shape of the parcel is square or rectangular, square or rectangular ponds are usually built (Fig. 4), but this often is not the case and many ponds take on irregular, odd shapes. In cross section, the walls typically consist of a footing below the pond bottom supported by pilings (Fig. 5). The exposed portion of the wall tapers upward from the footing and is capped by a walkway on top. The concrete is reinforced with steel rod. Wall height ranges from about 1.5 m on earlier ponds, to 2.0 m on most newer ponds.

Shrimp yields on well run Taiwan intensive shrimp farms average about 15,000 kg/ha/yr (Fast et al. 1989); but farm yield ranges from 5,000 to more than 20,000 kg/ha/yr. During 1985, profits on well run farms were very good,

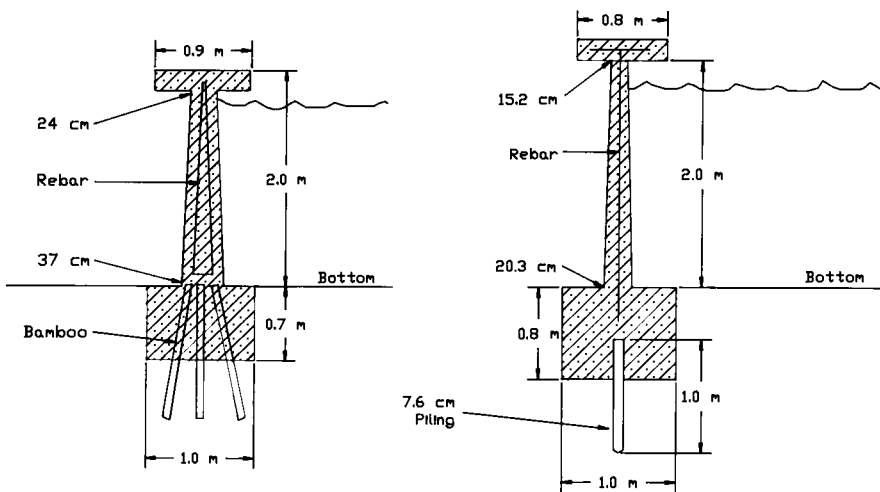


Figure 5. Cross-section of two 2 m high reinforced concrete walls used on Taiwanese intensive shrimp ponds. Each wall has a sub-soil footing supported by pilings, a wall portion, and a walkway on top. (Fast et al. 1989).

with net profits of more than \$16,000/ha. By any account, this resulted in an attractive return on investment. It caught the attention of businessmen and investors, and Taiwanese style intensive shrimp farms soon sprung up elsewhere. Thailand, the Philippines and Indonesia now have many hectares of these farms. More recently, as a result of demonstrations at South Carolina's Waddell Mariculture Research and Development Center, Taiwanese intensive shrimp culture farms have now been built in South Carolina, U.S.A. (Sandifer et al. 1988).

Small pond experiments in South Carolina with the Mexican white shrimp, *Penaeus vannamei* using Taiwanese methods, produced single crop yields of more than 12,000 kg/ha (Sandifer et al. 1988). Yields in larger commercial farms with the same species and methods produced yields of about 5,000 kg/ha/crop, but expectations are that with experience these yields will approach 10,000 kg/ha/crop.

While Taiwanese intensive culture was very profitable in Taiwan during 1985, and in most other Asian countries where it transferred, simulated transfer to Hawaii (U.S.A.) resulted in projected profit losses (Fast et al. 1989). Projected losses were \$11,891/ha/yr with earthen dike ponds in Hawaii and \$31,900/ha/yr with concrete walled ponds in Hawaii (Table 2). This compared with positive profits in Taiwan of \$16,511 for concrete walled ponds. Greater labor costs, and secondarily higher energy costs in Hawaii accounted for these differences.

Profitability of shrimp culture in Taiwan changed drastically during 1987 as a result of serious disease problems in Taiwan, and due to devaluation of Taiwan currency against the U.S. dollar. These problems have reduced production by more than 50% against 1986 levels, and even more if we

Table 2. Estimated annual gross revenue, production costs, and net profits for concrete walled intensive shrimp ponds in Taiwan, and concrete walled and earthen ponds in Hawaii. Data from Fast et al. (1989).

	Taiwan	Hawaii	
		Earthen Ponds	Concrete Pond
Production (kg/ha/year)	15,000	18,750	18,750
Farm price (/kg)	\$6.25	\$6.25	\$6.25
Gross revenue (/ha/yr)	\$93,750	\$117,188	\$117,188
Cost of production (/ha/yr)	<u>\$77,239</u>	<u>\$129,079</u>	<u>\$149,088</u>
Profit (/ha/yr)	\$16,511	(\$11,891)	(\$31,900)

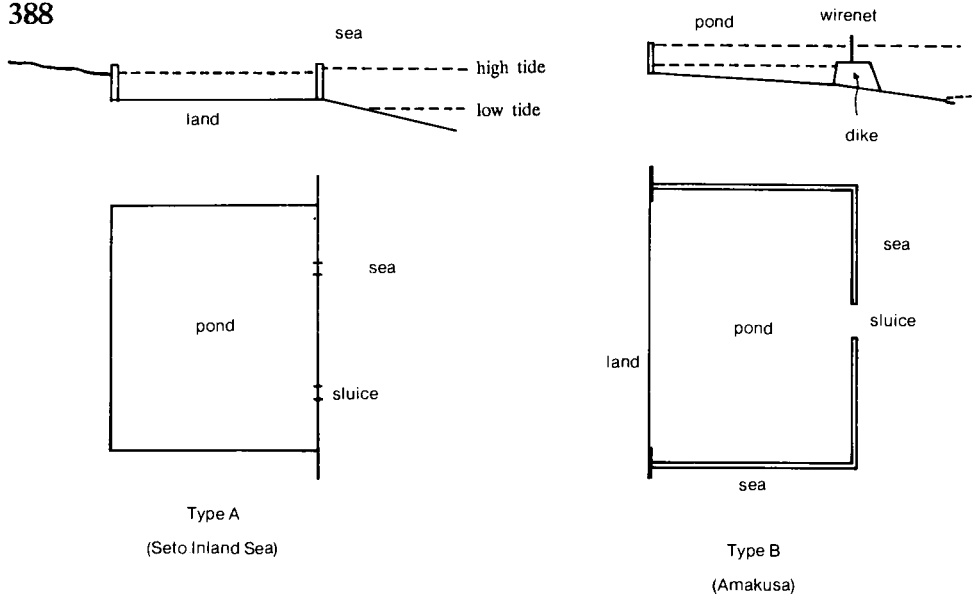


Figure 6. Two types of Japanese intensive ponds. Type A has a high wall with gates for water exchange; Type B has a low wall with a screen for water exchange at high tide (Hirasawa 1985).

consider likely production expansions in Taiwan if these problems had not occurred.

During the spring and summer of 1989, severe price drops occurred in shrimp exports from Thailand, the Philippines and Indonesia. These price drops were brought on by an oversupply, which was related to reduced imports by Japan combined with large volume shrimp exports from the People's Republic of China and Indonesia. Intensive shrimp farms were particularly hard hit by these price drops because of their small profit margins per kg. The market price dropped well below their break-even cost in almost all cases.

17.3 JAPANESE INTENSIVE CULTURE

Although we normally think of Taiwan as the birthplace of intensive shrimp culture, two earlier systems evolved in Japan for the culture of *Penaeus japonicus*. These two systems were the Amakusa, or pond in ocean systems; and the Seto Inland Sea, or pond on shore system (Hirasawa 1985). Yield from these two systems were similar, ranging from 3,000 to 10,000 kg/ha/yr, with average values of 5,000 kg/ha/yr.

The Amakusa system consists of a low concrete and stone wall built on the ocean bed within the intertidal zone (Fig.'s 6 and 7). The top of the wall is elevated such that high tides rise above the wall. Metal posts with screen are attached to the top of the wall such that water can freely exchange with the pond at high tide, but the shrimp cannot escape. This system results in

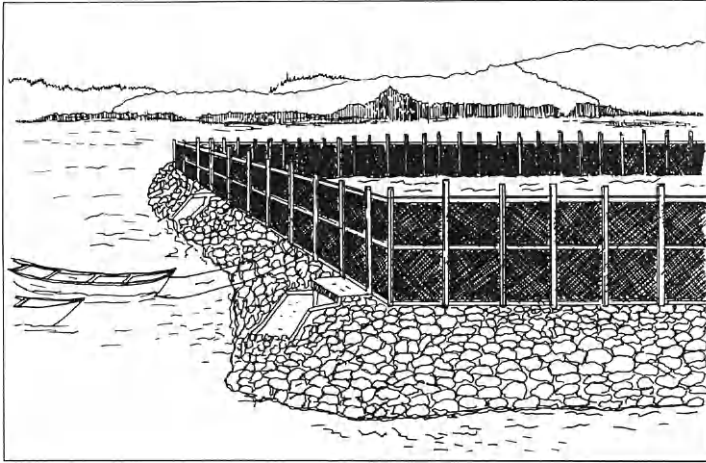


Figure 7. Amakusa style of semi-intensive, Japanese shrimp pond with a low wall, topped with a wire-screen fence that allows water inflow and outflow during high tide (Kungvankij 1985).

water exchange rates of 90%/day. Water exchange cannot be controlled, however, and feed conversion ratios in these ponds are poorer, presumably due to loss of natural productivity.

With the Seto Inland Sea system, the pond is also built within the intertidal zone, but the pond walls are built higher (Fig. 6). Water can only enter the pond through sluice gates, with the ponds being drained at low tide and filled during high tide. The pond operators regulate water exchange by this means within a range of 25% to 50%/day. This lower water exchange is associated with higher natural productivity and better feed conversion ratios compared with the Amakusa method.

Both the Amakusa and Seto Inland Sea shrimp culture systems use tidal water exchange rather than pumped water, which is contrary to the trend of increased use of water pumps with production intensification. Most of the sites in Japan which are suitable for this application have already been taken. Newer ponds of this design must be built at higher elevations and pumps used (see Chapter 30).

Intensive culture ponds in Japan are still profitable because of the very high price of live *Penaeus japonicus* in the Japanese market. This is a limited market. Frozen or fresh chilled *P. japonicus* do not sell for such a high price. The long range profitability of intensive culture systems for frozen shrimp sold on the world market is questionable. If production continues to increase from semi-intensive ponds at a greater rate than market demand, then shrimp prices will show the same downward trend they did during 1989. Unless substantial costs reductions occur in production techniques with intensive

shrimp culture, intensive shrimp culture may not remain competitive with less intensive systems.

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CHAPTER 18

Arlo W. Fast

PENAEID ULTRA-INTENSIVE GROWOUT SYSTEMS

18.1 INTRODUCTION

Ultra-intensive marine shrimp culture systems are at the opposite end of the spectrum from extensive culture. If extensive culture ponds can be compared with naturally balanced ecosystems, then ultra-intensive culture systems are comparable to factories. Ultra-intensive culture "ponds" are little more than culture vessels through which large amounts of materials and energy are passed under the close attention of skilled attendants and business managers. These shrimp factories produce large amounts of shrimp on very small land areas. Ultra-intensive systems are impressive examples of bio-engineering achievements.

Ultra-intensive culture is capable of yielding from 30,000 to 150,000 kg/ha/yr or more, compared with perhaps 50 kg/ha/yr for most extensive ponds (see Chapters 14 and 15). A 10 ha ultra-intensive farm producing 100,000 kg/ha/yr is comparable to 20,000 ha of extensive ponds producing 50 kg/ha/yr. With these yield levels and the large potential profits that are possible from shrimp culture, it is not difficult to understand the strong corporate interest in ultra-intensive shrimp culture.

To date, however, ultra-intensive culture systems have been technical successes, but economic failures. None of the systems developed and operated commercially have proven economically viable. Production costs and risks were too great in every case. Ultra-intensive systems simply have not competed with the low production costs per kg of extensive and semi-intensive production (Hirasawa 1985). These conditions notwithstanding, ultra-intensive shrimp culture is a scientifically interesting development.

Development of ultra-intensive shrimp culture systems started at about the same time that development of semi-intensive and intensive began, during the late 1960's and early 1970's. In all three cases, technological breakthroughs in seed production, high shrimp prices, and a large market fueled development interest. Early work led to the development of two systems of ultra-intensive shrimp culture which reached commercialization. One round pond system was developed in Japan, and is commonly referred

to as the Shigueno culture system after one of the people who helped pioneer its development (Shigueno 1975, 1985). The other system developed in the United States and Mexico through the University of Arizona's Environmental Research Laboratory. Controlled environmental work with agriculture crops was extended to shrimp culture at Puerto Penasco, Mexico as a joint venture between the University of Arizona, the government of Sonora, and private investors. The venture was later moved to Hawaii after a dispute between the cooperators in 1981, and continued operations as Marine Culture Enterprises (MCE; U.S. Dept. of Commerce 1988). Ownership of MCE has changed twice. During 1989, the Hawaii facility was operated as Pacific Seafarms by a Norwegian company. The Shigueno and MCE systems are discussed more fully below.

Ultra-intensive culture uses stocking densities in excess of 100 late-PL or juveniles/m², with survival similar to intensive culture (80 to 90%). PL and juveniles are all hatchery reared. It is important that hatchery production meet or exceed the PL needs to keep the growout portion of the system fully stocked. Optimal production and a constant flow of product (shrimp) through the system depends on this. A nearly complete or complete diet is fed but may be supplemented with fresh feeds. The energy required for water exchange and aeration is more than 25 HP/ha. Water exchange, which may include partial recirculation, usually exceeds 100%/day. Aeration may rely in part on pure oxygen injection.

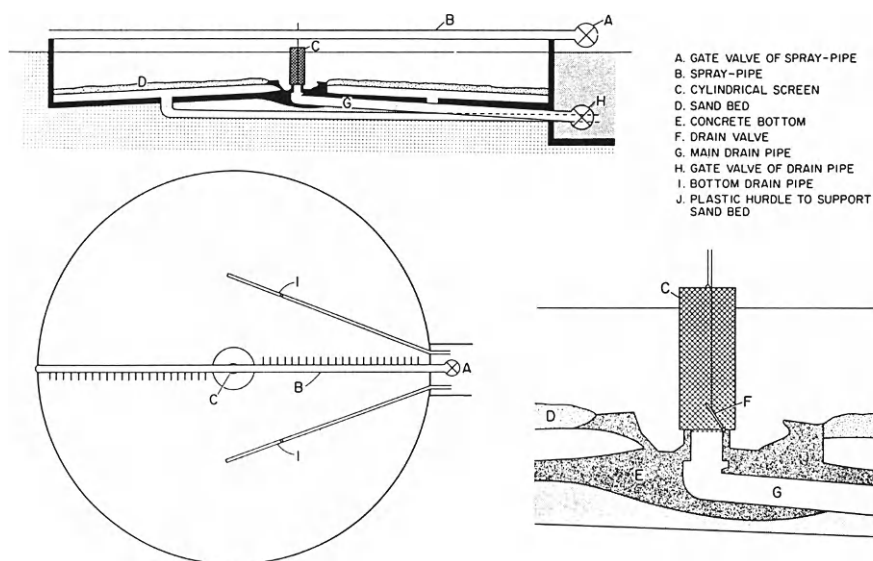


Figure 1. Tank and water supply system used for the culture of *Penaeus japonicus* in Japan. Tank is 23 m diameter, 1.0 to 2.5 m water depth (After Shigueno 1985; Kurata et al. 1975; Kafuku and Ikenoue 1983).

18.2 ROUND POND ULTRA-INTENSIVE CULTURE

The Shigueno round pond culture system (see Chapter 30) evolved in Japan after the semi-intensive Amarusu and Seto Inland Sea systems discussed earlier (see Chapter 16) in an area of higher land cost and warmer water temperatures (Hirasawa 1985). This allowed year round shrimp culture. The pond, or more appropriately the tank, is circular with concrete walls and bottom (Fig. 1). Above the true bottom is a false bottom over which a bed of sand is placed. The only species cultured in this system, *P. japonicus*, needs to burrow in the sand for best growth and survival. Water is exchanged at 300% to 400%/day through an overhead spray pipe, which also imparts a circular motion to the water (Fig. 2). Water outflow is by two means: a central drain, and an under-bottom collector system which receives water flowing down through the sand and the false bottom. Water flow through the sand keeps it aerobic, an essential requirement for good shrimp survival and growth (Shigueno 1969). The waste water may be partially recirculated or discharged.



Figure 2. Ultra-intensive round tanks of the Shigueno design in Japan. Photograph courtesy of K. Shigueno.

The Shigueno growout tank is typically small, 0.2 ha or less surface area, and has a water depth of 1.0 m (Kurata et al. 1980). Stocking densities are high, 100 PL/m². The shrimp are fed a 60% protein diet which gives a wet weight feed conversion ratio of 17:1 to 20:1. The bottom is carefully tended with a rake towed by a boat, and by divers who remove dead shrimp. The Shigueno method achieved production levels of 3.5 kg/m², or 35,000 kg/ha/crop. Traditionally, one crop a year was produced to coincide with the highest prices for kuruma prawn, just before the start of the fishing season in May and June. Later, a system of continuous stocking and harvesting began which both extended the harvest period and increased overall production. The high energy and feed costs of the Shigueno system made it marginally profitable at best, even in Japan, where high quality, live kuruma prawns sometimes bring more than \$80/kg for the sashimi market (Hirasawa 1985).

More recently, another type of round pond was developed and tested experimentally in Hawaii (U.S.A.). This newer round pond has concrete sides, earthen bottom and 1 m water depth (Wyban et al. 1988). Trials were conducted with *P. vannamei*, a non-burrowing white shrimp species at PL stocking densities of 45, 75 and 100/m² in 0.03 and 0.2 ha pond. Water exchange rate averaged 61%/day, and feed conversion ratios ranged from 2.0:1 to 2.2:1. During 80 to 88 day growouts, crops could reach an average size of 18.2 g. These crops yielded between 9,120 and 16,136 kg/ha. Assuming 3.75 crops per year, annual yield would range from 34,200 to 60,510 kg/ha/yr.

Although yield and profitability in a commercial farm setting with this new Hawaiian round pond design is unknown, Wyban et al. (1988) simulated production and costs during 1987 on a 4.8 ha farm with 24, 0.2-ha round ponds. This simulation indicated yields of 60,000 kg/ha/yr with total pond-side production costs of \$7.19/kg for 20 g shrimp (live weight) was obtainable. This is equivalent to \$11.07/kg for 35 count (#/lb) tails, not including processing or shipping costs, and profits. By comparison, the world market pond-side price of 20 g live weight shrimp during 1987 was approximately \$4.31/kg, while the overall wholesale price for 35 count frozen tails at New York was \$9.64/kg (Fast, in press; Vandruska 1987). Wholesale prices have decreased since 1987, while production costs have increased. While this type of culture system may be used to satisfy certain specialty or pocket markets, like other ultra-intensive culture systems, it cannot compete against extensive and semi-intensive culture systems in the world commodity market.

18.3 MCE ULTRA-INTENSIVE CULTURE

The other ultra-intensive shrimp culture system which has been tested commercially, the MCE system, uses growout modules consisting of 0.2 ha, plastic-lined raceways covered by an inflated plastic roof (Salser et al. 1978,

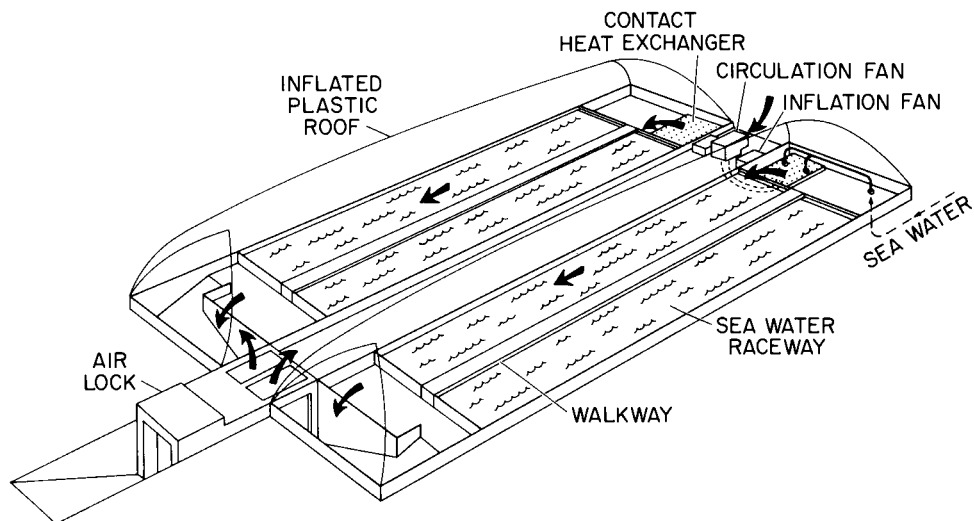


Figure 3. Aquacell used for ultra-intensive culture of marine shrimp by Marine Culture Enterprises (MCE) of Kahuku, Hawaii. (after Mahler et al. 1974).

Fig.'s 3, 4 and 5). High water exchange rates with partial recirculation, pure oxygen injection, and a high quality formulated diet are used. Production of 4 kg/m^2 standing crop is common, with occasional live weight standing crops of $70,000 \text{ kg/ha}$ (Colvin 1985, Liao 1986). Many species were tried in this system, but *Penaeus stylirostris* has given the best performance. Recent viral disease problems with that species, however, may lead to the use of other species to avoid the costly shut-downs and clean-ups associated with disinfection. With such high density culture, disease can be devastating. Despite more than 15 years of research and millions of dollars expended, the MCE system has yet to prove financially successfully. They have, however, proven that it is technically possible to produce very large amounts of shrimp on small areas of land.

18.4 INTENSIFICATION OF TAIWANESE CULTURE

Although we normally think of the Shigueno and MCE systems of ultra-intensive shrimp culture, recently ultra-intensive yields were obtained with modified Taiwanese intensive culture technology. The results were from experimental trials in small (0.14 ha) concrete walled ponds. Chen et al. (1989) stocked *Penaeus monodon* PL at densities of 124 and $143/\text{m}^2$ and produced average yields of $20,978 \text{ kg/ha}$ and $13,714 \text{ kg/ha}$ in 183 and 177 days



Figure 4. MCE's ultra-intensive shrimp farm on Oahu, Hawaii. Culture tanks are covered by inflated covers. Semi-intensive shrimp and freshwater prawn ponds are visible in the background. Photograph courtesy of Hawaii Aquaculture Development Program.

respectively. Shrimp averaged 24 to 25 g. Assuming two crops per year, this is equivalent to annual yields ranging from 34.6 to 42.0 MT/ha/yr. Chen et al. (1988) also conducted similar production trials in the same ponds with a smaller, slower growing shrimp, Penaeus penicillatus (red tailed shrimp). These shrimp were stocked at 171 and 286 PL/m² and produced average yields of 11,071 kg/ha and 12,286 kg/ha in 131 and 141 days respectively. Shrimp averaged 9.7 to 10.0 g. Assuming 2.5 crops per year, this is equivalent to annual yields ranging from 27.7 to 30.7 MT/ha/yr.

Efforts to scale up production from small experimental units to much larger commercial units was generally not successful. Experimental trials generally receive more care and maintenance. Disease, water quality, and many site specific problems often emerge away from the controlled, watchful environment of a research laboratory. Nevertheless, the work of Chen and his colleagues shows that these two species are suitable for intensification in earthen ponds. The main consideration, then, might be economics.



Figure 5. Inside view of MCE aquacell. Unit consists of two covered raceways in which the shrimp are cultured at densities of 4.5 kg/m^2 or greater. Photograph courtesy of Hawaii Aquaculture Development Program.

18.5 RISKS

Risk of partial or complete crop loss is much greater with ultra-intensive or intensive culture systems than with semi-intensive or extensive systems. Risk of disease, risk of equipment failure, risk of PL shortage, and risk of management mistakes are all much greater with the more intensive culture systems, with resultant loss of crop and loss of profits. The consequences of these losses on overall business profitability is also much greater with the more intensive systems. For example, if the profit margin is 15%/kg with an intensive culture system, then it would require almost 7 profitable (non-loss) crops to break even from the complete loss of one crop near harvest time. With an extensive or semi-intensive culture system which has a higher profit

margin of perhaps 40%/kg, the recovery period under the same scenario is only 2.5 crops. Furthermore, the probability of such loss is much less with the less intensive systems. Although accurate cost data are largely lacking on ultra-intensive culture systems, it appears that average profits could be even less than 15%, if positive profits exist at all.

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CHAPTER 19

Arlo W. Fast

POND HARVESTING TECHNIQUES

19.1 INTRODUCTION

The price that a shrimp farmer will receive for his crop, and therefore his profitability, will depend in part on the size and quality of his shrimp. Shrimp size is related to species specific growth, stocking density, culture techniques, and proper timing of the harvest. Shrimp quality is largely related to harvest techniques and post-harvest handling. A major advantage of shrimp culture over shrimp capture from the wild is the greater potential control that the culturist has over many of the factors affecting size, quality and value of the shrimp.

Harvest size is one of the most important considerations concerning the scheduling of a harvest (Fig. 1). In general, if the crop is still growing at an adequate rate, and there is little risk of catastrophic loss (e.g. oxygen depletion), then it is better to postpone the harvest until the shrimp reach a larger size. Larger size shrimp, without increased mortality, means not only

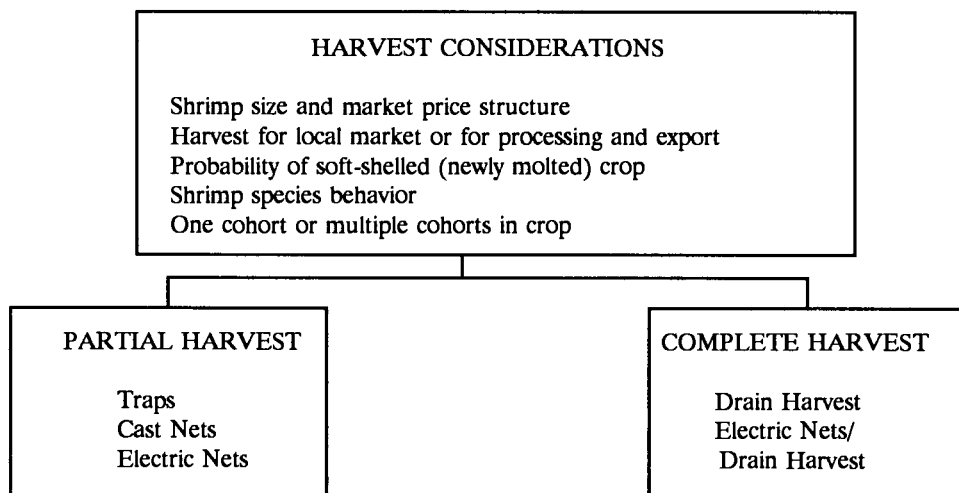


Figure 1. Factors affecting the quality and value of cultured shrimp, and selection of harvest techniques.

Table 1. Average wholesale Price (\$/kg) for raw, headless Gulf brown shrimp at New York during 1986-1987 (Vondruska 1987).

Shrimp Tail Sizes		Average Price Per Quarter (\$/kg)						2 years Average	Average Price Increase*
		1986		1987					
		g/tail	#Tail/lb	3	4	1	2		
>30.3	<15	16.26	16.30	17.32	-	20.97	20.57	17.37	
22.7-28.4	16-20	15.85	15.16	16.41	17.38	18.04	15.96	15.86	10.8
18.2-21.6	21-25	15.25	13.66	13.96	14.50	13.38	13.01	13.86	14.4
15.1-17.4	26-30	13.32	12.64	12.33	11.83	10.80	10.54	12.11	14.4
13.0-14.6	31-35	11.91	10.57	10.19	9.82	9.12	9.33	10.57	14.6
11.4-12.6	36-40	10.87	10.16	9.68	9.09	7.89	7.77	9.57	10.4
9.1-11.1	41-50	9.70	9.74	9.36	8.73	7.05	7.07	8.79	8.9
7.6-8.9	51-60	7.68	8.37	8.55	8.10	6.86	6.83	7.75	13.4
6.5-7.4	61-70	6.31	7.11	8.08	7.10	6.53	6.45	6.81	13.8
5.7-6.4	71-80	5.04	5.50	5.79	5.83	5.81	5.81	5.55	22.3

* Difference between average price of a given size and the next larger size divided by the average price of the smaller size, converted to percentage.

a greater yield, but also a greater price per unit production. Shrimp with live weights of 46.6 g or larger during 1986-87 had an equivalent wholesale (New York headless) prices of \$17.37/kg, compared with only \$5.55/kg for 9.8 g shrimp (Table 1). For each increase in size category (number of tail per pound), price per kg increased between 8.9% and 22.3%.

Some species, such as Metapenaeus ensis will not grow to a large size in ponds under any circumstances. Harvest size for Metapenaeus ensis is usually 10 g or less (6.5 g headless). Penaeus monodon on the other hand, can grow to several hundred grams in ponds under certain conditions, but this species is generally harvested in the range of 25 to 50 g. It is usually harvested when its growth rate decreases due to food, space, water quality or some other limitation.

Larger shrimp harvest size also means that the contribution of certain operating costs is reduced; in particular the cost of postlarvae (PL) as a percentage of total production costs. For example, if PL cost \$20/1,000, there is 75% survival to market size, and the shrimp are harvested at 15 g, then the cost of PL per kg of yield is \$1.78. If on the other hand, the shrimp are harvested at 30 g, then the PL cost/kg of production is only \$0.88

Another harvest size consideration is that shrimp prices/kg vary over time, but not all sizes vary the same. During 1986/87, live weight shrimp prices/kg increased an average of 22.4% for shrimp larger than 28 g; while for shrimp in the range of 11.7 to 26.8 g, the price decreased (14.4%). Below 11.4 g, there was a slight increase of 1.4%. A farmer might consider these trends

when deciding on what shrimp to culture, to what size. Time and type of harvest technique also depends on whether the crop is intended for local consumption, or for processing and export (Fig.1). Often times the local market is for small quantities, and/or for live shrimp, but at premium prices. The higher price may more than compensate for the added labor involved in partial harvest of the crop, a possible longer growout period, and the extra efforts needed to bring the shrimp to market live. Harvest for export, on the other hand, usually means a complete harvest of a given crop on one date; where the crop is shipped dead, on ice to the processor. Techniques for partial and complete harvests are discussed below.

The time of the month when the crop is harvested can have a major impact on shrimp quality, since shrimp molting is apparently synchronized to some extent with the spring tide during the new moon. Recently molted, or soft shelled shrimp command a lower price; sometimes as low as 1/2 that of hard shelled shrimp. Soft shell shrimp are more easily damaged during handling, and the flesh is softer, apparently due to water absorption following the molt (Neal and Maris 1985). If harvest timing is off, as much as 20% to 50% of the crop can be soft shelled, with a corresponding decrease in sale price (Apud 1985). The farmer can, however, guard against this situation by inducing the shrimp to molt before harvest and by regularly checking the shrimp before harvest to determine their molt stage. Shrimp can be induced to molt by rapidly raising and lowering the water level in the pond 4 to 5 days before harvest. This induces molting, and allows time for shrimp to thereby be in the hard-shell stage for harvest. This procedure may not be possible, however, with very large ponds or where source water and water delivery are limited. Other stresses, such as chemical treatments with copper sulfate or permanganate, reportedly can also cause synchronous molting; but this has not been documented.

Species specific behavior is an important consideration when selecting a shrimp species for culture, as well as selecting a harvest method. Some species such as *P. vannamei* and *P. merguensis* are relatively easy to harvest by draining the pond. These species normally run with the drain water and do not "hang-up" in the pond by burrowing into the bottom, or by stranding. Other species, such as *P. japonicus*, *P. indicus* and *P. monodon* do not always run readily with the drain water and may either strand or burrow into the bottom. With these species, night drains, partial harvests with various nets, and rapid water draw-down to create faster currents may be needed to guard against crop loss, or lost quality due to picking dead shrimp off or out of the pond bottom. The use of canals within the ponds can also aid harvest with these species since they create faster water currents at the termination of the drain harvest, as well as a much reduced bottom area where the shrimp are likely to remain.

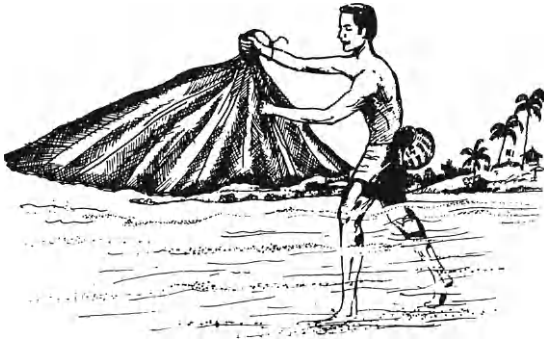


Figure 2. Cast net used for partial harvest of shrimp from ponds (dela Cruz 1983).

The type of harvest is also influenced by whether the crop consists of one cohort, or multiple cohorts; and whether the farmer uses a strategy of "thinning" or periodic selective harvesting of the crop. Most shrimp crops are reared as a batch process, where the PL's or juveniles are all stocked at one time, the crop grows to some point, and then all are harvested at about the same time. Alternative strategies to this one includes; (i) stocking at a high density, but all at one time. As the crop approaches carrying capacity of the pond, begin partial harvest to reduce the biomass below the sustainable maximum. Continue partial harvest on a regular basis until the biomass and numbers are greatly reduced, and then drain harvest, (ii) stock repeatedly over some time period, such as once or twice a month for 3 or 4 months, and then begin partial harvest, selecting for the largest shrimp as the first cohort reaches marketable size. The selective partial harvest is achieved by using nets with mesh sizes which allows the smaller shrimp to escape. This strategy, like (i) will result in not only a more uniform flow of crop to market, but also a greater annual yield since the pond is at or near carrying capacity for greater time each year. Both strategies are now used in Japan with P. japonicus culture (Hirasawa 1985).

Based on the foregoing, we have seen that shrimp pond harvest can either be partial or complete. The following is a description of techniques and equipment used for each method.

19.2 PARTIAL HARVEST

19.2.1 Cast Nets

Perhaps the oldest and most simple method of partial harvest is by cast-nets (Fig. 2). Harvest success can be improved by placing food in selected locations, which are then netted after the shrimp are drawn to the food. Cast-netting is not very efficient in terms of kg harvested per man-hour, but it can be cost effective where labor is inexpensive. It can be

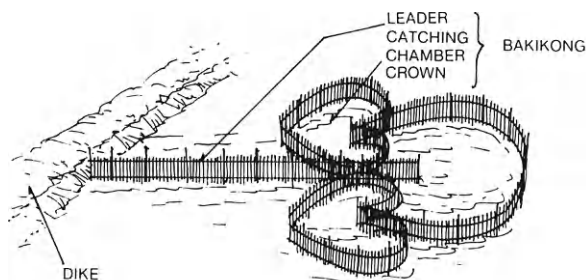


Figure 3. Bamboo shrimp trap (bakikong) of the type used to capture pond shrimp in the Philippines (Apud 1985).

done with one person, and is best used when small quantities of shrimp are needed.

19.2.2 Traps

The simplest shrimp traps consist of a bamboo fencing or screen leader, running from the pond bank into the catch chambers (Figs. 3 and 4). Shrimp moving along the bank will be led to the chambers, where they can be collected. Sometimes a grating is placed at the entrance to guard against the entry of large crabs, which might prey on the shrimp. The pound-net, originally developed in Japan (Shigueno 1978), is an improvement over bamboo traps (Fig. 5). Pound-nets use netting rather than bamboo, and can therefore select preferred shrimp sizes more effectively by changing the mesh size of the catch chambers.

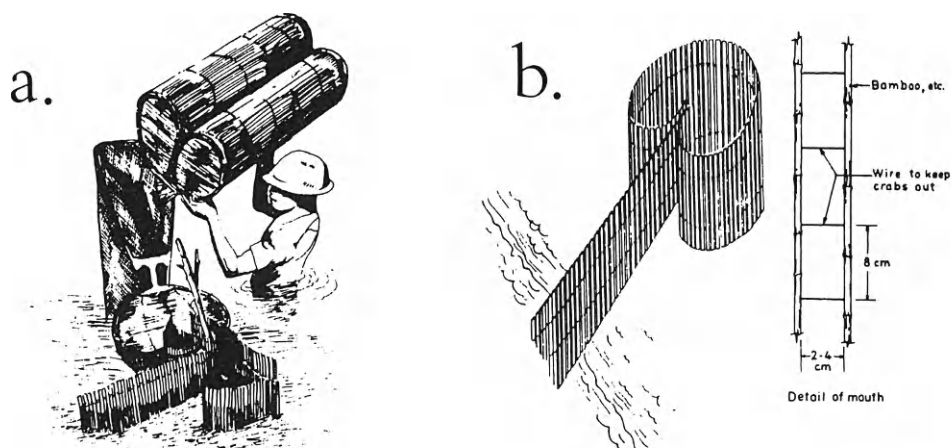


Figure 4. Bamboo shrimp Fykes of types used to capture pond shrimp in a) Indonesia (babu udang), and b) the Philippines (dela Cruz 1983).

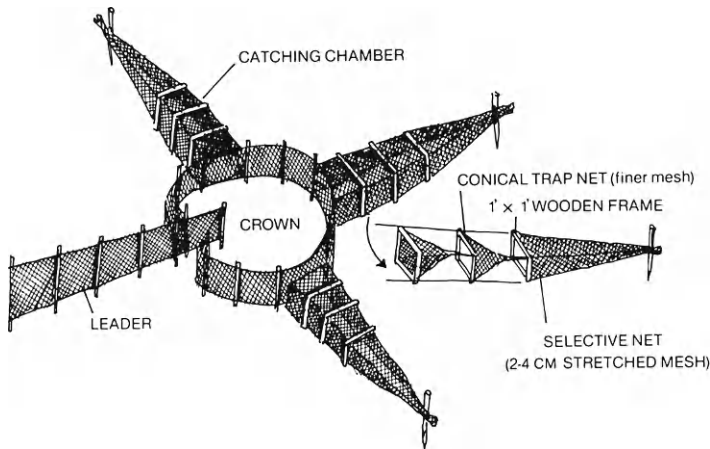


Figure 5. Pound-net used for selective harvest of pond shrimp (Apud et al. 1983).

Chien and Liao (1988) describe another type of pound-net used in Taiwan. This net is similar to that shown in Fig. 5, except that it has a single trap chamber, and two wing leads set at 45 angles to the net. The central lead (central guide screen) is set against the pond dike to lead shrimp toward the trap. This trap is especially effective for *P. monodon* since they like to move along the pond dike. Six to eight nets are used per ha. These nets are especially popular in ponds where shrimp and clams (*Meretrix pusoria*) are polycultured. Shrimp traps are most effective during the new moon time of month. Shrimp are most active then, and can often be seen swimming in schools in those ponds with bioluminescent phytoplankton. The swimming action of the shrimp causes the algae to bioluminesce thereby illuminating individual shrimp. Shrimp tend to swim in a large circle around the pond, or even try to crawl out of the pond even though oxygen and other water quality parameters are adequate. Trap catch efficiency can also be increased by placing a light over the catch chamber to attract the shrimp. Traps are labor non-intensive, but normally capture only a small portion of the population during a given set.

19.2.3 Pump Net

A pump-equipped drag net, towed by a boat over the pond bottom has been used to harvest *P. japonicus* in Japanese shrimp ponds (Fig. 6). The apparatus consists of a sled portion, and an attached bag net on the back of the sled. A horizontal pipe with spray nozzles is attached to the forward, bottom part of the sled. A water pump in the boat jets water ($0.3 \text{ m}^3/\text{min}$) under pressure (4 kg/cm^2) into the pond bottom to a depth of 6 to 8 cm,

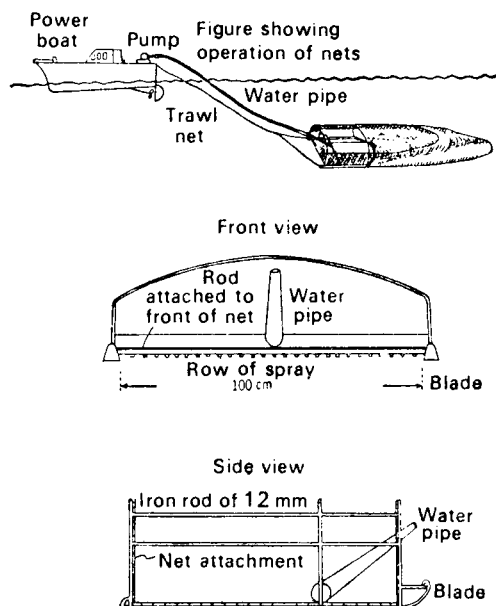


Figure 6. Pump-equipped drag net of the type used to harvest Penaeus japonicus in Japan (Shigueno 1969).

where the shrimp are thus encouraged to leave the bottom. The net is towed at 20 to 30 m/min. This forward motion, plus a tickler chain on the lower leading edge of the net effectively causing shrimp to be captured in the conical net. This net is effective on P. japonicus during the day, when the shrimp are normally inactive and burrowed in the pond bottom.

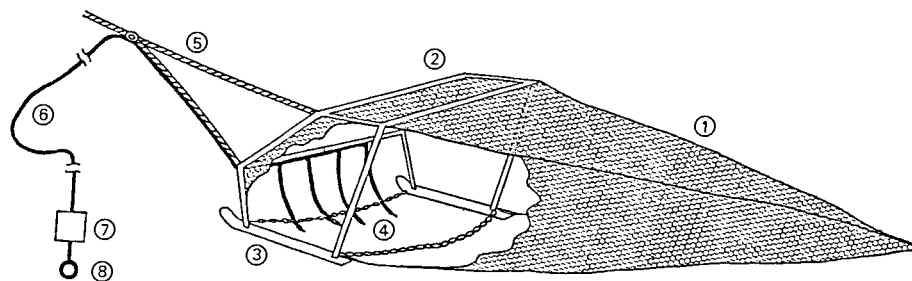
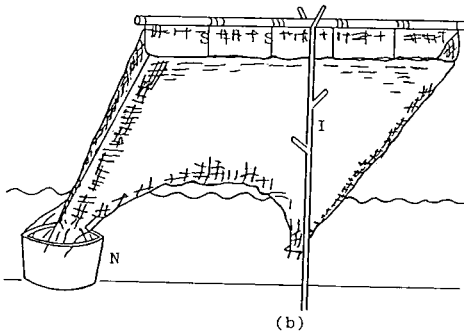
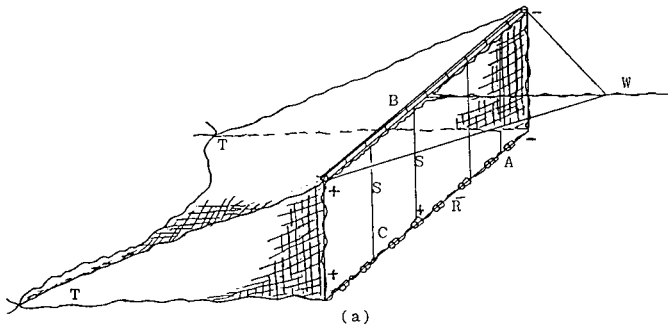


Figure 7. Electric drag net of the type used to harvest Penaeus japonicus in Japan. 1. Net; 2. Iron frame; 3. Iron ski; 4. Electrode; 5. Rope; 6. Electric code; 7. Transformer; 8. Power source (Kafuku and Ikenoue 1983).



A: Anode	R: Roller
B: Bamboo Pole	S: String
C: Cathode	T: Tail Bag
I: Branched Iron Stick	W: Insulated Wire
N: Top Netted Basket	

Figure 8. Electric net of the type used to harvest Penaeus monodon in Taiwan. The net is towed by a harvester (Chien and Liao 1988).

19.2.4 Electric Nets

There are two principal types of electric nets, one towed by boat as in Japan, and a second type pulled by people as in Taiwan. The Japanese electric drag net is very similar to the Japanese pump net described above, both in physical form and method of use. The "net" consists of a sled portion to which the electrodes are attached, and a conical net portion (Fig. 7). Instead of the horizontal water pipe with nozzles, however, the electric sled contains a set of four or more (+) and (-) electrodes that penetrate the bottom near the front of the sled. Wire leading from the electrodes is insulated and runs along the tow line into the boat where it is attached to batteries. The voltage, amount of current and frequency of the current can be adjusted by the operator (Shigueno 1975). Tickler chains are attached to the sled. Electric trawl nets have also been used to some extent in the ocean capture fishery (Neal and Maris 1985, Seidel and Watson 1978).



Figure 9. Electric net in use at Taiwanese shrimp pond during harvest (Photo from Fast et al. 1989)

In Taiwan, an electric net is used to harvest P. monodon from intensive culture ponds. The net is constructed like a beam trawl, with a 3.5 m wide mouth (Figs. 8 and 9). A man walking in the pond tows the net. The man also pushes a float that contains a 12-volt battery, and a device to control the voltage and frequency of the current going to the net. The electrodes, which consist of bare copper wire are located on the lower, bottom edge of the net and on the two sides. The weak current is enough to cause the shrimp to be stunned, lift off the bottom, and drift into the net as it is towed through the water. Chien and Liao (1988) and Fast et al. (1989) describe this harvest technique in more detail. Normally, these electric nets are used to harvest

90% to 95% of the crop about a week before the pond is drained. Prior to starting harvest with the electric nets, the pond water depth is lowered to less than one meter. After harvesting with the net, the pond is re-filled with water, and then drain harvested one week later. It is not possible to harvest 100% of the prawns using these nets. Furthermore, if the pond were drained immediately after netting, there would be a high percentage of soft shelled shrimp in the drain harvest. Stress caused by water draw-down plus netting, induces the shrimp to molt.

19.2.5 Other Methods

Partial harvests are sometimes achieved in large shrimp ponds that rely on tidal water exchange. In these ponds, shrimp swim against incoming water currents. A bag-net placed on the inside of the sluice gate will capture these shrimp. Likewise, during water discharges from the ponds, shrimp run with the drain water and can be collected by nets on the outside of the sluice gates. These partial harvest methods are most efficient at night during the new moon time of month.

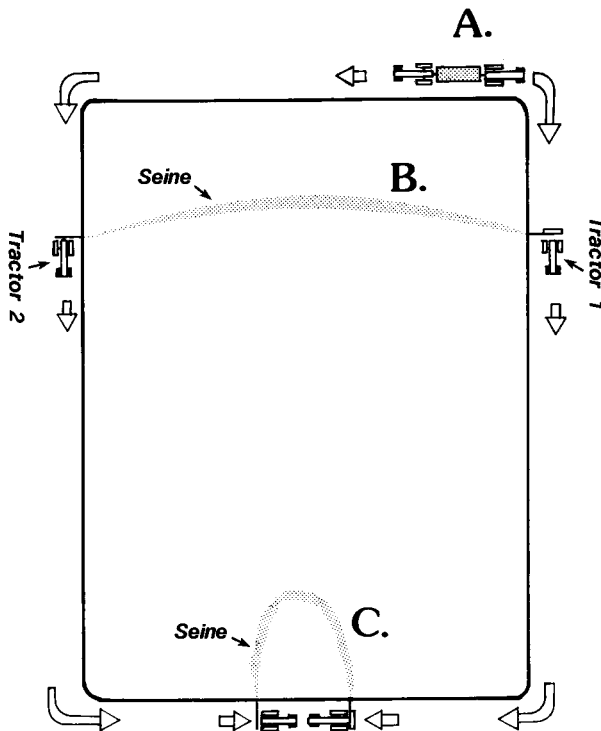


Figure 10. Seine harvesting of a large pond using two tractors to pull the seine from one end of the pond to the other (from Reisinger 1985).

Seines are also used for partial harvest of shrimp ponds. If the ponds is small, the entire pond may be seined. Lowering the water level may be necessary if it is deeper than 0.5 m. In ponds with peripheral or diagonal canals, seining success is greatest if the water level is first lowered so that the water and shrimp are confined to the canals (Menasveta and Higuchi 1983, SEAFDEC 1984). It is, however, difficult to capture more than 50% of the shrimp in a pond by seining alone. Seining normally must be followed by drain harvesting (see below) in order to capture all the shrimp. Seining is perhaps the second most common method of shrimp harvesting, after drain harvesting. It is the harvest method of choice in ponds which cannot be drained, or can only be drained during limited times. It is typically accomplished by placing the seine across one end of the pond and drawing the seine to the other end (Fig. 10). The seine can be drawn by hand or by vehicles, but special care must be taken to assure close contact with the pond bottom and sides at all times. Shrimp have an uncanny way of streaming around or under the net if any opening occurs. Once the seine is drawn through the pond, it is drawn into a U-shape, from which shrimp are scooped by hand net. Alternatively, a "bag" attached to the center of the seine at the bottom of the "U" collects the shrimp, and shrimp are removed from the bag.

Reisinger (1985) describes a corraling method of seining used in Ecuador, where two seines are drawn towards each other from opposite ends of the pond. When almost at mid-point of the pond, a third seine is then swept down the gap between the other two and the shrimp are thus harvested. This method is more appropriate in very large ponds where nets of 150 to 200 m or more are needed. A 200 m long seine requires about 8 men to operate.

Seine harvesting is not a preferred method since much mud and detritus are often mixed with the shrimp, and shrimp are often damaged. Also, it cannot be used in ponds with tree stumps and other obstacles. In ponds with peripheral canals, seining is often used in combination with cast-nets after the water has been lowered below the upper level of the canal.

19.3 COMPLETE HARVEST

The most common harvest method of all is drain harvest where all the water is released from the pond at once and most or all of the shrimp exit the pond with the water. This technique requires that pond bottom be above the water level in the receiving ditch. In extensive ponds serviced by tidal water exchange, drain harvest can often only occur a few times a month, at appropriate tidal stage. Timing is critical in large ponds since complete draining may take 3 to 4 days. Once draining begins, shrimp will tend to move with the current and any cessation in flow may cause the shrimp to

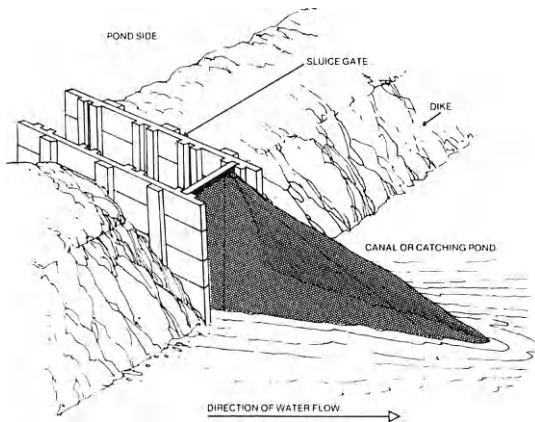


Figure 11. A bag-net attached to a wooden sluice gate and used to capture shrimp during a drain harvest (Apud 1985).

re-dispense in the pond and be stranded, with sometimes disastrous results. Close attention must also be paid to dissolved oxygen levels during draining. If these fall too low, new water must be pumped into the pond even if this means halting the drain. It may then be necessary to refill the pond and harvest latter to avoid excessive stress induced molts, or stranding problems.

19.3.1 Bag Nets

The most common method of collecting shrimp during a complete drain is by bag net (Fig. 11). This is a small mesh net which is usually attached to a wooden or metal frame, fitted into slots on the sluice gate. The net may be 6 to 10 m long. Force of the water exiting the pond keeps the net "inflated", and shrimp from leaving the net once they enter.

Before beginning the final drain, water may be pumped into the pond, or allowed to enter by tidal action. This new influent water stimulates shrimp, and results in a higher percentage existing through the sluice gate during the drain. Completion of the drain is best scheduled for nighttime during the new moon time of the month, since shrimp (especially *P. monodon*) are more likely to run with drain water at this time. A light placed at the sluice gate will help attract shrimp to the bag net. Completion of the drain just before dawn is best since shrimp remaining in the pond can be most easily removed before the heat of the day, and before their quality deteriorates beyond redemption.

Care must be taken when using bagnets, however, to avoid overloading the net with shrimp. This causes shrimp to die, and to even be crushed by the water force. This is one of the main factors causing deteriorated quality in

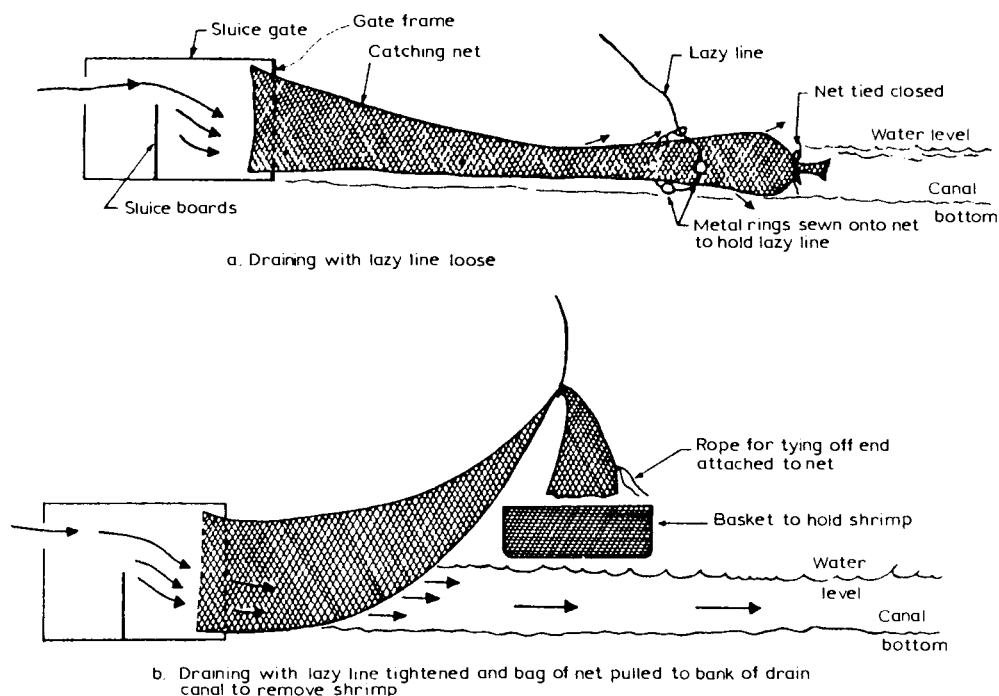


Figure 12. A bag-net used to capture shrimp during a drain harvest. The shrimp are transferred from the bag-net without interfering with the drain (dela Cruz 1983, after ASEAN National Coordinating Agency for the Philippines 1978).

pond cultured shrimp (Hirasawa 1985). If the nets are carefully attended, the shrimp can be periodically removed before overloading. This is easily accomplished using a lazy line to remove the shrimp from the cod end of the net, without stopping the drain (Fig. 12). In this way, small quantities of 10 kg or so of live shrimp can be transferred to net bags where they can clear mud and debris from their gills and bodies before they are chilled and processed (Apud 1985). Especially near the end of the drain, there is much suspended silt and debris which tends to accumulate around the shrimps gills. Often, a high percentage of shrimp exit the pond at the end of the drain. It is not uncommon for more than 50% of the shrimp to leave with the last 10% of pond water volume. If shrimp are sold whole bodied, this debris detracts from their appearance and lowers price.

19.3.2 Suspension Net

Sometimes a large catching or trapping area is created on the drain side of the sluice gate where shrimp exiting the pond during a drain can be collected live with scoop nets. An improvement on this technique is use of suspension nets attached outside the sluice gate (Fig. 13). This net is much larger than a bag net, has four sides and a bottom, but is open on the top.

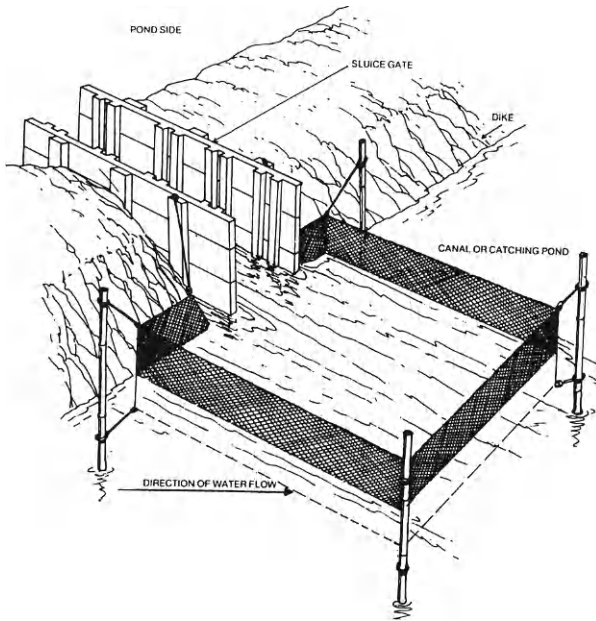


Figure 13. A suspension net on the outside of a shrimp pond gate during a drain harvest (Apud 1985).

Shrimp entering the suspension net are less likely to be damaged by water force. They are also more likely to stay alive, and to self-clean before transfer to processing tanks. Shrimp are removed from suspension nets by scoop nets.

Suspension nets are commonly used for partial harvests also, especially in ponds where the bottom of the drain canal or receiving water is at about the same height as the pond bottom.

19.3.3 Fish Pumps

Some farms use vortex-type fish pumps to collect shrimp at the sluice gate during drain harvest. These pumps can pump live fish or shrimp without damage. The suction end of the pump intake may be attached to the cod end of the bag net, such that shrimp accumulating in the net are pumped along with a small water volume to a tank or sorting machine where the shrimp are separated from the water.

Alternatively, shrimp may be concentrated in a screen cage on the discharge side of the sluice gate, and then pumped to a sorting and processing trailer (Fig. 14). Such a system is commercially available from Sort-Rite

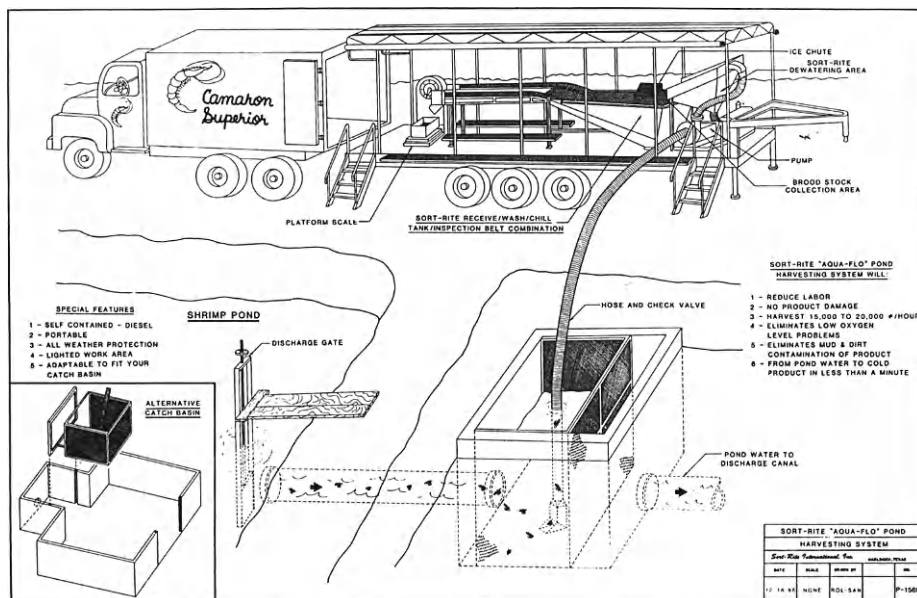


Figure 14. Fish pump system which pumps shrimp from a box at the sluice gate. Shrimp are dewatered, chilled, inspected, weighed and placed in iceboxes for transport to the processing plant (courtesy of Sort-Rite International, Inc.).

International of Harlingen, Texas, and is used by the Laguna Madre Shrimp Farm, the largest shrimp farm in the U.S. (Reisinger 1985). This system is capable of handling between 5,000 and 9,000 kg of shrimp per hour. Processing includes pumping the shrimp from the concentrator net or box, dewatering, chilling in an ice bath, de-watering again, transferring across an inspection area, weighing, and packing in boxes in which they are iced down and transported to the processing plant. The principal advantages of this type of harvesting system are; damage free shrimp, reduced harvest time, and reduced labor cost. Combined, these mean a higher quality product, at less cost and higher profit. Larger farms, and farms where vehicle access and contract harvesting are available will most likely rely on this method more as a shrimp culture infrastructure continues to develop.

Care must be taken during all drain harvest not to block the drain exit. Any obstacle near the gate can cause shrimp to avoid exiting the pond, and thus remain in the pond after the drain is completed. Shrimp picked out of, or off a mud bottom always have lower quality than those that run with the water and are properly handled.

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CHAPTER 20

Jaw-Kai Wang and Arlo W. Fast

SHRIMP POND ENGINEERING CONSIDERATIONS

20.1 INTRODUCTION

Aquaculture pond design evolved, until recently, outside the influence of engineers or scientists. Ponds may be large or small, irregularly or uniformly shaped, earthen or concrete, shallow or deep, and have water supplied either by gravity or by mechanical pumps. The wide variety of pond types are discussed more fully in the chapters on pond culture systems (see Chapters 14 to 18).

There are good ponds, and there are bad ponds. It is not always clear why yields, survival and crop performance are so different for different ponds, especially when these ponds are located on the same farm or are perhaps even contiguous. Sometimes we know very well why a pond does not perform as desired. Some ponds are poorly located, poorly designed, poorly constructed, and/or poorly managed. Csavas (1985) summarized these problems well:

"Engineering is a weak link in the development of aquaculture. Despite the rapid proliferation of consulting engineering ventures, real expertise in this area is still rare and as a result, several traditional mistakes continue to be made, especially in pond design. What seems to be happening is that instead of giving the necessary attention to the proper drainage and strict separation of the supply and drainage network, too many compromises are being made. One grave error is the continuing priority given to tidal-fed ponds in coastal aquaculture. It has been convincingly demonstrated more than once that a pump-fed system is not only cheaper to build but it is also more economical in the sense that higher yields more than compensate for pumping costs. A pump-fed system also eliminates the dangers of hitting acid sulphate soils, a situation which has often caused spectacular fiascoes in coastal aquaculture development."

While the application of engineering principles may be a weak link in aquaculture practices, we do know quite a bit about how to site, design, construct and operate ponds. Much, but not all, of this knowledge has been quantified and committed to print. The problem is largely one of access and

application. Aquaculturists like to build and operate their own ponds at what they hope will be the least cost. This usually means without help from a qualified engineer or other knowledgeable professional who could help them avoid problems. It often means that ponds and farms are built in the wrong place, using the wrong design, with the wrong materials, for culture of the wrong species.

While it is beyond the scope of this chapter to consider all aspects of good and bad pond engineering and operation, we will try to address some of the more important considerations. The reader is also referred to other publications that address certain issues in more detail, as well as to other chapters concerned with ponds found in this volume.

20.2 SITE SELECTION

20.2.1 Water quality and availability.

The importance to aquaculture enterprises of water quality and availability is well known. Nonetheless, many farms are still sited at locations where source waters are inadequate. Inadequacies can involve not only water volume and costs to develop source waters, but also water constituents. Boyd (1990) and Boyd and Fast (Chapter 23) discuss some of these considerations. When selecting a farm site, seasonal and yearly fluctuations in water quality and availability need to be carefully considered.

20.2.2 Soil characteristics

One of the most important characteristics is the ability of the soil to hold water. Good soil should contain a layer of impervious material thick enough to prevent excessive seepage. Clays and silty clays are excellent impervious materials, while sandy clays are sometimes satisfactory. Kovari (1984) stated that a soil permeability of less than $K = 5 \times 10^{-6}$ m/sec is desirable. Linings and soil treatments are available but usually at high costs.

Pond soil should be carefully examined for peat, muck, and other organic materials. Should excessive amounts of these materials be found, they must be removed before construction starts. A thorough soil investigation by a competent engineer or soils specialist is highly recommended. When constructing a shrimp pond, the levee or dike foundation should be strong enough to support the structure and provide resistance against water passage. Good foundation materials are a mixture of coarse and fine-textured soils, such as gravel-sand-clay, gravel-sand-silt, sand-clay, and sand-silt.

20.2.3 Climate

In addition to temperature and wind, the importance of which are well known, cloud cover (solar insolation) and rainfall are not to be overlooked.

They are especially important in estimating necessary flood protection measures and time requirements for maintenance and repair purposes. An estimation of the dry and rainy seasons should be as accurate as possible so that all phases--construction, operation, and maintenance--are properly planned.

20.2.4 Topography

Topography is one of the most important criteria in site selection. A gentle slope of less than 2% is highly desirable. Such a slope allows for gravity water conveyance to and from the ponds, and provides for efficient drainage. Coastal areas where marine aquaculture is practiced often have a slope of far less than 1%, and potential problems with flood drainage must be carefully investigated. Providing for proper flood drainage can be very expensive.

Land elevation (above mean sea level), topography, and tidal conditions are all important, whether the culture area is supplied by tidal water exchange or by mechanical pumps (see Chapter 15 for tidal considerations). Pond elevations and distances must be carefully considered since these can affect capital construction costs, as well as operating costs. Over the life of the farm, pumping costs can be substantial.

20.2.5 General Considerations

Other important site selection criteria that relate to pond design and construction are the availability of soil to borrow, the disposal of the excavated material, and access to roadways, electricity, and domestic water supply.

20.3 POND DESIGN

Ponds should be designed so that their bottoms slant toward the drain with a slope between 1000:3 and 1000:6, but not less than 1000:1. Should an operator prefer a steeper bottom slope, the construction costs must be considered. The bottom should be smooth and the slope even, so the pond will drain completely. It is important that the bottoms are dried out and renovated after each harvest. The pond bottom slope requirement puts a practical limit on the pond size. Steep slopes, even in small ponds, and gentle slopes, even in large ponds, can result in a wide range of water depths throughout the pond. This can lead to undesirable thermal and chemical stratification in the deeper water areas, and to undesirable plant growth on the bottom in shallow water areas. Depending on the topography, steep slopes on large ponds may be difficult or expensive to construct. To facilitate harvesting, a drainage basin or connecting ditches may be dug in the pond

bottom. This should not be required, however, for ponds with sufficient bottom slope.

Sometimes the only available site has soil with excessive permeability. When this is the case, seepage from the bottom can be minimized by using compaction, clay blankets, bentonite or other chemical additives, and linings. A good source of information concerning this and other pond design questions is the Soil Conservation Service's Agriculture Handbook 590 (U.S. Department of Agriculture, 1981).

20.3.1 Embankment ponds

Embankment or above-ground ponds use a levee or a dike to contain water. Depending upon the soil type, the embankment may or may not be lined. Embankments keep flood run-off from entering the pond. This can be a crucial design factor if heavy floods or sanitation is a likely problem. The embankment slope is determined by soil properties. Embankment ponds can be constructed to fit a wide range of topographic conditions and, for this reason, they are probably the most common aquaculture pond. To increase land efficiency, elevated roadways or vehicular passageways are often needed. These can be built on the dikes, which not only requires a wide bund, but also increases construction costs.

Excavated or below-ground ponds are constructed by removing soil and/or rocks from the ground. Excavation costs can be high. Because this type of pond is generally constructed on relatively flat grounds, drainage can be a problem. Drainage canals or pipes must be dug deep into the ground and, in many cases, effluent may have to be pumped out. This type of pond does not use land efficiently.

The most efficient way to build aquaculture ponds may well be a combination excavation/embankment pond, where the excavated soil is used to construct the embankments. With a gentle slope and good soil, an efficient aquaculture pond can be constructed at lower cost.

Side slopes of levees must conform to the angle of repose of the levee soil. For ordinary clay soil, a slope of 1.5:1 or greater is acceptable, but clay-sandy soil requires a slope of 2:1 or more, and sandy soil should have a slope of 3:1 or more. When land price is high, vertical sides may be most appropriate, constructed with concrete, concrete blocks, or stone masonry.

Embankment linings are becoming increasingly popular. During design, the engineer should consider the lining cost against the construction and maintenance cost of unlined ponds. Proper pond maintenance is easier with pond lining. Without linings, the levee bank will need compaction to prevent leakage. While bank compaction may be less expensive than lining, it does demand very exact soil and workmanship requirements. Clean, non-sweating clay soil without organic material is required, and precise construction

procedures must be followed. One of the best references available on the subject is available from the U.S. Army Corps of Engineers (1978).

The levee foundation is important. Permeable material under the foundation requires that seepage underneath the levee be controlled, which can involve the use of an impermeable blanket in front of the levee. The length of this blanket should be about 10 times the head on the dike. A cut-off wall consisting of sheet piling, or a clay "puddle" trench containing impervious material may also be used to control seepage.

The foundation strength will determine the berm base width, since the critical failure circle, due to slip, increases in diameter as the dike height increases. Drainage ditches near the levee increase the effective height of the bank, thereby increasing the likelihood of slips. During levee construction, care must be taken when using materials significantly different from that of the foundation. If the levee material is appreciably stiffer than the foundation material (i.e. the foundation material is more compressible) differential settlement can occur across the bank section, causing cracks.

For most aquatic ponds, the U.S. Soil Conservation Service (USDA, 1981) recommends a minimum of 2.4 m top width for levees less than 3 m in height. In aquaculture pond design, however, levee top width will most likely be determined by vehicular passageway needs. Frevert et al. (1962) recommended a minimum 3.7 m levee top width for roadways. Freeboard is the added levee height required to prevent overtopping. For water depths less than 2 m, Wang and Hagan (1981) recommend a freeboard of either 0.3 m or 0.4 times the normal water depth, whichever is greater.

20.3.2 Excavated ponds

Excavated ponds are the simplest to build if the topography is relatively flat, if drainage can be handled efficiently, and if flood protection can be provided easily. Ease of construction and low maintenance requirements have made excavated ponds the choice of many farmers. Enough impervious soil at the site is essential to avoid excess seepage losses. Sites where fine-textured clays and silty clays extend well below the proposed pond bottom are most desirable.

Side slopes of excavated ponds, like embankment ponds, must be no more than the natural angle of repose for the soil materials. For most ponds, the slope should be 1:1 or greater.

Excavated ponds have several limitations. High ground water tables in coastal areas often make adequate drainage difficult. Flood protection may present another difficult and/or costly design problem for the engineers.

20.3.3 Harvesting considerations

Harvesting is often one of the most labor-intensive operations on an aquaculture farm. It is, therefore, vital that harvesting requirements are taken into consideration in the pond design. Controlled pond draining rate may be important to the harvest operation. It is often desirable to drain water quickly at the beginning of the drain cycle and to gradually reduce the drain rate toward the end. This can be accomplished by providing two types of drain: a traditional bottom drain and a side drain that will accelerate the drain rate at the beginning.

A well-sloped pond bottom will help to concentrate shrimp toward the drain, thus facilitating harvest. The pond bottom must also be able to withstand harvest equipment operation.

20.3.4 Shrimp pond size

For economic reasons, intensive or semi-intensive shrimp ponds probably should not be smaller than 0.1 ha (0.25 acre). On the other hand, given the difficulties in maintaining a smooth and evenly-sloped bottom and the hardship in harvesting, there is usually little reason to make these ponds any larger than 2 ha.

Extensive shrimp ponds, by definition, require much less care than semi-intensive or intensive ponds. The need for pond bottom maintenance is much less with extensive culture and these ponds are often much larger in size than semi-intensive or intensive ponds.

Harvesting methods are another important consideration in shrimp pond sizing. Electric net use or concentrating the shrimp at the drain basin for harvest with a vortex pump are common harvesting methods for shrimp. Neither method would work well in a large pond.

20.3.4.1 Marketing considerations

Most markets require a consistent and frequent flow of product from the farm to the market. This is especially true for perishable products like shrimp when they are satisfying a local, specialty market. The consumers, especially commercial ones, are likely to expect at least weekly deliveries, if not more often. To meet such a schedule, the farmer must have a sufficient number of ponds of the right size in production.

Recent economic analyses at the University of Hawaii (Leung et al., 1989) found that for intensive and semi-intensive shrimp farms, optimal size for shrimp marketing is highly dependent upon shrimp price, and price differential between sizes of classes. Since differential prices between small and large shrimp vary perhaps weekly, smaller sized ponds would allow the farmers more management and marketing flexibility, and greater profits.

20.3.4.2 Disease control

Shrimp culture intensification has led to more frequent disease problems. Some disease problems can be reduced by proper water delivery and drainage, and by appropriate pond sizing. For example, drainage systems should be isolated from all water intakes. Disease control and treatment are most efficient in small ponds. Semi-intensive and intensive culture ponds do not need to be large. On the contrary, as the intensity increases, pond size should be reduced.

Animals in small ponds can be monitored more effectively, not only for stress which is the forerunner of disease, but also for the disease itself. The two most effective and practical shrimp disease control measures at this time are isolation and sterilization. Both of these measures can be conducted more quickly and effectively in small ponds.

It is impossible to keep disease-causing bacteria and viruses from entering shrimp culture operations. Because of this, disease control must be one of the most important considerations in the pond design. Pond size should be such that animal monitoring, pond drainage, and sterilization can be executed with relative ease. Effective drainage requires a well maintained pond bottom slope, and that, in many cases, precludes large ponds.

20.3.5 Storm run-off protection

Storm run-off and flood protection are important considerations in aquaculture facility design. Flood flow predictability depends largely upon weather analysis techniques and the length of time during which weather data are available. Although a long record is preferable, it should be noted that a long record does not always account for changes in the physical condition of the basin, or in data collection methods (Searcy and Hardison, 1960).

Wang and Hagan (1981) give a concise review of procedures useful in flood flow prediction and watershed development. Although their emphasis was on irrigated rice production systems design, much of their discussion is applicable to aquaculture systems.

20.3.6 Drainage requirement

Proper pond maintenance requires thorough drying of the pond bottom after harvest, except with acid-sulfate soils. This can only be done if there is proper drainage. The advantages of pond bottom desiccation have been well documented. Avault (1988) provides a review of that topic.

Proper drainage is perhaps the most neglected and, in that sense, the most important element in pond design. People intuitively understand that an aquatic pond must be able to hold water. Too often we forget that except for very extensive operations, good drainage is also an important part of good water management and disease control.

All ponds accumulate sediments. Influent water carries particulates into the pond, as does the wind. Bank erosion and water currents redistribute sediments within ponds. Plants and animals die and sink to the bottom; while feed and animal wastes decompose and contribute humus. A complex of clay soil particles, humus, and micro-organisms form pond sediment.

Pond water quality management is directly affected by pond sediment management. Nutrient rich sediment sustains algal growth and contributes to the development of benthic organisms which may cause low dissolved oxygen, especially near the pond bottom.

Two important parameters for designing a pond drainage system are drain time and drain velocity. Drain time is often determined by pond size, bottom slope, gate size, and harvest needs. Slow draining results in a concentration of shrimp in an increasingly smaller water volume with possible oxygen deprivation and physiological stress if the drain is prolonged. These conditions can lead to mortalities, induced molting, and lowered quality. A drain time of six-hours or less would be most desirable.

20.4 POND CONSTRUCTION

20.4.1 Building the pond

Attention to construction details and strict adherence to specifications are extremely important in pond construction. Most aquatic ponds do not receive the attention they require. This neglect is the primary cause of operational and maintenance difficulties. It is more costly to correct a construction mistake than it is to avoid committing one. In most cases, pond construction should be supervised by a qualified engineer.

The first step in pond construction is to clear all vegetation from the site, followed by careful surveying and staking. Staking transfers information on the construction plan to the job site. It provides the lines, grade, and elevation required for construction in accordance with the plan.

If fill material is needed from a borrow area, the area must be clearly marked and staked to indicate the excavation depth. Soil boring of the borrow area is necessary to check the quality of borrowed material. Excavation and placement of waste material must be planned before construction starts.

Construction should be planned for the low rainfall or dry seasons. For small ponds, a track type tractor equipped with a bulldozer blade can usually be used.

20.4.2 Sealing the pond

Excessive seepage often results from improper site selection, therefore, soil properties should be clearly investigated and identified during site

selection. Situations do arise where no satisfactory site is available and, in those cases, we must deal with poor soils.

Agriculture Handbook #590 (1981) describes several approaches to reduce seepage. These include compaction, clay blankets, the application of bentonite or chemical additives, and the installation of waterproof linings.

20.4.2.1 Compaction

Pond seepage can be greatly reduced by compaction, provided that bottom soil material contains particle sizes that range from small gravel or coarse sand to fine sand, with at least 10% clay. For aquatic ponds with a normal average water depth of less than 1.5 m (5 feet), about 20 cm (8 inches) of compacted layer is required to provide a good seal. First, clear the pond area of all vegetation and fill all stump holes and other cracks with impervious material. Scarify the surface to a depth of 20 to 25 cm (8 to 10 inches) with a disk or rototiller. Remove all rocks and tree roots. Roll the soil under optimum moisture conditions to a dense, tight layer with four to six passes with a sheepsfoot roller.

20.4.2.2 Clay blankets

If the soil material at the site contains a high percentage of coarse-grained particles, but not enough clay to produce a compaction layer, one of the alternatives is to blanket the seepage area with a well-graded material containing at least 20% clay. For aquatic ponds, a depth of 30 cm (12 inches) is recommended.

Remove all vegetation and fill in all holes with impervious material before hauling in the blanket materials. Spread the material uniformly over the area in layers 15 to 20 cm (6 to 8 inches) thick. Compact each layer thoroughly under optimum moisture conditions with a sheepsfoot roller before adding another layer.

Protect clay blankets against cracking caused by drying, by spreading a cover of gravel 30 to 45 cm (12 to 18 inches) thick over the blanket, below the anticipated high water mark. Use riprap or a concrete inlet pad to prevent erosion by influent water.

20.4.2.3 Bentonite

Bentonite can reduce seepage in coarse soil. Bentonite is a fine-textured colloidal clay. When wet, it absorbs several times its own weight of water, and at complete saturation, swells as much as 8 to 20 times its original volume. When mixed in correct proportions with well-graded, coarse-grained material, then thoroughly compacted and saturated, the particles of bentonite swell until they fill the pores to the point that the mixture becomes impervious to water. For this reason, use of bentonite to seal aquatic ponds

may not always be appropriate, since frequent pond bottom drying has already been deemed important.

In those cases where bentonite is appropriate, applications generally range from 2 to 5 kg/m², with the exact amount determined by laboratory tests. To apply, clear the site of all vegetation and thoroughly mix the bentonite with the surface soil to a depth of at least 15 cm (6 inches). A rototiller is best for this operation, but a disk can also be used. Next, compact the treated area with four to six passes with a sheepfoot roller. Soil moisture level is very important with bentonite applications, therefore, following application, the treated area must be prevented from drying.

20.4.2.4 Chemical additives

If fine-grained clay particles are arranged at random with end-to-plate or end-to-end contacts, they will form an open, porous, or honeycombed structure said to be "aggregated". Small applications of sodium polyphosphate (such as tetrasodium pyrophosphate, sodium tripolyphosphate, or technical grade soda ash) or 99 to 100% sodium carbonate may collapse the open structure and rearrange the clay particles, thereby reducing soil permeability.

For effective chemical treatment, the soil should have more than 50% fine-grained material (silt and clay), and at least 15% clay. Sodium polyphosphates are usually applied at a rate of 0.25 to 0.50 kg/m², and sodium chloride at 1.0 to 1.6 kg/m². Soda ash is applied at 0.5 to 1.0 kg/m². Soil and chemical mixture 15 cm (6 inches) thick is recommended for aquatic ponds. Chemical selection and the application rate should be determined by laboratory tests. Previous comments regarding mixing, compaction, protection against damage, and site clearing should be followed.

20.4.2.5 Waterproof linings

Polyethylene, vinyl, butyl-rubber, and asphalt-sealed fabric liners are slowly gaining acceptance as linings for small aquatic ponds. There is argument, however, about the importance of the earthen bottom. The main problems with plastic linings are cost and the potential for puncture and breakage. Black polyethylene is less expensive and has better aging properties than vinyl, which is more resistant to damage and can be easily repaired with a solvent cement. Plastic membranes must be protected against puncture with a layer of soil and gravel no less than 15 cm (6 inches) thick. Butyl-rubber and asphalt-sealed fabrics are more resistant to puncture, and special protective measures are generally not required.

Before installing vinyl lining, the ground should be sterilized, cleaned, smoothed and covered with a cushion layer of fine-textured material to serve as a base for the lining. Butyl-rubber and vinyl linings should be laid down smoothly but with some slack; polyethylene linings require 10% slack.

Anchor the top of the lining by burying it in a trench 20 to 25 cm (8 to 10 inches) deep and about 30 cm (12 inches) wide, dug completely around the pond, at or above the normal high water level.

20.5 POND MAINTENANCE AND WATER MANAGEMENT

Water quality problems in shrimp ponds are often related to culture intensity. Extensive culture ponds have few problems with water quality. Oxygen concentrations are typically above any critical level, plankton density is moderate, ammonia and other metabolites are present in low concentrations, and sediments are well oxidized and aerobic. With increased intensification and concomittant feed and fertilizer applications, these conditions change and water quality becomes a greater concern. With intensity levels of semi-intensive and greater, oxygen concentrations can reach critically low values and even cause mass mortality. Algal densities can become very dense and ammonia and other metabolites can reach toxic concentrations. Pond bottoms, through increased deposition of organic materials may accumulate thick layers of reduced, anoxic, black material. Although a variety of water quality problems can develop during intensification, most problems can be attributed to two basic conditions: i) settlement of suspended solids to the pond bottom, and ii) instabilities associated with excessive accumulations of algae and other suspended solids.

20.5.1 Pond maintenance

A shrimp pond's carrying capacity will decrease if organic matter is allowed to accumulate on the pond bottom (Lin 1989). Therefore, it is important that the pond bottom be maintained after each harvest. Sediment accumulations should be removed, and the pond thoroughly dried. Pond bottom soil should also be lightly disked. Lime may also be applied to the pond bottom.

In earthen ponds, it is important that the pond bank be well maintained. Suitable cover vegetation should be established and maintained on the pond bank. Bank erosion is an important contributor to silt accumulation and overall pond deterioration.

20.5.2 Suspended solids in effluent management

Control of suspended solids and algal densities is vital to proper shrimp pond management and pond water quality. Total suspended solids concentration, its size distribution, and its chemical and microbiological characterization are all important to shrimp pond management. High concentrations of suspended solids lead to sediment accumulation, a condition that can be detrimental to pond water quality. On the other hand, some such

materials may be necessary for good shrimp pond performance. Leber and Pruder (1988) found that within one to two hours of feeding, shrimp guts were 30 to 70% full of detritus and sediments, which are the primary components of suspended solids. Chamberlain (1988) concluded that these findings underscore the importance of frequent feeding. More importantly, they show the significance of detritus in the shrimp diet.

In related trials, Wyban et al. (1988) reported feed application rates as high as 67 g/m²/day (0.67 MT/ha/day) during ultra-intensive shrimp culture. During the final 45 days of culture, less than 50% of the feed was consumed directly. Some of this feed undoubtedly was cycled through the food web to the shrimp, while some was also flushed from the pond through water exchange (60% exchange/day). With feed costs of \$0.95/kg and direct feed consumption of 50% or less, as much as \$320/ha/day of feed was used inefficiently, or even wasted.

Maintaining shrimp pond water quality by flushing can be expensive and wasteful of resources. Waste treatment of effluent water can likewise be very expensive, and add another level of management concern. For example, with the 60%/day water exchange rate reported in the above ultra-intensive culture trials, 1 ha of such ponds would discharge 6,000 m³/ha/day. A 10 ha farm would thus discharge 42 m³/min (>11,000 gpm). Treatment costs for this water volume could be substantial.

Data on semi-intensive shrimp pond effluents in Hawaii, collected by the Aquacultural Engineering Laboratory, University of Hawaii, showed that this water contained 140 to 220 mg/l of suspended solids (Wang, unpublished data). When these suspended solids are allowed to accumulate at the bottom of the shrimp pond, an anoxic layer can form. Much of the suspended solids can be removed by sedimentation devices, although there are few direct applications for pond situations at this time.

20.5.3 Conventional waste management processes

Many mechanical devices have been developed for adding oxygen to the pond water. Generally, mechanical devices move water and enhance the water-air interface to improve oxygen transfer. Oxygen balance in shrimp pond water is a complex process. Pond oxygen dynamics and conventional means of maintaining adequate dissolved oxygen in pond waters are discussed elsewhere in this volume (see Chapters 21 and 22). In general, keeping pond water well circulated and maintaining algal populations in a growth phase will help maintain adequate dissolved oxygen levels in shrimp ponds. Presently, suspended solids are most economically removed from waste effluents by settling ponds. Rubel and Hager (1979) reported that a 1 ha settling pond would be required to handle 900 m³ (240,000 gal) of effluent per day. In another study, Rubel and Hager (1980) reported pilot studies using a 0.4 ha

(1.0 acre) experimental shrimp farm to evaluate the effectiveness of several existing technologies for shrimp farm effluent treatment. The principal contaminants studied were total suspended solids and soluble organic carbon. Processes evaluated for settling included dual-media filtration, screening, dissolved air flotation, and biological as well as chemical coagulation. They concluded that:

a. High rate filtration was the best treatment process to reduce suspended solids. An average effluent value of 10 mg/l was produced by filtration over a wide range of incoming water conditions.

b. Pre-treatment before high rate filtration, with either dissolved air flotation or screening, was necessary in order to treat an acceptable water volume before backwash is required.

c. The dissolved air flotation treatment can reduce total suspended solids by an average of 46%. It also produces average effluent concentrations of 20.9 mg/l.

d. Chemical addition and settling was found to be ineffective.

20.5.4 Cost estimates

20.5.4.1 Injection well

For a 10 ha (24.7 acre) shrimp pond in Hawaii, using effluent water re-injection, Rubel and Hager (1980) recommend screening followed by high speed filtration and injection. Projected costs for screening/filtration/injection effluent from the entire 10 ha were estimated at:

Capital Cost - \$1,375,000 (\$54,656 per acre)

Annual operating Cost - \$750,000 (\$30,364 per acre)

However, AECOS (1986) reported that during the first six months of operation, the former Marine Culture Enterprises (MCE) farm in Hawaii (see Chapter 18), used three injection wells to obtain a design capacity of 37,800 m³/day (10 million gal/day). At a much lower discharge rate, one well was totally clogged and could not be cleared. The other two wells were only marginally serviceable.

20.5.4.2 Suspended solids removal

In yet another study, Rubel and Hager (1979) concluded that the particulate material found in shrimp pond effluent was so fine, and its specific gravity so similar to that of sea water that the financial investment in a waste water treatment process would be prohibitive.

20.5.5 Water exchange requirement

Shrimp feeding rate is determined by shrimp body weight and total shrimp biomass. Because the primary function of water exchange is to

remove excessive feed, wastes, and algae, the water exchange rate required to maintain pond water quality can be estimated as a first approximation from shrimp biomass. One crude approximation of water exchange rate can be made by exchanging sufficient water to maintain Secchi disc measurements within a certain range, and then correlating water exchange with shrimp density. Wyban et al. (1988) conducted an ultra-intensive grow-out trial with marine shrimp in which they attempted to adjust the water exchange rate to maintain a pre-determined range of Secchi disc readings. The water exchange was zero at the start of the trial and 106%/day at harvest, with a 60%/day average for the entire crop cycle. At harvest, shrimp biomass was 1.6 kg/m² (16,000 kg/ha). Using these data, we see that water exchange at higher shrimp densities was 66.25%/day/kg shrimp/m². Water exchange at higher or lower shrimp densities can be estimated from this ratio.

While the above rationale for water exchange rate is overly simplistic, it does provide one quantifiable approach. This needs to be further refined to more accurately reflect water quality parameters and algal growth status. This refinement must also include consideration of energy consumption and benefits of mechanical aeration versus energy consumption and benefits from water exchange. This refinement will undoubtedly require a more realistic and appropriate conceptual model than now exists, and ultimately, real-time application of micro-computer monitoring and control of pond management functions (Fast in press).

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CHAPTER 21

Arlo W. Fast and James E. Lannan

POND DYNAMIC PROCESSES

21.1 INTRODUCTION

Water quality in aquaculture ponds is determined by complex physical, chemical, and biological processes. The study of these processes and their dynamic interactions is sometimes referred to as pond dynamics. Understanding the principles of pond dynamics is essential to the eventual control, manipulation, and management of pond systems based on quantified principles rather than on experience and intuition alone.

In this chapter, we will present an overview of what is known about some of the more important processes. This treatment is not intended to be exhaustive, but rather it is intended to provide an introduction to the subject, while at the same time giving some insight into important differences between extensive and intensive culture systems. In the context of this discussion, the term intensity is used to denote the degree of environmental control or management of culture systems. Extensive systems receive little or no external inputs; more intensive systems may receive significant amounts of fertilizers, feeds, or such treatment as supplemental aeration and increased rates of water exchange which alter the dynamic processes that influence water quality.

Modern views of pond dynamics are based on principles of aquatic ecology and limnology. The processes occurring in a production pond, as well as their effects on the biological community in the pond, are in a continual state of flux and are all interdependent. Thus changes in direction or amplitude of a given process may influence other processes occurring in the pond; and changes in patterns of pond processes are likely to effect changes in the growth and composition of the biological community in the pond, including the species being produced. Therefore, it is appropriate to view production ponds as aquatic ecosystems, and to study the various processes with respect to their influence on the entire system.

21.2 TROPHIC DYNAMICS AND NUTRIENT CYCLES

Conceptual models can be useful in describing the dynamic processes that occur in aquaculture ponds and for synthesizing knowledge about pond dynamics. Such models are representations of a system that are based on

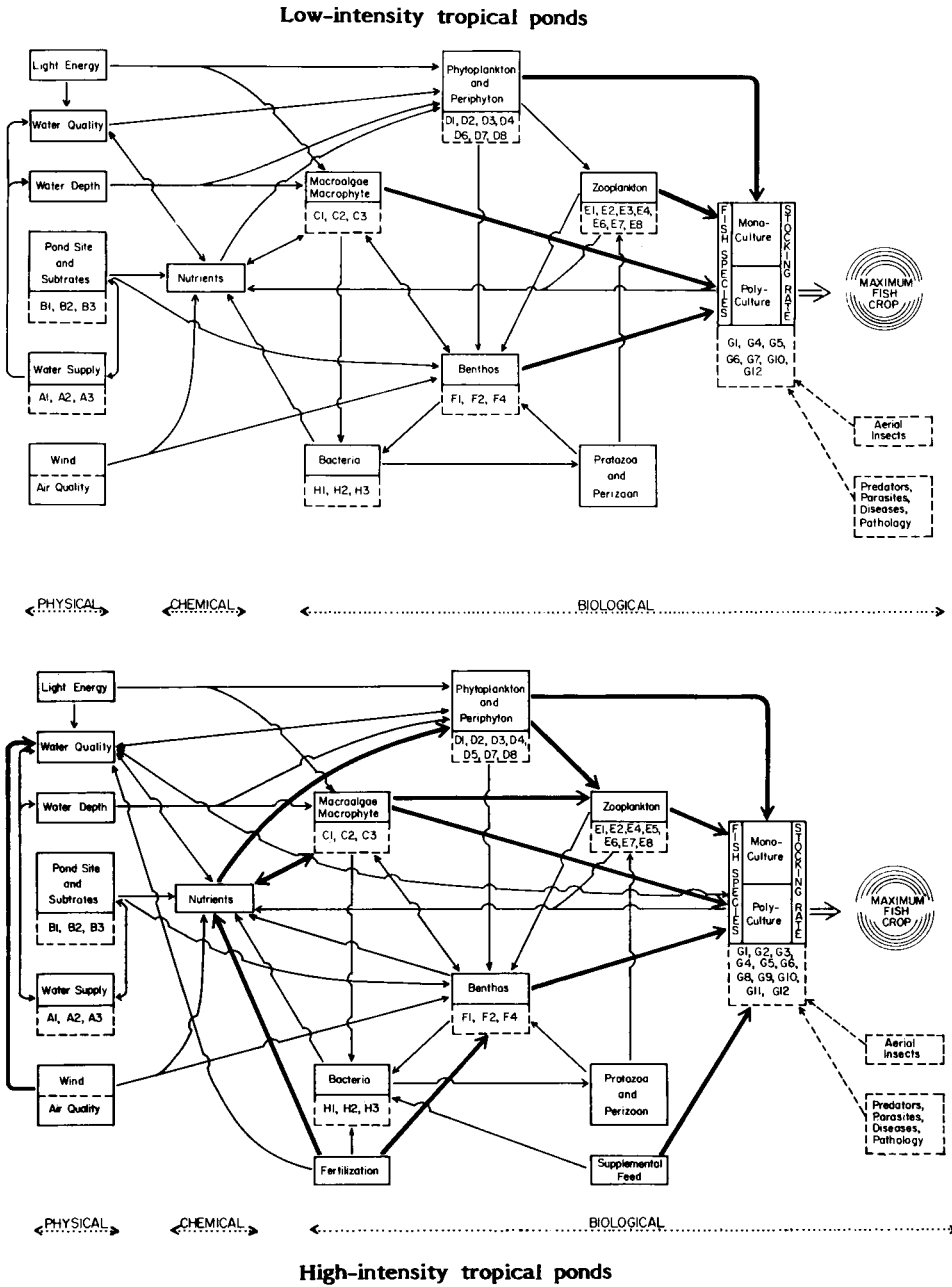


Figure 1. Conceptual models of low-intensity, tropical, extensive pond systems (top) and high-intensity, tropical, intensive ponds (bottom) (Chang 1986).

scientific knowledge of how variables or components of the system are interrelated and how they are affected by external conditions. Chang (1986) presented some conceptual models of dynamic processes in extensive and intensive tropical ponds (Fig. 1). In Chang's conceptual models, the boxes are used to partition selected variables or components of pond systems, and the lines connecting the boxes describe the movements of mass or energy through the system. Conceptual models, such as Chang's, illustrate how trophic and nutrient dynamics influence the productivity of pond aquaculture systems.

Extensive aquaculture ponds have relatively small capacities to produce food. At low standing crop biomass, there is no competition for food resources produced within the pond, and cultured species can often grow at the maximum rate permitted by temperature and age or body size. There is, however, a threshold standing crop in such ponds above which food resources start to become limiting. This point is termed the critical standing crop (CSC). At a standing crop above CSC, there is competition for food resources, and the fish/shrimp crop no longer achieves maximum growth rate. There are three widely accepted methods of increasing the CSC, and thus the yield of extensive aquaculture ponds. These include (1) stocking with a polyculture of selected species such that each species utilizes different feeding niches in the pond, (2) enhancing the production of natural foods in the pond by application of fertilizers, and (3) supplemental feeding with prepared rations.

Flow of mass and energy from fertilizers and feeds are illustrated in Figure 1. The primary inorganic nutrients (carbon, nitrogen, and phosphorus) enter the photoautotrophic pathway, whereas organic nutrients are processed through the heterotrophic (detrital) pathways or are consumed by the target species directly. In practice, unused supplemental feeds are a source of organic and inorganic nutrients that can enter both the autotrophic and heterotrophic food chains. This underscores the importance of feeding practices in determining production efficiency. Prepared feeds should be applied in amounts and frequencies such that all of the feed is consumed by the target species quickly. Careless feeding practices may result in incomplete consumption of the prepared feeds. In this case, the pelleted feeds will degrade giving rise to dissolved and suspended nutrients in the water column, and increased organic loading of the sediments. That is to say that the unused feeds effectively become fertilizers.

Fertilization and supplemental feeding are not mutually exclusive alternatives, and in many applications, both are used simultaneously to increase yields. There is, however, an important distinction between fertilization and supplemental feeding. Fertilization is intended to relieve the nutrient limitations to autotrophic and heterotrophic processes, whereas supplemental feeds are consumed directly by the target species. Thus the

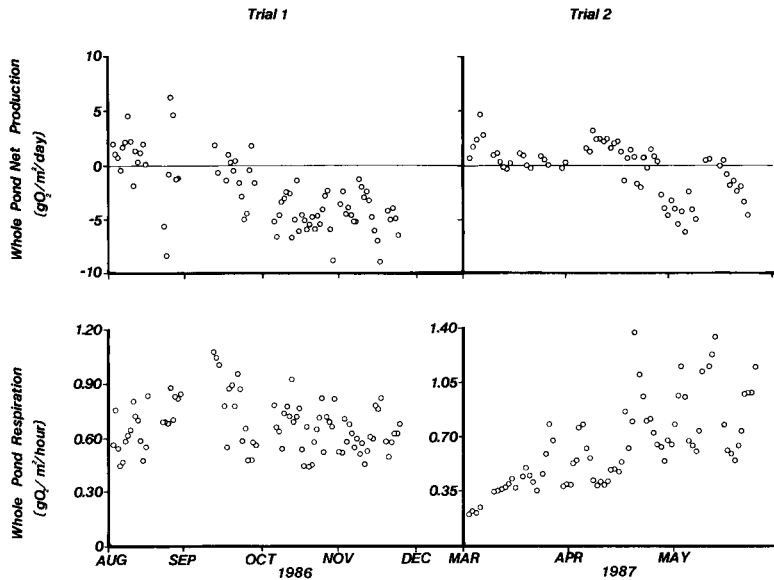


Figure 2. Net pond productivity and pond respiration in brackishwater shrimp ponds in Hawaii during two culture trials. The first trial was August through December 1986. The second was March through June 1987. (Adapted from Madenjian 1988).

distinction is one of feeding the pond in the case of fertilization, and feeding the crop in the case of supplemental feeding. In extensive systems, a major proportion of mass and energy flows through the autotrophic paths. This is also illustrated in Figure 1 by the heavier lines leading from the autotrophic components to the cultured species and to crop yield. As production intensity increases, these autotrophic components continue to be important, but the energy and mass balance gradually shifts toward feed and fertilizer inputs as crop yields increase. Not only do the total number of interactions increase during intensification, but also the number of dominant or "important" interactions. At very high intensity, the major pathways can be dominated by feed inputs alone. Thus pond systems will shift from mainly autotrophic to mainly heterotrophic production during intensification.

Madenjian (1988) demonstrated shifts in trophic status in semi-intensive/intensive brackishwater marine shrimp ponds. With shrimp yields in the range of 850 to 2,600 kg/ha/crop and feed inputs of 3,200 to 5,500 kg/ha/crop, the ponds were mainly autotrophic with net positive primary production (photosynthesis > respiration) during early growout, but were strongly heterotrophic during late growout (photosynthesis < respiration; Fig. 2). Respiration during growout tended to increase as food applications and total shrimp biomass increased, although this increase was

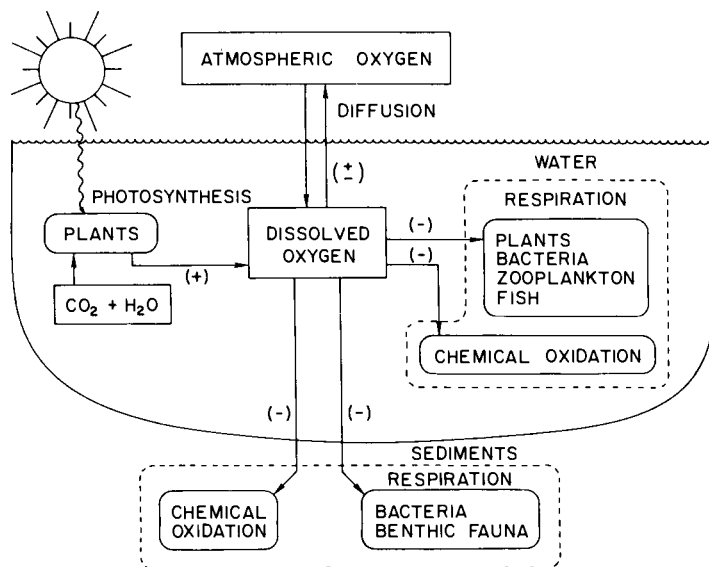


Figure 3. Principal sources and sinks of dissolved oxygen in marine shrimp ponds (Fast 1986).

masked to some extent during the fall period by declining water temperatures (Fig. 3). Madenjian attributed the trophic shift primarily to organic loading of the pond related to feeds. This observation is consistent with the conceptual model of Chang (Fig. 1). Under extremely high feed inputs, heterotrophy will dominate and most of the shrimp nutrition will come from the feeds.

Systems where dissolved inorganic nutrients represent the predominant nutrients available for pond productivity tend to be autotrophic, even at fairly high production levels (Weisburd 1988, Oviatt et al. 1986, Welch 1968). In ecological terms, extensive pond systems driven by inorganic nutrients will most likely remain autotrophic with photosynthesis equal to or exceeding respiration, like the closed systems described by Odum (1969). Intensive pond systems driven by organic nutrients will tend towards heterotrophy. This concept might change however, if the "system" is considered to include not only the ponds themselves, but also the land and water areas used to produce the feeds. Consideration of autotrophy and heterotrophy is of more than academic interest; it has practical considerations, especially with regards to oxygen dynamics and oxygen management as we will see below and in Chapter 22.

21.3 OXYGEN DYNAMICS

The movements of energy and mass through aquaculture systems involves both autotrophic and heterotrophic pathways. Photoautotrophs (photosynthesizers) consume inorganic carbon and produce oxygen. On the other hand, heterotrophs consume oxygen and organic carbon and produce carbon dioxide. Therefore, the oxygen dynamics of aquaculture ponds depends on the balance of autotrophic and heterotrophic production. Observation of the patterns of dissolved oxygen (DO) production and consumption provides aquaculturists with a powerful tool for monitoring pond dynamics and managing water quality.

There are many processes that can potentially limit the rates of autotrophic and heterotrophic production in aquaculture ponds. In biological systems, there can be only one rate limiting process at a give instant of time. The rates of some of the processes in aquaculture ponds may be regarded as intrinsic properties of the pond because they are determined by variables such as wind, solar irradiation, ambient temperature, and rainfall, which are beyond the control of pond managers. The managers must attempt to maximize production given these constraints. Other pond variables such as dissolved and suspended nutrients and dissolved gas concentrations can, at least in principle, be controlled by appropriate management actions.

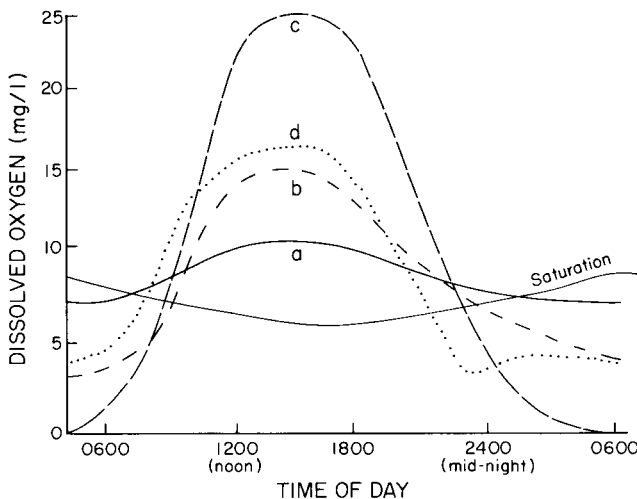


Figure 4. Typical diurnal oxygen concentrations in shrimp ponds under; (a) extensive culture, (b) semi-intensive culture without mechanical aeration, (c) intensive culture without aeration, and (d) intensive culture with aeration (Fast in press).

The principal sources and sinks of dissolved oxygen include photosynthesis, diffusion, water inflows/outflows, respiration and chemical oxidations (Fig. 3). In extensive ponds where net productivity is positive or near zero, oxygen fluxes are well balanced diurnally with most of the oxygen additions to the pond coming from daytime photosynthesis and nighttime diffusion into the pond from the atmosphere (Fig. 4, line A). With increased fertilization and/or feeding, a point is reached where respiration exceeds photosynthetic oxygen production and oxygen diffusion into the pond, and the pond becomes a net consumer of oxygen. This shift is illustrated in Figure 2 for semi-intensive/intensive shrimp ponds in Hawaii. Under these conditions, without artificial aeration or other corrective measures, pond oxygen concentrations range from near zero at night to more than 300% saturation during the day (Fig. 4, line C). There will be considerable diffusional loss of oxygen during the day and diffusional oxygen gain at night, but diffusion alone without supplemental aeration will be insufficient to meet respiratory oxygen losses. These conditions cannot be tolerated in shrimp ponds because shrimp are stressed by even short-term oxygen concentrations below 2 mg/l, and generally die quickly at less than 1 mg/l (Seidman and Lawrence 1985). Mechanical aeration and/or water exchange is then necessary to prevent crop loss.

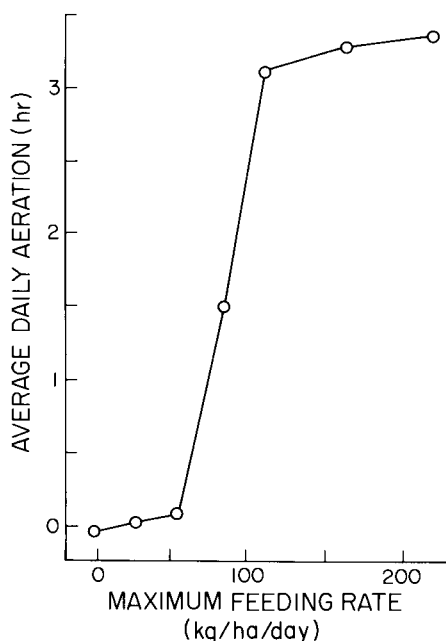


Figure 5. The relationship between feed application rates and the need for mechanical aeration in channel catfish ponds at Auburn, Alabama (Cole and Boyd 1986).

Cole and Boyd (1986), working with channel catfish (*Ictalurus punctatus*) in Alabama freshwater ponds, defined the need for aeration relative to feed inputs in their system which used a 227 day growout and feeding rates ranging from 0 to 224 kg/ha/day. They found that little or no aeration was needed at feeding rates of 50 kg/ha/day or less (Fig. 5). There was then a sharp increase in aeration needs between 50 and 100 kg/ha/day of feed, but a leveling off at between 100 and 224 kg/ha/day. Net catfish production decreased at the higher feeding rates even though adequate oxygen concentrations were maintained. At high feeding rates and low water exchange, metabolic wastes appeared to limit catfish survival and growth. In the ponds observed by Cole and Boyd, maximum feed input of perhaps 50 kg/ha/day appears to mark the point where a pond changes from autotrophy to heterotrophy. Although similar data are not available for shrimp culture, one can expect the same trend as observed for the catfish.

Principal oxygen losses from ponds during semi-intensive to intensive culture are diffusional losses when the ponds are supersaturated, and respiratory losses to the biota in the sediments and the water and to the shrimp. Although shrimp respiration can account for more than 10% of total respiratory loss at high shrimp standing crops, sediment and water respiration

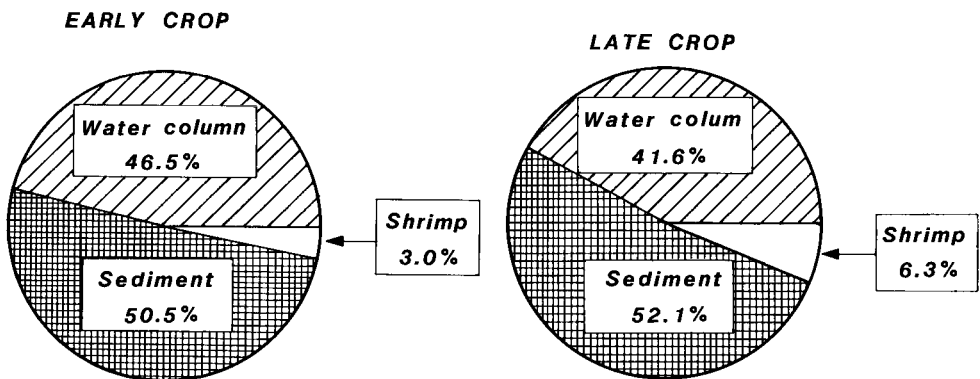


Figure 6. Consumption of dissolved oxygen by respiration components during first 2 and last 2 months of growout. Data obtained at night from four shrimp ponds during semi-intensive and intensive growout (Madenjian 1988).

are the principal respiratory oxygen sinks (Madenjian 1988; Fig. 6). Madenjian (1988) found an average whole pond sediment respiration rate of $298.5 \text{ mg O}_2/\text{m}^2/\text{hr}$ during 279 sample days in four ponds, during two crop growouts. With water depth of 0.75 m, this is equivalent to an average oxygen loss from water to sediments of 0.4 mg/l/hr . These estimates were based on indirect measurements using improved techniques (Madenjian et al. 1988, 1987a, 1987b). They are also substantially higher than assumed or observed by other authors for freshwater aquaculture ponds in which values were generally less than $0.1 \text{ mg O}_2/\text{l/hr}$ (Schroeder 1975, Boyd et al. 1978b, Mezainis 1977, Costa-Pierce et al. 1984, Smith and Piedrahita 1988), but they agree well with values measured in both freshwater and brackishwater ponds by Fast et al. (1983) and Fast et al. (1988).

Not only do the measurements of benthic respiration in brackishwater ponds by Madenjian et al. and Fast et al. indicate a far greater importance for pond sediment respiration than was formerly realized, but they also indicate substantial daily variation. The variation complicates quantitative description of oxygen dynamics because constant or simple functions for sediment respiration cannot be assumed. Piedrahita (1989, personal communication) developed a dynamic model, however, in which he used empirical models of respiration within the several pond components to describe whole pond oxygen balance. Diel variations in dissolved oxygen concentrations predicted

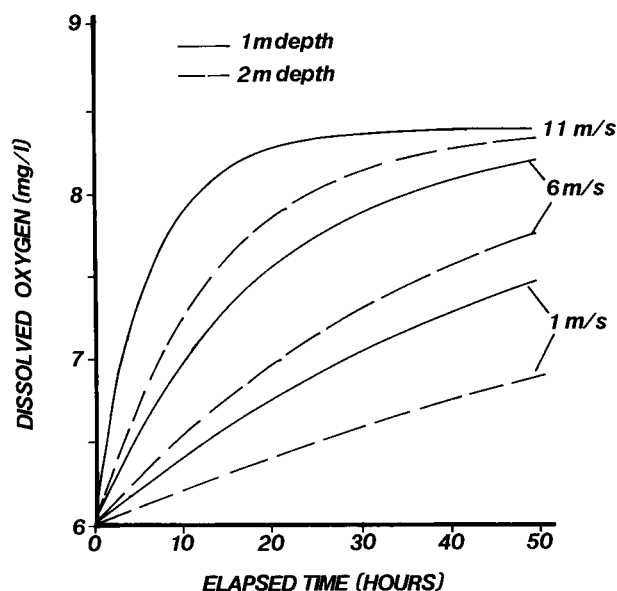


Figure 7. Simulated effects of wind on dissolved oxygen in fish ponds with 1m and 2m water depths (Meyer and Brune 1982).

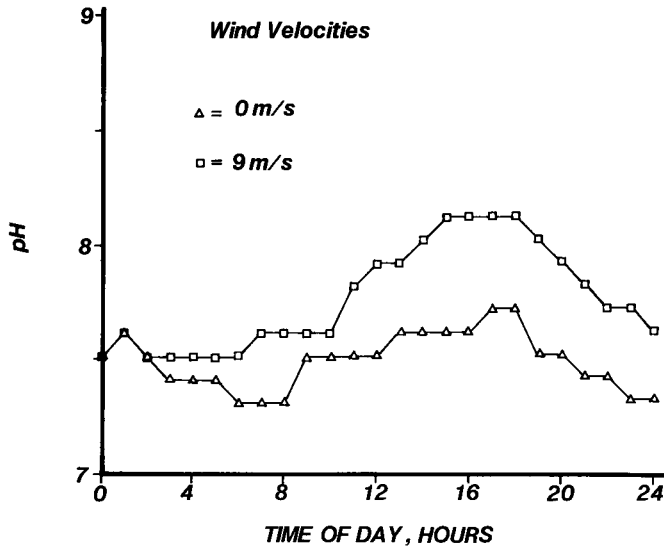


Figure 8. Simulated effects of wind on pH in fish ponds at 30 C and 50% cloud cover (Piedrahita et al. 1984).

by Piedrahita's model are in close agreement with variation observed in fertilized ponds in Thailand.

21.3.1 Wind Effects

Diffusional oxygen losses and gains can also be quite substantial, especially at windy sites when oxygen values are substantially different from 100% saturation. Madenjian (1988) found that overnight diffusional oxygen gains during windy conditions (8.25 m/s) exceeded one third of the whole pond respiration rate on 10 of 30 trial dates. Artificial aeration can also greatly increase oxygen diffusion into or out of a pond, as discussed further in the next chapter. Meyer and Brune (1982) simulated the effects of wind speed on dissolved oxygen concentrations at two pond water depths (1 and 2 m), and at 3 wind speeds, 1, 6 and 11 m/sec (2.2, 13.4, and 25.0 mph). They found that when reaeration from the wind was the sole contributor to pond DO, higher wind speeds contributed substantial oxygen to the pond, and that depth affected the rate of total oxygen gain (Fig.7). Piedrahita et al. (1984) predicted similar wind effect on oxygen diffusion into the pond. They also predicted that wind speeds of 9 m/sec compared with 0 m/sec would cause a pH increase of more than 0.5 due to diffusional loss of CO_2 from the pond (Fig.8). Fast et al. (1983) also found that, with wind speeds below 5 m/sec (11 mph), 1 m deep ponds in Hawaii tended to remain thermally stratified and had low DO concentrations near the sediment/water interface (Fig.9). At wind speeds greater than 5 m/sec, thermal stratification was reduced and

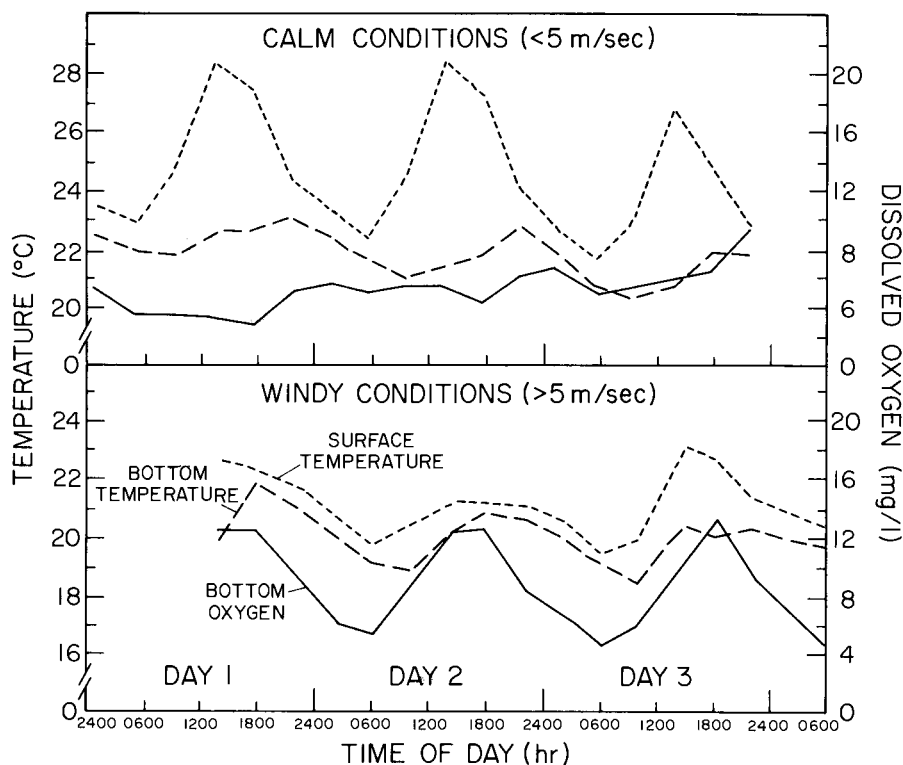


Figure 9. Effects of low wind velocities (< 5m/sec) on surface and bottom water temperatures and bottom dissolved oxygen in a Hawaiian freshwater prawn pond (Fast et al. 1983).

bottom oxygen concentrations increased. Thus wind influences oxygen dynamics in two important ways; wind affects diffusion at the air-water interface, and stimulates circulation and mixing of pond waters.

Chang and Ouyang (1988), working with freshwater aquaculture ponds in the Pearl River Delta of the People's Republic of China, found that 1 m deep ponds would stratify thermally on a daily basis during the summer with oxygen depletion of the bottom water. Thermal stability, and mixing depth were related to water temperature, water temperature gradient, and wind speed. The water column stability was much stronger at 30 C than at 15 C, and required much greater wind velocities to achieve the same mixed depth (Fig.10). Ponds in this region of China typically mixed down to the 0.75 m depth each night during normal wind conditions due to convective cooling of the surface waters, but ponds 1.0 m or deeper typically remained stratified for long periods. Even with shallow ponds which mixed diurnally, bottom oxygen concentrations seldom exceeded 2 mg/l due to the combined effects of

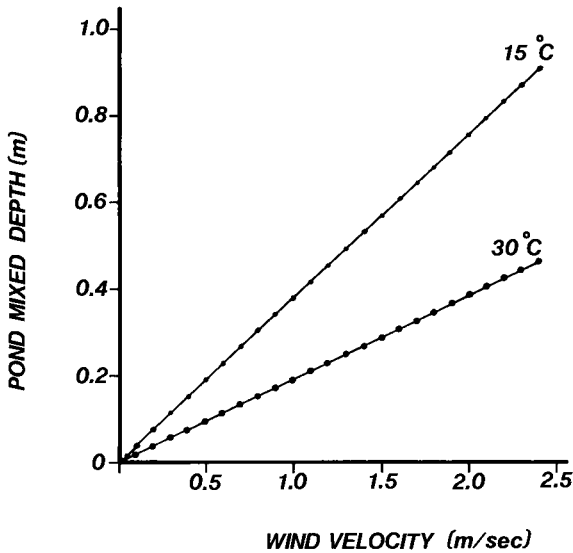


Figure 10. Simulated effects of wind speed on mixed depth of freshwater ponds at 15 and 30°C (Chang and Ouyang 1988).

thermal stratification, high oxygen demand near the bottom (water and sediments), and the nature of the diurnal oxygen curve for the whole pond.

Wind can also have a substantial impact on water temperatures due to evaporative cooling. In Hawaii, pond water temperatures on the same island can differ by 2 to 3 °C due to this affect (Madenjian, C.P. 1988, personal comm.). In extreme cases with geothermal waters in colder climates, the wind can affect water temperatures by more than 5 °C (Klemetson and Rogers 1983).

At a windy site in Hawaii with average wind speeds of up to 8.25 m/sec, Madenjian (1988) found that wind induced diffusional oxygen gains exceeded one third of the overnight whole pond respiration. Diffusion, especially during windy conditions, is clearly not an inconsequential component of oxygen dynamics in aquaculture ponds as suggested by some (Pruder 1986). Wind can affect not only the diffusional gain or loss of oxygen, but the distribution of oxygen within the pond as well.

21.3.2 Light

Light levels can either inhibit or promote algal growth. At very high light levels, algae can be damaged by photo-oxidation of cell materials. In mixed ponds of adequate depth, this normally does not occur. An exception to this rule is described by Boyd et al. (1978a) when calm conditions allowed bouyant algae to float to the surface where they were killed by sunlight. More often, algae growth and oxygen production are inhibited by water turbidity

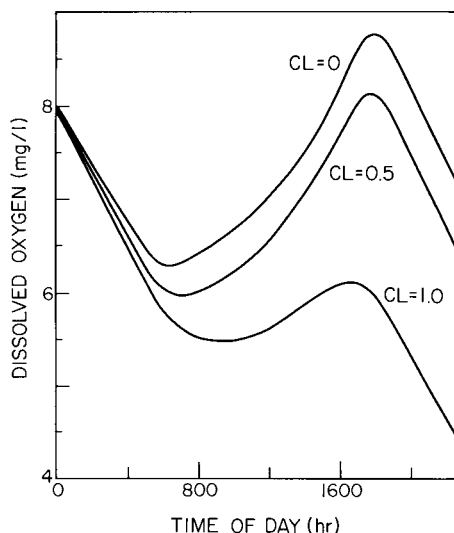


Figure 11. Simulated effects of cloud cover (CL) on dissolved oxygen in fish ponds. Cloud covers are 0, 50 and 100%. (Meyer and Brune 1982)

(self-shading or abiotic turbidity), and by cloudy conditions. A simulation of the latter condition is shown in Figure 11 in which the effects of three levels of cloud cover are predicted. Observational experience confirms this trend, particularly when cloud cover is heavy for several consecutive days (Boyd 1979).

21.3.3 Algal Production

Primary production is important even when ponds become net heterotrophs through intensification. In the first place, most of the world's production of cultured shrimp comes from extensive and semi-intensive ponds where all or a substantial portion of the shrimp yield is derived from the food chain, starting with primary production. Although intensive culture can be very profitable and is fashionable at present (Chiang and Liao 1985, Fast et al. 1989), economic analysis indicates that semi-intensive production methods will prevail, if and when production exceeds demand, and shrimp prices decline (Hirasawa 1985, Fast in press). This is expected to occur within the next few years, if not sooner, although it could be postponed by technological breakthroughs in intensive culture methods. Even in intensive culture, algal growth and algal health are important for water quality management.

Maintenance of healthy, rapidly growing algae is important for water quality, even with net heterotrophy. Algae maintained in a growth phase will contribute substantial amounts of DO to the oxygen budget, while at the same time removing metabolites which can become toxic to the shrimp. These

conditions can reduce the energy requirements and costs to maintain suitable water quality for the shrimp, if properly managed. Cole and Boyd (1986) attribute reduced production of catfish under high feed applications, at least in part, to the accumulation of metabolites, especially ammonia. Along with oxygen, ammonia concentrations are generally considered among the most important measureable water quality parameters for fish and other aquaculture crops (Boyd 1982, Meade 1985, Avnimelech and Zohar 1986). At optimum net primary production, for every atom of oxygen released, 0.15 atoms of nitrogen are incorporated by the algae.

Some algal growth models for aquaculture ponds predict optimal algal densities in terms of net oxygen production. This optimum is a result of interactions between net algal production rate (oxygen production) and algal respiration (oxygen consumption). These rates are affected by algal density, nutrient limitations, algal respiration and other factors. One set of relationships based on a model by Bannister (1979) and presented by Laws and Malecha (1981) is shown in Figure 12. This particular model, which assumes that light limitation was the primary limiting factor through self-shading, predicted that morning DO would be depleted below 2 mg/l at chlorophyll-a concentrations greater than 2 g/m³, when all nighttime respiration is due to the algae and the water is oxygen saturated at dusk.

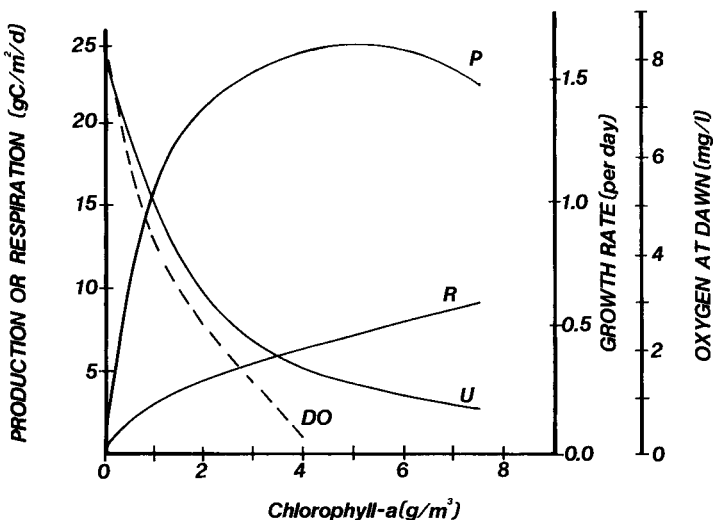


Figure 12. Simulated relationships between planktonic net production (P), respiration (R), growth rates (u), and DO at dawn in a 1m deep pond based on a model by Bannister (1979). (Laws and Malecha 1981)

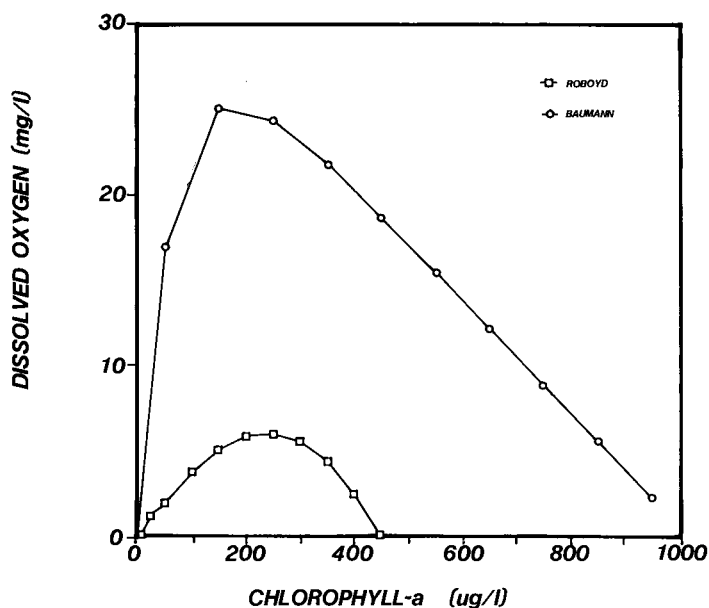


Figure 13. Simulated dissolved oxygen concentrations at dawn for different chlorophyll-a concentrations (Figure from Smith and Piedrahita 1988).

The empirical model of Boyd et al. (1978b) and Romaine and Boyd (1979), and the theoretical model of Baumert and Uhlmann (1983) are perhaps more realistic in that they predict optimum oxygen conditions in fish ponds at chlorophyll-a concentrations between 150 and 250 ug/l (Fig. 13). Chlorophyll-a concentrations below this range result in reduced DO at dawn due to other respiration losses, while values above the maximum result in reduced DO at dawn due to reduced oxygen production by algae, coupled with increased algae respiration at high biomass. The two models, although they show similar chlorophyll-a optima, clearly show major differences in DO magnitude. This is attributed to the theoretical model's simplified assumptions which predicts theoretical oxygen maxima based on "ideal" conditions for algal growth (Smith and Piedrahita 1988), a condition which does not often exist in practice. The empirical model, on the other hand, takes all existing conditions into consideration including observations of actual pond performances. Both models are useful. The main point here is that the pond manager should strive to keep the pond healthy by maintaining rapid algal growth. Among other things, this involves trying to maintain algal densities within some optimum range.

In practice, pond managers measure chlorophyll-a seldom, if at all. They do, however, measure water transparency by Secchi disc and make less

quantifiable judgements about algal health based on water color and other conditions. Secchi disc transparencies as a function of chlorophyll-*a* concentrations can vary considerably between sites, or at a given site depending on many factors. Average Secchi disc transparencies at 200 $\mu\text{g/l}$ chlorophyll-*a* varied by a difference of 10 cm at a windy site in Hawaii and a calm site in Alabama (Fig. 14). This difference reflects in part differences due to non-algal, suspended materials. Secchi disc transparency is also a crude measure of photic depth, the depth above which oxygen production exceeds respiration. Photic depth is about equal to twice the Secchi disc depth (Chang and Ouyang, 1988). A pond manager at a given site will develop from experience an informed opinion about when algae density is too high or too low, and will then take some corrective actions.

Extensive growout ponds are often characterised by chlorophyll-*a* concentrations below 200 $\mu\text{g/l}$ and Secchi disc transparencies greater than 30 cm. As crop production intensifies through fertilization and feed inputs, these values can easily increase to more than 400 $\mu\text{g/l}$, and less than 15 cm respectively. Water quality management is usually much more difficult at the higher levels of intensity because of reduced net oxygen production as discussed above, and because of the greater tendency of the algae for catastrophic collapse, or "crash" at the higher densities.

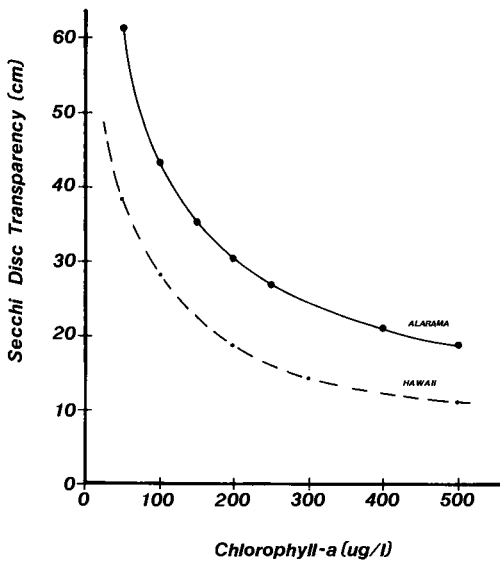


Figure 14. Relationships between chlorophyll-*a* concentrations and Secchi disc transparencies in channel catfish ponds (Alabama; Alamazan and Boyd 1978), and a freshwater prawn pond (Hawaii; Fast et al. 1983). The prawn pond was a windy site.

The models discussed above do not take these catastrophic algal crash events into consideration, but practical experience has shown that they do occur with greater frequency at higher algal standing crops. As algal density increases, algal diversity and stability typically decreases. At very high algal densities (>400 $\mu\text{g/l}$), algal communities are often dominated by one or two species. Even with continuous attention, these populations are prone to rapid die-off, cell lysis, and loss of oxygen production by the algae. This not only exerts a very high net oxygen flux, but it also can result in the accumulation of toxic metabolites which are no longer absorbed by the algae. Maintaining healthy, rapidly growing algae at optimal net oxygen production is not an easy task, even under laboratory conditions (Goldman 1979a, 1979b). Under field conditions in earthen production ponds the task is even more difficult.

At present, we know very little about how to optimize the costs/benefits of water exchange, algal production, and algal densities at different levels of intensification. Control of excessive algae densities by biological means has not as yet proven successful (Smith and Piedrahita 1988; Smith 1985, 1987). Most of these attempts involve cropping of the algae by fish (Costa-Pierce et al. 1985, Edwards et al. 1981, Smith 1987), bivalves (York 1983, Buttner 1986) or micro-crustacea (Smith 1987). The problem seems to be one of keeping all components within some optimal range of activity, a condition not easily achieved when the number of potentially important interactions is large (Fig. 1). The problem is probably confounded by the prey preferences of some species.

Control of excessive algae densities by chemical means is even more problematic (Boyd 1979). Use of algae toxicants such as herbicides (Tucker and Boyd 1978), copper sulfate (McIntosh and Kevern 1974), or the use of dyes (Boyd and Moor 1982) not only increases respiration through decomposition of the dead algae, but it also greatly reduces algal growth and net oxygen production. Use of these toxicants can cause man-made algal crashes.

Control of excessive algal growth through mechanical means such as water exchange can be effective, as discussed in more detail in the next chapter. This is now perhaps the only good means of managing excessive algal density, although its application is still largely an art-form. Furthermore, water exchange and algal wash-out waste a resource which potentially could contribute nutrition to both the primary crop (shrimp) and to secondary crops, such as bivalves or fish. Algal control through water exchange is also energy intensive, and results in the loss of nutrients such as nitrogen and phosphorus.

21.3.4 Temperature

Water temperature is one of the principal factors limiting shrimp culture worldwide. Although growth responses to temperature and salinity have not yet been well defined for commonly cultured shrimp species (see Chapter 24), the consensus is that most cultured shrimp grow best in a temperature range of 24 to 32 C. A notable exception is *Penaeus chinensis* which can survive prolonged temperatures as low as 10 C, and can grow well in the range of 18 to 25 C, well below the optimum for most other cultured shrimp (Liu 1983). Temperate climate has been perhaps the largest impediment to the development of a shrimp culture industry in the continental United States, where normally only one summer crop is achieved each year. Two crops are possible with greenhouse nursery start-up and/or two-phase growout, but the economics of this are questionable. Even in Taiwan and Japan, winter water temperatures are unsuitable, or are marginally suitable from two to four months each winter. Countries such as Thailand, the Philippines, Indonesia, and Ecuador have some of the best water temperatures for shrimp culture, combined with excellent broodstock sourcing and seed availability.

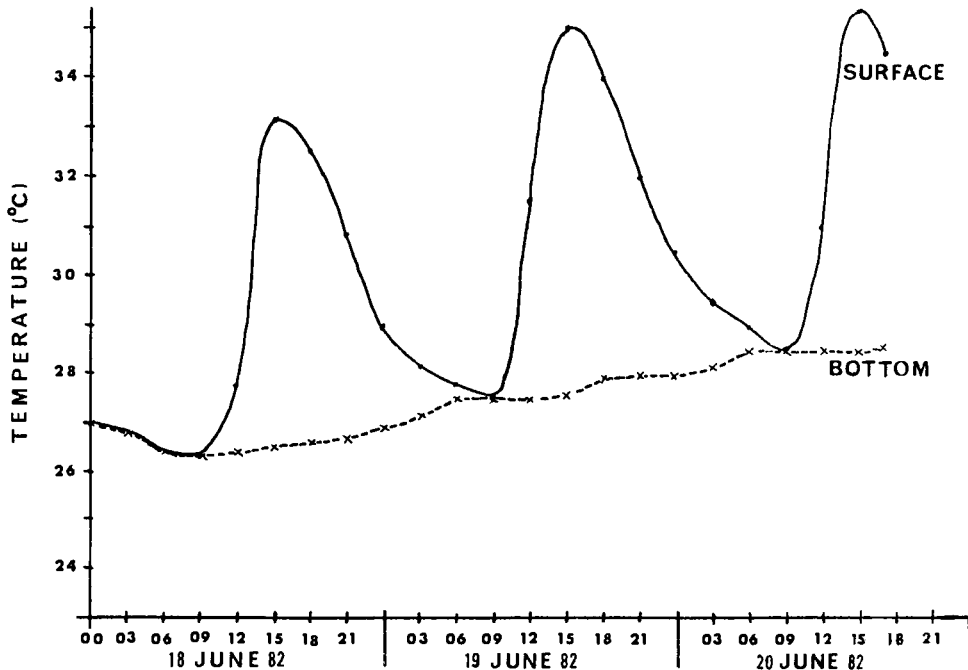


Figure 15. Surface and bottom water temperatures in a 1m deep freshwater prawn pond in Hawaii during calm wind condition, June 1982 (Fast et al. 1983).

In addition to seasonal temperature variation, ponds can also exhibit strong diurnal temperature patterns. These are generally of lower magnitude, but can range from 3 to 5 C per day. Diurnal temperature changes express themselves both as surface water temperature differences during the day, and perhaps more importantly as vertical stratification of ponds. These two conditions are clearly illustrated for a 1 m deep Hawaiian prawn pond over three days (Fig. 15). Each day, the pond stratified thermally about 0900 hrs. Surface/bottom temperatures increased to a +6 C δT peak by 1500 hrs, and then began to cool. Sometime during the night the pond mixed due to convective cooling of the surface waters. Bottom temperatures changed little during the day, but showed a long term trend over the 3 day period. Concomitant with this thermal stratification, the pond also exhibited oxygen stratification since the water column below the "thermocline" was effectively sealed off from atmospheric oxygen exchange, and was below the photic depth. Stratification was largely related to absolute water temperatures, wind and cloud cover as noted earlier, with the thermocline normally extending from the 30 to 50 cm depth. Secchi disc transparencies were typically 25 cm or less, which means little or no net photosynthesis below 50 cm.

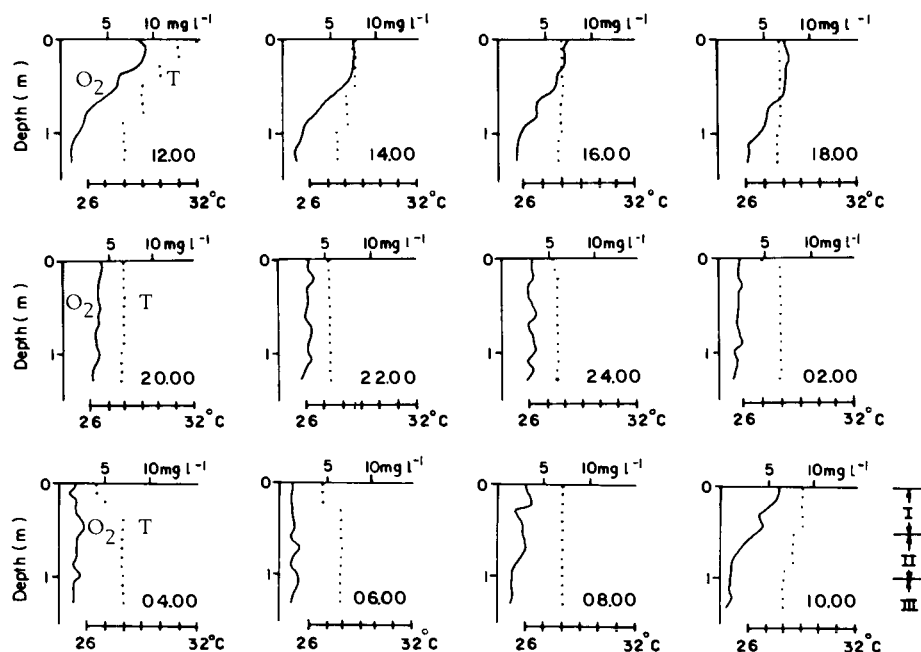


Figure 16. Development of thermal and oxygen stratification in a Chinese fish pond during June 1985 between 10am. and 2pm (Chang and Ouyang in press).

Chang and Ouyang (1988), in their study of Chinese ponds, also found daily thermal and DO stratification. The ponds typically mixed during the night due to convective cooling, but stratified soon after sunrise (Fig. 16). Bottom DO seldom exceeded 2 mg/l due to high oxygen demands, and lack of photosynthesis in the bottom waters.

The importance of diurnal thermal and oxygen stratification is that the lowest temperatures and lowest oxygen concentrations are always found at the pond bottom, which is where the shrimp reside during most of the day. The shrimp's metabolism may be negatively impacted by the low temperatures, while their activity, feeding and health may be negatively impacted if the DO falls below 2 mg/l (Sediman and Lawrence 1985). Diurnal thermal and DO stratification has not been widely studied, but it is common in areas with calm conditions and high solar radiation. Besides its potential impact on the cultured crop, especially bottom dwelling crustaceans, stratification greatly complicates most ecological systems models. Considerations such as whole pond respiration, gas exchanges, and photosynthesis are complicated considerably by stratification, especially diurnal stratification. These factors confound our ability to understand and predict events in the pond. Thermal stratification can be reduced or eliminated by water aeration or water mixing. This is discussed more fully in the next chapter.

21.3.5 Water depth

The effects of water depth on pond dynamics has been little studied, yet water depth is one of the most basic aspects of pond design and management. Even without knowledge of quantitative water depth effects, aquaculture pond designs with different water depths have evolved. This evolution was largely by trial and error, which integrated the biological requirements of the cultured species with local tradition and economic factors.

In the Philippines and Southeast Asia, traditional brackishwater aquaculture ponds are typically 0.3 to 0.6 m deep (Bardach et al. 1972, Apud 1985, Colt 1986). These ponds are used for extensive milkfish (Chanos chanos), tilapia, and marine shrimp culture. In the U.S., aquaculture ponds with water depths ranging from 1.0 to 1.5 m are the standard. These depths are common for channel catfish (Ictalurus punctatus; Boyd 1983, Stickney 1979), and for freshwater prawns (Macrobrachium rosenbergii; Shang 1981). In Taiwan, the average water depth of intensive pond growout systems for tiger prawns (Penaeus monodon) is now more than 1.8 m, whereas 1 m depths were more common when yields were less (Chiang and Liao 1985, Fast et al. 1989). Why these deeper ponds give better production results when intensified is not well understood.

Fast et al. (1988) conducted a 2x3 factorial design experiment on brackishwater shrimp ponds in the Philippines to evaluate the effects of water

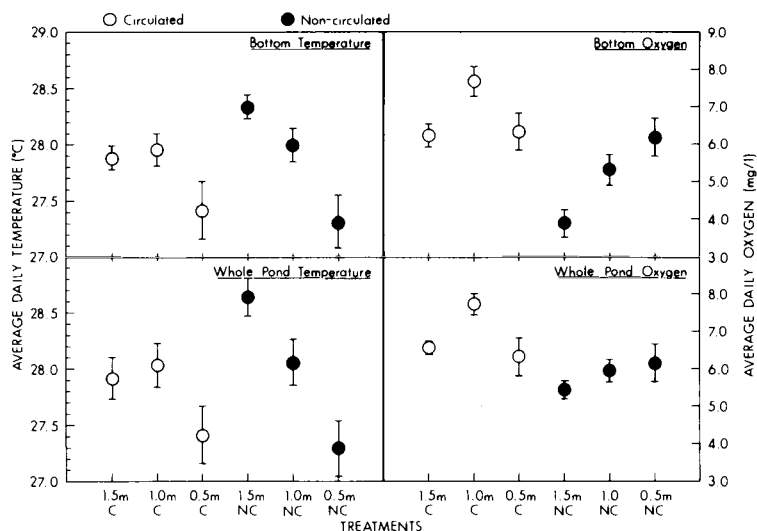


Figure 17. Mean and 95% confidence interval of whole pond and pond bottom oxygen concentration and temperature in Philippines shrimp ponds for each of six treatments: three water depths, with (C) and without (NC) mechanical circulation (Fast et al. 1988).

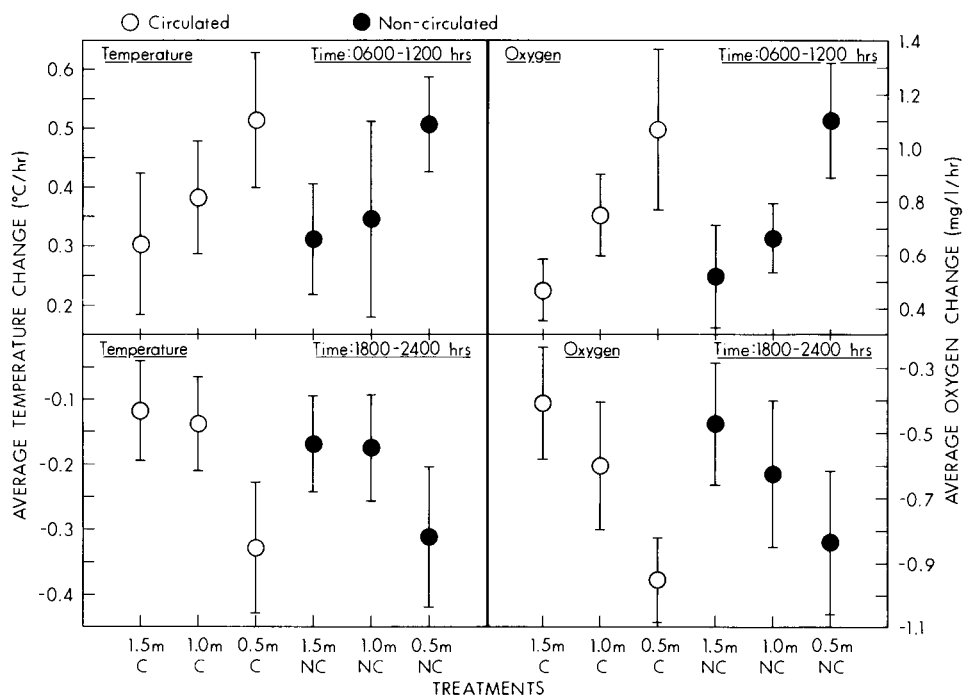


Figure 18. Mean and 95% confidence interval of rates of change in temperature and dissolved oxygen during morning and evening in Philippine shrimp ponds for each of six treatments: three water depths, with (C) and without (NC) circulation (Fast et al. 1988).

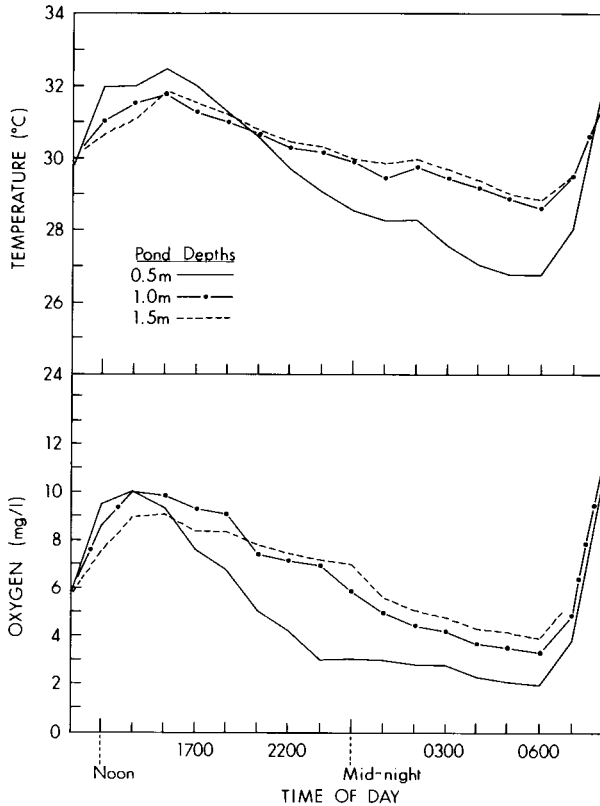


Figure 19. Diurnal average whole pond oxygen and temperature patterns in 0.5, 1.0 and 1.5 m deep philippine brackishwater shrimp ponds on 5 October 1985. All ponds were mechanically circulated as described by Fast et al. (1988).

depth and artificial mixing on oxygen and temperature conditions in 18-0.1 ha ponds. Treatments included 3 pond depths (0.5, 1.0 and 1.5 m), and 2 mixing conditions; ambient and with pond mixers as described by Rogers and Fast (1988). The results indicated some substantial differences in oxygen and temperature conditions, as related to pond depth.

On the average, shallow ponds (0.5 m) tended to have cooler water temperatures than deeper ponds, but greater rates of change in temperature (Fig.'s 17 and 18). This was related to the ratios of water volume to water surface area, and to sediment respiration. Shallow ponds also tended to have greater ranges of temperature and oxygen values (Fig. 19). Stratification of oxygen and temperature was most pronounced at pond depths of 1 m or deeper, unless they were artificially mixed. Stratification in these Philippine ponds was typically diurnal, even with ponds 1.5 m deep (Fig. 20); although

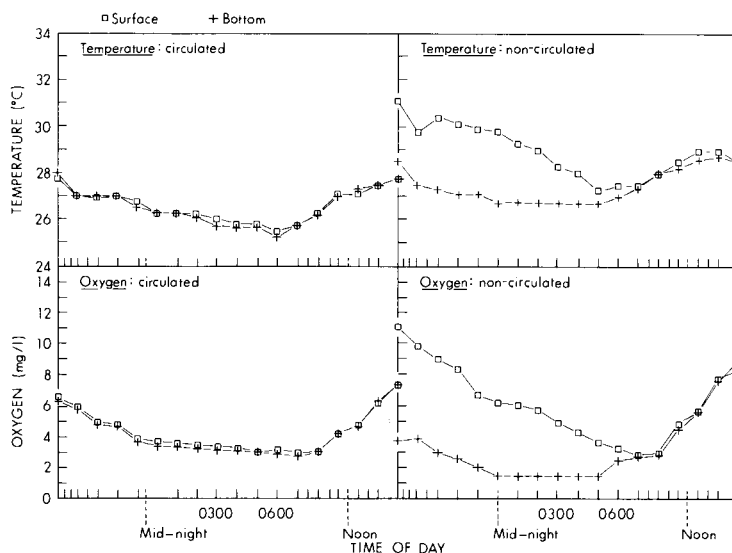


Figure 20. Diurnal surface and bottom oxygen and temperature patterns in 1.5 m deep. Philippine brackishwater shrimp ponds on 29 November 1985. Values for circulated and non-circulated ponds are shown (Fast et al. 1988).

in China, ponds deeper than 1.0 m remained stratified much longer (Chang and Ouyang, 1988). In Alabama, ponds 2 m or deeper often remained stratified throughout the summer (Boyd 1979). Although Fast et al. (1988) found some major differences in oxygen and temperature dynamics, they did not observe significant differences in shrimp yields between ponds of different depths (Carpenter et al. 1986). They attribute this to the relatively low intensity, which averaged less than 850 kg/ha/crop with stocking densities of 10 PL/m². Their conclusion was that the impact of water depth would be more important at higher intensity, but this conclusion was not verified experimentally. The full implication of water depth for fish and crustacean culture, and its economic consequences, remains largely unresolved.

21.3.6 Other Pond Dynamic Considerations

The above discussion does not exhaust all that is important or is known about pond dynamics. Considerations of nutrient cycling, sediments, acid soil hydrology and other factors are perhaps of equal importance. A full treatment of all of the complex considerations is beyond the scope of this chapter. Good sources of information that provide a starting point for understanding many

of these considerations include Boyd (1979, 1982, 1988), Tucker (1985), Lannan et al. (1986), Wetzel (1975), Simpson et al. (1983), and Singh (1985).

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CHAPTER 22

Arlo W. Fast and Claude E. Boyd

WATER CIRCULATION, AERATION AND OTHER MANAGEMENT PRACTICES

22.1 INTRODUCTION

Production of aquaculture crops, with desirable levels of survival and yield requires application of suitable pond management techniques. For the most part, this means appropriate water and sediment management. The use of inappropriate or inadequate techniques can lead to a host of problems, including low dissolved oxygen (DO) and toxic conditions in the water and sediments. In addition, needs for management attention increase greatly as intensification level increases. Extensive shrimp ponds with low productivity require very little management intervention, while intensive and ultra-intensive ponds require large amounts of labor, energy, and materials.

Extensive shrimp culture is characterized by relatively low levels of nutrient cycling, DO fluxes, and risks of crop failure (see Chapters 15, 21 and 27). Photosynthesis and decomposition processes are nearly in balance. Organic matter produced by photoautotrophs cycles mostly through aerobic pathways, and pond conditions are relatively stable (Fig. 1). As culture intensifies, especially through feed applications, ponds become more eutrophic and anaerobic decomposition plays a bigger role in processing uneaten food, feces and other organic matter (Pruder 1986, Chamberlain 1988). Plant nutrient concentrations increase, as does photosynthesis, to the point where algae become self-limiting through self-shading, or some other factor (Smith and Piedrahita 1988). Organic debris also accumulates faster than the pond system can oxidize it, and a thick layer of black, reduced material accumulates on the pond bottom. These accumulations are avoided by shrimp, especially burrowing species (Shigueno 1975) and can have a negative effect on feeding as well. Feed which falls into reduced sediments may not be found and consumed by shrimp. At high feed application rates (organic loading), toxic levels of hydrogen sulfide, ammonia, and nitrite may develop in pond water (Cole and Boyd 1986). Pond management practices most commonly used to correct or counter these negative influences include; water circulation, water aeration, water exchange and sediment treatments.

Although pond managers often have a good intuitive or qualitative feel for these interactions and how to manipulate them with the desired results,

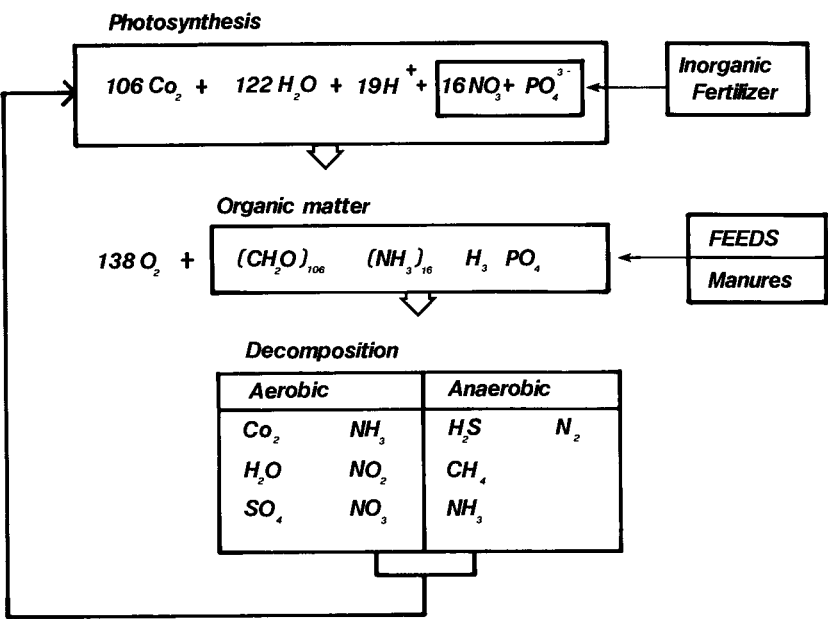


Figure 1. Simplified relationships between photosynthesis, organic matter production, inputs and decomposition pathways in ponds.

we are only starting to understand them quantitatively, often only through indirect measures. An example of the latter is given by Cole and Boyd (1986). They measured aeration need as a function of feeding rate (see Chapter 21). This empirical relationship is instructive, but it does not fully define the interactions leading to aeration needs.

22.1.1 Water Circulation vs. Aeration Considerations

There seems to be some confusion about differences between water circulation and aeration, and when it is most appropriate to use each (Chamberlain 1988). The decision logic is not complicated. The main problems involve logistics of applying circulation or aeration on a timely basis. Decision logic involves a consideration of only two pond water conditions; DO concentrations and thermal stratification.

When pond water is supersaturated with DO at the air/water interface, mechanical aeration or natural diffusion will drive oxygen from the water and into the atmosphere (Fig. 2). The greater the % supersaturation, the greater the oxygen loss from the pond through use of "aeration" equipment. Aeration in this case is actually a misnomer, and should more accurately be termed de-aeration or de-oxygenation. Aeration equipment, or aerators are those devices that through mechanical means increase water/air surface area by

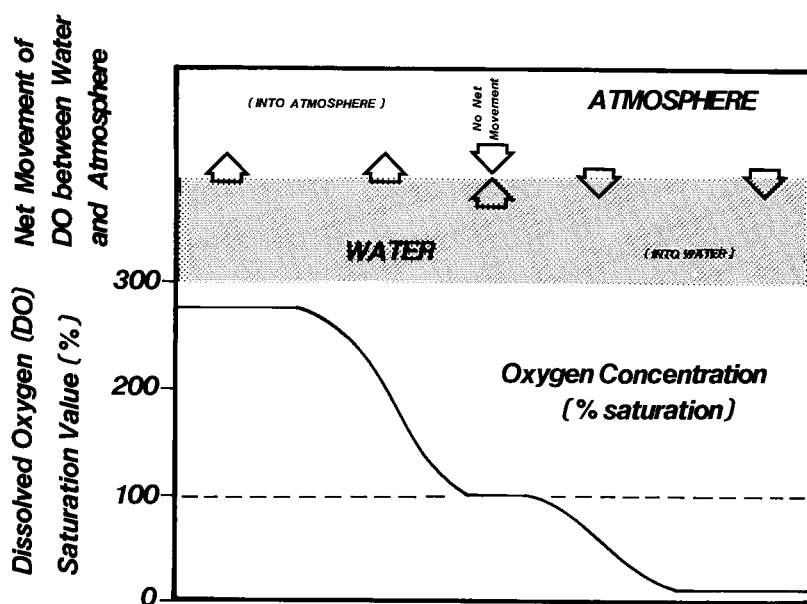


Figure 2. Direction of oxygen flux relative to dissolved oxygen saturation.

either creation of water droplets in air, or air bubbles in water. Aerators also create turbulence and circulation patterns within the pond, factors which also affect oxygen exchange between pond water and atmosphere.

Circulating pond water only when the surface is supersaturated, without increasing pond water/atmosphere surface area, will lead to a slight increase in oxygen loss to the atmosphere. Furthermore, the process will mix much of the "excess" oxygen into the pond depths, thus reducing % saturation at the pond surface. Experience indicates that this mixing conserves more DO within the pond than if the pond were not mixed (Gary L. Rogers 1988, personal comm.). Circulation effects on oxygen and temperature depth distributions in freshwater prawn (*Macrobrachium rosenbergii*) ponds in Hawaii are shown in Figure 3. In the uncirculated pond, temperatures ranged from 32 C at the surface to 27 C at the bottom, while DO was 16.5 and 6.8 mg/l respectively. Surface DO was 226% saturated. In the circulated pond, temperatures ranged from 30.3 to 29.0 C, while DO was nearly uniform at 10 to 11 mg/l. Surface DO was 147% saturated. While total oxygen fluxes were not measured, the implications of this and subsequent work with both freshwater and brackishwater aquaculture ponds in Hawaii (Rogers and Fast 1988), are that when pond water is supersaturated with DO, circulation alone does not cause much diffusional oxygen loss from the pond.

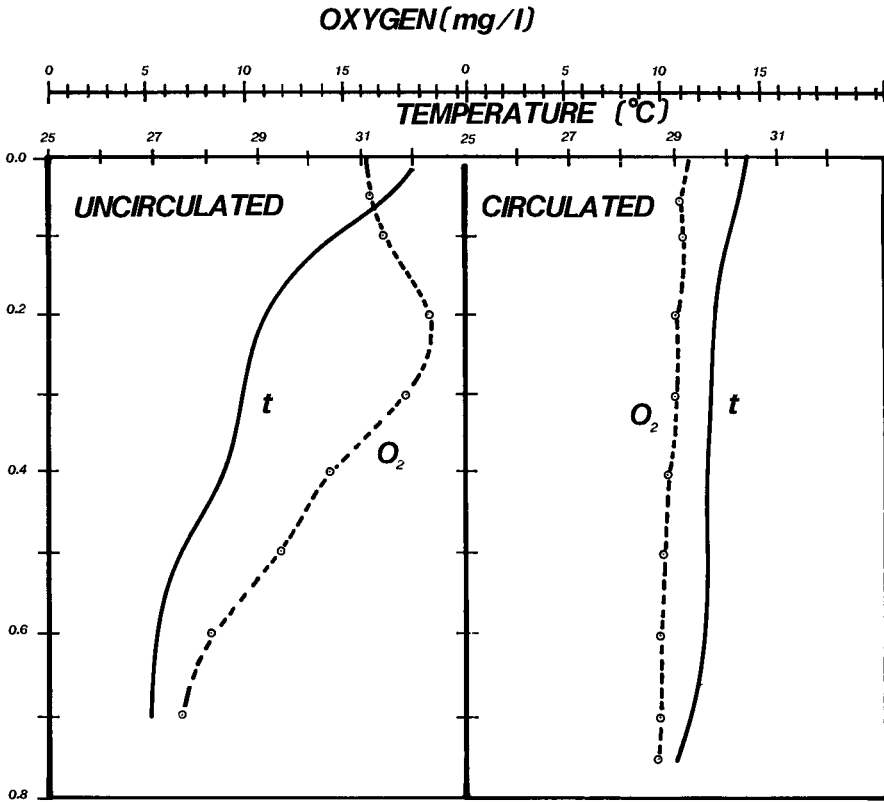


Figure 3. Comparison of mid-afternoon oxygen and temperature values with depth between an artificially circulated pond and an uncirculated pond in Hawaii during August 1982 (Fast et al. 1983).

When DO is 100% saturated at the air/water interface, neither aeration nor circulation will have any effect on oxygen content of water. There will be no net movement of oxygen either into or out of the pond (Fig. 2). When DO is <100% saturated at the air/water interface, oxygen will diffuse into water in proportion to the oxygen deficit. Oxygen deficit is defined as the difference between actual DO concentration, and DO concentration at 100% saturation. Circulation alone, when water is <100% saturated with DO adds a small amount of oxygen to the pond water, but the amount is quite small. Total air/water interface area is unaffected by circulation alone, although there is increased turbulence near this interface.

The other consideration is thermal stratification. Often during calm wind and sunny conditions, a pond will stratify thermally with as much as 5 to 7 C

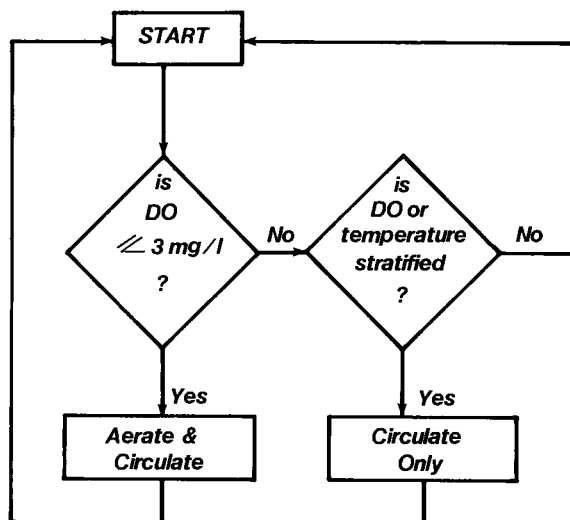


Figure 4. Logic pathway for deciding whether a shrimp pond should be circulated only or circulated and aerated.

difference between pond surface and bottom. Oxygen stratification often accompanies thermal stratification. Under these conditions, it may be desirable to circulate the pond (without aeration) even if surface water is saturated or supersaturated with DO, in order to increase temperature and/or DO near the bottom. This is especially true with bottom dwelling species such as shrimp. In Figure 3 we see that circulation increased bottom temperatures from 27 to 29 C, and bottom DO from 6.8 to 10.0 mg/l.

Circulation is not a substitute for aeration, nor does aeration serve the same purpose as circulation only. Circulation and aeration are complimentary treatments which accomplish different objectives. Most aeration devices also circulate pond water very well, which aids aeration; but for optimization of energy expenditure, care must be taken when deciding which management technique to use in a given instance. Time of day, algal density and health, and weather conditions are other considerations. During mid-day, if algae are healthy, circulation only is sufficient in most cases; while at night, aeration may be more appropriate, especially late in the crop cycle. Aeration needs, even during daytime, increase as feeding rates increase. Energy costs for circulation are less than 20% of the costs of aeration. Therefore, appropriate use of circulation, rather than aeration, can result in considerable energy and cost savings.

Decision logic about whether to aerate or circulate is rather simple (Fig. 4). If DO falls below some lower limit (3 mg/l in the example), then aerate. Aeration also causes circulation. If DO is above the lower limit, and the

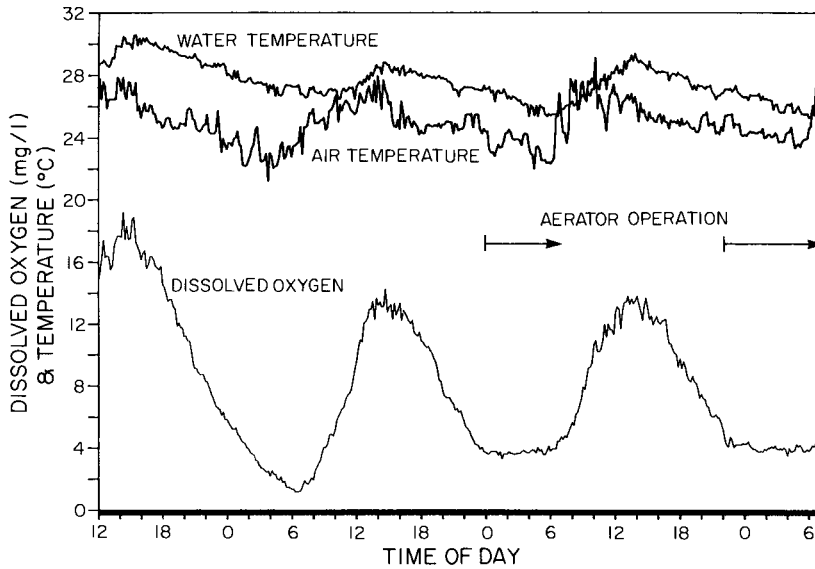


Figure 5. A recording of DO and water and air temperature in a 0.2 ha brackishwater pond in Hawaii. Between 2200 and 0700 on day 2 and 3, aeration occurred; circulation was continuous. (Rogers unpublished data).

pond is well mixed thermally and chemically, no action is required. If DO is above the lower limit, but stratification is present, then circulate only.

While decision logic about whether to aerate or circulate a pond is very simple, the problem comes from its application. If the object is to use the most appropriate technique only when needed in order to minimize energy consumption, then decision making should be applied often during the day at relatively short time intervals. We see from Figure 5 the dynamic nature of DO with healthy algal conditions and continuous mixing. Conditions should be monitored at hourly, and perhaps more often, if we wish to optimize aeration/circulation. This is impractical on conventional farms relying on farm labor or technicians for monitoring. Because of this limitation, the result has been that either circulators (if present) are run continuously because of their relatively low energy consumption, and aerators are run as needed; or aerators are run on some preset schedule. While these operational strategies result in more energy consumption than needed, they do minimize risk of crop failure. To date, shrimp culture profits have generally been great enough to justify excessive energy consumption. As profits decline, farmers will be forced to seek more efficient culture techniques to remain profitable.

Fast (in press) proposed use of microcomputers for continuous monitoring and decision making in marine shrimp ponds to reduce energy and labor costs, and to reduce risk of crop loss. The proposed system includes

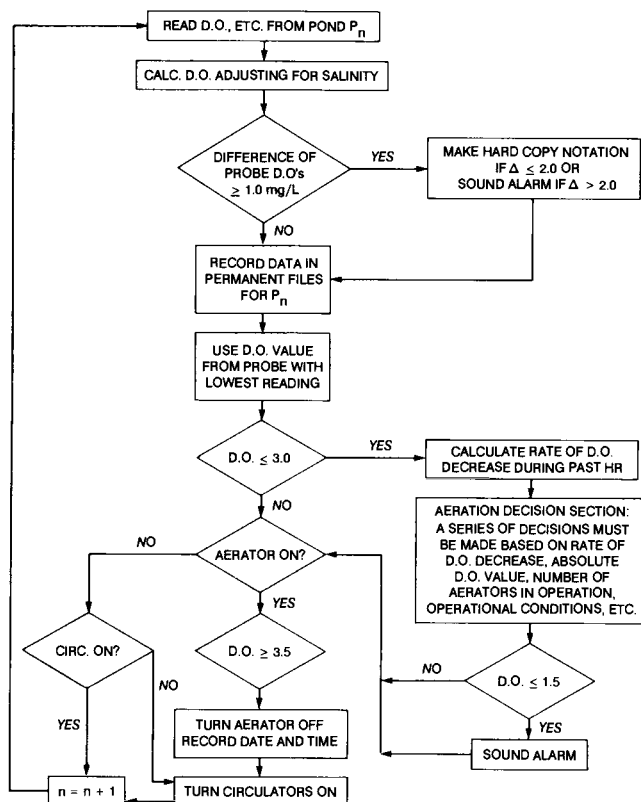


Figure 6. A model for decision making about aeration and circulation in a set of ponds. The logic considers rate of oxygen decrease and number of aerators or circulators to activate in each pond (Fast in press).

continuous monitoring of a set of ponds for DO, temperature, salinity, algal productivity and health, and perhaps other parameters that can be measured electronically. For each pond, a series of decisions would be made which incorporate those shown in Figure 4, but are larger in scope and more complex. They would include the rate of oxygen decline, number of aerators or circulators available in each pond, whether to exchange water and at what rate, whether to add fertilizer, etc. An example of a slightly more sophisticated decision logic than that shown in Figure 4 is shown in Figure 6. Technology now exists for microcomputer monitoring of and decision making on aeration and circulation, but we need to know more about other parameters, such as water exchange and photosynthesis rate, before the full benefits of microcomputers will be realized. Even so, microcomputer applications can now save energy and labor costs while at the same time

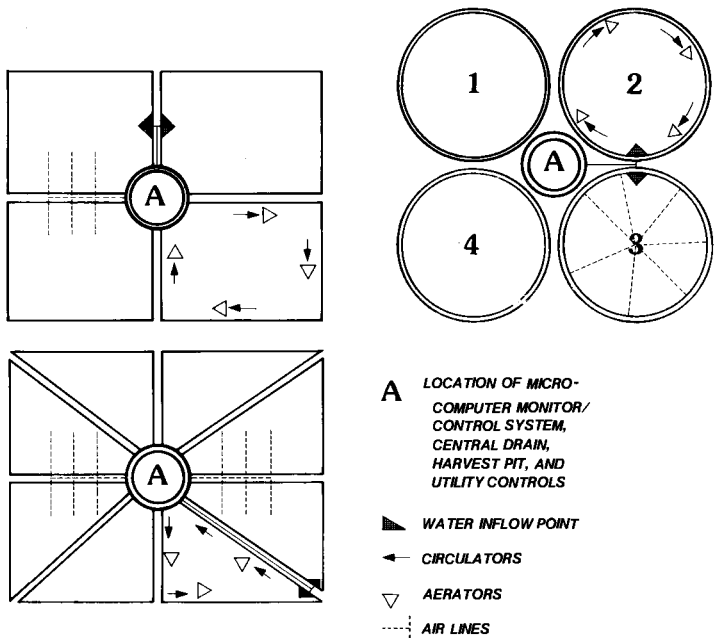


Figure 7. A plan view of three pond configurations which would incorporate a central "service" area containing microcomputer monitoring and controls, harvest facilities and utilities (modified from Fast in press).

reducing crop loss risks. We have already accomplished this on a research level in four 0.2 ha earthen shrimp ponds at the University of Hawaii, but the technology needs to be improved before being extended to commercial operations.

Application of microcomputer technology may result in the redesign of ponds and pond configurations. One set of configurations, designed around a central pond monitoring and service area is shown in Figure 7. The ponds might be square, triangular, or round. Although square or triangular shapes would make better use of land area, round ponds might facilitate better water circulation patterns and management of settleable solids. While application of microcomputer technology to pond management is interesting, this chapter will discuss current knowledge of pond circulation, aeration, water exchange, and other pond management techniques.

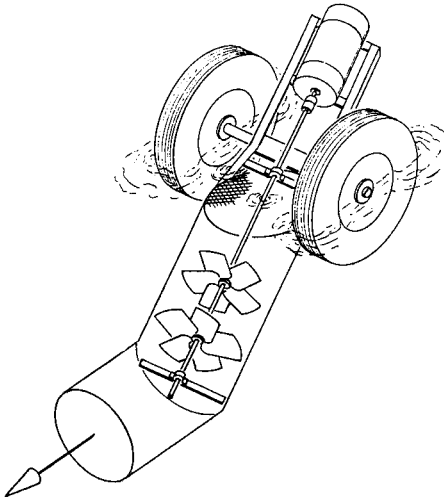


Figure 8. A pond circulator device (PC-I) used in Hawaii. It had two 40.6 cm diameter fan blades rotating at 60 rpm and pumped $5.7 \text{ m}^3/\text{min.}$ of water (from Fast et al. 1983).

22.2 POND CIRCULATION

Artificial circulation and mixing of impounded water originated with lake and reservoir destratification activities. Most of this development took place during the 1960's and 1970's in an effort to improve drinking water quality and to improve impoundment fisheries. Large lakes and reservoirs typically follow an annual cycle of thermal and chemical stratification that results in colder water near the bottom. This bottom water is often anaerobic, with high concentrations of hydrogen sulfide, ferrous iron, manganese, and plant nutrients. In temperate zones, warm season stratification may persist from 6 to 9 months each year, while in tropical areas it can persist all year. This stratification causes deterioration of water quality for domestic and industrial use, and it can negatively impact fisheries in many ways. Solutions to this problem include complete mixing of the lake or reservoir by diffuse air injection or mechanical pumping, and it includes aeration/oxygenation of bottom waters only by air or oxygen injection (Fast 1979).

One lake destratification method devised by Dr. James Garton of Oklahoma State University involved an axial flow water pump which would force warm surface water into the stratified depths. This caused a gradual erosion of stratification. Eventually, the entire lake or reservoir became thoroughly mixed, if pumps were properly sized and operated long enough. Basic design for Garton pumps involved a propeller (a fan blade does nicely),

an electric motor, and a speed reduction gear to provide a slow propeller speed relative to motor speed (Steichen et al. 1974, Garton and Rice 1976, Garton and Strecker 1976, Garton and Jarrel 1977, Strecker et al. 1977). The main advantages of Garton pumps for lake destratification were their simplicity of design, low capital costs, low energy consumption, and low operating costs. Most early use of these pumps was for lakes, but Kelley and Wright (1981) later used one to mix a watershed catfish pond in Alabama.

About the same time that Kelley and Wright (1981) used a Garton pump to mix a catfish pond, Dr. Charles D. Busch of Auburn University developed a small pond circulator that used a paddlewheel impeller rotating at 90 rpm, and a 1/8 hp electric motor (Busch 1980, Busch and Goodman 1981). This device drew water through a submerged shroud from the 0.5 m depth and discharged it near the surface at 1.9 m³/min. These mixing devices were energy efficient and dependable, but they were expensive to construct, drew water from a limited depth, and were not amenable to variable sizing.

Following work in Alabama with pond mixers, Fast et al. (1983) modified the Garton pump to mix freshwater prawn ponds in Hawaii. The first model had a 42 cm diameter rolled steel tube which extended from 15 cm below the pond surface to the pond bottom (PC-I, Fig. 8). A 1/4 hp electric gear motor drove two 40.6 cm diameter fan blades at 60 rpm and pumped 5.7 m³/min. Two polyurethane foam filled tires kept the upper end afloat, and facilitated movement into and out of the pond. The bottom of the steel tube rested on the pond bottom and was self-adjusting with regards to water level fluctuations. This model worked well, but was costly to construct, heavy, and prone to clogging with weeds.

A second pond circulator model (PC-II), eliminated the long steel tube, and had one 61 cm diameter (dia.) fan blade. This circulator also used a 1/4 hp gear motor with 60 rpm output speed. Water flow rates were 7.6 m³/min. The lower end rested on the pond bottom, and the upper end was suspended by two foam filled tires, as with the PC-I. This pond circulator was used in both freshwater and brackishwater ponds (Fast et al. 1983, Rogers and Fast 1988).

A third pond circulator (PC-III) developed at the University of Hawaii had the same gear motor and impeller configuration as the PC-II, but it was post mounted either on-shore or within the pond (Fig. 9). The cost to produce this model was less, and servicing on-shore was easier. This model was used in freshwater prawn and marine shrimp ponds in Hawaii (Rogers and Fast 1988), and in Philippine marine shrimp ponds (Fast et al. 1988, Carpenter et al. 1986). Versions ranging from 1/8 hp to 1/3 hp were constructed and tested.

Another version of the Garton pump applied to shrimp ponds involved an underwater fan blade driven by a gear motor and belt arrangement. Guy

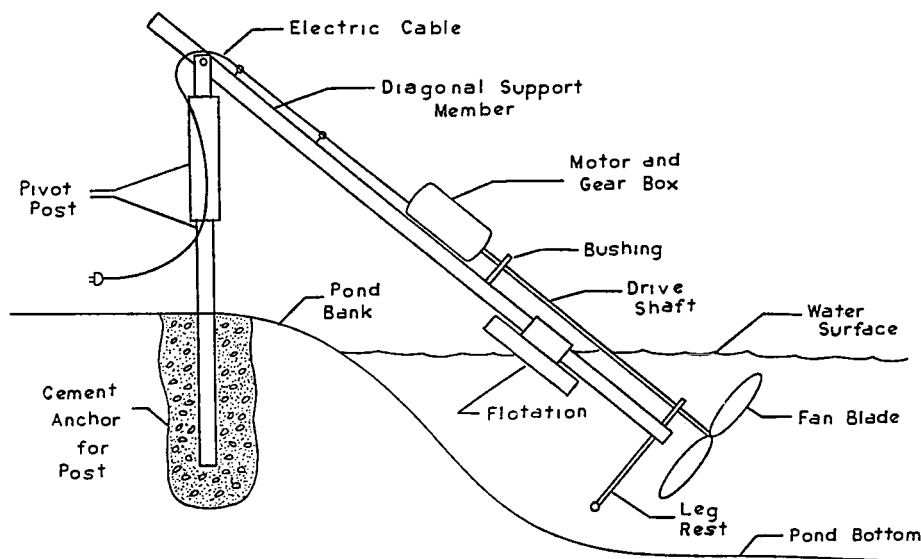


Figure 9. A pond circulator device (PC-III) using the gearmotor and impeller configuration of PC-II (see text). It was post-mounted on shore or within the pond (Rogers and Fast 1988).

Rothwell (personal communication) of ORCA Sea Farms, Hawaii developed this model with a 1/3 hp motor and 76 cm dia. blade which pumped 8.7 m³/min or water. A later frame mounted version of this design was used in Texas (Chamberlain 1988).

22.2.1 Benefits of Pond Circulation

Beneficial effects of mechanical circulation without aeration on pond conditions have been well documented. Artificial circulation eliminates thermal and chemical stratification and increases both oxygen and temperature at the pond bottom (Fast et al. 1983, Rogers and Fast 1988, Fast et al. 1988). If used properly, induced circulation aids deposition of organic sediment and other debris near the pond center. All of these effects are considered beneficial. Yet, despite beneficial effects of artificial circulation on pond conditions, improved shrimp yields were not documented.

Fast et al. (1983) observed that freshwater prawns were largely confined to pond banks during stratified pond conditions, and prawns distributed more widely when ponds were mixed. They also found a higher percentage of large prawns in circulated ponds. Rogers and Fast (1988) observed the same situation. These prawn size increases were attributed to a more uniform distribution of prawns in the ponds, and reduced aggressive interaction between the prawns. Prawn production in circulated ponds was, however, only

about 10% greater than in uncirculated ponds. This production increase covered the added costs of circulation, but it did not result in greater profits.

Carpenter et al. (1986) found that while circulation improved water quality conditions in Philippine marine shrimp ponds, yields were not significantly different. Reasons for this were unclear, but probably related to low stocking density of shrimp (*P. monodon* at 4 PL/m²), and low feed inputs. Carpenter et al. felt that significant differences would occur at higher stocking and feeding rates.

Our experience with shrimp (mostly *P. vannamei*) at the University of Hawaii's pond research station (Mariculture Research and Training Center) at a calm site, was that we had fewer water quality problems with circulated ponds. In unmixed ponds, we had complete shrimp kills several times due to undetected acid soil problems, but this did not happen in circulated ponds even though acid soil conditions existed there as well. We also found that circulation was not a substitute for emergency aeration when needed, but instead the two management techniques were complimentary. Despite our strong positive opinion about pond circulation effects, we are not able to clearly document yield benefits, because of confounding factors. Documentation of possible benefits of pond circulation on shrimp yields under various culture conditions, therefore, is still lacking.

22.3 POND AERATION

While the potential benefits of pond circulation on shrimp yield may still be somewhat equivocal, the need for emergency aeration in shrimp culture is without doubt. As production increases above extensive levels, aeration by some means becomes progressively more essential. With intensive culture, production would be all but impossible without mechanical aeration.

Cole and Boyd (1986), and Boyd and Watten (1989) have clearly documented the need to aerate channel catfish ponds as production intensifies through feed inputs. At maximum feed application rates of less than 20 kg/ha/day, little or no mechanical aeration was needed. At feeding rates of more than 100 kg/ha/day, aeration was needed perhaps daily. Although comparable data are not available for marine shrimp ponds, we would expect a similar trend. Extensive and some semi-intensive shrimp ponds are characterized by feeding rates of 20 kg/ha/day or less at maximum standing crop, while feeding rates of 100 kg/ha/day or greater characterize intensive shrimp culture.

Aquaculture ponds have four principal sources of oxygen: photosynthetically produced oxygen from aquatic plants, oxygen diffused into the pond from the atmosphere, oxygen in influent water, and oxygen added

by mechanical means. Dissolved oxygen is lost or consumed by respiration, chemical oxidations, diffusion to the atmosphere, and in effluent water.

Mechanical aeration is needed most often during the following conditions:

- (1) at night during high feed inputs, due to high respiration by plankton, benthos and shrimp crop (Although a pond may be supersaturated several hundred percent during daytime through photosynthesis, DO concentrations can drop to near zero each night due to high whole pond respiration.),
- (2) during anytime of day when algae are in an unhealthy condition and photosynthesis is considerably less than whole pond respiration (This condition often occurs during intensive culture when algae "crash" or die suddenly.), and
- (3) following several days of reduced solar radiation because of cloud cover (In this case, algae may be healthy, but their photosynthetic oxygen production is reduced below that required for whole ponds respiration.) (Romaine and Boyd 1979).

Should a low-DO condition occur, pond managers generally have but two options; aerate by mechanical means, and/or exchange pond water with water of higher DO. Water exchange by pumps without mechanical aeration is commonly practiced in large, extensive and semi-intensive ponds, but requires more energy expenditure than with mechanical aeration alone, and perhaps a longer response time. Mechanical aeration alone, or combined with water exchange, is more commonly used in smaller, intensive culture ponds.

22.3.1 Principles of Oxygen Transfer

Several models exist that describe oxygen transfer into water. These models are based on the principle of mass transfer, or the rate of gas movement into a liquid as described by Fick's first law. This relationship describes the rate of mass transfer as being proportional to the concentration gradient as expressed by:

$$dm/dt = D_m A dC/dt \quad (1)$$

where; dm/dt = mass transfer rate (g/sec).

D_m = molecular diffusion constant of the gas (cm^2/sec).

A = area through which the transfer occurs (cm^2).

dC/dt = the concentration gradient of the gas (g/cm^4).

One of the earliest models for gas mass transfer into a liquid was presented by Lewis and Whitman (1924), and is based on the assumption of

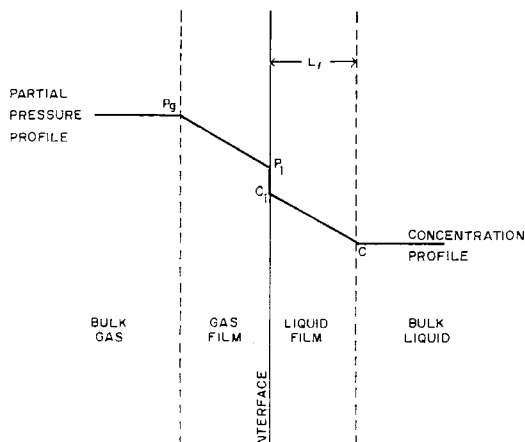


Figure 10. Two film models of gas transfer into a liquid (after Lewis and Whitman 1924).

two laminar films of gas and liquid at the interface between the two. Their model is referred to as the "two film model". Transfer of oxygen from air into water can be viewed as a 3-step process, where; (i) oxygen in air is transferred to the gas-liquid interface through a gas film, (ii) oxygen is transferred across the gas-liquid interface, and (iii) oxygen is transferred into the bulk liquid through the liquid film (Fig. 10). The first step is accomplished by diffusion and convection currents and is relatively rapid (Wheaton 1977). Transfer across the gas-liquid interface, and through the liquid film is relatively slow, and is the principal rate limiting step, especially with quiescent conditions. Diffusion of oxygen through bulk liquid is also very slow under calm conditions.

We see from equation (1) that oxygen transfer into liquid is related directly to surface area of the gas-liquid interface, and to the oxygen concentration gradient within the liquid. The greater the surface area and concentration gradient, the greater the oxygen transfer rate into the liquid. Mechanical aeration devices increase oxygen transfer by increasing surface area, and by creating a high concentration gradient at the gas-liquid interface. Surface area is increased by aerators, either by breaking water into droplets which are thrown into air, or by injecting air into water to form air bubbles. In the first case, oxygen diffuses into water droplets if droplets are under-saturated with oxygen, while in the second case oxygen diffuses out of air bubbles and into water if the water is under-saturated with oxygen. Aerators create high concentration gradients near the gas-liquid interface through creation of turbulence within the water mass. This turbulence reduces the liquid film thickness, while at the same time transferring

Table 1. The solubility of oxygen in mg/l from moist air at standard, sea level pressure (760 mm Hg) and different temperatures and salinities (Colt 1984)

Temp (C)	Salinity, parts per thousand (ppt)								
	0	5	10	15	20	25	30	35	40
0	14.60	14.11	13.64	13.18	12.74	12.31	11.90	11.50	11.11
1	14.20	13.72	13.27	12.82	12.40	11.98	11.58	11.20	10.82
2	13.81	13.36	12.91	12.49	12.07	11.67	11.29	10.91	10.55
3	13.44	13.00	12.58	12.16	11.76	11.38	11.00	10.64	10.29
4	13.09	12.67	12.25	11.85	11.47	11.09	10.73	10.38	10.04
5	12.76	12.34	11.94	11.56	11.18	10.82	10.47	10.13	9.80
6	12.44	12.04	11.65	11.27	10.91	10.56	10.22	9.89	9.57
7	12.13	11.74	11.36	11.00	10.65	10.31	9.98	9.66	9.35
8	11.83	11.46	11.09	10.74	10.40	10.07	9.75	9.44	9.14
9	11.55	11.18	10.83	10.49	10.16	9.84	9.53	9.23	8.94
10	11.28	10.92	10.58	10.25	9.93	9.62	9.32	9.03	8.75
11	11.02	10.67	10.34	10.02	9.71	9.41	9.12	8.83	8.56
12	10.77	10.43	10.11	9.80	9.50	9.21	8.92	8.65	8.38
13	10.52	10.20	9.89	9.59	9.29	9.01	8.73	8.47	8.21
14	10.29	9.98	9.68	9.38	9.10	8.82	8.55	8.29	8.04
15	10.07	9.77	9.47	9.19	8.91	8.64	8.38	8.13	7.88
16	9.86	9.56	9.28	9.00	8.73	8.47	8.21	7.97	7.73
17	9.65	9.36	9.09	8.82	8.55	8.30	8.05	7.81	7.58
18	9.45	9.17	8.90	8.64	8.38	8.14	7.90	7.66	7.44
19	9.26	8.99	8.73	8.47	8.22	7.98	7.75	7.52	7.30
20	9.08	8.81	8.56	8.31	8.06	7.83	7.60	7.38	7.17
21	8.90	8.64	8.39	8.15	7.91	7.68	7.46	7.25	7.04
22	8.73	8.48	8.23	8.00	7.77	7.54	7.33	7.12	6.91
23	8.56	8.32	8.08	7.85	7.63	7.41	7.20	6.99	6.79
24	8.40	8.16	7.93	7.71	7.49	7.28	7.07	6.87	6.68
25	8.24	8.01	7.79	7.57	7.36	7.15	6.95	6.75	6.56
26	8.09	7.87	7.65	7.44	7.23	7.03	6.83	6.64	6.46
27	7.95	7.73	7.51	7.31	7.10	6.91	6.72	6.53	6.35
28	7.81	7.59	7.38	7.18	6.98	6.79	6.61	6.42	6.25
29	7.67	7.46	7.26	7.06	6.87	6.68	6.50	6.32	6.15
30	7.54	7.33	7.14	6.94	6.75	6.57	6.39	6.22	6.05
31	7.41	7.21	7.02	6.83	6.64	6.47	6.29	6.12	5.96
32	7.29	7.09	6.90	6.72	6.54	6.36	6.19	6.03	5.87
33	7.17	6.98	6.79	6.61	6.43	6.26	6.10	5.94	5.78
34	7.05	6.86	6.68	6.51	6.33	6.17	6.01	5.85	5.69
35	6.93	6.75	6.58	6.40	6.24	6.07	5.91	5.76	5.61
36	6.82	6.65	6.47	6.31	6.14	5.98	5.83	5.68	5.53
37	6.72	6.54	6.37	6.21	6.05	5.89	5.74	5.59	5.45
38	6.61	6.44	6.28	6.12	5.96	5.81	5.66	5.51	5.37
39	6.51	6.34	6.18	6.02	5.87	5.72	5.58	5.44	5.30
40	6.41	6.25	6.09	5.94	5.79	5.64	5.50	5.36	5.22

dissolved oxygen throughout the water mass by convection. The most energy efficient aeration systems are those that accomplish an increase in surface area and turbulence without "excessive" energy expenditures for either function.

Atmospheric air contains 20.95% oxygen. At standard barometric pressure (760 mm of mercury), atmospheric oxygen partial pressure is equal to 159.3 mm of mercury. When the partial pressure of oxygen dissolved in water is equal to the partial pressure of overlying air, oxygen in the two phases (air and water) are in equilibrium and there is no net movement into or out of water (Fig. 2). Water is then said to be oxygen saturated. Saturation values for oxygen in water are primarily related to water temperature, salinity, and barometric pressure. Oxygen saturation values (100% saturation) at one atmosphere are given in Table 1, while the approximate correction for barometric pressure is:

$$C_s = C_{tab} \times \frac{BP}{760} \quad (2)$$

where; C_s = DO concentration at saturation (mg/l).
 C_{tab} = DO concentration at existing temperature, salinity, and one atmosphere pressure (from Table 1).
 BP = observed barometric pressure (mm of mercury).
 760 = standard barometric pressure at sea level (mm of mercury)

For marine shrimp culture, barometric pressure corrections can normally be ignored since most farms are at sea level where barometric pressure changes are small. For rigorous calculations, corrections must be made for barometric pressure, water vapor, and other factors (Colt 1984). Percentage saturation of DO in water may be estimated by;

$$S = \frac{C_m}{C_s} \times 100 \quad (3)$$

where; S = percentage saturation.
 C_m = measured DO concentration in water (mg/l).
 C_s = value from Table 1.

Oxygen deficit is the difference between DO concentration at 100% saturation, and measured DO in water, or;

$$OD = C_s - C_m \quad (4)$$

where; OD = oxygen deficit (mg/l)

When OD is positive, water is <100% saturation, in which case forces are created for oxygen movement from air into water (Fig. 2). When OD is negative, water is supersaturated (>100%) with oxygen, and there are forces for oxygen diffusion out of water and into air. At OD = 0, there is no net movement into or out of water. Rate of oxygen movement into or out of water increases as a function of the size of OD.

22.3.2 Aerator Efficiency Measurements.

Aerator efficiencies are normally measured in tanks with hard bottoms and side walls, using clean water (ASCE 1983; APHA 1985; Boyle 1979; Boyd 1982; Stuckenburg et al. 1977). With appropriate corrections, efficiencies can also be measured using pond water, or directly in ponds. Ideally, aerator efficiencies should be determined using pond conditions that reflect their most probable application, but these conditions are difficult to achieve and prone to certain inaccuracies.

Aerator efficiency measurements in tanks are valuable for two reasons. First, they provide a means of estimating aeration capacity of a given aerator under field use. Secondly, they can be used to evaluate relative energy efficiencies of different aerators. These values are in some ways comparable to gas mileage ratings which permit comparisons between automobile performances; actual performance can vary considerably depending on application. Tank configuration can greatly affect a given aerator's performance. Special care is needed when applying tank values to pond conditions. In lieu of something better, aerator efficiency values from tanks are useful. The two most useful values in this regards are (1) the standard oxygen transfer rate, or SOTR (kg O₂/hr), and (2) the standard aeration efficiency, or SAE (kg O₂/kw-hr).

Clean water procedure for estimating SOTR in tanks involves reducing tank water DO with sodium sulfite and cobalt chloride as catalyst. The aerator is then operated until the DO is nearly saturated (Fig. 11). Resulting DO measurements are converted to OD values (eq. 4), and plotted on a logarithmic scale against time on a linear scale. A least squares line is then drawn through these points, and overall oxygen transfer rate calculated as follows:

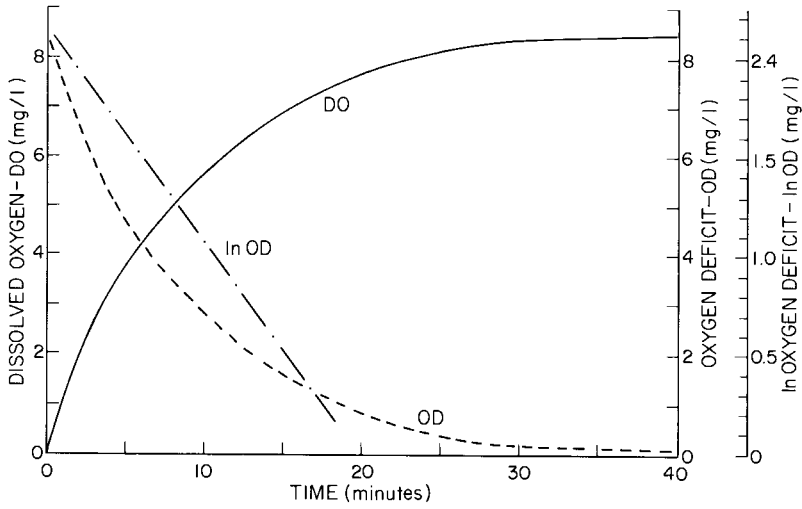


Figure 11. Plot of DO increase, DO deficit decrease (OD), and the log decrease in OD during a re-aeration tank test. Values between 10% and 70% of saturation are normally used to calculate oxygen transfer values.

$$(K_L a)_T = \frac{\ln OD_{10} - \ln OD_{70}}{t_{70} - t_{10}} \quad (5)$$

where; $(K_L a)_T$ = overall oxygen transfer coefficient for the existing water temperature (hour^{-1}).

OD_{10} = oxygen deficit at 10% saturation (mg/l).

OD_{70} = oxygen deficit at 70% saturation (mg/l).

t_{10} = time when DO reaches 10% saturation (hour).

t_{70} = time when DO reaches 70% saturation (hour).

Overall oxygen transfer coefficient is then adjusted for 20 C as follows;

$$(K_L a)_{20} = (K_L a)_T + 1.024^{T-20} \quad (6)$$

where; $(K_L a)_{20}$ = overall oxygen transfer coefficient at 20 C (hour^{-1}).

T = water temperature for test ($^{\circ}\text{C}$).

From these values, we can now calculate SOTR and SAE.

Table 2. Power consumption, power output, standard oxygen transfer rate, standard aeration efficiency and operating costs for 25 electric powered pond aeration devices in freshwater. Data from Boyd and Ahman (1987).

Aerator Type	Power Consumption (kw)	Power at Aerator Shaft (hp)	SOTR ¹ (kg O ₂ /hr)	SAE ² (kg O ₂ /hr/hp-hr)	Operating Costs ³ (\$/kg O ₂)
<u>Splasher</u>					
Paddlewheel - Taiwan	2.09	2.0	2.4	1.2	0.066
Paddlewheel - House	10.58	11.4	23.3	2.0	0.033
Paddlewheel - Geddie	8.18	9.2	18.8	2.0	0.033
Paddlewheel - Dan	5.61	6.4	10.2	1.6	0.042
Paddlewheel - Martar	7.76	8.6	18.1	2.1	0.033
Paddlewheel - S & N	8.60	8.6	19.1	2.2	0.031
Paddlewheel - Beaver Tail	9.43	9.0	9.3	1.0	0.077
Paddlewheel - Rogers	7.15	7.5	7.5	1.0	0.073
Paddlewheel - Spree	9.83	10.0	8.8	0.9	0.084
Paddlewheel - AEMCO-PVC	9.69	10.0	12.9	1.3	0.057
-Steel	9.18	8.8	19.6	2.2	0.035
Vertical Pump - Air-o-later	0.33	0.33	0.3	1.0	0.079
Vertical Pump - Otterbine	1.86	2.0	2.1	1.0	0.066
Vertical Pump - PowerHouse	0.70	0.75	0.9	1.1	0.057
Pump Sprayer - Airmaster	7.6	10.0	14.5	1.4	0.040
Pump Sprayer - House	18.9	20.0	13.5	0.7	0.106
<u>Bubblers</u>					
Propeller Aspirator	---	1.0	1.0	1.0	0.070
	(Aire-O ₂)				
Propeller Aspirator	---	2.0	2.5	1.3	0.055
	(Aire-O ₂)				
Propeller Aspirator	---	3.0	4.2	1.4	0.051
	(Aire-O ₂)				
Propeller Aspirator	---	5.0	5.0	1.0	0.070
	(Aire-O ₂)				
Propeller Aspirator	---	7.5	9.9	1.3	0.053
	(Aire-O ₂)				
Propeller Aspirator	---	10.0	10.5	1.0	0.066
	(Aire-O ₂)				
Propeller Aspirator	---	20.0	24.5	1.2	0.057
	(Aire-O ₂)				
Air Diffuser - Hinde	---	0.75	0.6	0.9	0.079
Air Diffuser - Micro-shear	---	1.7	1.1	0.8	0.110

¹ standard oxygen transfer rate.

² standard aeration efficiency (=SOTR v horsepower at shaft)

³ based on electricity costs of \$.075 per kilowatt hour.

$$\text{SORT} = (K_L a)_{20} \times C_s \times V \times 10^{-3} \quad (7)$$

where; SORT = Standard oxygen transfer rate at 0 mg/l DO, 1 atmosphere pressure, 20 C (kg O₂/hour);
 C_s = DO concentration (g/m³) at 20 C, one atmosphere pressure, and test salinity (Table 1).
 V = tank volume (m³)
 10^{-3} = factor to convert grams to kilograms.

and,

$$\text{SAE} = \text{SORT/Power} \quad (8)$$

where; SAE = standard aeration efficiency (kg O₂/kw-hr, or kg O₂/hp-hr).

Power = energy produced, or consumed by the aerator. This may be expressed in kilo-watt-hour, or in horsepower-hour.

Most often power is expressed as power at the aerator shaft, rather than total energy consumed by the aerator. Care needs to be taken when comparing performances that comparable power values were used.

22.3.3 Types of Aerators and Their Efficiencies

Pond aeration devices are conveniently categorized as those that aerate by dispersing water in air (splashers), and those that aerate by dispersing air in water (bubblers).

22.3.3.1 Splashers

The most widely used splasher-type aerator in marine shrimp ponds today is the "Taiwan Paddlewheel" aerator (Fig. 12). This aerator has evolved through use in Taiwan intensive shrimp culture. Standard configurations are 1 or 2 hp, with the smaller size being more popular. Oxygen transfer efficiency (SOTR) for a 2-hp model in freshwater was 2.4 kg O₂/hr, with a SAE of 1.2 kg O₂/hp-hr (Table 2). Operating costs were \$0.066/kg O₂ dissolved.

Another type of paddlewheel aerator was developed within the channel catfish industry in the southern United States, and through research efforts at Auburn University (Ahmad and Boyd 1987, Boyd and Ahmad 1987). This aerator uses a spiral arrangement of blades on the paddlewheel rotor (Fig. 13). Motor and speed reducer can either be mounted on the float at one end of the rotor, or on-shore with a drive shaft extending out to the aerator. These aerators are typically configured in 7.5 to 10.0-hp range. Their SAE's are considerably better than Taiwan paddlewheels, with SAE values as high as 2.2 kg O₂/hp-hr, and operating costs as low as \$0.031/kg O₂ dissolved (Table

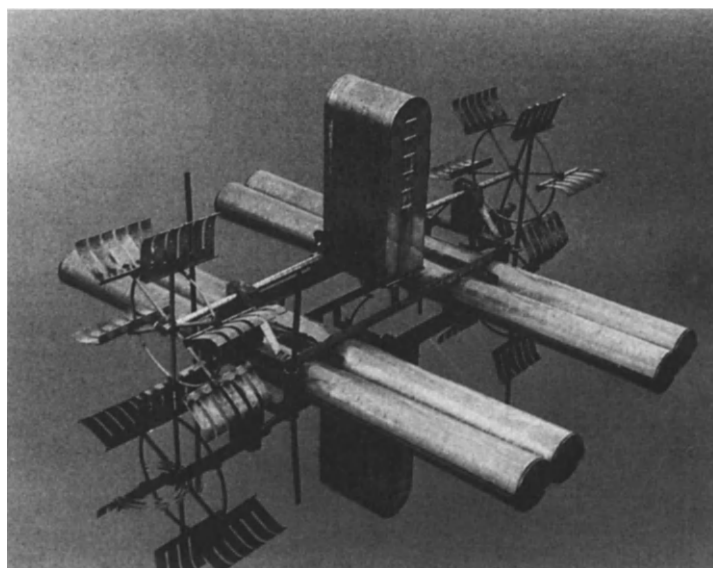


Figure 12. A one-horsepower paddlewheel aerator of Taiwanese design (with permission from Fast et al. 1989).

2). Most of these new spiral rotor, paddlewheel aerators are intended for freshwater applications, and do not have corrosion resistant parts. One manufacturer, however, recently produced corrosion resistant models of 1 to 20 hp that should be particularly well suited for marine applications.

Vertical aerators are infrequently used in shrimp ponds (Boyd and Ahmad 1987). Their applications are limited. These aerators do not distribute water throughout ponds efficiently and have low SAE. Aeration tests with three types of vertical pump aerators yielded SAE values of 1.0 to 1.1 kg O_2 /hp-hr (Table 2). Some will not withstand corrosive conditions in shrimp ponds.

Another type of splasher aerator commonly used in catfish ponds in the U.S. is the pump-sprayer (Boyd and Ahmad 1987). With these units, water is pumped from the pond and sprayed horizontally and/or vertically onto the pond surface. Efficiencies for these devices are comparable to the Taiwan paddlewheel aerators in some cases. Pump-sprayers have not been used much in marine shrimp ponds.

22.3.3.2 Bubblers

The second most commonly used pond aerator in marine shrimp ponds today is the propeller-aspirator aerator. These operate on the venturi

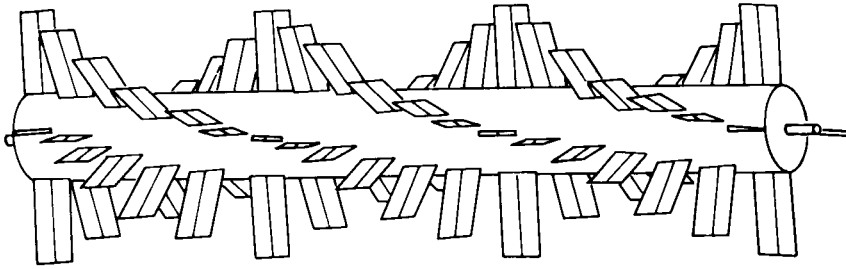


Figure 13. A "new" paddlewheel rotor design with paddles arranged spirally along and around the long shaft (Boyd and Ahmad 1987).

principal using a high speed, submerged impeller blade to create a high velocity water current past the blade (Fig. 14). This high velocity current produces a low pressure zone which draws air through a hollow drive shaft. Air enters the water at the drive shaft tip and is broken into a plume of fine bubbles by turbulent water flow. This process leads to aeration by air injection into water, and it creates strong horizontal water currents. SAE for these aerators in freshwater tank tests ranged from 1.00 to 1.4 kg O₂/hp-hr, with operating costs ranging from \$0.051 to \$0.070/kg O₂ dissolved (Table 2). Corrosion resistance and lack of a speed reducer result in fewer maintenance problems than with Taiwan paddlewheels.

Air diffuser systems have found limited use in marine shrimp ponds, but have some operational advantages. These systems typically consist of one or more air blowers at a convenient shore location. Air is delivered to the ponds through PVC pipe and injected into the pond through either a grid network of diffuser hose, or through "point-source" diffusers (Fig. 15). Coarse bubble diffusers yield low SAE in the range of 0.8 to 0.9 kg O₂/hp-hr, and high operating costs of \$0.079 to \$0.110/kg O₂ dissolved (Table 2). These systems require low air pressure, and do not easily clog. The Oxyflo diffuser system illustrated in Figure 15 produces much finer bubbles and undoubtedly higher SAE values, but it is very prone to clogging and requires somewhat higher operating pressures. One commercial farm in Hawaii had satisfactory results with the Oxyflo system when used in combination with a water circulator system. Continuous operation and periodic air stream ozonation may help control clogging, or the diffuser line may be replaced frequently since it is low cost.

22.3.4 Salinity Effects on Aeration

There has been surprisingly little work with salinity effects on SOTR, SAE and/or operating costs. Almost all published information is for freshwater aquaculture and/or sewage treatment applications. Unpublished test results at the University of Hawaii for several sizes of propeller-aspirator

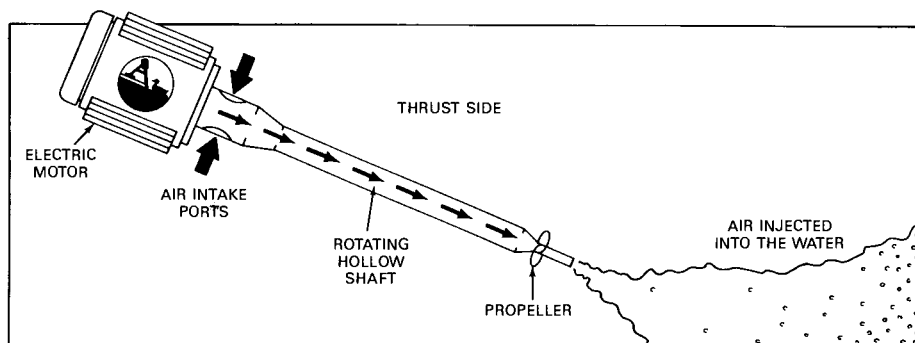


Figure 14. A 2-horsepower propeller-aspirator aerator which uses a high speed submerged propeller and hollow drive shaft to inject air into the water (courtesy of Aeration Industries, Chaska, Minnesota).

(bubbler) aerators in salinities ranging from fresh to full-strength seawater indicated that salinity can have a profound effect on aeration efficiency. These tests indicated two phenomenon. First, that SAE was almost twice as great at 35 ppt salinity compared with freshwater; and secondly, several of the aerators had their highest SAE at salinities in the range of 15 to 20 ppt (Fig. 16). The 7.5-hp aerator, for example, had SAE values in 0, 16 and 36 ppt salinities of 0.85, 2.90 and 1.85 lb O_2 /hp-hr respectively (based on total power consumption).

Higher SAE values with increasing salinity appeared to be related to bubble size. Visual inspection clearly indicated a much smaller bubble size (i.e. greater air/water interface area) at higher salinities. Higher SAE values at intermediate salinities has implications with regards to why the Taiwanese intensive shrimp culture technology prefers to use salinities in the range of 15 to 20 ppt whenever possible (Fast et al. 1989).

Boyd and Watten (1989) report that SOTR and SAE of a splasher aerator was not affected by salinity and suggest that a simple correction factor can be used to correct these oxygen transfer values for these aerators. The correction is based on the ratio of oxygen solubility in water at a given salinity and in water at which the transfer values were measured. Such corrections may not be appropriate for bubble-type aerators. Boyd and Daniel (1987) also observed an oxygen transfer efficiency maximum with an air diffuser system at 15 ppt. Oxygen transfer was less efficient above and below this salinity. These observations by Boyd and Daniel confirm that "bubbler" aerators perform differently than "splasher" aerators with respect to salinity.

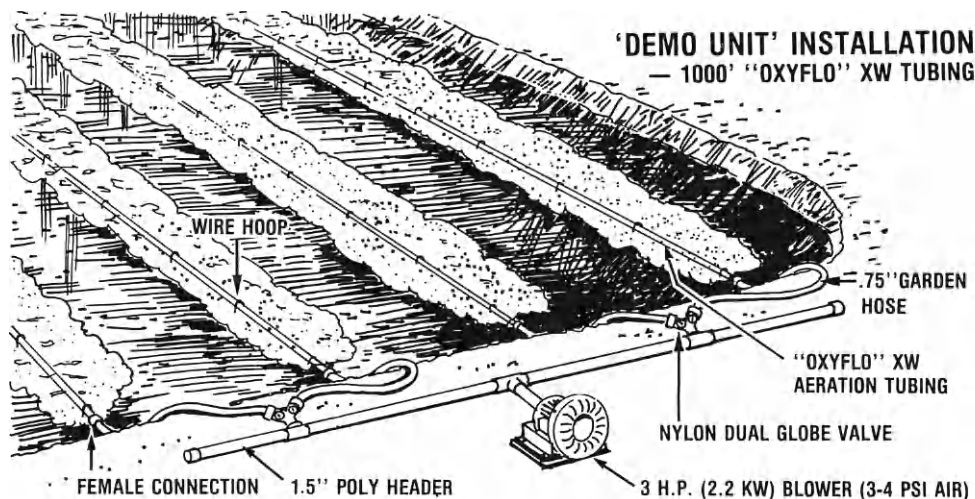


Figure 15. Oxyflo air injection system which uses an air blower on shore and an air distribution system on the pond bottom (courtesy of International Irrigation Systems, Niagara Falls, New York).

22.3.5 Aerator Pond Performance

Performance of aeration devices in ponds does not always correlate well with their performance in clean water tank tests. As an illustration of this situation, Figure 16 shows that a 1-hp propeller aspirator aerator had a SAE value of about 1.6 lb O_2 /hp-hr at 20 ppt salinity. In a 0.2 ha commercial sized shrimp pond at 21 to 23.5 ppt salinity, however, oxygen transfer rate of this same aerator far exceeded this value. Oxygen transfer rate (OTR) values (lb O_2 /hp-hr) were measured at DO values ranging from 2.5 to 9.0 mg/l based on procedures developed by Madenjian et al. (1987 a,b) and Madenjian (1988). Extrapolation of these OTR values back to 0.0 mg/l DO yields an approximate SAE value under pond conditions (Fig. 17). Clearly, SAE estimates in the pond would exceed 3 lb O_2 /hp-hr, while those in our tank tests were about 1/2 this amount.

Reasons for discrepancies between clean water tank tests and pond field tests are not entirely clear, but are perhaps related to pond size and depth, and water mixing capabilities of this particular aerator.

While the transfer of clean water tank test results to field applications is sometimes questionable, there can also be large discrepancies between tests in tanks with different configurations. This problem is illustrated when data from Table 2 are compared with those in Figure 16. Freshwater SAE values for propeller-aspirator aerators measured in a large tank ranged from 1.0 to 1.4 kg O_2 /hp-hr (Table 2), while freshwater SAE values for similar aerators tested in a much smaller tank were all below 0.5 kg O_2 /hp-hr (Fig. 16). A small part of the discrepancy was due to the use of "rated" or shaft hp in the first

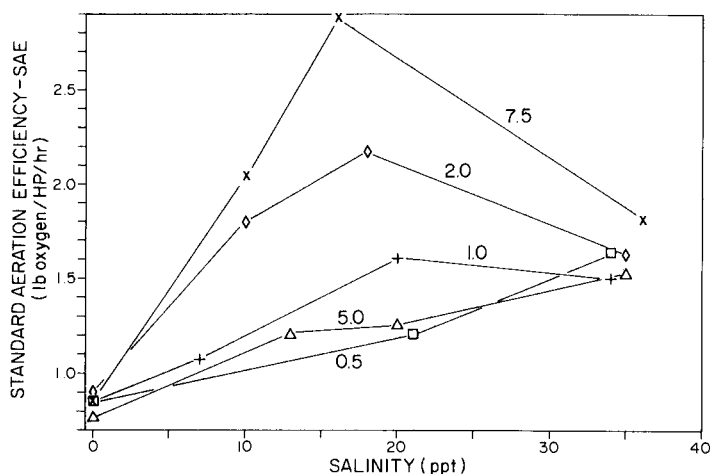


Figure 16. Effect of salinity on oxygen transfer and standard aeration efficiencies (SAE) using propeller-aspirator aerators from 0.5 to 7.5 hp (unpublished data, University of Hawaii).

case, and use of total hp consumed in the latter. This accounts for only a small part of the discrepancy, however, with most of the difference due to the use of different tank configurations. The large tank results from Table 2 are most similar to pond performance of these aerators, but still gave an underestimate of field performance (Fig. 17).

Tank tests are also deficient in measuring the pond mixing attributes of a given aerator. Boyd and Martinson (1984) measured mixing capacity of a 2-hp propeller-aspirator aerator in a 0.2 ha (1 acre) pond using both dye and salt-mixing tests. They found that this aerator produced a well mixed condition with dye within 32 minutes (Fig. 18), and nearly uniform pond salinity within 75 minutes (Fig. 19).

22.4 MINIMUM OXYGEN REQUIREMENTS OF SHRIMP

Minimum dissolved oxygen requirements for different shrimp species are not established. Requirements for fish have received considerably more study, and indicate that any DO reduction below air saturation can reduce growth and survival of certain fish species (Warren et al. 1973). Andrews and Matsuda (1975) found that channel catfish reared at 100, 60 and 36% DO saturation concentrations had growth reductions and increased feed conversions with decreasing DO concentrations. For adequate growth, feed conversion, and reproduction, channel catfish appeared to require minimum DO concentrations of 5 mg/l (Swingle 1969, Louisiana State Agricultural Experiment Station 1988). Even short durations of low DO, especially below

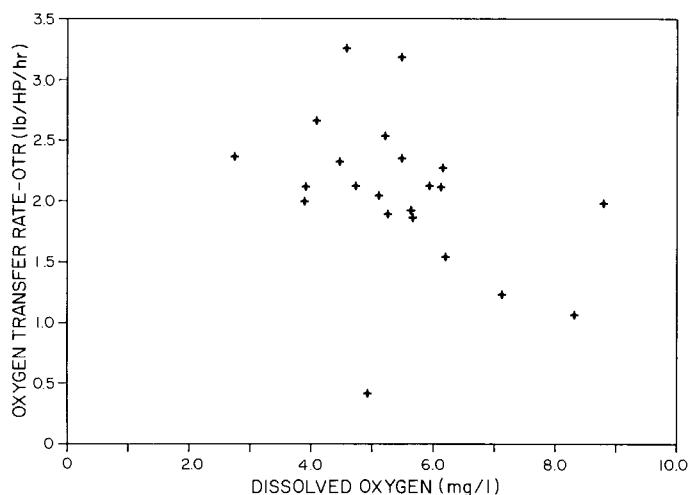


Figure 17. Oxygen transfer rates (OTR) under pond conditions in Hawaii using a 1 hp propeller-aspirator aerator in a 0.2 ha pond at 21 to 23.5 ppt, and DO between 2.5 and 9.0 mg/l (unpublished data, University of Hawaii).

1 mg/l, can significantly reduce catfish growth and survival (Tucker et al. 1979). Although oxygen requirement is higher per kg for small fish, large fish usually die first from low DO in ponds with mixed fish sizes.

The same phenomenon applies to marine shrimp with respect to size vs. mortalities from low DO stress. Smaller shrimp can withstand low DO better than large shrimp because of their higher gill area to body volume ratio (Cameron and Magnun 1983). Shrimp of all sizes can regulate oxygen uptake by increasing their ventilation rate, and perhaps decreasing their physiological oxygen requirement. This ability perhaps makes them more "independent" of absolute oxygen concentrations than fish, but they still have minimum DO requirements for good growth and survival.

Seidman and Lawrence (1985) observed critical DO levels for P. monodon and P. vannamei of 2.2 and 1.9 mg/l respectively for small shrimp (0.2 to 0.5 g), below which growth and survival were reduced. Oxygen concentrations for "normal" growth with P. monodon are probably 3.7 mg/l or higher, with lethal DO concentrations of 0.5 to 1.2 mg/l depending on exposure duration (Chamberlain 1988). Mackay (1974) found that P. schmitti were severely stressed by exposure to 1.2 mg/l DO, becoming immobile within 10 minutes. About 50% of the immobile shrimp died even when transferred into well oxygenated water.

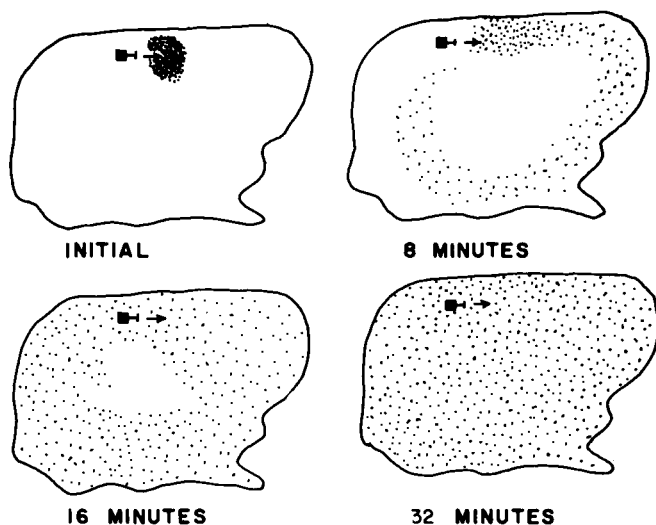


Figure 18. Results of dye mixing tests in 0.4 ha freshwater pond using a 2-horsepower propeller-aspirator aerator (Boyd and Martinson 1984).

Rigdon and Baxter (1970) found that P. aztecus developed white, degenerated tail muscle tissue from long-term exposure to low DO and high temperatures. These chronic symptoms of sub-lethal DO concentrations disappeared within 24 hrs, and shrimp became more active when placed in well aerated water. ASEAN (1978) found similar results with P. merguensis in pond culture. Penaeus japonicus may show stress reactions with DO concentrations as high as 1.4 mg/l (Egusa 1961). Shigueno (1975) observed P. japonicus mortalities in ponds with 2.7 mg/l DO.

The senior author observed (unpublished data) minimal mortalities of P. vannamei in Hawaii with short-term exposures (<30 min) to pond DO ranging from 0.6 to 1.0 mg/l. The shrimp recovered within 30 min after aeration began when DO concentrations were increased above 1.5 mg/l. Rapid DO increase was important for their recovery.

Although definitive minimal DO requirements for marine shrimp are still lacking, they most likely will relate to the following conditions: shrimp species, (some species having a much lower minimum requirement than other species); shrimp size (small shrimp having a lower minimum); duration of exposure; physiological and health status; water temperatures; and water quality conditions (with particular regard to ammonia, nitrite, pH, hydrogen sulfide,

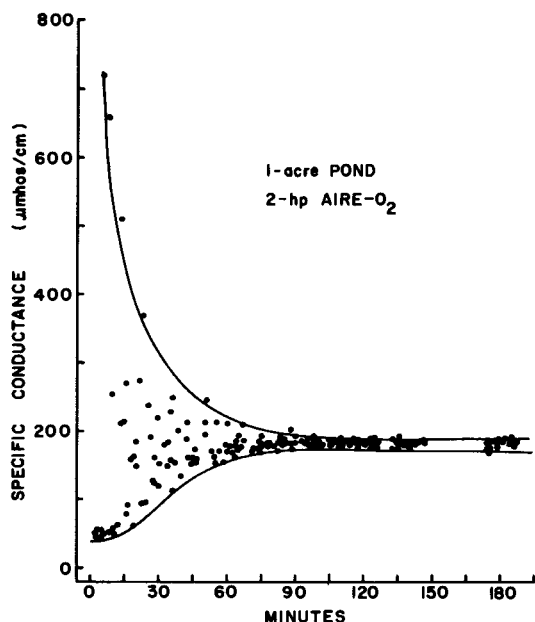


Figure 19. Results of salt mixing tests in a 0.4 ha freshwater pond using a 2-horsepower propeller-aspirator aerator (Boyd and Martinson 1984).

and dissolved organic metabolites).

Although some of the above conditions are often known at a given time, others are not. Furthermore, basic interactions are still not well defined. With these limitations in mind, a minimum DO standard of 3 mg/l for good growth, low feed conversion ratio, and high survival is probably a reasonable value. Short-term (30 min) exposures of <1.5 mg/l should also be avoided.

22.5 AERATOR SIZING

When sizing an aeration system to a given pond, the most important factors are potential oxygen demand of the pond, minimum DO requirement, and SOTR of the aerator. Other factors such as energy efficiency, availability of electrical power, redundancy in aeration capacity are also important, but the primary concern is assurance that sufficient aeration capacity is available for worst case situations. Potential oxygen demand of the pond is related to the level of culture intensity, especially the feeding rate. This effects not only maximum standing crop, and oxygen demand from that source, but oxygen

Table 3. Oxygen consumption rates for various pond components that consume oxygen either directly or indirectly.

Source of Respiration	Oxygen Consumption (mg O ₂ /l/hr) ¹			Reference
	Average	Minimum	Maximum	
<u>Shrimp</u>				
500 to 7,000 kg/ha	0.08	0.02	0.15	Liao and Murai (1986)
<u>Catfish</u>				
2,500 kg/ha	0.10	----	----	Boyd (1979)
<u>Water Column</u>				
brackishwater	0.56	0.01	0.86	Madenjian (1988)
brackishwater	0.13	0.13	0.14	Fast et al (1988)
freshwater	0.51	0.05	2.80	Fast et al (1983)
freshwater	0.29	0.12	0.71	Schroeder (1975)
freshwater	0.14	0.02	0.33	Boyd (1973)
freshwater	----	----	0.70	Boyd (1978)
<u>Whole Pond</u>				
brackishwater	0.60	0.07	1.38	Madenjian (1988)
brackishwater	0.80	0.62	1.15	Fast et al (1988)
<u>Pond Bottom</u>				
brackishwater	0.30	0.00	0.78	Madenjian (1988)
brackishwater	0.56	0.47	0.70	Fast et al (1988)
freshwater	0.22	0.02	0.34	Fast et al (1983)
freshwater	0.06 ²	0.01	0.11	Mezainis (1977)
freshwater	----	0.04	0.12	Schroeder (1975)
<u>Feed</u>				
12.5 g/m ² ³ (ultimate BOD)	0.34	----	----	Chamberlain (1988)

¹ Assumes a 1-m deep pond for those cases where original data are in units other than volume.

² Median value for two studies cited.

³ Equivalent feed application rate for 25 shrimp/m² and 5% shrimp biomass/day.

demand of the pond system as a whole.

Shrimp standing crops in the range of 500 to 7,000 kg/ha, with 1 m water depth can consume 0.02 to 0.16 mg O₂/l/hr through respiration (Table 3). Shrimp can account for 10% or more of total oxygen demand at higher standing crops (Madenjian 1988). Water column respiration in brackishwater

typically ranges from 0.01 to 0.86 mg O₂/l/hr under semi-intensive to intensive culture conditions. Pond sediment respiration in brackishwater of 0.78 mg O₂/l/hr is possible under semi-intensive to intensive culture conditions, with 1 m water depth; while average values ranged from 0.30 to 0.56 mg O₂/l/hr. Whole pond respiration under semi-intensive to intensive conditions in brackishwater ranged from 0.07 to 1.30 mg O₂/l/hr. Whole pond respiration includes all sub-components, crop, water column and sediments. For brackishwater conditions listed in Table 3, a typical worst case oxygen demand for shrimp, water, and sediments would be;

$$0.16 + 0.86 + 0.78 = 1.80 \text{ mg O}_2/\text{l/hr.}$$

Converting this into total oxygen demand of the pond;

$$\text{TOD} = \text{OD} \times V \times 10^{-3} \quad (9)$$

where; TOD = total oxygen demand (kg O₂/hr).
 OD = oxygen demand (mg O₂/l/hr).
 V = pond volume (m³).
 10⁻³ = conversion factor from g to kg.

If, for example, the pond has one ha surface area, and 1 m depth;

$$\text{TOD} = (1.80) \times (10^4) \times (10^{-3}) = 18 \text{ kg/hr}$$

The next step is to size the aerator configuration to meet this demand, and not allow DO to fall below some minimum value. For discussion, we will assume a minimal oxygen concentration 3 mg/l and pond salinity of 18 ppt. As an example, we will "use" a 2 hp propeller-aspirator aerator with a SAE of 2.18 mg O₂/hp-hr at 18 ppt (Fig. 20). We next convert these SAE values to SOTR values in kg oxygen;

$$\text{SORT} = \frac{(\text{SAE}_{20}) \times (\text{HP})}{2.2} \quad (10)$$

where; SORT = standard oxygen transfer rate (kg O₂/hr) at same salinity, zero mg/l O₂, 20 C and one atmosphere pressure.
 SAE = standard aeration efficiency (lb O₂/hr) at same salinity, zero mg/l O₂, 20 C, and one atmosphere pressure. (See Fig. 20).
 HP = power consumption (or output) of aerator.

2.2 = conversion from pounds to kilograms.

These calculations yield SORT values of 0.88, 1.85, 2.22 and 1.61 kg O₂/hr at salinities of 0, 10, 18 and 35 ppt respectively. For our example, we next need to calculate oxygen transfer rate at 3 mg/l, rather than at zero;

$$\text{OTR}_{20} = \frac{\text{SORT} (C_s - C_i)}{C_s} \quad (11)$$

where; OTR_{20} = predicted oxygen transfer rate at a specific salinity, DO concentration C_i , 20 C, and one atmosphere pressure (kg O₂/hr).

SORT = standard oxygen transfer rate at a specific salinity,

DO = zero mg/l, 20 C, and one atmosphere pressure (kg O₂/hr)

C_s = theoretical DO saturation value at some specific salinity, 20 C, and one atmosphere pressure (Table 1)

C_i = DO concentration for which OTR_{20} is of interest (mg/l).

Resultant oxygen transfer rates at 20 C for the aerator in the example, at the four salinities, and at DO concentrations ranging from 0 to >9 mg/l are shown in Figure 20. We see that maximum OTR_{20} occurs at DO values of 0 mg/l, and that OTR_{20} are zero at DO saturation for each salinity. For our example, OTR_{20} at 18 ppt salinity and DO of 3 mg/l is 1.41 kg O₂/hr. We need to next convert the OTR_{20} to oxygen transfer rate at the pond temperature in question as follows:

$$\text{OTR}_T = (\text{OTR}_{20}) \times (1.024^{T-20}) \quad (12)$$

where; OTR_T = oxygen transfer (kg O₂/hr) at some specific salinity and T

OTR_{20} = oxygen transfer at some specific salinity at 20 C (kg O₂/hr).

T = temperature (C)

In our example at 28 C, $\text{OTR}_T = 1.70$ kg O₂/hr. From this value, and from our earlier calculation of worst case total oxygen demand (TOD = 18 kg/hr), we can now calculate the number of aerators needed to meet this demand;

$$\text{Number of Aerators} = \frac{\text{TOD}}{\text{OTR}_T \text{ per aerator}} \quad (13)$$

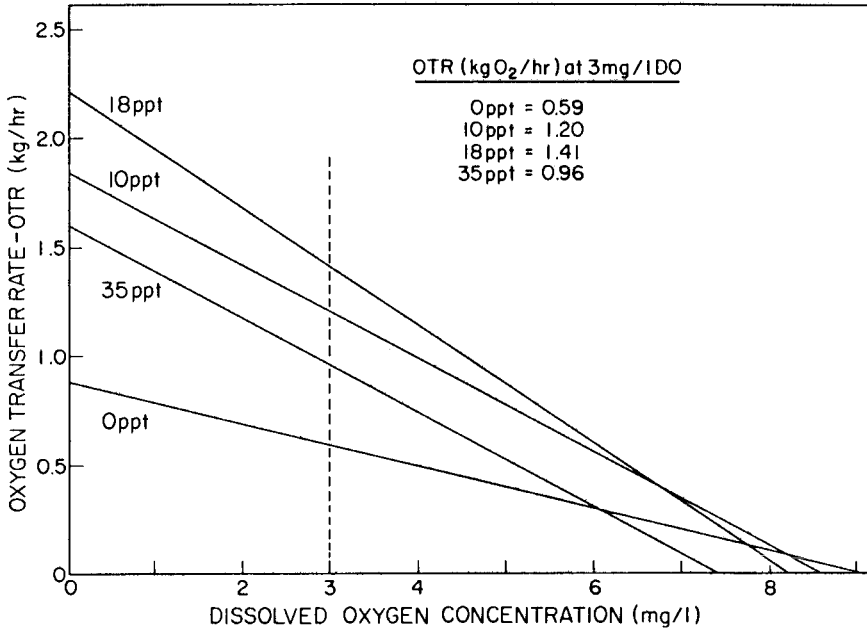


Figure 20. Oxygen transfer rates (OTR) for a 2-hp propeller-aspirator aerator at 20 C, four salinities, and dissolved oxygen (DO) from 0 to >9 mg/l. The OTR rates at 3 mg/l DO are shown (unpublished data, University of Hawaii).

$$\begin{aligned} &= \frac{18 \text{ kg/hr}}{1.70 \text{ kg/hr/aerator}} \\ &= 10.6 \text{ aerators} \end{aligned}$$

This would be an unusually large number of 2-hp aerators for a 1-ha size pond, since total power provision per ha would be 21. In practice, aerator power with Taiwan intensive culture ranges from 2 to 20 hp/ha, with a 10 hp average (Fast et al. 1989). The fact that our calculations yield a value more than twice the average indicates that we have either over estimated TOD, and/or we have under estimated aerator performance. In our calculations, we assumed that high demands for crop, water column, and sediment would all occur at the same time; perhaps an unlikely event. Furthermore, we have not accounted for the effects of water exchange on TOD. Water exchange would undoubtedly greatly reduce TOD, especially water column demand since algae, bacteria and their substrates will be removed from the pond with effluent water. Lastly, and perhaps most importantly, the aerator values shown in Figure 20 are from clean water, tank test situations which may not accurately reflect in-pond performance of these aerators. Aerators

performance in a pond could conceivably be more than twice that of its performance in a test tank. For that reason, the values shown in Figure 20 are used only to illustrate a suggested sizing procedure, and should not be strictly followed in an actual sizing situation.

Range of hp/ha of aerators, in practice, is from zero in extensive ponds, to more than 10 in intensive ponds. These conditions correspond respectively to situations where the oxygen gains and losses are in balance, and where there is a maximum net loss of perhaps 1.0 mg/l/hr. The latter situation is common in intensive cultures, and at times could conceivably reach a maximum of 1.8 mg/l/hr calculated above.

Although the above exercise in aerator sizing may be instructive, it is unfortunately not presently possible to use this procedure for most aerators since we lack SOTR data for most salinities of interest in marine shrimp culture, and because of the problems associated with using test tank values for field situations. Nevertheless, as we learn more about TOD of ponds, and as reliable data become available for aerators, we can use this information to more systematically size and operate aeration systems.

22.6 WATER EXCHANGE

Aeration and water exchange are the two most common techniques of water quality management in marine shrimp ponds. As shrimp production intensifies, so does the need for greater aeration and water exchange. Although aeration needs are easily understood, calculable and often provided for, it is not as easy to understand and quantify water exchange needs. Aeration primarily affects one parameter, DO concentration, with less impact on other parameters. Water exchange, on the other hand, affects many parameters, such as DO, metabolites, ammonia, water temperature, algae, and nutrients. Although we do not fully understand all the reasons for improved shrimp production with increased water exchange, we do know that it is essential during intensification.

Cole and Boyd (1986) have shown strong positive correlation at low water exchange rates between feeding rates of channel catfish and water quality parameters, such as ammonia, nitrite, chlorophyll a, chemical oxygen demand and carbon dioxide. Data for total ammonia are shown in Figure 21. Dissolved oxygen at dawn was negatively correlated with feeding rate. Greater water exchange with higher quality water would reduce these undesirable concentrations and would allow a greater standing crop of fish. The same relationships should exist for crops such as shrimp. With the exception of DO, aeration would have little effect on these parameters.

Hirasawa (1985) has demonstrated production increases for P. monodon at one farm in Taiwan from 10 to 25 MT/ha corresponding to increased

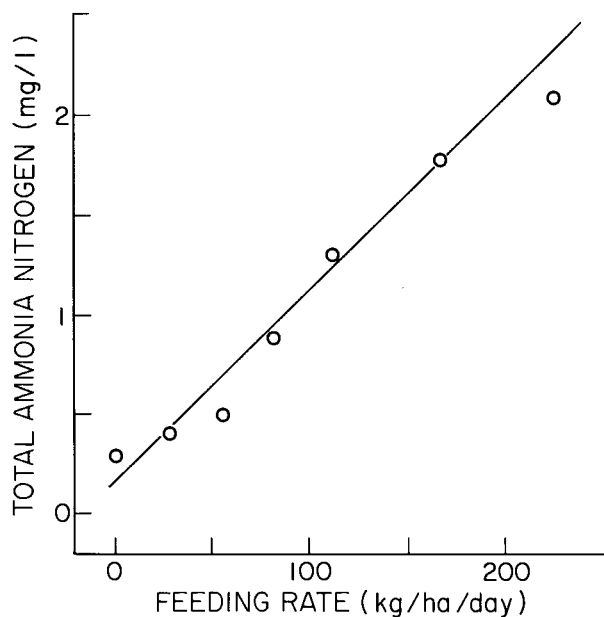


Figure 21. Relationship between total ammonia-nitrogen concentrations and maximum feeding rates in freshwater channel catfish ponds (Cole and Boyd 1986).

water exchange rates of 20%/day and 100%/day respectively (Fig. 22). Some production increase may have been due to warmer well water temperatures in the winter compared with ambient surface water temperatures, but this does not account for all production increases.

Low water exchange rates of 5% per day or less do not seem to have much beneficial effect on water quality, or standing crops. McGee and Boyd (1983) found no significant differences in water quality parameters or channel catfish yield with water exchange rates varying from zero to 5%/day. The same situation almost certainly exists with marine shrimp.

Extensive shrimp ponds that use tidal exchange typically exchange water once or twice a month. At these times, 20% to 50% of the water volume is exchanged over one to three days. Water is discharged during low tide, and then replaced during high tide. Shrimp may be harvested during these times, especially in low lying ponds that cannot be fully drained. On "daily" average, extensive ponds exchange perhaps 1% to 5% of their volume.

With semi-intensive shrimp ponds, greater water exchange rates are normally used. In Ecuador where mechanical aeration is rare, up to 40%/day of pond volume may be exchanged in closely managed ponds. Water exchange in these ponds is related to algal health and DO concentrations. Water exchange is accomplished using large diesel water pumps which pump water

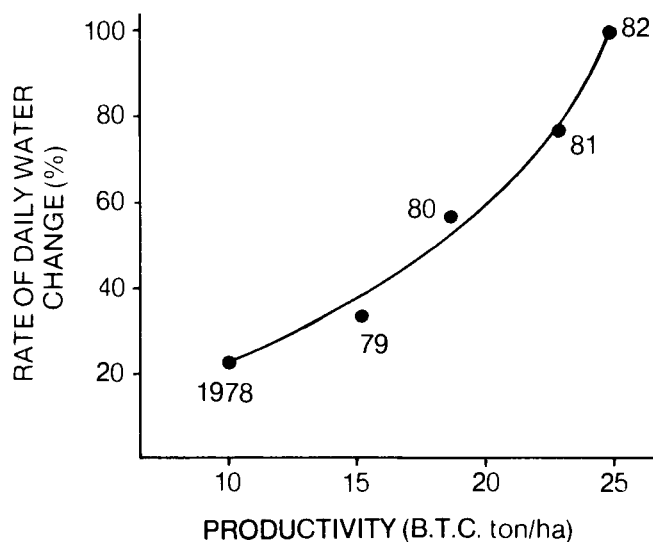


Figure 22. Relationship between rate of water exchange and shrimp yield at a Taiwanese intensive shrimp culture farm in Taiwan (Hirasawa 1985).

into a central reservoir canal. Water exchange accounts for perhaps 90% of all energy consumption on these farms.

In Malaysian semi-intensive shrimp ponds, Gedrey et al. (1983) found that water exchange by pumps gave higher economic returns than with ponds managed by tidal water exchange. Pumped ponds also provided much greater control over water quality, and greater flexibility in pond location. Pumping allows ponds to be located beyond the mangrove zone and on soils less prone to acid conditions.

With Taiwanese intensive culture, water exchange is typically zero during the first month, and increases to 20%/day or more during the last month of growth, with a 10%/day average for the entire crop cycle (Chiang and Liao 1985, Fast et al. 1989, Hirasawa 1985). Pump horse-power per ha ranges from 3 to 26, with 7 hp average. About half the farm's energy expenditure is for water exchange.

22.7 SEDIMENT MANAGEMENT

Sediment and bottom treatment, as well as sedimentation manipulation, is most vigorously practiced with intensive and ultra-intensive shrimp culture. In Taiwanese intensive culture ponds, highly organic and chemically reduced

sediments are removed between crops by suction dredging and/or by flushing through the drain using pressurized water (Fast et al. 1989). Remaining sediments are oxidized and neutralized with powdered lime. The bottom is then left to dry and crack, and is sometimes tilled before refilling.

During intensive culture growout, circular water currents are established, which promotes organic deposition at the pond center. As these sediments accumulate faster than they can be oxidized or decomposed, a thick layer of chemically reduced, black sediment builds up at the pond center. At the same time, bottom areas along the banks remain relatively free of this material because of greater water currents there. Bottom sediments near the banks are well oxidized and brown. Shrimp are thought to avoid reduced sediments at pond center, and prefer oxidized sediments along the banks. Feed thrown into the pond is usually from the bank, where it will sink onto the oxidized sediments rather than onto or into reduced sediments further from the bank. This situation is thought to increase feed detection and consumption by shrimp, and give better growout performance. Manipulation of sedimentation is most effective in small, square or round ponds of 0.25 to 1.0 ha where strong circular water flow can be created.

With ultra-intensive culture using round ponds and a burrowing species of shrimp (*P. japonicus*), sediment condition is of special importance. Pond bottom areas with reduced organic matter accumulations had low redox potentials and high levels of toxic hydrogen sulfide (Shigueno 1969, Kurata and Shigueno 1986). These areas were avoided by shrimp, and if they are not carefully controlled, shrimp growth and survival was greatly reduced. Pond bottom management included a "false" pond bottom with water flow through the sand bottom, dredging to remove organic matter during crop growout, and dragging a chain across the sand periodically to discourage macrophyte growth.

Even with extensive and semi-intensive ponds, much attention is paid to pond bottom conditions between crops. With the exception of some acid soil ponds, these ponds are typically dried between crops either for seven days in the sun to a point where a man will not sink 1 cm when standing on the soil, until the top 1 cm is dry, or until the soil cracks 1 to 2 cm deep (ASEAN 1978). Reasons for doing this are to mineralize organic matter and to thus promote better plant growth upon refilling, to decompose and oxidize organic matter and thus reduce hydrogen sulfide production, and to kill unwanted predators, competitors and disease organisms. Mineralization and decomposition rates are much faster when soil is exposed to high atmospheric oxygen concentrations and elevated temperatures. Ultraviolet light in sunshine also kills disease organisms.

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CHAPTER 23

Claude E. Boyd and Arlo W. Fast

POND MONITORING AND MANAGEMENT

23.1 INTRODUCTION

Bottom soil and water quality management in shrimp ponds is less understood than many other aspects of shrimp farming. This is unfortunate, because sound soil and water management are essential to effective shrimp production. If water and soil quality are not maintained, shrimp will not feed well or assimilate food efficiently, they will be more susceptible to diseases, and survival may be poor. Our purpose here is to discuss briefly some important environmental variables in shrimp ponds, to suggest a monitoring program, and to consider some pond management techniques.

23.2 ENVIRONMENTAL VARIABLES

The list of environmental factors that affect shrimp production in ponds is long. The most widely recognized factors are: soil and water pH, temperature, salinity, dissolved oxygen, carbon dioxide, hydrogen sulfide, ammonia, nitrite, nutrient concentrations, plankton abundance, settleable matter, organic matter concentrations in soil and water, soil texture, soil acidity, redox potential of soil, and condition of soil at the beginning of each crop. Several of these variables, including pH, temperature, salinity, and soil texture, are related primarily to site selection. The others are determined mainly by the shrimp culture system employed and especially by the fertilization or feeding rate.

Shrimp responses to different concentrations of each water quality variable have not been ascertained exactly (Boyd 1989, 1990). Information provided below is largely experience based, but it can serve as a useful guideline for pond management.

23.2.1 Effect of Water Quality Variables

pH: Values below 4 and above 10 may be lethal. The best range is 7 to 9.

Salinity: Salinity requirements vary among species, but some of the commonly cultured species can survive exposure to 5 to 10 ppt or even lower for extended periods. Salinities above 45 to 60 ppt can be lethal. Most species will grow best at salinities of 15 to 30 ppt. (See Chapter 24.)

Temperature: Shrimp species commonly cultured in ponds grow best at temperatures in the range of 25 to 30 C. Some species will grow at less than 20 C, but temperatures of 35 C or greater are lethal. (See Chapter 24.)

Dissolved oxygen: Dissolved oxygen concentrations of 0.0 to 1.5 mg/l can be lethal depending upon exposure time and other conditions. Best survival and growth is obtained at dissolved oxygen concentrations between 3.5 mg/l and saturation. High levels of dissolved oxygen supersaturation are potentially harmful.

Carbon dioxide: Concentrations of carbon dioxide below 20 mg/l probably are not harmful provided that dissolved oxygen concentrations are sufficient.

Hydrogen sulfide: This substance is extremely toxic to shrimp. Any detectable concentration probably has adverse effects on growth. The lethal concentration for shrimp is not defined.

Ammonia: The un-ionized form (NH_3) is most toxic. Concentrations of un-ionized ammonia above 1 mg/l are potentially lethal; concentrations greater than 0.1 mg/l may adversely affect growth. At pH 9.0 and salinity 20 ppt, about 25% of total ammonia is un-ionized. Therefore, total ammonia concentrations above 0.4 mg/l could negatively affect growth when pH is high.

Nitrite: Nitrite in shrimp ponds is seldom at concentrations great enough to kill shrimp, but growth may be adversely affected by concentrations above 4 or 5 mg/l.

Nutrients: Inorganic nitrogen compounds (nitrate and ammonium) and phosphate are nutrients that commonly determine phytoplankton abundance. With high feeding rates, there is normally no need to apply these nutrients in fertilizers. In ponds with little or no feeding, fertilizers may be added to encourage phytoplankton growth. Optimum nutrient concentrations are undefined.

Phytoplankton and organic matter: Plankton creates water turbidity, produces organic matter and dissolved oxygen, and absorbs deleterious substances. Optimum phytoplankton densities are associated with Secchi disk values of 25 to 35 cm.

Settleable solids: High concentrations of settleable solids in influent pond water result in high sedimentation rates in ponds. This causes loss of pond volume, destruction of benthic organisms, and often, greater oxygen demand in bottom soil.

While the water quality variables listed above, and perhaps others that we know even less about, are important so is the condition of the pond bottom soil. Pond bottom conditions have long been a concern of fish culturists (Schaeperclaus 1933; Boyd 1990). This concern is not only with the bottom condition per se, but also with the effect of the bottom on the condition of the water where the fish usually live. With shrimp, bottom conditions take on even greater importance because shrimp are bottom dwellers. Some

species even burrow into the pond bottom. Adequate bottom conditions must be maintained for acceptable shrimp survival and growth.

The relationship between pond bottom conditions and shrimp yield is less understood than the relationship between yield and water quality variables. We know little about the relative importance of bottom soil properties and their interactions with water quality variables. Nevertheless, through experience and observation we do know some things about the effects of bottom conditions on water quality and shrimp production. We have commented below on some of the soil properties known to be important.

23.2.2 Comments on Soil Properties

Texture and organic matter: Texture refers to the proportion of sand, silt, and clay in a soil. Almost any type of soil apparently makes an adequate substrate for most shrimp species, but soils must contain a fairly high clay content for suitable pond construction. Shrimp farms seem to be concentrated in tropical regions with heavy clay soils. High concentrations of organic matter lead to large oxygen demands. Peat soils usually are unsuitable for pond construction.

Acidity: Brackishwater is exchanged in shrimp ponds at 5 to 30% per day. Brackishwater is highly buffered. Acidity released by bottom soils is normally neutralized by the water which does not become acidic if it is exchanged frequently. Where ponds are constructed on acid-sulfate soils, waters may become excessively acidic unless remedial steps are taken.

Redox potential: The redox potential of water at the soil/water interface is a measure of the degree of oxygenation or reduction of the soil. Where dissolved oxygen concentrations are high, redox potential is about 500 millivolts (mv). When the redox potential drops below 340 mv, dissolved oxygen will be 2 or 3 mg/l and nitrite appears. A redox potential of about 200 mv corresponds to 0 mg/l dissolved oxygen and the appearance of ferrous iron compounds that give the soil a black color. Hydrogen sulfide will appear when the redox potential falls to about 100 mv. A brown surface crust on the soil or a crust of the natural soil color indicates oxidized conditions, while a black surface is a sign of reduced conditions. If the surface crust of an oxidized mud is broken, a black, reduced layer usually is found at a depth of 1 to 5 cm below the surface.

Soil condition: After ponds are drained for shrimp harvest, farmers often resort to bottom treatments such as sediment removal, drying, tilling, and liming. The idea is to remove sediment mechanically, and to oxidize remaining organic matter by stimulation of microbial activity through air exposure and soil neutralization.

23.3 POND MONITORING

Although all shrimp ponds require some monitoring, the type and frequency of monitoring varies greatly. Large, extensive ponds require the least amount of monitoring. Conditions critical for shrimp survival seldom develop in these ponds because chemical and biological mass flux rates are low (see Chapter 21). Furthermore, there are few practical management options, except water exchange, should water quality problems arise. The type of monitoring needs, as well as monitoring frequency, increase as the intensity of culture increases. Intensive culture ponds require nearly constant human attention, while ultra-intensive systems often need both constant human attention and constant electronic monitoring.

Whatever the monitoring needs, a given monitoring program should be well designed and include only those variables necessary to provide essential decision-making information. Inclusion of other data collection can waste much time and money without substantial contribution to crop production and profits.

The water quality variables most often monitored in shrimp ponds are pH, salinity, dissolved oxygen, plankton abundance, water clarity, ammonia, nitrite, and hydrogen sulfide. These variables can be measured with satisfactory accuracy using uncomplicated means, and it is possible to make meaningful management inferences from these data. It usually is impossible to interpret soil analyses, and soil analyses are not recommended as a routine practice. Recently, several companies have started selling inexpensive devices for measuring bottom soil pH and redox potential. Experience from traditional agricultural applications suggests that such devices are worthless.

23.3.1 pH Monitoring

With ponds constructed in or near acid-sulfate soil, pH monitoring of pond water is necessary to assure that excessively acidic conditions do not develop. Weekly pH measurements of surface water will provide sufficient information. These measurements are of little value where acid-sulfate soils do not occur. Brackishwater normally has a high alkalinity, pH near 8, and is well-buffered against drastic pH changes. Nevertheless, in ponds with heavy plankton blooms, pH can fluctuate between 7.5 and 9.5 over a 24-hour period, with lowest pH occurring near dawn and the highest pH occurring in the afternoon. Also, pH tends to decrease with water depth in all but well-mixed ponds. These diel and vertical pH patterns result from the influence of light on photosynthesis and from the effects of community respiration.

Plants remove carbon dioxide from water during photosynthesis and cause pH to rise. At night, carbon dioxide from respiratory processes accumulates

in the water and the pH falls. Normal diel pH fluctuation generally has no detectable influence on shrimp. With intensive ponds where total ammonia concentrations are high, however, the proportion of un-ionized ammonia (the toxic form) increases with increasing pH and can potentially create problems. Nevertheless, daily monitoring of pH is not necessary.

Measurements of pond water pH can be made with standard laboratory pH meters, portable pH meters, colorimetric water analysis kits, or universal pH paper. A pH meter gives greatest accuracy. The meter should be calibrated routinely at pH 7.0 and then the accuracy verified by testing a pH 8.0 buffer. Colorimetric analysis kits typically give pH readings that are 0.5 to 1.0 pH units too high. Universal pH paper is reliable only for determining if a water is acid, neutral or basic.

With ponds in or near acid-sulfate soils, the best time of day to measure pH is at dawn. At this time, pH will be at its lowest point and low pH problems are most easily identified. With intensive culture, the best time to measure pH is in the early afternoon, because problems are associated with excessively high pH values and pH is normally at its highest by early afternoon.

23.3.2 Salinity

Shrimp farms usually take their water from estuaries which are subject to seasonal influences. Salinity declines during the rainy season and increases in the dry season. In some places, salinity may vary from 5 to 10 ppt or less at the end of the rainy season to 30 to 40 ppt or more at the end of the dry season. Salinity changes are normally gradual, so it is not necessary to measure salinity more than once or twice weekly unless the water source is strongly influenced by tidal flows. Also, most ponds on a given farm will have almost identical salinities, and it is therefore unnecessary to measure salinity in each pond. The exception to this rule is where farms have multiple water sources of different salinities, such as in Taiwan. Salinity can be estimated from chloride concentration:

$$\text{Salinity in mg/l} = 30 + (1.805)(\text{chloride in mg/l}). \quad (1)$$

Salinity also can be measured directly with hydrometers, hand-held salinometers (refractometers), or electronic salinometers (conductivity meters). Hand-held salinometers are recommended for practical use on shrimp farms. Conductivity meters are more useful in research applications.

23.3.3 Dissolved Oxygen

The major factors affecting dissolved oxygen solubility in water are temperature, salinity, and pressure. Shrimp ponds normally are at sea level

and variation in pressure is slight. Shrimp pond water is seldom at saturation, because of the combined effects of oxygen production by photosynthesis and oxygen consumption by respiration. Biological processes can change dissolved oxygen concentrations so quickly that diffusion of oxygen between air and water cannot maintain saturation.

Pond dissolved oxygen concentrations are dynamic. They exhibit both diel cycles and vertical stratification. Concentrations are greatest in the afternoon and least near dawn as a result of community photosynthesis and respiration. During daylight hours, oxygen concentrations are greatest near the surface because of light extinction with depth and thermal stratification. The magnitude of dissolved oxygen fluctuation during a 24-hour period and the degree of vertical stratification increases with increasing phytoplankton abundance. Fertilization and feeding increase phytoplankton abundance. Therefore, problems with low dissolved oxygen increase with increased shrimp production per unit area. (See Chapters 21 and 22.)

Dissolved oxygen monitoring is most important in semi-intensive, intensive, and ultra-intensive ponds. Since shrimp live near or on the pond bottom and dissolved oxygen concentrations normally are lowest at the bottom, dissolved oxygen measurements made a few centimeters above the bottom are most useful for management purposes. With intensive culture, dissolved oxygen concentrations should be measured at 2 to 3 hour intervals during the night. These and other data may be used to predict whether aeration or water exchange will be necessary before dawn (Boyd et al. 1978; Madenjian et al. 1988). If concentrations less than 3 mg/liter are projected, emergency measures to increase oxygen concentrations should be taken.

Dissolved oxygen concentrations can be measured with water analysis kits or with polarographic oxygen meters. The kits employ traditional wet chemistry and provide sufficiently accurate data (Boyd and Daniels 1988). It takes considerable time, however, to measure dissolved oxygen by wet chemistry techniques. Where there are many ponds and many measurements, it is more convenient to use oxygen meters. Oxygen meters differ greatly in cost. The inexpensive meter can provide accurate data, but they are of poor quality and not durable. The most expensive meters normally have analytical options not needed for pond management. Suitable dissolved oxygen meters are available at \$750 to \$1,000.

Dissolved oxygen meters are sophisticated instruments, and they should be treated accordingly. Membranes and batteries should be changed routinely, and readings should be checked for accuracy. When meter readings are suspect, the meter should be checked against another meter or a water analysis kit. If this is not possible, take two pails and pour a sample of water back and forth between them 40 to 50 times. Measure the temperature and salinity of the water and determine the dissolved oxygen concentration at

saturation from Table 1 in Chapter 22.. The water in the pail should be approximately saturated. Test the water in the pail with the dissolved oxygen meter in question. The reading should be near saturation if the meter is functioning properly.

23.3.4 Phytoplankton Abundance and Nutrients

On some large farms, technicians make frequent estimates of phytoplankton type and abundance. Such analyses are labor intensive, and it is often difficult or impossible to interpret results. A more simple approach is to observe water color and to estimate turbidity from Secchi disk readings. Phytoplankton abundance can change rapidly, so measurements should be made daily. No one knows for certain the best color for shrimp pond water. Most pond managers prefer a dull green, yellowish green, or brownish green color because these colors are associated with desirable green algae and diatoms. Color may be used to distinguish turbidity caused by suspended soil particles from that of phytoplankton. Color changes also suggest changes in plankton community composition. Secchi disk visibility is a measure of plankton abundance because visibility increases when plankton abundance declines and decreases when plankton abundance rises. Secchi disk visibilities of 25 to 35 cm are considered desirable by most shrimp farmers. Higher visibilities suggest inadequate plankton, scarce natural food organisms, and a threat of macrophyte infestation. Lower visibilities indicate excessive plankton and potential problems with low dissolved oxygen.

A shrimp farmer can easily make a Secchi disk. It is a 20-cm diameter disk painted with alternate black and white quadrants. Traditionally, the disk has been tied to a calibrated line and a weight attached on the underside. However, shrimp ponds are shallow and Secchi disk readings will normally be less than 1 m. An alternate method is to attach a meter stick or calibrated rod vertically in the center of the disk. When using water color and Secchi disk visibility for management purposes, the analyst should standardize his observation methods (Almazan and Boyd 1978). Measurements should be made at the same time each day by the same person using the same procedure. The following procedure is adequate: make readings between 0800 and 1000 hr or between 1400 and 1600 hr; select observation position with sun behind observer; wear polarized sunglasses; lower disk into the water until it just disappears and read depth; raise disk until it just reappears and read depth; average the two readings to get the Secchi disk visibility. It is not necessary to use sunglasses. However, if you do use sunglasses, use them for all readings. Some method for standardizing water color identification also is needed. Some farmers have made color charts, and names of colors are selected from the chart. The value of the color chart technique is unproven.

Color measurements are highly subjective and meaningful interpretation of such data is difficult.

Nutrient measurements are too difficult to make and interpret for routine practical use. It is more feasible to use phytoplankton abundance as an indirect measure of nutrient availability, because phytoplankton responds to nutrient concentrations. Nutrient limitations are suggested when phytoplankton abundance declines.

23.3.5 Toxic Metabolites

Carbon dioxide, ammonia, nitrite, and hydrogen sulfide are the common toxic metabolites in shrimp ponds. Carbon dioxide is produced through respiration by all aerobic microorganisms, plants, and animals. Ammonia is an excretory product of shrimp. It also is produced during microbial decay of organic matter. Nitrite and hydrogen sulfide are produced by microorganisms when dissolved oxygen concentration is low. Toxic metabolite concentrations increase at higher stocking and feeding rates. Thus, there are seldom problems with toxic metabolites in extensive and semi-intensive shrimp culture.

Water analysis kits are adequate for determining concentrations of toxic metabolites (Boyd 1980; Boyd and Daniels 1988). Samples should be collected from near the pond bottom. The sampling time is unimportant, except for carbon dioxide, which should be measured in the early morning. Toxic metabolite concentrations will change quickly during sample storage, so measurements should be made at once or the samples preserved. The best way for preserving samples for a few hours is to place them on ice and in the dark.

In intensive shrimp ponds, toxic metabolite concentrations can build up over time. Measurements made at one week intervals usually will provide an accurate assessment. Toxic metabolite measurements in extensive or semi-intensive ponds sometimes are needed to explain problems with mortality or slow growth of shrimp.

Measurements of pH are necessary to interpret ammonia and hydrogen sulfide data. Analytical methods give total concentrations (ionized + un-ionized) of ammonia and sulfide. Table 1 shows how the proportion of toxic, un-ionized ammonia increases with increasing pH while that of toxic un-ionized hydrogen sulfide decreases with increasing pH. Approximate percentages of un-ionized ammonia and hydrogen sulfide given below are for 30 C. The percentages will decline with decreasing temperature. For example, if the total ammonia nitrogen concentration measured with a water analysis kit is 5 mg/l and the pH is 8, the un-ionized ammonia concentration is: 5 mg/l total ammonia nitrogen $\times$ 0.09 = 0.45 mg/l un-ionized ammonia.

Table 1. Relationship of pH, unionized ammonia, and unionized hydrogen sulfide in shrimp ponds.

	pH					
	5	6	7	8	9	10
Un-ionized ammonia (%)	0	0.1	1	9	50	90
Un-ionized hydrogen sulfide (%)	99	90	50	9	1	0

Ammonia is seldom a problem unless the pH is 8.5 or more. Any detectable concentration of hydrogen sulfide is undesirable, but hydrogen sulfide is a greater problem when pH is below 7.

23.3.6 Visual Observation

One of the most uncomplicated and useful pond monitoring approaches is simple visual observation. Visual observations and salinity measurements are the only routine monitoring done by most intensive shrimp farmers in Taiwan (Fast et al. 1989). In addition to color or turbidity changes, visual inspection can yield information about the condition of the shrimp. Conditions such as distress, lethargy, hyperactivity, feeding or disease can be observed. Feeding observations normally are made using a small "feed net". The feed is placed on top of a net suspended in the water, and the feeding activity of the shrimp can be ascertained. (See Chapter 31 for a discussion of this technique in Taiwan.)

Visual observations should be made frequently during the day and night, with shorter observation intervals for intensive culture systems. While visual observations can suffice for experienced pond managers, they are most useful when coupled with chemical and physical observations such as dissolved oxygen, Secchi disk, salinity, and water temperatures.

23.4 POND MANAGEMENT

There are relatively few economical management operations in shrimp farming. Pond waters can be fertilized, aerated, exchanged and mechanically circulated. Sediment can be removed from ponds or treated between crops. Fertilization can increase nutrient concentrations, enhance plankton growth, and increase natural productivity. Aeration can improve dissolved oxygen concentrations and prevent mortalities. Water exchange has several effects including reducing nutrient concentrations and excessive plankton abundance, lowering concentrations of toxic metabolites, preventing excessive salinity in

the dry season, providing water circulation, and improving dissolved oxygen concentrations. Mechanical water circulation provides greater uniformity of water quality variables throughout the pond volume, helps maintain oxygenated conditions at the mud surface, and increases bottom temperatures. Sediment can be removed from influent water before it enters ponds to reduce sedimentation rates, or it can be allowed to accumulate in ponds and removed between crops. Pond bottom treatments between crops may improve bottom conditions for each new crop. The following is a discussion of some common pond management problems and treatments.

23.4.1 Acid-Sulfate Soils

Many coastal shrimp ponds are developed in brackishwater swamps, especially mangrove forests. Soils in such places often contain high concentrations of iron pyrite which oxidizes upon air exposure to produce sulfuric acid. Often times, the pyrite in surface layers of these soils has oxidized over time and the acidity has been leached out by rainfall and tidal exchange. Lower soil layers, however, which may be exposed during pond construction, often have a high potential acidity.

There are three possibilities for dealing with acid-sulfate soils (Dent 1986; Boyd 1990). First, after pond construction, the bottom and levees are exposed to frequent and repeated drying to oxidize iron pyrite and flushing with seawater to remove acidity. The bottom can be reclaimed in 3 to 6 months. It may take longer to remove acidity from levees. Secondly, ponds may be limed, but the amount of agricultural limestone needed usually is prohibitive. The upper 15-cm layer of bottom and levee soil may have a lime requirement of 50 to 150 tons/ha. The third approach is to prevent or minimize the oxidation of the pyrite. This can be achieved through a combination of layering the pond bottom and/or levees with non-acidic soil and by keeping the pond soils submerged with water as much as possible. If surface soils at the prospective pond site are suitable, they can be scraped off and stockpiled for later use in layering the levees or bottom. If these soils are too acidic, then good quality soil may be brought in for layering. After construction and layering, it is important to keep the pond full of water except for short periods during drain harvest or for pond repairs. When water is maintained in the pond, the soils remain waterlogged and dissolved oxygen concentrations are at or near zero in the soil. These conditions greatly reduce pyrite oxidation and acid formation. If acid production is low enough, it can be handled by the high buffering capacity of the brackishwater and by water exchange.

Using this approach to acid-sulfate soil management, it is particularly important to properly manage and contain the acidity of levees, because the levees are exposed to repeated cycles of air drying and rainfall. This can

result in considerable acid formation, and the acid can seep into ponds or enter in runoff. Fish and shrimp kills are common in acid-sulfate soil areas at the beginning of the rainy season when the first rains wash acid from levees into ponds. This acid had accumulated during the dry season through soil cracking, air exposure and pyrite oxidation. A solid cap of good quality soil on the levee and subsequent establishment of good grass cover will help prevent this problem. If the levees cannot be capped with good quality soil, they should be limed and planted with an acid-resistant grass. The grass should be fertilized and irrigated to encourage its establishment.

After one or more of the above soil management practices is used, normal water exchange through the pond usually will control pH of water. Of course, if pond bottoms are permitted to dry between crops, acid will be produced through oxidation and water must be flushed through ponds to remove this acid.

23.4.2 Other Types of Acidic Soils

Soils also may be acidic because they contain high concentrations of organic matter and/or acidic clay. These soils normally have lower acidity than acid-sulfate soils. In freshwater ponds with acidic bottom soils of this type, lime must be applied to maintain sufficient total alkalinity in water for optimum growth of plankton and benthos (Pillai and Boyd 1984). This practice has been transferred unnecessarily to brackishwater aquaculture. Brackishwater has a high total alkalinity and routine water exchange normally provides continuous replenishment of alkalinity neutralized by organic matter, nitrification of ammonium, and acidic clays. Liming usually is not necessary to maintain total alkalinity and pH in these brackishwater ponds. Sometimes, as discussed later, lime should be applied to dry pond bottoms between shrimp crops.

23.4.3 Water Exchange

Water exchange is a common practice in shrimp farming. Average daily water exchange rates of 5% to 30% are common. Despite wide use, the benefits of water exchange are poorly understood, and it is often used ineffectively.

Pond water salinity often increases in dry seasons. The influence of evaporation on salinity may be quite drastic. The water level in ponds is commonly maintained with just enough water to replace evaporation and seepage. Seepage does not affect salinity. Evaporation causes salinity to increase because salts are not lost when water evaporates. If the evaporation rate in an 80 cm deep pond is 0.5 cm/day, daily water lost to evaporation will equal 0.62% of pond volume. Salinity will increase by an equal percentage. Suppose salinity is 30 ppt at the beginning of the month. By the end of the

month salinity would be 35.6 ppt. Even with water exchange in a pond with 30 ppt salinity, salinity will increase during the dry season, but at a lesser rate.

Water exchange is also a means of improving other water quality conditions. If dissolved oxygen concentration in a pond is low and the water in the supply canal has a high dissolved oxygen concentration, high water exchange rates can improve dissolved oxygen concentrations in the pond. Likewise, excessive nutrients, plankton and toxic metabolites can be flushed from ponds through water exchange. Influent water should enter ponds at the surface and effluent pond water should be discharged from a drain located near the pond bottom and on the opposite side of the pond. The most beneficial means of exchanging water in a pond is to first drain out the volume to be exchanged and then pump or let in an equal volume of high quality water.

Water should not be exchanged if water quality in the pond is good because nutrients and plankton needed for shrimp production will be flushed out. It is wasteful to exchange water in ponds where fertilizers have just been applied. Also, pond water sometimes may be of better quality than water in the water supply canal. In this event, water should not be exchanged.

Definitive experiments to demonstrate the benefits of various water exchange rates in ponds with different shrimp densities and feeding rates have not been conducted. In extensive and semi-intensive culture, water exchange is likely much less beneficial than thought by pond managers. Research in this area is badly needed.

The water exchange rate in a pond where water is introduced by a pump may be estimated as follows if the pond is initially full to the top of the overflow structure:

$$ER = \frac{[(PR \times T) + P] - (S + E)}{V} \times 100 \quad (2)$$

where,

- ER = exchange rate (% pond volume/day)
- PR = pumping rate (m³/hr)
- T = time of pump operation per day (hr)
- P = precipitation (m³/day)
- S = seepage (m³/day)
- E = evaporation (m³/day)
- V = pond volume (m³)

In most tropical, coastal areas, seepage will be insignificant in well-constructed ponds, but evaporation may be as high as 0.7 cm/day. Where pumps are not used to introduce water directly into ponds, the pumping rate

term of the above equation must be replaced by the inflow rate. Usually the water will flow into the pond across a water control structure which can serve as a weir for estimating inflow rate. For example, in Ecuador ponds usually have concrete inlet and outlet structures which can be filled with flash boards to regulate inflow or outflow. When water flows over the top of the flash board, the structure can serve as a rectangular weir for measuring inflow. The weir equation (Schwab et al. 1971) is presented below:

$$Q = 1.84(L - 0.2H)(H)^{3/2}(60) \quad (3)$$

where,

Q = discharge in m³/min

L = width of weir crest (the width of the flash board over which water flows) in m

H = head (depth of water flowing over flash board) in m.

From a practical viewpoint, precipitation, seepage and evaporation normally will be relatively unimportant, and the exchange rate may be calculated with sufficient accuracy as follows:

$$ER = \frac{IR \times T}{V} \times 100 \quad (4)$$

where,

IR = inflow due to gravity flow or pump operation (m³/hr).

Usually, shrimp farmers do not maintain accurate records of water exchange rate. They simply use an inflow rate that seems appropriate. In view of the lack of data on the water exchange rate/benefit relationship, this procedure is probably as good as any.

23.4.4 Aeration and Water Circulation

This subject is considered in detail in Chapter 22, but a few comments will be made here. In fertilized and manured ponds which are not fed, phytoplankton abundance and oxygen demand usually are not excessive and aeration is not needed. If low dissolved oxygen problems do arise, water exchange alone normally will prevent shrimp stress and mortality.

In ponds with feed applications, phytoplankton abundance and oxygen demand increase as feeding rates increase. When feeding rates exceed 40 to 50 kg/ha/day, problems with dissolved oxygen begin to occur, and the frequency and severity of low dissolved oxygen is a function of feeding rate.

Aeration can be applied on an emergency, nightly or continuous basis to supplement natural sources of dissolved oxygen, reduce stress in shrimp, and prevent shrimp mortalities. Aeration increases the potential for shrimp production, and if stocking and feeding are not excessive, aeration can prevent oxygen stress and result in better feed conversion. When stocking and feeding rates are increased to take advantage of the additional oxygen supplied by aeration, concentrations of toxic metabolites, and especially ammonia, will increase. Water exchange, therefore, is critical in intensive shrimp culture. Unless water exchange is adequate, high ammonia concentrations will stress shrimp and reduce the benefits of aeration. A quantitative relationship between aeration and water exchange which can be used to optimize oxygen and metabolite concentrations has yet to be determined.

Aeration also circulates pond water and provides more uniform distribution of water quality variables. In addition, circulation improves dissolved oxygen concentrations at the pond bottom. This helps decompose organic detritus and reduces hydrogen sulfide production at the soil-water interface. Recently devices that circulate pond water but provide a minimum amount of aeration have been developed, e.g. air lift pumps and slow-speed, low-head pumps. These devices blend and circulate pond water to provide a uniform environment, and they consume considerably less energy than aerators. Further research and experience with these devices are needed.

23.4.5 Fertilization

Little research has been conducted on the fertilization of brackishwater ponds, but experience suggests the following:

- (i) both nitrogen and phosphorus are important in shrimp pond fertilization;
- (ii) in areas where water receives domestic or municipal wastes, fertilization may not be necessary;
- (iii) diatoms are good food for shrimp and can be encouraged by increasing nitrogen concentrations relative to phosphorus;
- (iv) excessive fertilization can lead to dissolved oxygen depletion;
- (v) low salinity coupled with high rates of phosphorus fertilization favors blue-green algae blooms;
- (vi) plankton blooms resulting from fertilization create turbidity and help control underwater weeds;
- (vii) water exchange flushes out nutrients and plankton;
- (viii) fertilization normally is not necessary in ponds receiving feed applications;
- (ix) fertilization schedules must be developed through trial and error because research findings are inconclusive.

Urea, triple superphosphate, and diammonium phosphate are good chemical fertilizers for use in shrimp ponds. Liquid fertilizers are a better source of phosphorus than granular ones because the phosphorus in liquid fertilizers dissolves immediately. When broadcast into ponds, granular phosphate fertilizers settle to the bottom before dissolving completely. They finish dissolving on the bottom, but the phosphate is strongly adsorbed by the bottom soil (Boyd 1981). Granular urea is readily soluble. Where available, a good choice of fertilizer is 10-34-0 (10% N, 34% P_2O_5 , and 0% K_2O) liquid fertilizer and urea. Applications of 8 to 12 kg/ha of nitrogen and phosphorus (expressed as P_2O_5) can produce good phytoplankton blooms. Where water exchange is used, it is probably best to apply the monthly dose of fertilizer in two or three small increments every 10 to 15 days. Also, water exchange should be stopped or reduced for a few days after fertilization to reduce nutrient loss. For those that desire to experiment, different nitrogen:phosphorus ratios can be used to determine if diatom abundance can be increased.

Fertilizers should be applied so that the nutrients mix throughout the pond. Liquid fertilizers should not be applied directly, because they are heavier than water and will sink to the bottom. They should be mixed with water (1 part fertilizer to 3 or 4 parts water) and splashed over the pond surface. Granular fertilizers can be broadcast over the pond surface, or they may be placed on an underwater platform near the water inlet or near an aerator so that water currents distribute the nutrients as the fertilizer dissolves. Alternatively, a slurry of granular fertilizer may be used as follows: combine 1 part fertilizer and 3 or 4 parts water in a container; let stand for several hours; mix thoroughly; splash slurry over the pond surface.

Manures must be applied to ponds in larger quantities than chemical fertilizers, because they are less concentrated in plant nutrients. Initial applications of 500 to 1,000 kg/ha of fresh manure are commonly made, followed by applications of 200 to 300 kg/ha at 1 to 2 week intervals. Manure contains a high percentage of organic matter. Excessive application rates can result in depletion of dissolved oxygen.

23.4.5 Sediment Control

Sediment control methods include removing sediment after ponds are drained for harvest, dredging sediment from undrained ponds, and passing water through sedimentation ponds or canals before use. Sedimentation of suspended soil particles in sediment ponds or canals is the best approach where possible. Sediment must be periodically removed from sedimentation areas, but this is easier than removal from production ponds, and it does not disrupt crop cycles. Sedimentation pond size must be determined on a farm by farm basis. Pond area will depend upon sediment pond depth and

volume, size of production area, sedimentation rate, wind induced resuspension of sediment, water exchange rate in production ponds, and nature of sediment. Saline water facilitates the flocculation and sedimentation of suspended soil particles, and water retention times of 1 to 2 hours often are adequate. The major factor favoring rapid sedimentation is reduction of velocity and turbulence of water. Baffle levees can be used to reduce velocity and turbulence where only a small area is available for sedimentation (Boyd 1989). If possible, water supply canals or sedimentation ponds should be paired. In this way, one canal is available to supply the farm while accumulated sediment is removed from the other.

23.4.6 Pond Bottom Treatment

Pond bottom drying with application of various treatments to the dry bottom between crops is a common practice. Research findings to support these practices are not available, but it is logical that drying and oxidation of the pond bottom through air exposure would encourage mineralization of organic matter by bacteria and the oxidation of reduced substances. With the exception of some acidic soils, benefits of bottom treatment should be greatest where bottoms can be dried and the upper 5 to 10 cm of soil tilled. This procedure enhances the contact of soil with atmospheric oxygen to favor bacterial activity. When soil pH is below 7.0, liming with agricultural limestone at 500 to 1,000 kg/ha will increase pH and favor bacterial activity. Applications of calcium hydroxide or calcium oxide will initially increase pH to such a high level that bacterial activity is halted. Unless it is desirable to kill pathogenic agents in the mud, agricultural limestone should be applied to pond bottoms instead of calcium hydroxide or calcium oxide.

23.4.7 Miscellaneous Treatments

Several companies sell products that allegedly improve water quality in shrimp ponds. These products include zeolites, bacterial suspensions, solutions of saponified fatty acids, iron dust, calcium peroxide, and potassium permanganate. There is no evidence that any of the products can economically improve water quality in shrimp ponds.

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CHAPTER 24 L. James Lester and Ma. Josefa R. Pante

PENAEID TEMPERATURE AND SALINITY RESPONSES

24.1 INTRODUCTION

Marine shrimp culturists know that environmental conditions influence the survival and growth of shrimp during the culture cycle. Nevertheless, there is a lack of information on how much variation a specific change in an environmental parameter can cause in survival or growth of shrimp in tanks or ponds. Eventhough a set of simple environmental parameters is monitored to alert the culturist to potential problems, the environment of a pond or tank is so complex that causal relationships are very difficult to determine (see Chapter 21).

There are four parameters that are considered to be of primary importance in the culture environment: temperature, salinity, dissolved oxygen and turbidity (or algal concentration). The latter two are largely dependent on the biological community in the pond or tank. Only temperature and salinity offer the opportunity to conduct simple experiments to isolate the effect of the environmental parameter.

In this chapter, we will review research findings on the effects of these commonly measured environmental variables. Understanding how shrimp respond to temperature and salinity would aid culturists in establishing conditions for optimum growth and survival of shrimp.

Results from the literature and unpublished experiments are summarized by stage in the life cycle. It is important to distinguish among the environmental responses of the larvae which are adapted to oceanic salinity and surface temperatures, juveniles which are adapted to estuarine salinities and coastal temperature patterns, and adults which are adapted to oceanic salinities and bottom temperatures. These patterns of adaptation differ for a few penaeid species that do not have an estuarine phase.

There are numerous studies of the effects of temperature and salinity on the survival of non-penaeid crustacea. In general these show survival peaks at salinities and temperatures near those of the natural habitat (e.g. Guest and Durocher 1979, Macrobrachium amazonicum larvae; McKenney and Neff 1979, Palaemonetes pugio larvae; Chittleborough 1975, Panulirus longipes juveniles). Tolerance to variation in temperature and salinity often differs

among closely related species due to genetic differences. Vanhaecke et al. (1984) studied Artemia from different geographic populations of four species formerly lumped under Artemia salina. The Artemia strains differed greatly in their tolerance to low and high temperatures. Despite these differences, the authors were able to generalize about the conditions of temperature and salinity under which survival of all Artemia species exceeds 90%; conditions favoring high survival are 20 to 26 C and 40 to 110 ppt (Vanhaecke et al. 1984).

A similar comparison of Macrobrachium species by Yagi and Uno (1980, 1981, 1983) also demonstrates the strong differences that may exist among closely related species. They conclude that Macrobrachium nipponense has larvae adapted to low salinities (0 to 15 ppt) and a wide temperature regime (23 to 37 C); M. rosenbergii larvae survive better at intermediate salinities (3 to 18 ppt) and temperatures (26 to 34.5 C); M. japonicum survive very poorly at salinities below 18 ppt and at temperatures below 26 C and above 33 C. Ogasawara et al. (1979) report very different results on M. nipponense. The responses to salinity were measured at 26 to 28 C and included no survival at 0 ppt, and the best survival to PL at between 40 and 70% sea water (approximately 14 to 24 ppt). The difference between the studies is attributed to genetic differences between the geographic populations that were analyzed (Yagi and Uno 1983). Obviously there are requirements that would be common to the rearing of all Macrobrachium larvae, but there are differences among species and strains that could produce large problems if they are not understood. A similar statement could be made about penaeid larvae.

Most studies of temperature and salinity responses have measured changes in survival or growth. Only a few have examined how the molting process is affected.

Studies conducted on molting of crustacea indicate that there is a direct relationship between increasing temperature and decreasing intermolt period, until temperature becomes stressful (studies on euphausiids by Lasker 1966 and Fowler et al. 1971). Similarly Rothlisberg (1979) observed a decreased intermolt period for Pandalus jordani larvae with increased temperature. This effect may not directly lead to increased growth rate.

It would be worthwhile for penaeid culturists to understand the responses to environmental parameters of the particular species and strain being grown. Nevertheless culturists often generalize about the hatchery and pond conditions required for successful growth and survival of penaeid species.

24.2 TEMPERATURE EFFECTS

Temperature is both a limiting factor, setting high and low temperature lethal limits, and a determinant of growth rate through its impact on molecular activity. In most hatcheries and nurseries, temperature regulation is practised if possible. In ponds, temperature is monitored. This is in keeping with the recognition that growth and survival are strongly affected by this environmental parameter. Poor growth and survival at low temperatures are significant problems in the U.S. (including Hawaii), Panama, Mexico, China, and other localities. High pond temperature can also be a problem, but is cited much less frequently by growers.

24.2.1 Survival

At lethal low temperatures, metabolic processes slow down below the level required for cellular maintenance and the shrimp die. At lethal high temperatures, proteins denature more quickly and membranes become more fluid which results in metabolic dysfunction and death. Between the lethal extremes, shrimp are able to maintain proper metabolic function, but survival and growth are still affected.

24.2.1.1 Egg and Larval Survival

Three species of penaeid, Penaeus plebejus, Metapenaeus macleayi and Metapenaeus bennettiae, were studied for the effects of temperature and salinity on hatching success and larval survival and growth by Preston (1985). Experiments were conducted with a factorial design using five salinities, 20, 25, 30, 35 and 40 ppt, and four temperatures, 19, 24, 29 and 34 C. For each of these species, temperature had the primary effect on the hatching time of eggs, but both low and high salinity increased hatching time. Hatching success shows a peak for P. plebejus between 19 and 24 C and for M. macleayi between 24 and 29 C. The optimal temperature for hatching of M. bennettiae eggs was significantly affected by the conditions which existed at spawning. Eggs that were spawned at low temperature and salinity showed peak hatching success between 19 to 24 C, but eggs spawned at higher temperature had peak hatching success at 24 to 29 C.

Survival was studied in three stages of the larval development process, from nauplius 1 (N1) to protozoa 1 (Z1), from Z1 to mysis 1 (M1), and from M1 to postlarva 1 (PL1). There was a more marked temperature effect on the M1 to PL1 studies than on the early stages. Both 19 and 34 C caused lower survivals than 24 and 29 C. However, whether the optimal temperature was 24 or 29 depended upon the species and/or the stage of development. For P. plebejus, 24 C appears to be the optimal temperature. Optimal

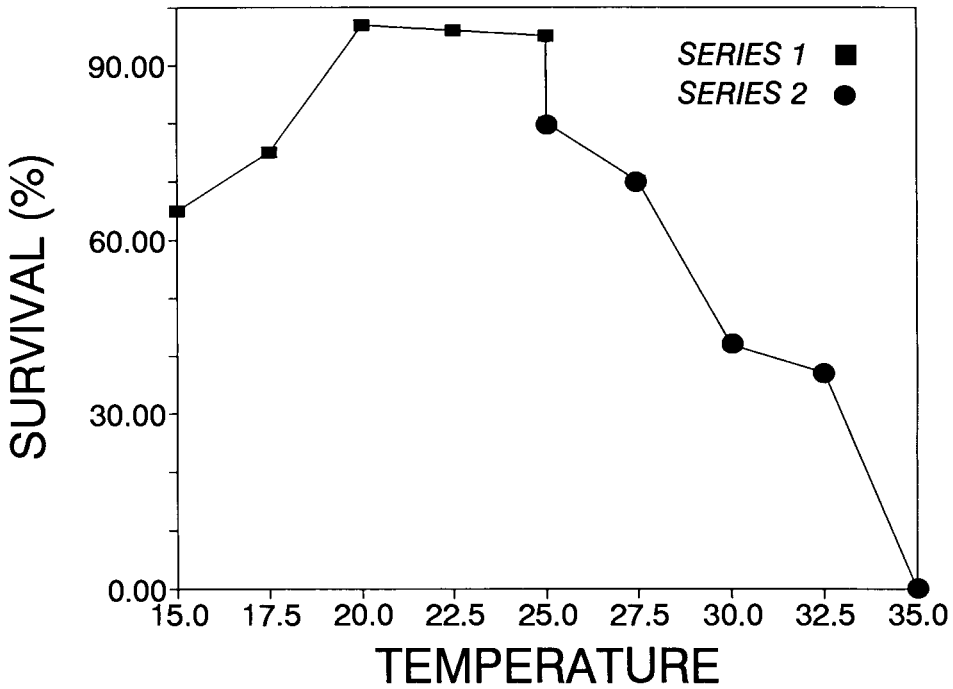


Figure 1. Survival of *Penaeus aztecus* PL reared at nine temperatures from 15 C to 35 C at 25 ppt. Series 1 was conducted for 31 days and series 2 for 29 days. (from Zein-Eldin and Griffith 1966).

conditions for *M. macleayi* appear to shift from 29 C toward 24 C at later stages. For *M. bennettiae* hatched at low temperatures, the maximum survival shifts from 24 C at the early stages to 29 C at later stages. Those *M. bennettiae* spawned at higher temperatures maintain 29 C as the best temperature for survival. Among the larvae of these species, the strongest effect of temperature was on *M. bennettiae* (Preston 1985).

24.2.1.2 Postlarval Survival

The short-term temperature tolerance of *P. aztecus* PL has a broad range (Zein-Eldin and Aldrich 1965). Survivals of 80 to 100% were observed at temperatures of 7 to 35 C. However, over a long-time period, survival rate was greatly reduced as the temperature approached 35 C when combined with salinities below 30 ppt.

In another study of *P. aztecus* PLs which were exposed to various temperatures for a month, the survival rate increased with temperature from 65% at 15 C to 98% at 20 C (Fig. 1; Zein-Eldin & Griffith 1966). Survival

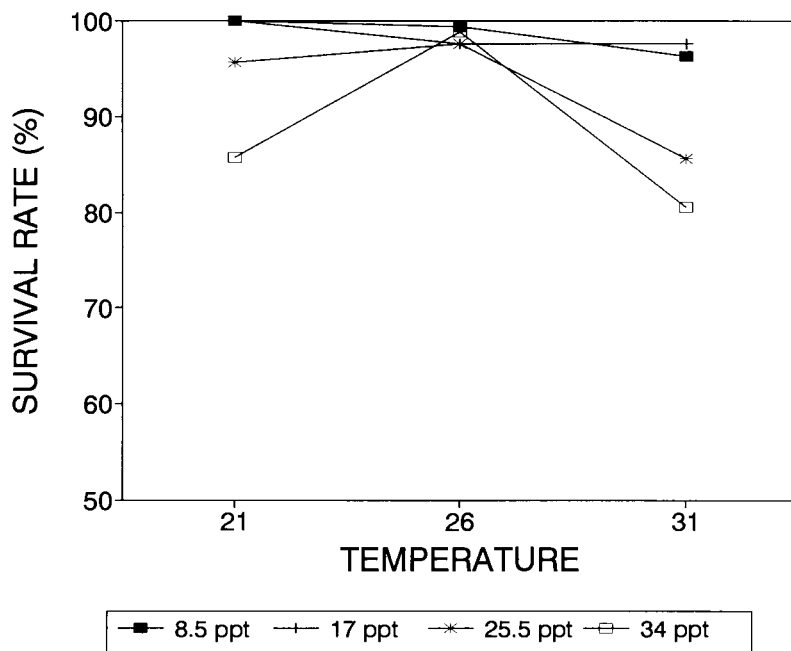


Figure 2. Survival rate of juvenile *P. aztecus* reared at three temperatures and four salinities for a period of six weeks. (from Venkataramiah et al. 1974).

rate was 97 % at 22.5 C, but dropped when temperatures went to 25 C and above. No survivors were observed at 35 C after the 15th day.

Thermal tolerance studies (both high and low temperatures) were conducted by Motoh (1981) on three age groups (postlarva, early juvenile, and juvenile) of *P. monodon*. All three age groups could tolerate a low temperature of 10 C for a short period of time. Survival rate was 98% at 39 C for all three stages studied. Beyond 39 C, there was heavy mortality. The thermal tolerance attributed by this author to *P. monodon* PL seems extreme.

24.2.1.3 Juvenile and Adult Survival

Venkataramiah et al. (1974) studied the survival rate of *P. aztecus* at three temperatures, 21, 26 and 31 C, and four salinities. These shrimp were collected from the wild had a size range of 16 to 39 mm. Survival rates were above 90% at 26 C at all test salinities. High and low temperatures in combination with high salinity produced a decrease in survival below 90% (Fig. 2).

Penaeus monodon juveniles are reported to survive temperatures as low as 11 C in ponds (G. Maguire, Tasmanian State Institute of Technology, pers. comm.). No experimental studies of mortality of *P. monodon* due to extreme

temperature were found. M. macleayi juveniles will tolerate 6 C in ponds (G. Maguire, pers. comm.), but experimental studies in tanks have not been reported.

Aziz and Greenwood (1981) in their studies of M. bennettiae reported the significant effect of thermal acclimation in altering the lower and upper tolerance levels of both temperature and salinity. For example, acclimation to a very low temperature lowers the lower lethal limit whereas acclimation to above normal temperatures raises the upper lethal limit.

In a detailed study of toxicity of brine effluent, Howe et al. (1982) reported that P. aztecus and P. setiferus differ in the interaction between temperature and salinity. As temperature rises from 20 C to 30 C, survival of P. aztecus declines linearly at brine doses of 350 to 750 osmolality; however, in the same conditions, P. setiferus shows a peak of survival at 25 C and reduced survival at both 20 and 30 C.

24.2.2 Growth

In aquaculture, growth rate is the principal indicator of the species' performance in a culture environment. To allow for comparison of growth rates obtained with different sized animals over different time periods, growth rates will be standardized using the equation:

$$\text{Growth rate} = \frac{\text{size}_t - \text{size}_0 \times 100}{\text{size}_0 \times t}$$

where: size_t = final size, size_0 = initial size and t = number of observation days. Length and weight data were normalized by log transformation.

24.2.2.1 Larval Growth

Preston (1985) reports the effect of temperature during the naupliar stages on size at Z1 in three species of penaeids. There is a significant decrease in size of P. plebejus protozoa at 19 and 34 C compared to 24 and 29 C. M. macleayi shows the largest larvae at 29 C. M. bennettiae for this experiment were obtained from spawns at different temperatures. Larvae from low temperature spawns attained the greatest size at 24 C and those that hatched at higher temperatures exhibited their largest size at 29 C (Preston 1985).

24.2.2.2 Postlarval Growth

Growth rate of P. aztecus PLs was monitored by Zein-Eldin and Aldrich (1965) for a 28-day period. Length and weight increased more rapidly at higher temperatures (32 and 25 C) than lower temperatures (18 and 11 C)

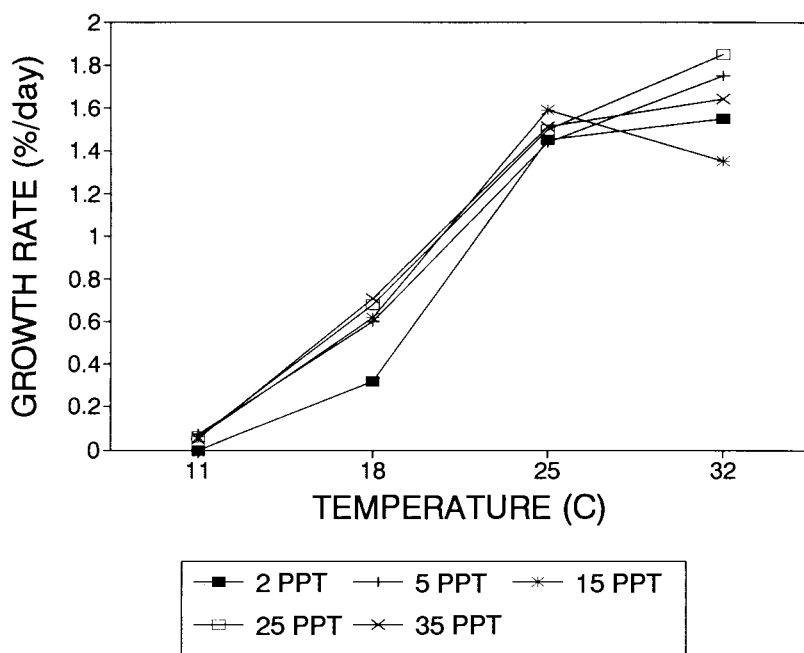


Figure 3. Growth in length of *P. aztecus* PL reared at four temperatures and five salinities for 28 days (Zein-Eldin and Aldrich 1965).

regardless of salinity conditions (Fig. 3). Average growth rate was higher at 32 C than at 25 C. Almost no growth was detected at 11 C. In this study, the effect of temperature on growth was much more pronounced than the effect of salinity, as one can see from the similarity of the line plots from different salinities.

In a related experiment (Zein-Eldin & Griffith 1966), growth of postlarval *P. aztecus* was followed for a month at 25 ppt in a temperature range of 15 to 35 C at 2.5 C intervals. In the first experiment on low temperatures, highest growth rate was observed at 25 C. In the second experiment with a temperature range of 25 to 35 C, a high growth rate of 1.98%/day was observed at 32.5 C. The results of these two experiments are combined in Figure 4. Increasing growth rates were observed over a temperature range of 25 to 32.5 C, but a precipitous drop occurred at 35 C. The PL survived for only 15 days at 35 C.

It is worthwhile to note that *P. aztecus* PL in the Zein-Eldin and Griffin (1966) experiment had good survival rates at 20 to 22.5 C (Fig. 1); whereas, survival declined from 25 C to 35 C. The higher temperature conditions promoted growth rates which increased from 25 C to 32.5 C (Zein-Eldin and

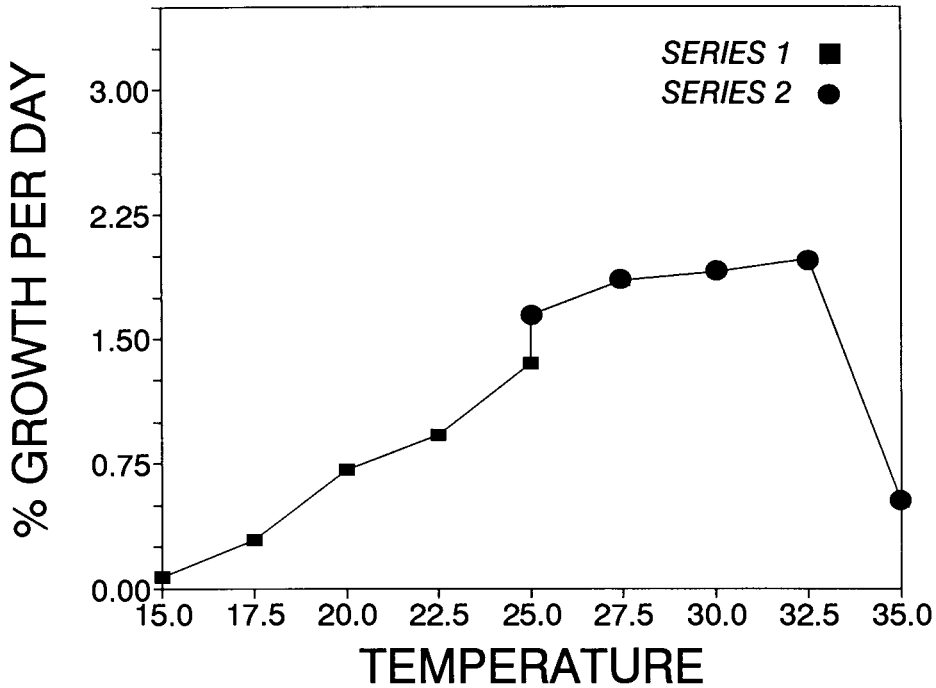


Figure 4. Growth in length of *P. aztecus* PL reared at 30 ppt and nine temperatures for 40 days (Zein-Eldin and Griffith 1966).

Aldrich 1965; Zein-Eldin and Griffith 1966), while having a negative effect on survival rate.

24.2.2.3 Juvenile and Adult Growth

Penaeus kerathurus from the Red Sea exhibited faster growth rates in salt ponds during summer months when average temperatures were above 20 C and salinity ranges from 36.4 to 45.2 ppt (Rodriguez 1981). There was low growth during winter months when average temperatures are below 17 C. High temperature seem to favor growth for this species.

Growth of *M. macleayi* juveniles (1 to 15 g) has been studied in aquaria over a range of 15 C to 30 C at 3 degree increments. Between 21 and 27 C growth rates were high and not significantly different. Higher and lower temperatures produced lower growth rates. FCR was not significantly different between 18 and 27 C, but was reduced at 15 and 30 C (Maguire and Allen, unpublished data).

Aquaria studies of 1 to 5 g *P. monodon* over 18 to 33 C showed the highest growth at 27 to 33 C. Pond growth rate increased with temperature in the range 21 to 27 C. FCR was not significantly different between 24 and

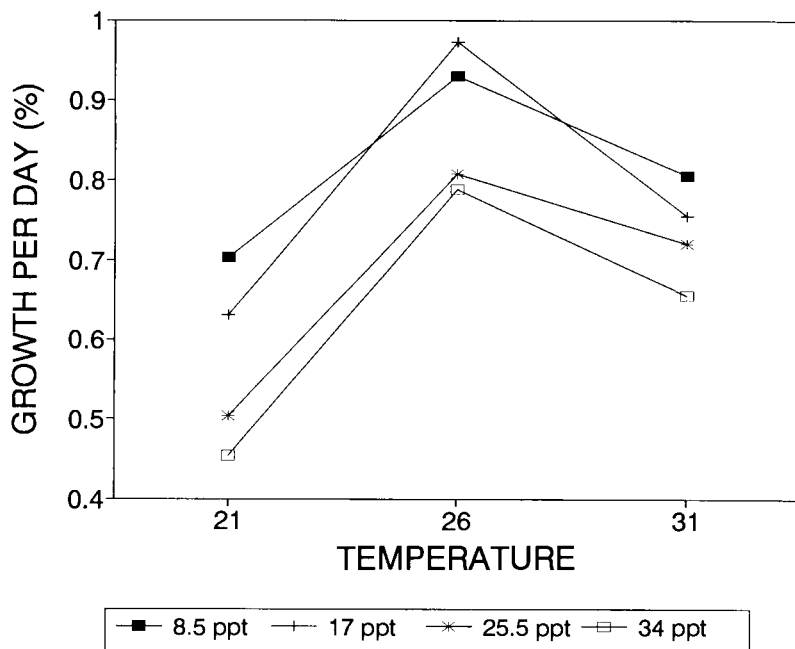


Figure 5. Growth in weight of juvenile *P. aztecus* reared at three temperatures and four salinities for 40 days (Venkataramiah et al. 1974).

33 C and dropped at 21 and 18 C (Maguire and Allen, unpublished data).

Chakraborti et al. (1985) reported on the relationship between environmental parameters monitored in shrimp ponds during 28 crops of *P. monodon*. Pond production of *P. monodon* and mean water temperature did not show a significant correlation. A regression of production on temperature, which ranged from 21 to 31 C during the study, gave a negative slope (Chakraborti et al. 1985) which is not consistent with laboratory studies of temperature effects on penaeid growth.

The *P. aztecus* studied by Venkataramiah et al. (1974) exhibited declines in growth rate at a lower temperature than the PL in the experiment described above (Zein-Eldin and Griffith 1966). When juvenile *P. aztecus* were compared at the same salinities, their weight increments at different temperatures had the following ranks: 26 > 31 > 21 C (Fig. 5; Venkataramiah et al. 1974). Several feeding rates were used in this study and the interaction with temperature is interesting. Growth at 31 C increases linearly with increased feeding, while the ad lib feeding rate caused growth to decline at 26 and 21 C. The accumulation of excess food apparently caused the growth rate at 26 C to decline to less than the rate at 31 C. The four feeding rates used at the outset of the experiment were 20%, 30%, 40% and

75 to 100% of initial weight. The percentages declined after that, but the relative differences remained. It is possible that the shrimp were food limited at 31 C even at the highest feeding rate. Food conversion ratios were lowest at 26 C, followed by 31 C, then 21 C (Venkataramiah 1974).

24.2.3 Molting

A strong negative correlation has been reported between temperature and intermolt period of euphausiids (Fowler et al. 1971). Similar observation was made in the author's experiments using *P. vannamei* PL raised under high (29 to 31 C) and low (24 to 26 C) temperatures (Pante 1990).

In a study of the relationship between molting and growth of *Penaeus japonicus*, Choe (1971) found it necessary to calculate separate regressions for weight increase on intermolt period at 20 to 24.9 C and 25 to 28 C. In the former case,

$$\log MC = 0.2808 \log W + 0.8276$$

where, MC = the length of the molting cycle in days, and

W = the weight of the shrimp in grams.

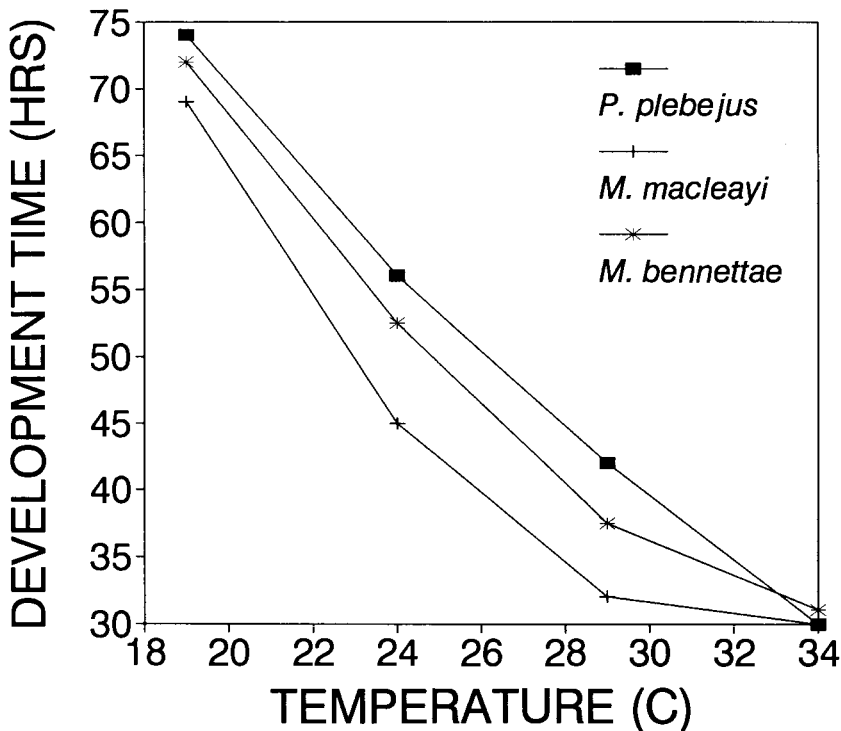


Figure 6. Decrease in time of development of three penaeid species from the first naupliar stage to first protozoa over a temperature range of 18 C to 34 C (Preston 1985).

At 25 to 28 C, the regression equation was

$$\log MC = 0.2114 \log W + 0.8405.$$

In the higher temperature range, a shrimp of a given weight molted more quickly.

The study by Preston (1985) of survival and growth of larvae from three penaeid species documented a very strong effect of temperature on intermolt period of larvae. The time from N1 to Z1 of the three species, at 30 ppt, is shown in Figure 6. The same pattern of decreasing time per stage as temperature increases is seen in the later stages. As the temperature rises from 19 to 34 C, the time from Z1 to M1 decreases by 30 to 40%. The time required to change from an M1 to a PL1 decreases by 40 to 50% as the temperature rises from 19 to 34 C (Preston 1985).

24.3 SALINITY EFFECTS

Salinity seems to have a lesser effect than temperature on survival of shrimp. Some species may only have an upper lethal limit for salinity, but no lower one, despite the designation of penaeids as marine shrimp.

The effect of salinity on growth is unclear. The experiments described below seem to reach conclusions that conflict with the opinions of pond culturists about the significance of salinity for growth. Certainly osmoregulation and ion transport require energy expenditure which could have supported growth; but shrimp are estuarine for an important part of their life cycle and may be euryhaline through the low cost adaptation of osmoconformity. The period of estuarine habitation occurs during that portion of the life cycle which is the most important period for pond culture. Therefore it is important to understand the impact of salinity on growth and survival, independent of its impact on the osmolarity of the shrimp's body fluids.

There are few studies on the effect of salinity alone. Most combine the effects of salinity and temperature. Also, more studies have been conducted on larval and postlarval stages than on adult stages. Reasons for this may be the ease of maintaining smaller animals and the lesser space requirement in the laboratory.

24.3.1 Survival

High and low salinities are most deleterious to the life cycle stages that are adapted to oceanic conditions, the larval and adult stages.

24.3.1.1 Egg and Larval Survival

Salinity has a dramatic effect on the percentage of eggs that hatch after spawning and the survival of the resulting larvae. This was carefully

documented in a study of Metapenaeus ensis. In experiments conducted at 29 C, there was no hatching at 10 and 15 ppt. Hatching was observed at 20 ppt, reached approximately 35% at 25 ppt, peaked at around 70% at 30 ppt and declined to approximately 50% at 35 ppt (Chu and So 1987).

Groups of larvae at each stage were exposed to the test salinities for 24 hours. Number of surviving larvae and the proportion of those that had metamorphosed to the next stage were recorded. Only the protozoa 2 (Z2) and M2 substages had any survival at 10 ppt. At 15 ppt, survival was zero for nauplii, less than 10% for Z1, more than 60% for Z2 and protozoa 3 (Z3), and more than 80% for all mysis substages. The nauplii and protozoae exhibited the same pattern of survival at salinities of 20 to 35 ppt; survival increases from 20 to 25 to 30 ppt and declines slightly at 35 ppt. For the mysis stage, survival was consistently high at salinities from 20 to 35 ppt. Acclimation to 20 ppt significantly increased survival at 10 ppt of all substages except nauplii for which the condition remained lethal (Chu and So 1987).

In the study by Preston (1985), the effect of salinity on hatching success of eggs of P. plebejus, M. macleayi and M. bennettiae is described. Salinities tested range from 20 to 40 ppt and both low and high salinities have a negative impact on hatching. The maximum hatching rates are observed at 30 ppt with the exception of eggs spawned by M. bennettiae at 22 ppt which show higher hatch rates at 25 ppt than at 30 ppt. The survival rates of the larvae of these species are also studied. Salinity tolerances become broader as larval development proceeds. Penaeus plebejus and M. macleayi, exhibit peak larval survival at around 35 ppt in the naupliar stages which shifts to 30 ppt or less for the mysid stages.

Metapenaeus bennettiae shows a similar, but smaller, shift in peak survival if the larvae were spawned at high salinity, but the larvae derived from a low salinity spawn show peak survival at 25 ppt for nauplii shifting to 30 ppt for mysis (Preston 1985).

24.3.1.2 Postlarval Survival

The salinity tolerance of P. aztecus PL has been reported in two studies (Zein-Eldin and Aldrich 1965; Venkataramiah et al. 1974). They survived at salinities as low as 1.7 ppt and as high as 59.5 ppt in 96 hour tolerance tests (Venkataramiah et al. 1974). At intermediate salinities, survival rates rise from 1.7 to 15 to 17 ppt, then are high until more than 50 ppt (Zein-Eldin and Aldrich 1965; Venkataramiah et al. 1974). Mortality rates are dependent on the temperature and salinity of acclimation and on exposure time.

Laboratory experiments on P. monodon PL (Motoh 1981) showed tolerance to very low salinity. Survival rate was 64% at 0 ppt. Survival remained high at salinities > 0 ppt until 38 ppt, at which mortality began to increase. In a 20-day culture period under controlled conditions, P.

monodon PL (16.1 mm) demonstrated a higher survival rate at 15 ppt (82%) than at 20 ppt (74%) and 0 ppt (68%) (Rajyalakshmi and Chandra 1987). Survival rate decreased when the rearing time was extended. These studies indicate that P. monodon could survive very low salinities, even freshwater, but only for a short period.

In experiments by the authors (Pante 1990), P. vannamei PLs were gradually acclimated to various test salinities (40 ppt to 68 ppt at 4 ppt intervals). For a short period, they were able to tolerate a salinity range of 40 to 52 ppt. In another experiment, PLs were grown at 25 ppt and 50 ppt. Survival rate for a 10-day period at an average temperature of 29 C was 90% and 91%, respectively.

24.3.1.3 Juvenile and Adult Survival

Survival of juvenile P. aztecus exceeded 75% over a salinity range from 8.5 to 47.6 ppt under all test conditions of Venkataramiah et al. (1974). One hundred percent mortality was observed at salinities of 59.5, 1.7 and 0.34 ppt when the shrimp had been acclimated to 25.5 or 34.0 ppt. Acclimation at lower salinities was used to increase survival at 1.7 ppt. Shrimp tested at low salinities were more tolerant of low and high temperatures and of the accumulation of excess food and metabolic wastes (Venkataramiah et al. 1974).

Aziz & Greenwood (1981) report that juvenile M. bennettiae tolerated a salinity range of 1.0 to 62 ppt regardless of temperature and salinity acclimation levels.

P. monodon juveniles exhibited the greatest tolerance to lower salinity yet reported, with a survival rate of 100% at 0 ppt (Motoh 1981). At 52 ppt, there was mortality. LT₅₀ value (24 hours) was found to be 75 ppt. These observations suggest that older stages show greater tolerance to high salinity (Motoh 1981).

In a study by Deshimaru et al. (1985) it was reported that survival and growth were lower when P. monodon juveniles (0.65 g) were reared at higher salinities (34 to 35 ppt) than at lower salinities (19 to 21 ppt).

24.3.2 Growth

24.3.2.1 Larval Growth

Preston (1985) reports that Z1 of P. plebejus differed in size among the test salinities in the following order: 35 ppt > 40 ppt = 30 ppt > 25 ppt > 20 ppt.

24.3.2.2 Postlarval Growth

High salinity (>40 ppt) appears to retard the growth of PL whereas normal growth was exhibited at low salinities of 2, 5, and 10 ppt (Zein-Eldin

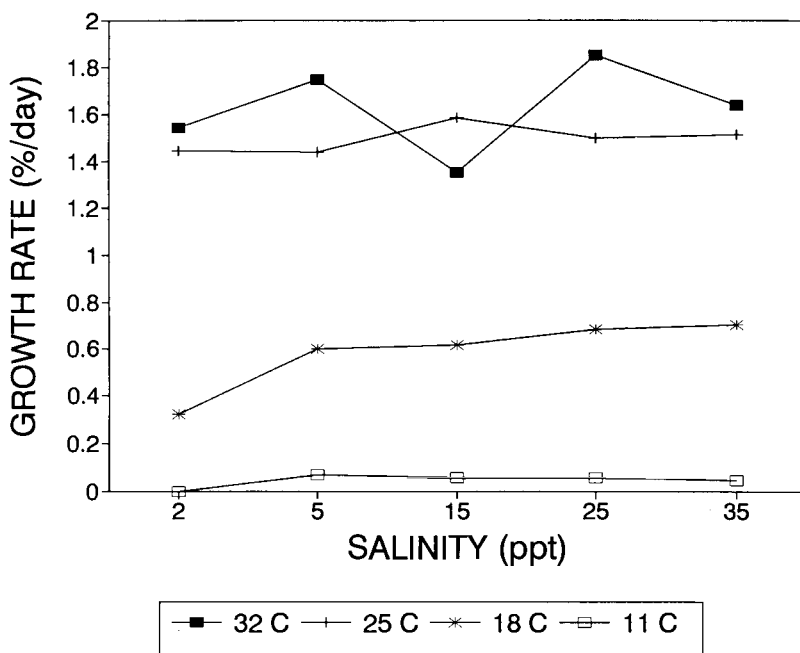


Figure 7. Growth rate (percent per day increase in length) of *P. aztecus* PL grown at five salinities and four temperatures for 28 days (Zein-Eldin and Aldrich 1965).

1963). In another study, PL growth rate of *P. aztecus* was above 1.2% per day at salinity levels of 2, 5, 15, 25 and 35 ppt when temperatures were 25 and 32 C (Fig. 7, Zein-Eldin and Aldrich 1965). Low salinity (2 ppt) appears to depress growth at all but optimal temperatures. There may be an effect of salinity on growth at high temperature (32 C) also.

In a 20-day laboratory growth experiment at different salinities, the percent growth rate of *P. monodon* is ranked as follows: 15 ppt > 20 ppt > 0 ppt (Rajyalakshmi and Chandra 1987). The average temperature condition was 28 to 30 C.

24.3.2.3 Juvenile and Adult Growth

A correlation between salinity and pond production of *P. monodon* was reported by Chakraborti et al. (1985). During the study period, 28 crops were produced and salinities in the ponds ranged from 2 ppt to 22 ppt. The correlation between kilos produced and salinity is 0.56 ($p < 0.05$).

Low salinity was associated with faster growth in the study of *P. aztecus* by Venkataramiah et al. (1974) shown in Figure 8. Over all test temperatures, weight increments at the test salinities had the following

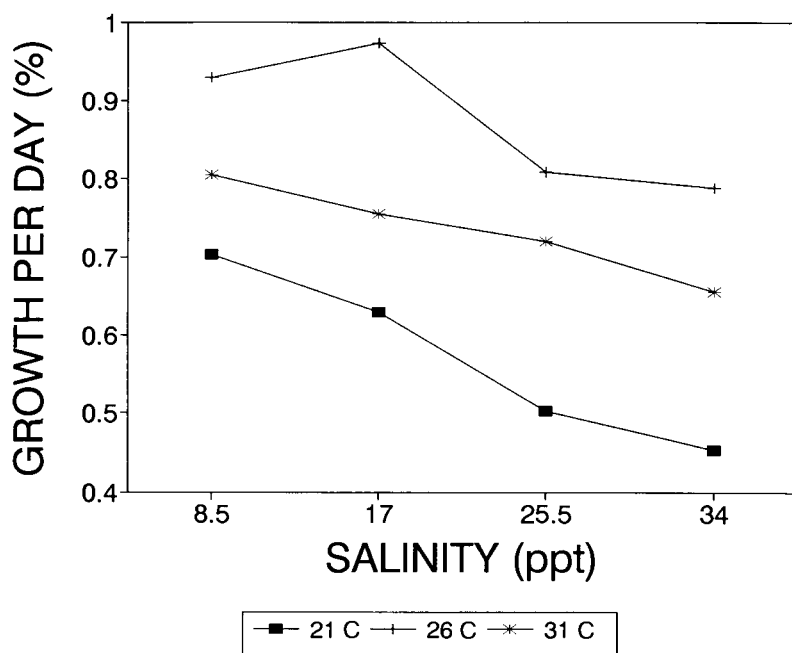


Figure 8. Growth in weight of juvenile *P. aztecus* reared at four salinities and three temperatures for 40 days (Venkataramiah et al. 1974).

ranking: 8.5 ppt > 17 ppt > 25.5 ppt > 34 ppt when feeding rate was high. Low salinity appears to favor growth, especially at high temperatures and high feeding rates. High salinity appears to retard growth in this species.

The above result in *P. aztecus* is similar to the lower survival and slower growth rate observed in *P. monodon* when grown in a brackishwater pond having a salinity range of 32 to 40 ppt and temperature range of 25.5 to 32.2 C (Manik et al. 1979).

Comparisons of growth of 1 to 5 g juvenile *P. monodon* in aquaria at 15 ppt versus 30 ppt showed no significant differences. Similar studies on *M. macleayi* over 10 to 30 ppt at 5 ppt intervals showed growth rate increased with increasing salinity, but the difference between growth at 25 and growth at 30 ppt was not significant. In experimental pond studies, a comparison of growth at 30 to 33 ppt versus 15 to 18 ppt resulted in better growth at the high salinity (Maguire and Allen unpublished data).

24.3.3 Molting

In the study of *M. ensis* by Chu and So (1987), the effect of salinity on ability to metamorphose to the next larval stage was examined. The results

indicate that ability to molt improves with increasing salinity up to 30 ppt. Nauplii showed an inability to metamorphose in 24 hours at 15 ppt, but exhibited a 100% rate of metamorphosis at 20 to 35 ppt. All other larval stages showed the same pattern in this study. The proportion of larvae undergoing ecdysis declines from 30 to 15 ppt and was always 0 at 10 ppt. In all cases except Z3, the percent ecdysis at 35 ppt is slightly, but significantly, less than at 30 ppt. Acclimation to 20 ppt increased percent ecdysis at 10 ppt in Z1, Z2 and all mysis substages.

Salinity has a much smaller effect than temperature on the time of intermolt in most peneaid species (Preston 1985). In general, salinities below 30 ppt and above 35 ppt have a delaying effect on the molting cycle of the larvae of P. plebejus, M. macleayi and M. bennettiae.

Manik et al. (1979), in their growth studies of P. monodon in brackishwater ponds, observed a decreased molting frequency in ponds having a salinity range of 32 to 40 ppt versus ponds with a salinity range of 15 to 20 ppt.

Two series of studies were done by the authors to determine the effect of high and low salinity on molting frequency of P. vannamei (PL 5). The first experiment used 40 and 20 ppt, the second used 50 and 25 ppt. In both experiments, salinity did not have a significant effect on molting frequency (Pante 1990).

24.4 TEMPERATURE-SALINITY INTERACTION

24.4.1 Survival

The response surfaces presented by Preston (1985) of the effect of temperature and salinity on the survival of naupliar, protozoal and mysid stages of P. plebejus, M. macleayi and M. bennettiae provide clear evidence of the interaction of these two environmental factors. Survival of P. plebejus larvae is best at temperatures of 19 to 29 C and salinities of 30 to 35 ppt. The effect of salinity on mortality is stronger than the temperature effect for this species. M. macleayi exhibits mortality resulting more from a balanced effect of both temperature and salinity. It appears that this species prefers temperatures around 29 C and salinities of 30 to 35 ppt for larval development. The other species studied, M. bennettiae, is strongly affected by the conditions at spawning during the early larval development. As development proceeds the impact of salinity decreases and the effect of temperature increases. During mysis stages, the best conditions for survival center around 30 ppt and 29 C (Preston 1985).

Juvenile Metapenaeus bennettiae were subjected to high and low levels of temperature and salinity after acclimation to 12 combinations of salinity (5, 20, 35 ppt) and temperature (17, 22, 27, 32 C) (Aziz and Greenwood 1981).

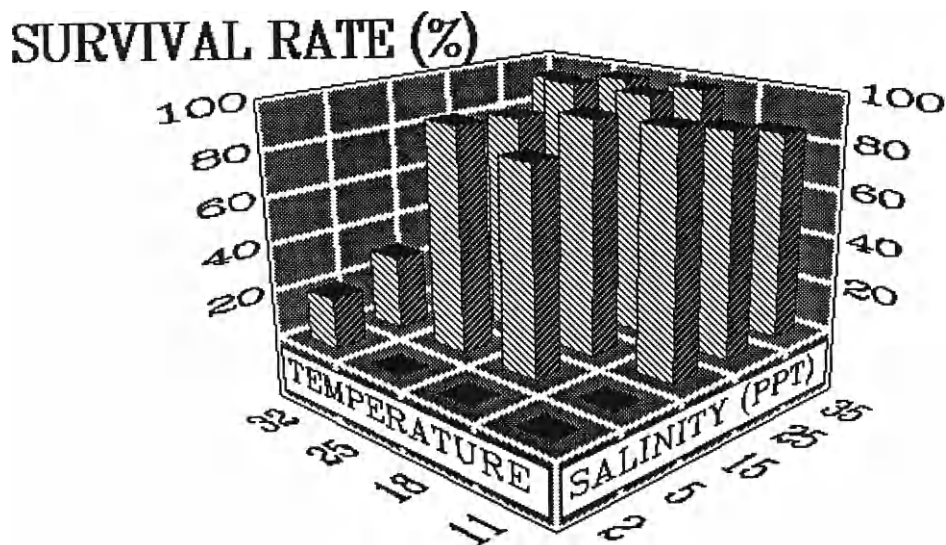


Figure 9. Three dimensional plot of survival of *P. aztecus* PL reared for 28 days at four temperatures and five salinities (Zein-Eldin and Aldrich 1965).

Results showed that acclimation temperature had a great influence on the lethal levels of both temperature and salinity; whereas, salinity acclimation only had a significant effect on the lethal salinity levels. Lethal temperature could be raised by raising the temperature of acclimation. Lethal salinity could be raised by raising acclimation salinity and lowering acclimation temperature.

While acclimation at salinities and temperatures nearer the test conditions improved survival, it was not sufficient to significantly alter the lethal limits of *P. aztecus* (Venkataramiah 1974). Acclimation was shown to improve survival rates at salinities near the lethal limits. High test temperatures narrow the range of salinities which are tolerated. Combining changes of temperature and salinity between acclimation conditions and test conditions increased mortality. This means that a change from high to low salinity will cause more mortality when it is combined with a change in temperature than when the water temperatures are the same.

The study by Zein-Eldin and Aldrich (1965) to determine growth and survival rates of *P. aztecus* was conducted using four temperatures (11, 18, 25, 32 °C) and five salinities (2, 5, 15, 25, 35 ppt). Good survival rates (80 to 100%) were observed at 18 to 25 °C over a salinity range of 5 to 35 ppt .

Extremely low salinity, in combination with low temperatures proved lethal to the PL. A dramatic effect of salinity on survival rate was observed also at high temperature. At 32 C, survival rate increased from 20% at 2 ppt to more than 90% at 35 ppt. Thus there is an interaction between the effects of temperature and salinity on survival (Fig. 9).

24.4.2 Growth

Temperature and salinity may interact to retard growth. The effects of temperature and salinity on growth during naupliar stages is reported by Preston (1985). Depending upon the species, maximum size at Z1 is obtained at high salinity/medium temperatures (P. plebejus), moderate salinity/high temperature (M. macleayi) or low salinity/moderate temperature (M. bennettiae spawned at low temperature, low salinity) (Preston 1985). Both salinity and temperature are shown to have significant effects on larval size in this study.

There is a slight salinity-temperature interaction effect on growth seen in P. aztecus PL (Zein-Eldin and Aldrich 1965). Highest growth rate was observed at 25 ppt at 32 C from among the various temperature and salinity combinations. Low temperatures at all salinities inhibit growth. Low salinities appear to have a slight depressing effect at low and high temperatures, and high temperature-high salinity seem to depress growth (Fig.8).

Venkataramiah et al. (1974) reported favorable growth rate for P. aztecus PL at mild temperature and low salinities. High salinity in combination with low or high temperatures retard growth whereas normal growth was observed at low salinity.

24.4.3 Molting

Very little interaction between salinity and temperature on the length of the molt cycle was seen in the study by Preston (1985). The contours of the response surfaces indicate that temperature has the dominant effect and low and high salinities only slightly retard the molting cycle.

24.5 CONCLUSIONS

Of the two environmental parameters considered in this chapter, temperature has the greater effect on survival and growth. Survival studies give bell-shaped curves with maxima in the 25 to 30 C range for tropical species. Growth rates continue to rise at temperatures which are associated with increasing mortality. Growth rates usually decline linearly with temperatures below the optima. Survivals may remain high at temperatures which permit very little growth.

Extreme salinities can increase mortality, particularly if they are experienced without acclimation. Salinities below 5 ppt are stressful for most stages of most species, although P. monodon appears to be an exception. Larval stages are the most intolerant of salinity stress. As penaeids mature, they gain a greater tolerance of high salinity, but salinities over 35 ppt usually have a negative effect on growth. The effect of salinity on growth is slight over the normal range of estuarine salinities. However, there is an interaction between temperature and salinity, such that combinations of high temperature and high salinity are more lethal than the separate conditions.

Temperature and salinity affect the molting frequency of shrimp, as well as survival and growth. The intermolt interval of all stages increases with decreasing temperature from 30 C. Temperature has a much stronger effect on molting frequency than salinity. Extreme salinities have an inhibiting effect on molting, but the effect may be due to the same processes that increase mortality.

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CHAPTER 25

PENAEID SHRIMP NUTRITION

25.1 INTRODUCTION

Nutrition encompasses the chemical and physiological processes which provide nutrients to an animal for normal function, maintenance and growth. It involves ingestion, digestion, absorption and transport of nutrients, and waste removal. Limitations to our knowledge of nutrition, particularly that of marine shrimp, underscore the need to continually develop, test and apply new nutrition concepts. This is particularly true for the rapidly expanding shrimp feed industry where feed formulations are presently based largely on intuition and "unknown growth factors", rather than nutritional science.

Nutritional studies of shrimp were initiated in the early 1970's. Comparisons of these with current studies are difficult due to differences in research methodologies and the absence of a standard research diet. Variables such as species, size, source and physiological state of the shrimp, environmental conditions, experimental design, experimental facilities, and diet form, composition and processing often make comparisons invalid. However, these studies have been used to form the principal assumptions used in commercial feed formulations.

This chapter provides basic information on marine shrimp nutrition to supplement the existing and rather limited published information. The information is based not only on the authors' research and practical experience, but on analyses of commercial feeds and extensive discussions with other shrimp nutritionists. It therefore will be of special relevance to the commercial feed industry. Its main limitation is the assumption that there are not major nutritional differences between individual species of shrimp.

Though nutritional principals are similar for all animals, the quantity of required nutrients vary with species. There are approximately 40 essential dietary nutrients required by fish and terrestrial animals. These essential nutrients are suspected to be similar for shrimp and would include amino acids, fatty acids, energy, vitamins and minerals. These nutrients are provided in various degrees by processed feeds and the natural culture environment. The nutritional requirements discussed are, in general, minimum requirements. They do not take into account nutrient availability from the

culture environment, culture method and conditions, processing losses and storage losses.

Nutrient levels greater than those discussed herein may be necessary under less than optimum culture conditions. Considering the availability of natural food to cultured shrimp, the nutrient requirements in ponds may be less than those discussed.

Use of feeds in aquaculture can increase both production and profits considerably. To achieve these objectives, feed must be nutritionally adequate and economical for the system of culture. The purpose of this manuscript is to provide shrimp growers and feed processors with a practical understanding of shrimp nutrition and nutritional principles in the hope that this information will lead to improvements in the nutritional quality and cost of shrimp feeds.

25.2 DIGESTIBILITY

Digestion involves mechanical breakdown, solubilization and absorption of nutrients. The nutrient profile of an ingredient may appear good, but, if these nutrients are not digested, absorbed, or utilized, they are of little value to the animal. Digestibility information is essential in evaluating the quality of an ingredient.

Akiyama et al. (1988), determined the apparent dry matter digestibility (ADMD), apparent protein digestibility (APD), and apparent amino acid digestibility (AAAD) of various ingredients for shrimp. The ingredients

Table 1. Apparent dry matter digestibility and apparent protein digestibility for *Penaeus vannamei*^a.

Major feedstuff in diet	Apparent dry matter digestibility	Apparent protein digestibility
Purified Feedstuffs		
Casein	91.4	99.1
Wheat gluten	85.4	98.0
Soy protein	84.1	96.4
Gelatin	85.2	97.3
Corn starch	68.3	81.1
Practical Feedstuffs		
Squid meal	68.9	79.7
Fish meal	64.3	80.7
Shrimp meal	56.8	74.6
Soybean meal	55.9	89.9
Rice bran	40.0	76.4

^aAkiyama et al., 1988.

evaluated were casein, corn starch, gelatin, soy protein, wheat gluten, fish meal, rice bran, shrimp meal, soybean meal and squid meal.

In terms of dry matter, diets containing purified ingredients high in protein: casein, gelatin, soy protein and wheat gluten, were more digestible than the high carbohydrate diet containing corn starch (Table 1). This suggests that proteins are more efficiently digested by shrimp than carbohydrates. The lower ADMD of soybean meal as compared to squid meal and fish meal is probably due to its lower protein content and higher carbohydrate content.

Table 2a. Apparent essential amino acid digestibility for *Penaeus vannamei*^a.

Major Feedstuff	Essential Amino Acids							
	ARG	LYS	LEU	ILE	THR	VAL	HIS	PHE
Casein	99.2	99.5	99.5	99.4	99.1	99.4	99.3	99.4
Wheat gluten	98.1	96.7	98.5	98.3	97.2	98.1	98.1	98.7
Soy Protein	97.5	97.5	96.7	96.8	95.3	96.4	96.7	96.6
Gelatin	98.4	96.9	96.2	95.8	94.5	96.1	93.6	96.3
Soybean meal	91.4	91.5	88.4	90.2	89.3	87.9	86.3	89.6
Fish meal	81.0	83.1	80.7	80.4	80.6	79.4	79.0	79.1
Shrimp meal	81.8	85.7	82.1	81.6	83.7	79.0	75.4	75.6
Squid meal	79.4	78.6	79.4	77.2	79.7	79.3	73.6	74.1
Rice bran	85.1	81.0	74.9	73.4	73.2	75.9	82.6	74.9

^aAkiyama et al., 1988

Table 2b. Apparent non-essential amino acid digestibility for *Penaeus vannamei*^a.

Major Feedstuff	Non-Essential Amino Acids						
	GLU	ASP	GLY	PRO	SER	TYR	ALA
Casein	99.5	98.9	98.4	99.3	99.2	99.5	97.9
Wheat gluten	99.2	96.0	97.3	99.1	98.0	98.3	94.1
Soy Protein	97.7	97.2	95.8	97.2	96.4	97.1	94.1
Gelatin	97.0	95.9	98.1	98.4	96.2	92.2	97.0
Soybean meal	91.9	92.2	87.0	89.1	88.5	91.1	85.9
Fish meal	82.4	80.6	82.2	84.1	81.6	78.4	81.4
Shrimp meal	82.0	78.6	80.3	78.8	78.0	76.7	55.4
Squid meal	82.2	83.2	80.4	78.5	77.2	73.5	77.0
Rice bran	79.5	75.5	75.9	68.7	72.7	75.8	71.0

^aAkiyama et. al., 1988

The APD and AAAD are presented in Tables 1 and 2. Results of this study indicate that APD was not influenced by animal or plant ingredient origin. For the diets containing practical ingredients, soybean meal had a higher APD than fish meal, squid meal, rice bran and shrimp meal. There were no differences between squid meal and rice bran or between rice bran and shrimp meal. For the diets containing purified ingredients, there were no differences between casein, wheat gluten, gelatin and soy protein. This digestibility similarity has been reported previously (Lee 1970; Condry et al. 1972). AAAD values further support the contention that ingredient origin has no effect on protein digestibility since similar trends, as discussed with APD, were observed in the AAAD (Table 2).

Based on ADMD, purified feedstuffs were more efficiently digested than the practical feedstuffs. This difference was also observed in the APD and AAAD. This indicates that proteins are more readily digested in the purified form. This is further demonstrated by the comparison of the purified and practical forms of soybean protein. Soy protein had a higher APD than soybean meal. This higher digestibility was also observed for all amino acids measured. This suggests that protein quality of the ingredient is important for the digestibility of these nutrients by shrimp. In general, the marine animal protein ingredients are usually of better quality than the plant protein ingredients.

Apparent mineral digestibilities (AMD) were also determined for shrimp meal, fish meal, squid meal, soybean meal and rice bran (Akiyama unpublished data). In general, shrimp meal appears to be the best source for minerals (Table 3). Squid meal had the highest AMD value of 76.8% for phosphorous. Mineral availability values for other ingredients or sources have not been determined.

Table 3. Apparent mineral digestibility for *Penaeus vannamei*^a.

Mineral	Shrimp meal	Fish meal	Squid meal	Soybean meal	Rice bran
Calcium	33.7	24.4	-253.8	-84.1	-38.1
Phosphorous	29.8	46.5	76.8	39.9	26.1
Magnesium	-26.9	-35.4	-121.9	-88.7	-12.6
Potassium	85.9	90.7	85.4	92.0	73.3
Sodium	74.0	36.8	20.6	-88.7	-90.3
Iron	31.0	-7.3	16.6	18.2	-29.5
Zinc	34.6	37.0	27.8	15.0	-19.6
Copper	67.6	-5.2	67.0	60.1	56.2
Manganese	26.8	38.5	32.0	33.0	34.2

^aAkiyama (unpublished data).

Table 4. Estimated phosphorous availability values for various ingredients.

Ingredients	Percent Availability
Plant products	30
Animal products	30
Microbial products	90
Inorganic sources:	
-monosodium phosphate ($\text{NaH}_2\text{PO}_4\text{H}_2\text{O}$)	5
-monocalcium phosphate ($\text{CaH}_4\text{O}_8\text{P}_2$)	94
-dicalcium phosphate (CaHO_4P)	45
-tricalcium phosphate ($\text{Ca}_3\text{O}_8\text{P}_2$)	15

The availability values of phosphorous supplements have not been determined for shrimp. However, phosphorous availability values should be more similar to those of the common carp than of other fish. Common carp do not have true stomachs which secrete acids. The digestive system of crustaceans, where the pH is approximately 5-7 is not very acidic (van Weel 1970; DeGuisti et al., 1962). Estimated available phosphorous values are listed in Table 4.

25.3 PROTEIN

Proteins, are large, complex molecules made up of amino acids. Twenty major amino acids make up most proteins. Proteins differ in size and function and in the relative proportions of the amino acids they contain. Some proteins lack certain amino acids while others contain all 20. Proteins are the major organic materials in some animal tissues, constituting about 65 to 75 percent of the total on a dry-weight basis. Animals must consume dietary protein to obtain a continual supply of amino acids. After ingestion, it is digested or hydrolyzed to release free amino acids that are absorbed from the intestinal tract of the animal. These are then distributed to the various organs and tissues. Amino acids are used by the tissues to synthesize new protein. Thus, animals do not necessarily require protein, but do require the amino acids which comprise proteins.

Since proteins are continually being used by the animal for growth and repair of tissues, a continuous supply of proteins or amino acids is needed in the diet. Inadequate protein in the diet results in a reduction or cessation of growth, followed by weight loss due to withdrawal of protein from tissues to maintain the vital functions. On the other hand, if too much protein is

Table 5. Summary of protein requirements for various species of penaeid shrimp.

<u>Penaeus</u> spp.	Size tested (g)	% protein investigated	Recommended % protein	References
<u>P. aztecus</u>	0.02, 0.14 0.6 4.0, 10.0, 15.0	40-48 24-63 22-36	40 51 30-36	Venkataramiah et al. 1975 Zein-Eldin and Corliss 1976 Smith et al. 1985
<u>P. californiensis</u>	10.0	25-40	35	Colvin and Brand 1977
<u>P. indicus</u>	1.0	21-53	43	Colvin 1976
<u>P. japonicus</u>	5.3 4.2	63-76 2-66	>60 52-57	Deshimaru and Shigeno 1972 Deshimaru and Yone 1978
<u>P. merguensis</u>	0.01	17-51	34-42	Sedgwick 1979
<u>P. monodon</u>	0.5, 1.8 1.3	2-62 25-60	45-50 40	Lee 1971 Alava and Lim 1983
<u>P. setiferus</u>	4.0 3.7, 9.8, 14.7	14-52 22-36	28-32 30	Andrews et al. 1972 Lee and Lawrence 1985
<u>P. stylirostris</u>	0.05	25-40	35	Colvin and Brand 1977
<u>P. vannamei</u>	0.03 4.0, 9.8, 20.8	25-40 22-36	30 30	Colvin and Brand 1977 Smith et al. 1985

supplied in the diet, only part of it will be used to make new protein and the remainder will be converted to energy or excreted.

25.3.1 Protein Level

Shrimp feeds are presently formulated to contain a high protein level. Protein is one of the major and most expensive components of feeds. A reduction in protein content of feeds or the use of less expensive protein supplements could considerably reduce feed costs. The most researched area in shrimp nutrition has been proteins. It is generally believed that postlarval shrimp require a higher protein level than larger shrimp. Recommended protein levels vary from 30% to 57% in various species and sizes of marine shrimp (Table 5). Regardless of differences in protein requirement, it is believed that sub-optimal growth occurs due to imbalance in, rather than deficiencies of, the essential amino acids.

Table 6. Recommended protein levels in commercial shrimp feeds.^a

Size of Shrimp (g)	Protein level (percent)
0 - 0.5	45
0.5 - 3.0	40
3.0 - 15.0	38
15.0 - 40.0	36

^a As fed basis.

Protein levels recommended for commercial feeds are listed in Table 6. If the culture system is not totally dependent on commercial feeds, i.e. if natural foods are available, these protein levels may be reduced.

25.3.2 Amino Acids

There are essential and non-essential amino acids. The essential amino acids either cannot be synthesized by the shrimp or are synthesized at a rate which results in less than optimal growth. Thus, essential amino acids must be provided in the diet. On the other hand, non-essential amino acids are readily synthesized by the animal for optimum growth.

Essential amino acids have been determined by radioactive assays, a technique which involves the administration of a labeled precursor, such as ¹⁴C acetate or glucose. Subsequent incorporation of radioactivity into an amino acid indicates synthesis by the shrimp from the precursor. Unlabeled amino acids which are not synthesized by the shrimp would be considered essential in the diet.

Amino acids considered dietary essentials for shrimp are methionine, arginine, threonine, tryptophan, histidine, isoleucine, leucine, lysine, valine and phenylalanine (Cowey and Forster 1971; Shewbart et al. 1972; Kanazawa and Teshima, 1981). In these studies, tyrosine did not incorporate ¹⁴C but was not considered to be essential. Tyrosine is believed to be synthesized from phenylalanine. These ten essential amino acids are similar to those reported for other aquatic animals (National Research Council 1983). Recommended essential amino acid requirements for commercial feeds are listed in Table 7.

Previously, the quantity of essential amino acids in feeds mimicked the essential amino acid profile of shrimp muscle. Shrimp feeds formulated with these profiles have produced good shrimp growth and survival rates. However, this is not the most efficient means of quantifying essential amino acids requirements. Studies with higher animals with better defined amino

Table 7. Recommended amino acid levels in commercial shrimp feeds.^a

Amino acid	Percent in protein	Percent in feed			
		36% ^b	38%	40%	45%
Arginine	5.8	2.09	2.20	2.32	2.61
Histidine	2.1	0.76	0.80	0.84	0.95
Isoleucine	3.5	1.26	1.33	1.40	1.58
Leucine	5.4	1.94	2.05	2.16	2.43
Lysine	5.3	1.91	2.01	2.12	2.39
Methionine	2.4	0.86	0.91	0.96	1.08
Methionine-Cystine	3.6	1.30	1.37	1.44	1.62
Phenylalanine	4.0	1.44	1.52	1.60	1.80
Phenylalanine-Tyrosine	7.1	2.57	2.70	2.84	3.20
Threonine	3.6	1.30	1.37	1.44	1.62
Tryptophan	0.8	0.29	0.30	0.32	0.36
Valine	4.0	1.44	1.52	1.60	1.80

^aAs fed basis.^bPercent protein level in feed.

acid requirements have shown that the ratio of the amino acids in the muscle was not very useful.

It is well known that there is a lysine and arginine dietary relationship known as the lysine-arginine antagonism. This antagonism occurs with excessive levels of either amino acid which results in depressed growth. Though this relationship has not been demonstrated in shrimp, it is believed that the lysine:arginine ratio should be maintained at 1:1 to 1:1.1. A relationship between the branched amino acids, leucine, isoleucine and valine, is also believed to occur.

The nutritional value of synthetic amino acids has been demonstrated with fish and terrestrial animal feeds, but not thus far with shrimp feeds. This can be attributed to several factors. First, optimal protein synthesis requires that necessary amino acids be simultaneously available at the site of protein synthesis. Due to different rates of absorption of synthetic amino acids and protein-bound amino acids, protein synthesis does not occur. It has also been reported that radioactive arginine was incorporated into shrimp muscle tissue at less than 1%, as compared to 90% for protein-bound arginine (Deshimaru 1982). Second, because shrimp are slow feeders and synthetic amino acids quickly leach out of feeds, these amino acids may no longer be present when feed is consumed. Excessive leaching of amino acids could result in a secondary problem of eutrophication in the culture environment. However, if cost effective, certain synthetic amino acids are a proven attractant.

25.4 ENERGY

Shrimp require energy for growth, muscle activity and reproduction. The biological process of utilizing energy is defined as metabolism, while the rate at which energy is utilized is called the metabolic rate. Metabolic rate in shrimp is influenced by factors such as water temperature, species, age or body size, activity, physical condition and body functions. Other parameters, such as oxygen or carbon dioxide concentration, pH and salinity, also influence metabolic rate.

Shrimp are believed to have a lower dietary energy requirement than terrestrial animals. This lower requirement is due to a number of factors. First, shrimp do not have to maintain a constant body temperature. Second, they require relatively less energy to maintain their position and to move in water as compared to terrestrial animals. Lastly, because they excrete most of their nitrogenous waste as ammonia instead of urea or uric acid, less energy is lost in the protein catabolism and excretion of nitrogenous wastes.

Digestible energy (DE) values have not been determined for shrimp for the various feed ingredients. Shrimp will utilize proteins, lipids and carbohydrates as energy sources. As protein is highly digestible by shrimp, excesses will be used for energy. The use of proteins for energy is not economically efficient. Therefore, adequate non-protein energy sources must be maintained in shrimp feeds.

The protein:energy ratio has not been determined for shrimp. This value would be dependent on "determined" digestible energy values for feed ingredients. The digestible energy requirement per unit of protein for warmwater fish ranges from 8 to 9.5 Kcal/g of protein (NRC 1983). Given that animals do not necessarily require protein, digestible energy requirements should be based on essential amino acids. It is believed that higher energy feeds would require higher levels of limiting essential amino acids.

25.5 LIPID

Lipids, are the generic name for fat soluble compounds found in living matter, broadly classified as fats, phospholipids, sphingomyelins, waxes and sterols. Dietary and tissue lipids are important in the nutrition of shrimp. Dietary lipids are a concentrated and highly digestible source of energy, and are a source of essential fatty acids necessary for normal growth and survival of all animals. Dietary lipids serve as a carrier of fat soluble vitamins and provide other compounds, such as sterols and phospholipids, which are essential for the normal metabolic function of shrimp.

Lipids, such as phospholipids and sterols, are important structural components of cell and organelle membranes. Phospholipids help in

Table 8. Recommended lipid levels in commercial shrimp feeds.^a

Size of shrimp (g)	Lipid level (percent)
0 - 0.5	7.5
0.5 - 3.0	6.7
3.0 - 15.0	6.3
15.0 - 40.0	6.0

^a As fed basis.

maintaining the fluid and flexible nature of membranes. Sterols are important in the synthesis of steroid hormones and the hormone-like prostaglandins. Dietary lipids also serve as an "attractant" and can affect the texture of the feed.

Recommended lipid levels for commercial feeds range from 6% to 7.5% (Table 8). Lipid levels should not exceed 10%. Decreased growth and increased mortalities are associated with lipid levels exceeding 10%. However, this is probably due to nutrient imbalances/deficiencies as they relate to energy and quality standards for lipid sources. This contention will probably change in the future as information on shrimp nutritional requirements is expanded.

25.5.1 Fatty Acids

The major functions of essential fatty acids are related to their roles as components of phospholipids and as precursors of prostaglandins. Essential fatty acids are found in the highest concentration in phospholipids and, as such, are important in maintaining the flexibility and permeability of biological membranes, in lipid transport, and in activation of certain enzymes. As precursors of prostaglandins they are probably involved in many diverse physiological and metabolic functions.

Four fatty acids are considered essential for shrimp; linoleic (18:2n6), linolenic (18:3n3), eicosapentaenoic (20:5n3) and decosahexaenoic (22:6n3) (Kanazawa et al. 1979; Jone et al., 1979). In general, plant oils are high in 18:2n6 and 18:3n3, while the marine animal oils are high in 20:5n3 and 22:6n3 (Table 9). Saturated fats, such as lard and tallow, are not suitable supplements in shrimp feeds. Recommended levels of fatty acids are listed in Table 10.

25.5.2 Phospholipids

Phospholipids consist of glycerol in which positions 1 and 2 are esterified with fatty acids and position 3 with phosphoric acid and nitrogenous base. If

Table 9. Essential fatty acid composition of various lipid sources.^a

Lipid source	18:2n6	18:3n3	20:5n3	22:6n3
Plant sources				
Coconut oil	2	0	0	0
Corn oil	58	1	0	0
Cottonseed oil	53	1	0	0
Linseed oil	17	1	0	0
Palm oil	10	56	0	0
Palm kernal oil	2	0	0	0
Rapeseed oil	15	8	0	0
Peanut oil	30	0	0	0
Soybean oil	50	10	0	0
Sunflower oil	70	1	0	0
Marine animal sources				
Capelin oil	5	0	7	5
Cod liver oil	5	1	16	14
Cuttlefish liver oil	1	2	12	18
Herring oil	1	1	8	5
Menhaden oil	3	1	13	8
Pollack liver oil	2	0	12	7
Salmon oil	3	0	10	10
Sardine oil	3	1	13	10
Short-neck clam oil	1	1	19	14
Skipjack oil	5	3	7	12
Squid liver oil	3	3	12	10

^a As fed basis. From Tacon (1987).

the nitrogen base is choline or ethanolamine it is called lecithin or cephalin, respectively. Both are components of cell membranes and have roles in lipid digestion, absorption, and transport in the hemolymph.

Table 10. Recommended fatty acid levels in commercial shrimp feeds. ^a

Fatty Acid	Percent of feed
18:2n6	0.4
18:3n3	0.3
20:5n3	0.4
22:6n3	0.4

^aAs fed basis.

Table 11. Recommended cholesterol levels in shrimp feeds. ^a

Size of shrimp (g)	Percent of feed
0 - 0.5	0.40
0.5 - 3.0	0.35
3.0 - 15.0	0.30
15.0 - 40.0	0.25

^a As fed basis.

The beneficial effects of phospholipids on growth and survival of shrimp are well documented. It has been reported that 1) phospholipids containing choline or inositol are most beneficial; 2) phospholipids containing the essential fatty acids are most effective; 3) the position of the fatty acid affects the phospholipids' effectiveness; and 4) though phospholipids are synthesized by shrimp, the rate of synthesis is slow (Kanazawa 1983).

Recommended total phospholipid content is 2.0%. If lecithin (phosphatidycholine) is used, the requirement is reduced to 1%. If the phospholipid contains 20:5n3 or 22:6n2 in the number 2 position of the phospholipid, only 0.4% is required.

Marine invertebrate animal oils are high in phospholipids. Squid, shrimp and clam oils contain 35% to 50% phospholipids. Soybean lecithin is often a cost-effective source of lecithin.

25.5.3 Cholesterol

Shrimp are incapable of synthesizing the steroid ring. Many sterols and essential components such as molting hormones, sex hormones, bile acids and vitamin D, are synthesized from cholesterol. Cholesterol also functions as a component of membrane and in the absorption and transport of fatty acids. Therefore, cholesterol is considered as essential nutrient which must be provided in the diet (Teshima and Kanazawa 1971).

Recommended levels of cholesterol in shrimp feeds range from 0.25% to 0.40% (Table 11). Marine invertebrate meals and oils, i.e. squid, shrimp, clam, crab, are all excellent sources of cholesterol (Table 12). The cholesterol content of squid meal and shrimp meal are 15% - 20% of the fat and 10% - 15% of the fat, respectively. Cholesterol supplements may be used when cost-effective.

Table 12. Cholesterol composition of various ingredients. ^a

Ingredients	Cholesterol (% of fat)
Protein Supplements	
Squid mantle	20.0
Squid viscera	3.0
Shrimp whole	9.9
Shrimp head	10.0
Crab	7.8
Clam	5.2
Mussle	1.7
Fish	
Pollock	7.1
Cod	6.2
Tuna	1.4
Herring	0.6
Mackerel	0.6
Fat Supplements	
Squid oil	2.0
Herring oil	0.8
Cod liver oil	0.6
Menhaden oil	0.5
Salmon oil	0.5

^a Actual sample analysis (Sidewell 1981).

25.6 CARBOHYDRATE

Carbohydrates are compounds of carbon, hydrogen and oxygen which form the major source of chemical energy needed by animals. Carbohydrates include the simple sugars or monosaccharides, the disaccharides and the polysaccharides. Important polysaccharides include starch, the major storage form of carbohydrates in plants; glycogen, the major storage form of carbohydrates in animals; and cellulose, the main structural component in plants.

Carbohydrates are considered the least expensive form of dietary energy for animals, but their utilization and metabolism by shrimp is limited and the process needs to be further studied. In the absence of adequate dietary carbohydrates or lipids, shrimp will utilize protein to meet their energy needs. When adequate energy is available, the protein will be utilized for growth. This relationship between protein and carbohydrates has been referred to as the protein-sparing action of carbohydrates. Carbohydrates may also serve as precursors for various metabolic intermediates necessary for growth, i.e. non-

essential amino acids, nucleic acids, chitin and gelatinized starch will help bind the feed. Although carbohydrates are not a dietary essential for shrimp feeds, their usefulness and cost-effectiveness are undeniable.

25.7 FIBER

Fiber refers to mixtures of cellulose, hemicellulose, lignin, pentosans and other generally undigestible fractions in the feed. The cellulose digesting enzyme, cellulase, has been identified in shrimp. However, cellulose is not digested in levels significant enough to be a factor in the nutrition of shrimp. Feeds with high levels of fiber will increase fecal production and, consequently, pollute the water environment.

A feed processing concern with high fiber levels is that feeds are difficult to bind. Fiber is difficult to grind finely and these fiber strands may act as a conduit for water to enter the pellet. This creates fractures and lowers the water stability of the feed. Feeds are usually formulated to limit the levels of fiber. However, a strict limitation of fiber will significantly increase the cost of feed formulations. Total fiber level of commercial feeds should not exceed 4%.

Chitin is a polymer of N-acetyl-D-glucosamine with linkages similar to the structure of cellulose. Chitin is the major structural component of the exoskeleton of shrimp. Chitin in shrimp feeds is believed to have a growth promoting effect. A minimum level of 0.5% chitin in shrimp feeds is recommended. Chitin is usually adequately supplied by various forms of shrimp meal.

25.8 VITAMINS

Vitamins are complex organic compounds required in minute amounts for normal growth, metabolism and reproduction. In culture systems where production levels do not exceed 250 g/m², natural foods may be abundant enough to provide some or all essential vitamins. In intensive, high-density culture, such as heavily stocked ponds and raceways, natural foods are limited, so vitamins must be supplied in the diet to achieve normal growth. Vitamin requirements for shrimp are affected by shrimp size, age, growth rate, environmental conditions and nutrient interrelationships. There are 11 water-soluble and 4 fat-soluble vitamins believed to be required by shrimp.

Very little is known about vitamin nutrition in shrimp. This is readily apparent in the commercial feed industry where different sources of vitamin premixes and recommended levels may vary by as much as 50% to 100%. Recommended supplementation levels of vitamins in commercial shrimp feeds are summarized in Table 13.

Table 13. Recommended supplementation level of vitamins in commercial shrimp feeds. ^a

Vitamin	Quantity per kg feed
Thiamin	50 mg/kg
Riboflavin	40 mg/kg
Pryidoxine	50 mg/kg
Pantothenic acid	75 mg/kg
Niacin	200 mg/kg
Biotin	1 mg/kg
Inositol	300 mg/kg
Choline	400 mg/kg
Folic acid	10 mg/kg
Cyanocobalamine	0.1 mg/kg
Ascorbic acid ^b	1000 mg/kg (100 mg/kg)
Vitamin A	10,000 IU/kg
Vitamin D	5,000 IU/kg
Vitamin E	300 mg/kg
Vitamin K	5 mg/kg

^a As fed basis.^b Coated ascorbic acid (heat stable ascorbic acid derivative)

Commercial shrimp feeds are usually over-fortified with expensive vitamins. Vitamin supplementation may be as high as 15% of the total ingredient cost. This over-fortification is done for several reasons. First, very little is known about vitamin requirements for shrimp. Shrimp culture generates considerable profits and the costs of over-fortification is regarded as "insurance" to maintain the quality and reputation of a feed. Second, shrimp are slow feeders and feed pellets could remain in the water for several hours. Vitamins, especially the water-soluble vitamins, will leach from the pellets. Over-fortification ensures that acceptable levels of vitamins remains in the feed. Third, vitamins are destroyed during feed processing and storage. This especially true of ascorbic acid. The oxidation of vitamins is affected by heat, moisture, pH, the presence of certain minerals, and by lipid oxidation. Fourth, the vitamin content of feed ingredients varies. It is expensive to analyze each ingredient and each batch of ingredients, thus it is simpler to over-fortify. Lastly, ingredients may contain anti-nutritional factors which reduce or interfere with the vitamin's functions. For instance, the effect of lipid oxidation increases the requirement for vitamin E.

25.8.1 Water Soluble Vitamins

25.8.1.1 Thiamin (B₁)

Thiamin plays a role controlling carbohydrate metabolism as a coenzyme for oxidative decarboxylation of pyruvic acid in energy metabolism. Thiamin is readily destroyed in the presence of minerals, especially copper and fresh fish tissues. Deficiency symptoms include anorexia, poor growth, pigmentation and mortality. Sources of thiamin include dried distillers solubles, fish solubles, rice bran, wheat middlings and yeast. Recommended supplementation level for thiamin in commercial feeds is 50 mg/kg.

25.8.1.2 Riboflavin (B₂)

Riboflavin is synthesized by all plants and many microorganisms, but not by animals. Riboflavin functions in the form of coenzymes flavin mononucleotide (FMN) and flavin adenine dinucleotide (FAD). These coenzymes function as prosthetic groups of oxidation-reduction enzymes that are needed for the degradation of pyruvate, fatty acids and amino acids. They are also involved in the electron transport system. Riboflavin incurs high losses during feed processing and prolonged exposure to sunlight, and is very soluble in water. Deficiency symptoms include anorexia, poor growth, abnormal swimming behavior and mortality. Sources of riboflavin include dried distillers solubles, fish meal, fish solubles, liver meals and yeast. Recommended supplementation level for riboflavin in commercial feeds is 40 mg/kg.

25.8.1.3 Pyridoxine (B₆)

Pyridoxine, or the active coenzymes pyridoxal phosphate and pyridoxamine phosphate, is required for many enzymatic reactions in which amino acids are metabolized. These include transaminations, deaminations, decarboxylations and sulfhydrations. Deficiency symptoms include poor growth, mortality and swimming hyperirritability. Sources of pyridoxine include dried distillers solubles, dehydrated fish solubles, fish meal, wheat middlings and yeast. Recommended supplementation level for pyridoxine in commercial feeds is 50 mg/kg.

25.8.1.4 Pantothenic acid

Pantothenic acid acts metabolically as part of coenzyme A (CoA) to transfer acyl groups in enzymatic reactions. This coenzyme is required in fatty acid oxidation, fatty acid synthesis, cholesterol synthesis, steroid synthesis, pyruvate oxidation and other biological acetylations. Acetyl-CoA is also required in reactions in which the carbon skeletons of amino acids enter into energy-yielding metabolic pathways. Deficiency symptoms include abnormal gill features, anorexia and mortality. Sources of pantothenic acid include

dried distillers solubles, cottonseed meal, fish solubles, fish meal, peanut meal, rice bran and polishings, soybean meal, wheat bran and by-products, and yeast. Recommended supplementation level for pantothenic acid in commercial feeds is 75 mg/kg.

25.8.1.5 Niacin

Niacin or nicotinic acid is a component of the two coenzymes, nicotinamide adenine dinucleotide (NAD) and nicotinamide adenine dinucleotide phosphate (NADP). These coenzymes are required for tissue oxidation, energy metabolism from carbohydrates, lipid and proteins, and the synthesis of fatty acids and cholesterol. Deficiency symptoms include poor growth, anorexia, lethargy and mortality. Sources of niacin include blood meal, dried distillers solubles, corn gluten, cottonseed meal, crab meal, fish solubles, fish meal, peanut meal, rice bran and polishings, soybean meal, wheat bran and by-products, and yeast. Recommended supplementation level for niacin in commercial feeds is 200 mg/kg.

25.8.1.6 Biotin

Biotin is an essential component of specific enzymes systems involved in carboxylation, transcarboxylation and decarboxylation reactions. Acetyl-CoA carboxylase, pyruvate carboxylase and propionyl-CoA carboxylase are enzymes requiring biotin. These enzymes are involved in carbon dioxide transfers within tissues. Deficiency symptoms include anorexia, slow growth and depigmentation. Sources of biotin include dried distillers solubles, cottonseed meal, rice polishings and yeast. Recommended supplementation level for biotin in commercial feeds is 1 mg/kg.

25.8.1.7 Inositol

Inositol is a water-soluble growth factor for which no coenzyme function is known. Inositol, sometimes called myo-inositol, is a sugar alcohol that is apparently not required in the diet of most animals but is required for shrimp. The function of inositol is as a component of the inositol phosphoglycerides and inositol phospholipids that are found in tissues, such as skeletal, heart and brain. Deficiency symptoms include slow growth and anorexia. Sources of inositol include fish meal, liver meals, wheat germ, and yeast. Recommended supplementation level of inositol in commercial feeds is 300 mg/kg.

25.8.1.8 Choline

Choline serves as a source of methyl groups and is involved in a number of transmethylation. It is an essential component of phospholipids and acetylcholine which have functions in lipid transport, cell structure and transmission of nerve impulses. Deficiency symptoms include poor growth,

anorexia and fatty tissues. Sources of choline include dried distillers solubles, cottonseed meal, fish solubles, fish meal, shrimp meal, soybean meal and yeast. Recommended supplementation level of choline in commercial feeds is 400 mg/kg.

25.8.1.9 Folic acid

Folic acid in its coenzyme form, tetrahydrofolic acid, acts as an intermediate carrier of one carbon units (hydroxymethyl or methyl groups) in a large number of metabolic reactions. These reactions are found in the metabolism of amino acids and the biosynthesis of purines and pyrimidines, the bases of nucleotides in DNA and RNA. Deficiency symptoms include poor growth, anorexia and lethargy. Sources of folic acid include dried distillers solubles, cottonseed meal, rice bran, soybean meal and yeast. Recommended supplementation level of folic acid in commercial feeds is 10 mg/kg.

25.8.1.10 Cyanocobalamine (B₁₂)

Cyanocobalamine is a large, complex compound consisting of a porphyrin ring containing cobalt. Cyanocobalamine functions as an integral part of the cobarnide enzymes. These enzymes are involved in nucleic acid synthesis, carbohydrate metabolism, lipid metabolism and amino acid metabolism. Deficiency symptoms include poor growth and anorexia. Sources of cyanocobalamine include blood meal, crab meal, fish solubles and fish meal. Recommended supplementation level of cyanocobalamine in commercial feeds is 0.1 mg/kg.

25.8.1.11 Ascorbic acid

Ascorbic acid is structurally one of the simplest vitamins. Ascorbic acid is soluble in water and ethyl alcohol but insoluble in most organic solvents. It is an important antioxidant and is easily oxidized. The principle function of ascorbic acid is in the formation of collagen, an essential component of capillaries and connective tissues. Ascorbic acid is also involved in the synthesis of steroid hormones. Deficiency symptoms include "Black Death", a disease characterized by melanized haemocytic lesion in collagenous tissues, problems with or decreased rate of molts, a lighter colored hepatopancreas, reduced growth and mortality.

Ascorbic acid is rapidly oxidized during feed storage and feed processing. The ascorbic acid loss in stored feeds is approximately 50% per month (Grant et al. 1989). Unprotected forms of ascorbic acid should not be used in feeds because 70% - 90% will be destroyed during feed processing. Coated forms of ascorbic acid (silicone, gelatin) are marginally better. Destruction of coated ascorbic acid during feed pelleting and extrusion would range from

30% - 50% and 50% - 80%, respectively. Two heat-stable ascorbic acid derivatives, L-ascorbyl-2-polyphosphate and L-ascorbyl-2-phosphate magnesium have been recently introduced. These ascorbic acid derivatives are utilized by shrimp, relatively stable during feed processing with only 20% destroyed, and stable during feed storage with 20% loss over 6 months. Another ascorbic acid derivative, L-ascorbyl-2-sulfate, is heat stable but its utilization by shrimp has not been demonstrated.

The requirement of ascorbic acid by shrimp is 50 - 80 mg/kg. However, ascorbic acid supplementation levels in shrimp feed will vary due to the form of ascorbic acid, processing conditions and feed storage time. Recommended supplementation level of coated ascorbic acid and the stable ascorbic acid derivatives are 1,000 mg/kg and 100 mg/kg, respectively.

25.8.2 Fat-soluble Vitamins

25.8.2.1 Vitamin A

Vitamin A occurs in two forms, vitamin A₁ (retinol) found in mammals and marine fish, and vitamin A₂ (retinol₂), found in freshwater fish. Vitamin A is required in vertebrates for regeneration of light-sensitive compound rhodopsin in the retina. Vitamin A is also involved in calcium transport across some membranes, in reproduction and embryonic development, and in cellular and subcellular membrane integrity. Deficiency symptoms could be related to depigmentation and soft exoskeleton. Sources of vitamin A include fish liver oils and liver meals. Recommended supplementation level of vitamin A in commercial feeds is 10,000 IU/kg.

25.8.2.2 Vitamin D

The two main compounds having vitamin D activity are vitamin D₂, or ergocalciferol, and vitamin D₃, or cholecalciferol. Cholecalciferol has more vitamin D activity than ergocalciferol for some animals and is the form found in animal tissues. Cholecalciferol is involved in calcium and phosphorous metabolism. In particular, cholecalciferol aids in the absorption and deposition of calcium into the exoskeleton, absorption of phosphorous, and the conversion of organic phosphorous to inorganic phosphorous. Deficiency symptoms include poor growth, soft exoskeleton and lethargy. Sources of vitamin D include fish liver oils, liver meals and fish meal. Recommended supplementation level of vitamin D in commercial feeds is 5,000 IU/kg.

25.8.2.3 Vitamin E

Vitamin E is a fat-soluble anti-oxidant and belongs to a group of compounds called tocopherols, which function to protect lipids of biological membranes from oxidation. Vitamin E helps to protect the content of highly unsaturated fatty acids in feeds. Deficiency symptoms include reduced

growth, mortality, depigmentation and fatty tissues. Sources of vitamin E include dried distillers solubles, cottonseed meal, rice bran and polishings, and wheat products. Recommended supplementation level of in commercial feeds vitamin E is 300 mg/kg.

25.8.2.4 Vitamin K

Vitamin K occurs in two natural forms, phyloquinone (K_1 , plants) and menaquinone (K_2 , microorganism), and a synthetic form, menadione (K_3). Vitamin K is required for normal blood coagulation in animals and may be associated with electron transport and oxidative phosphorylation (energy metabolism). Requirement of vitamin K by shrimp is questionable. Sources of vitamin K include liver meals and fish meal. Supplementation level of vitamin K in commercial feeds is 5 mg/kg.

25.9 MINERALS

There are approximately 20 recognized inorganic elements which perform essential functions in the body. Some minerals are required in considerable quantities, termed macro-minerals, while others, which are required in lesser amounts, are referred to as micro-minerals. Macro-minerals include calcium, phosphorous, potassium, magnesium, sodium, chlorine and sulfur. Microminerals include iron, copper, zinc, manganese, cobalt, selenium and iodine. Other minerals which could be required include nickel, fluorine, vanadium, chromium, molybdenum, tin and silicon.

The general functions of minerals are as constituents of the exoskeleton, for balance of osmotic pressure, as structural constituents of tissues, and for transmission of nerve impulses and muscle contractions. Minerals serve as essential components of enzymes, vitamins, hormones and pigments, and are metabolic co-factors, catalysts and enzyme activators.

As with most aquatic animals, shrimp can absorb or excrete minerals directly from the aquatic environment via the gills and body surfaces. Therefore, the dietary requirement of minerals is largely dependent on the mineral concentration of the aquatic environment in which the shrimp is being cultured. Recommended level of minerals in commercial shrimp feeds are summarized in Table 14.

An acidic digestive environment would considerably improve the availability of minerals. As noted earlier, the shrimp digestive system is not very acidic. Thus, mineral salt supplements which are water-soluble are most available to shrimp.

25.9.1 Calcium (Ca)

Calcium is an essential mineral required for the formation of skeletal tissues. In shrimp, the vast majority of body calcium is found in the exoskeleton. Calcium is also essential for blood clotting, activation of enzymes, muscle contraction and cell permeability, and is believed to be essential for the absorption of Vitamin B₁₂.

The shrimp culture environment usually has a high concentration of calcium which is directly absorbed by shrimp. Therefore, calcium is not considered a dietary essential. However, the calcium level in the feed needs to be monitored to maintain a calcium:phosphorous ratio of 1:1 to 1.5:1. Calcium should not exceed 2.3% in the feed and should be minimized.

25.9.2 Phosphorous (P)

A large portion of the total body phosphorous is associated with calcium and is required for exoskeleton formation. Phosphorous serves in many metabolic processes. Phosphorous is an essential component of phospholipids, nucleic acids, phosphoproteins, high energy compounds (ATP), many metabolic intermediates, and coenzymes. Inorganic phosphates also serve as important buffers to maintain normal pH of intra- and extra-cellular fluids.

Phosphorous salts may be absorbed directly from the aquatic environment, however, these concentrations are usually limited. Phosphorous is considered the most limiting mineral in feeds. Sources of phosphorous include dried distillers solubles, cottonseed meal, crab meal, fish solubles, fish meal, krill meal, rice bran and by-products, shrimp meal, squid meal, wheat bran and by-products, and yeast. Utilizing the values in Tables 3 and 4, the recommended level for available phosphorous is 0.8%. Sodium phosphate ($\text{NaH}_2\text{PO}_4\text{H}_2\text{O}$) or non-calcium phosphate supplements are recommended as phosphorous supplements. Total phosphorous (approximately 1.5% in feed) needs to be monitored to maintain acceptable calcium:phosphorous ratios as previously discussed.

25.9.3 Magnesium (Mg)

The distribution of magnesium is similar to phosphorous with the majority being found in the exoskeleton. Magnesium is found in many enzymes and is essential for several enzymatic processes including protein, lipid and carbohydrate metabolism, muscle and nerve functions, and osmoregulation. Sources of magnesium include crab meal, cottonseed meal, krill meal, rice bran, shrimp meal and wheat bran. Magnesium may be supplemented as magnesium sulfate. Recommended level of magnesium in commercial feeds is 0.2%.

Table 14. Recommended level of minerals in commercial shrimp feed. ^a

Mineral	Quantity per kg feed
Calcium	maximum 2.3%
Phosphorus - available	0.8%
- total	1.5%
Magnesium	0.2%
Sodium	0.6%
Potassium	0.9%
Iron	300 ppm
Copper	35 ppm
Zinc	110 ppm
Manganese	20 ppm
Selenium	1 ppm
Cobalt	10 ppm

^a As fed basis.

25.9.4 Sodium (Na), Potassium (K) and Chlorine (Cl)

Sodium, potassium and chlorine are found in the fluids and soft tissue of the body. They serve in regulating osmotic pressure and acid-base balance and also play important roles in water metabolism. These elements are closely related metabolically. Sources of sodium include crab meal, fish solubles, fish meal, krill meal and shrimp meal. Sources of potassium include dried distillers solubles, cottonseed meal, fish solubles, rice bran, soybean meal, wheat bran and yeast. Sources of chlorine include crab meal, fish solubles, fish meal and shrimp meal.

Recommended levels of sodium and potassium in commercial feeds are 0.6% and 0.9%, respectively. Chlorine levels are usually not limiting in feed formulations. Supplemented potassium sources include potassium chloride and potassium iodate. Salt (NaCl) may be supplemented at 0.2% as a flavor enhancer especially in high plant product formulations.

25.9.5 Sulfur (S)

Sulfur is utilized in proteins in the form of the amino acids, methionine and cystine. Other functions of sulfate, include glutathione, taurine, heparine and chondroitin sulfate, compounds derived from sulfur-containing amino acids. Inorganic sulfur supplementation may spare some of the methionine or cystine requirements, as demonstrated with other animals. Sources of sulfur include ingredients which are high in sulfur-containing amino acids (methionine, cystine) such as fish meal, cottonseed meal, rapeseed meal and yeast. Sulfur is usually not limiting in feed formulations.

25.9.6 Iron (Fe)

Iron is utilized in various enzymes including cytochromes, catalases, peroxidases and dehydrogenases. Iron absorption may be depressed by high levels of phosphates, calcium, phytates, copper and zinc. Sources of iron include blood meal, dried distillers solubles, crab meal, fish solubles and fish meal. Supplemented iron sources include ferrous gluconate and ferric sulfate; however, there may not be a need to supplement iron. Recommended level of iron in commercial feeds is 300 ppm.

25.9.7 Copper (Cu)

Copper is utilized in various oxidation-reduction enzyme systems and is a component of hemocyanin for oxygen transport in shrimp. Sources of copper include dried distillers solubles, fish solubles, krill meal and yeast. Copper may be supplemented by cupric sulfate and cupric chloride. Recommended level for copper in commercial feeds is 35 ppm.

25.9.8 Zinc (Zn)

Zinc is a component in more than 80 metalloenzymes and a cofactor in enzyme systems. These metabolic processes include protein, nucleic acid, lipid, carbohydrate and micropolysaccharide metabolism. Sources of zinc include dried distillers solubles, corn gluten meal, fish solubles, fish meal, krill meal, rice mill by-products, wheat bran and by-products, and yeast. Zinc may be supplemented by zinc sulfate and zinc gluconate. Recommended level of zinc in commercial feeds is 110 ppm.

25.9.9 Manganese (Mn)

Manganese serves as a cofactor for a number of enzymes including phosphate transferases and dehydrogenases, alkaline phosphatase, arginase and hexokinase. Sources of manganese include dried distillers solubles, crab meal, fish solubles, rice bran and by-products. Manganese may be supplemented as manganese sulfate. Recommended level of manganese in commercial feeds is 20 ppm.

25.9.10 Selenium (Se)

Selenium is a component of the enzyme glutathione peroxidase which serves to protect cellular tissues and membranes against oxidation. Selenium and vitamin E function synergistically. Sources of selenium include blood meal, corn gluten meal, fish solubles, fish meal, rapeseed meal and yeast. Selenium may be supplemented as sodium selenite. Recommended level of selenium in commercial feeds is 1 ppm.

25.9.11 Cobalt (Co)

Cobalt is an essential component of vitamin B₁₂ or cyanocobalamin. The significance of cobalt as a micronutrient is limited to its potential use in the microbial synthesis of Vitamin B₁₂ in the intestinal tract of shrimp. Sources of cobalt include cottonseed meal, soybean meal, fish meal and yeast. Cobalt may be supplemented as cobalt sulfate and cobalt chloride. Recommended level of cobalt in commercial feeds is 10 ppm.

25.10 FEED INGREDIENTS

Only in recent years has there been a consistent supply of commercial shrimp feed which yields growth rates needed for profitable shrimp culture. The nutritional evaluation of ingredients which is commonly used by the terrestrial animal and fish feed industry is limited for shrimp.

The following descriptions of feed ingredients are for those extensively used in commercial shrimp feeds. The discussion and recommendations are based on "good" quality feed ingredients. For example, there are no nutritional limits for the use of good quality fish meal, however, poor quality fish meal should not be used. The use of poor quality fish meal will result in reduced growth rates and increased mortalities.

25.10.1 Fish Meal and By-products

Fish meal is a by-product of the fisheries industry in which whole and cuttings of fish are cooked and dried. The method of drying and the freshness of the raw material affects the quality of the final product. Both vacuum and steam dried fish meal are recommended. Flame dried fish meal is exposed to higher temperatures which renders protein less available, oxidizes lipids and produces anti-nutritional factors, i.e. histamine. Fish meal is highly palatable to shrimp and serves as a desirable attractant. Fish meal should contain a minimum of 60% protein.

There are no nutritional differences between good quality white and brown fish meals. However, white fish meal is usually of better quality than brown fish meal. This quality difference is believed to be related to the quantity and quality of the lipids in the respective meals. Lipid supplementation of a solvent-extracted brown fish meal which produced poor growth resulted in comparable growth to a good quality fish meal. Apparently, the "anti-nutritional factor" in the brown fish meal is solvent extractable and possibly associated with lipids. It is not known if this problem can simply be ascribed to rancidity.

Fish meal levels in commercial feeds usually range from 10% to 40%. Although there are no nutritional limitations on the use of fish meal, there is a price limitation. Other fish products observed in commercial feeds

include fish flesh, fish protein concentrate, fish liver meal, condensed fish solubles, dried fish solubles, and fish silage.

25.10.2 Squid Meal and By-products

Squid meal is possibly the best shrimp feed ingredient. An unknown growth factor has been identified in squid meal (Cuzon pers. commun.). This unknown growth factor, which is believed to be a small peptide, increases the digestive efficiency of shrimp as well as enhances growth rate, and is more highly concentrated in the mantle as compared to the viscera. Squid meal is also an excellent attractant. However, the most critical factor in squid meal is the type and quantity of lipids, because it has the highest concentration of cholesterol, phospholipids and the fatty acids, 20:5n3 and 22:6n3, of any natural source. Squid meal should contain a minimum of 40% protein and 5% lipid. Protein and lipid levels vary considerably in squid meal products given the type of raw material. Lipid levels of more than 15% are common.

Squid meal levels in commercial feeds usually range from 2% to 10%. There are no nutritional limitations on squid meal, however, its use is limited by price and availability. Other squid products observed in commercial feeds include squid liver meal, squid viscera meal, squid mantle meal and squid solubles.

25.10.3 Shrimp Meal and By-products

Shrimp meal is the ground dried waste of shrimp including the head, exoskeleton and/or the whole shrimp. It is usually steamed or sun-dried with the former being preferred. Shrimp meal is an excellent source of minerals, chitin, cholesterol, phospholipids and the fatty acids, 20:5n3 and 22:6n3. Shrimp meal also serves as an attractant. Shrimp meal should contain a minimum of 32% protein and 4% lipid, and a maximum of 14% fiber.

Shrimp meal levels in commercial feeds usually range from 5% to 15%. Shrimp meal use is usually limited by fiber content. Other shrimp products observed in commercial feeds include shrimp head meal, shrimp shell meal, shrimp waste meal, mysid meal, krill meal and extracted shrimp head solubles.

25.10.4 Soybean Meal

Soybean meal has the best protein nutritional profile of all plant sources. Soybean meal is solvent-extracted and can be produced with or without hulls. Dehulled meal is recommended. Soybean meal is usually a cost-effective source of protein and should contain a minimum of 44% protein. Soybean meal levels in commercial feeds usually range from 10% to 25%. The maximum level of soybean meal in feeds should not exceed 40% (Akiyama 1988). Soybean meal is usually limited by processing constraints to produce

water stable feeds. Other soybean products observed in commercial feeds include full-fat soybean meal, soybean cake and soy protein concentrates.

25.10.5 Wheat Products

Wheat products are usually supplemented as a binder and filler of shrimp feeds. Wheat gluten is an excellent binder and a good source of protein, but its use is limited by price. Wheat gluten should contain a minimum of 60% protein. Wheat flour currently is the most common binder in shrimp feeds because of its cost effectiveness. The binding strength of wheat flour depends on its gluten content. Wheat flour should contain a minimum of 12% protein and a minimum of 30% of the protein is wet gluten. Wheat gluten and wheat flour levels in commercial feeds usually range from 0% to 5% and 20% to 30%, respectively. Other wheat products such as wheat bran, wheat pollards and wheat middlings are not commonly used because of their high fiber contents.

25.10.6 Other Crustacean Meals

Crab meal, crawfish meal and clam meal contain cholesterol, phospholipids, the fatty acids, 20:5n3 and 22:6n3, and attractants. However, use of these products is limited because of limited availability and variability in the nutritional profile between batches.

25.10.7 Blood Meal

Blood meal is made by drum-drying, spray-drying, or ring-drying blood. The latter two processes produce a better quality blood meal and are recommended. Blood meal is a concentrated source of protein. Blood meal is not commonly used in feeds and should not be used at levels exceeding 7%.

25.10.8 Yeast

Yeast are single-celled organisms which are by-products of the baking, brewing and distilling industries. Yeast is a source of vitamins and is associated with unknown growth factors. An advantage of yeast may be that there is less destruction and leaching of the vitamins and unknown growth factors because they are encapsulated in the yeast cell. Yeast utilization is limited by palatability (bitter flavor) of the feed, however, various culture media and processing methods can produce palatable yeast products. Yeast levels in commercial feeds usually range from 2% to 5%. The level of yeast should not exceed 5% in feeds unless the yeast product used is palatable to shrimp.

25.10.9 Other Feed Ingredients

Plant protein ingredients such as cottonseed meal, rape/canola meal, peanut meal and corn gluten meal have not been adequately evaluated for use in shrimp feeds. Although these ingredients may be used, the level of incorporation in feeds is unknown. Terrestrial animal by-products are not used in shrimp feeds. The saturated lipid contents of these ingredients are believed to reduce the production performance of shrimp. Rice products are not normally used in shrimp feeds because they are similarly priced with comparable wheat products but do not add to the binding of feeds.

25.11 FEED ADDITIVES

The continuing effort to improve animal performances (growth, survival) and feed efficiency has stimulated a search for new additives for shrimp feeds. These additives are used in small amounts and could improve performances and feed efficiency by 10% to 25%. Often these additives are used without sufficient evaluation or biological understanding of their effects. Concerns, such as residuals in animal tissues and effects on the human consumer, environmental concerns about the additives in the water systems, health concerns of those working with the additives, etc., need to be addressed before additives are routinely utilized.

Additives currently used in shrimp feeds are listed below. Although these may improve growth rate, survival and feed conversion, their cost effectiveness should be evaluated before they are incorporated into the feed. The use of some additives in aquatic feeds may be prohibited by law in certain countries.

25.11.1 Pellet Binders

Binders increase water stability of feeds. Adequate binding of shrimp feeds is more dependent on the processing technique than on the addition of a binding agent. Binders assist with the total concept of feed processing to produce a water stable pellet. Feed processing conditions such as ingredient particle size, conditioning time and temperature, die hole size and thickness, "cooking" or drying temperatures and time, and ingredients including binders all interact to produce a water-stable feed.

Binders such as bentonites, lignosulfonates, carboxymethyl-cellulose, cellulose derivatives and others which are commonly used to reduce "fines" in terrestrial animals and fish feeds, are not sufficient to produce water-stable shrimp feeds. Commonly used binders are wheat gluten, high gluten wheat flour, alpha-starch, gelatin, collagen, alginic acid, agar and fresh fish flesh.

High gluten wheat flour is the most utilized binder because of its cost effectiveness. Synthetic polymers have also recently been introduced.

25.11.2 Antioxidants

Antioxidants are widely used to prevent lipid rancidity and vitamin loss. Commonly used antioxidants are butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT) and ethoxyquin.

25.11.3 Pigments

Pigments may or may not have nutritional value to shrimp. For example, astaxanthin is naturally deposited by shrimp. It is found in shrimp and crab meals, and concentrated supplements are available. Feeds containing astaxanthin at 50 ppm fed to shrimp for 6 weeks improved coloration. Astaxanthin has also been reported to mask the effects of "blue shrimp". Beta-carotene found in corn gluten and Spirulina is converted to astaxanthin, but not very efficiently.

25.11.4 Attractants

Free amino acids and possibly small peptides serve as attractants for shrimp. These products naturally occur in fish meal, shrimp meal, squid meal, crab meal and clam meal. They also are highly concentrated in the dried solubilized or hydrolized marine animal products, such as fish solubles, squid solubles, shrimp solubles and fish silage. Marine animal solubles are the most common attractants used, generally at levels of 1% to 5%. Mixtures of synthetic amino acids (glycine, alanine, glutamate, betaine) may be used if cost effective.

25.11.5 Antibiotics

The use of antibiotics in feed for terrestrial animals has improved production and feed efficiency. Bacterial populations in the aquatic environment are believed to significantly contribute nutrients to shrimp; therefore, antibiotics in feeds will reduce the amount of available nutrients. Even if sub-therapeutic levels of antibiotics improve animal performance and feed efficiency, their use should still be deterred, because routine feeding will encourage development of resistant strains of pathogens.

25.11.6 Zeolite

Zeolites are naturally occurring hydrated sodium aluminosilicates. They are characterized by an ability to exchange constituent ions without any major change of structure. Zeolites have the ability to bind and remove ammonia from the water. Ammonia is produced by excretion and by the decomposition of fecal waste and uneaten feed. Zeolite supplementation to feeds will

ensure their presence at the site of decomposition of uneaten feed and, in the fecal waste. The effects of zeolites are well demonstrated in freshwater systems. However, sodium and calcium ions present in marine and brackishwater, compete for the binding sites with ammonia. Therefore, the efficiency of ammonia removal by zeolite in these environments is questionable. Zeolite is also a source of trace minerals. Zeolites are supplemented in commercial feeds in levels up to 2%. It may be used as the carrier for the trace mineral premix.

25.11.7 Enzymes

Proteolytic and amylolytic enzymes are added to feeds to improve protein and carbohydrate digestion, respectively. Two proteolytic enzymes, bromelin and papain, have been shown to improve the growth of shrimp. They are believed to help with decayed tissue removal and help to maintain inflammation. These enzymes may be supplemented at 0.1% to 0.2% of the feed. However, enzyme supplementation to feeds is expensive.

25.11.8 Phytosterols

Phytosterols are steroids which have been extracted from plant products. They contain a variety of steroids including ergosterol, stigmasterol, beta-sitosterol and diosgenin, but do not contain cholesterol, an essential nutrient for shrimp. Although phytosteroids are precursors of cholesterol, the rate and efficiency of conversion to cholesterol has not been determined. A sparing effect for cholesterol is possible.

25.11.9 Olaquinox

Olaquinox appears to partition energy in the animals for protein synthesis. The effects of this product are well-documented in swine and are believed to increase growth and feed efficiency in shrimp. Olaquinox may be supplemented at 20 g/MT of feed. There may be a residual effect with this product.

25.11.10 Thyroprotein

Thyroprotein or thyroglobulin is an iodinated protein, usually casein, which has thyroxine activity. This hormone is believed to increase metabolic rate, thereby increasing growth rate.

25.11.11 Bile acids

Bile acids assist with the assimilation and absorption of lipids and lipid-soluble substances, including cholesterol, phospholipids, fatty acids and fat-soluble vitamins. As bile acids are synthesized from cholesterol, their supplementation to feed may reduce the cholesterol requirement. They are

also believed to help maintain the proper functioning of the hepatopancreas. Bile salts have been demonstrated to increase growth rate in shrimp and may be supplemented at 400 g/MT.

25.12 LEAST-COST FEED FORMULATIONS

A shrimp feed formula is meaningless if we don't understand the nutritional principles involved. If "total nutrition" of a good feed formula is understood, least-cost formulation will make it cheaper.

Feed cost is the major variable cost in shrimp culture. Thus, formulations which produce equivalent shrimp performance at a lower cost will dramatically affect profitability. Least-cost poultry and livestock feeds are routinely formulated with computer programs. This enables a producer to take advantage of fluctuating feed ingredient prices. By utilizing the most cost efficient feed, production efficiency and profits can be maximized. Current commercial shrimp feed formulas are fixed or with a minimum deviation from fixed formulas.

Least-cost formulation of shrimp feeds has not been routinely practiced because of limited information on shrimp nutritional requirements and on nutrient availability of different ingredients. There are more than 15 species of shrimp being cultured worldwide, all of which have different nutritional requirements. Although there are probably more nutritional similarities than differences between species, most information is based on Penaeus monodon, P. japonicus and P. vannamei.

There are a number of limitations in utilizing least-cost feed formulations for shrimp. First, environmental conditions such as water temperature and salinity have a substantial effect on nutritional requirements. Second, there is limited information on feed ingredient interchangeability. Thus, the available nutrients from a feed ingredient such as amino acids, fatty acids, energy and minerals, are not known for all ingredients for all species of shrimp. Also, anti-nutritional factors of ingredients and tolerance levels by the different species of shrimp are relatively unknown. Lastly, if formulas were altered constantly, it would create processing inconveniences out of proportion to the limited amount of shrimp feed being produced. This would involve different nutritional data files for the different species of shrimp, the amount of storage capacity of feed ingredients and premixes, the time involved to alter formulas for a small batch of feed, etc.

Although these limitations presently exist, there is little doubt that least-costing of feeds will ultimately increase profits and result in the formulations of more nutritionally balanced feeds with no loss in production levels or shrimp performance.

Table 15. Least-cost restrictions for shrimp feed.^a

Nutrient	Percent in feed			
	36% ^b	38%	40%	45%
Protein-minimum	36.0	38.0	40.0	45.0
Lipid-minimum	5.5	5.8	6.2	7.0
-maximum	6.5	6.8	7.2	8.0
Fiber-maximum	4.0	4.0	3.0	3.0
Ash-maximum	15.0	15.0	15.0	15.0
Calcium-maximum	2.3	2.3	2.3	2.3
Phosphorous available-minimum	0.8	0.8	0.8	0.8
Potassium-minimum	0.9	0.9	0.9	0.9
Lysine-minimum	1.91	2.01	2.12	2.39
Arginine-minimum	2.09	2.20	2.32	2.61
Threonine-minimum	1.30	1.37	1.44	1.62
Methionine-minimum	0.86	0.91	0.96	1.08
Methionine/Cystine-minimum	1.30	1.37	1.44	1.62
Phospholipid-minimum	1.0	1.0	1.0	1.0
Cholesterol-minimum	0.25	0.3	0.35	0.4
20:5n3-minimum	0.4	0.4	0.4	0.4
22:6n3-minimum	0.4	0.4	0.4	0.4

^aAs fed basis.^bPercent protein level in feed.

25.12.1 Least-cost Formulation Restrictions

Formulation restrictions are classified as nutritional, processing, inherent problems with ingredients and others. Restrictions are usually given for limiting nutrients as either minimum levels, maximum levels, fixed levels, or ranges. Least-cost nutritional restrictions for shrimp are presented in Table 15. Shrimp do not have a dietary requirement for protein, but do have a dietary requirement for amino acids. A minimum level of protein is usually specified to meet the requirements of the consumer (farmer) and not the shrimp. The most critical essential amino acids are lysine, methionine, cystine, threonine and arginine. In general, if the requirements of these amino acids are met, the other essential amino acids should be in excess.

Lipids are the major energy source for shrimp and minimum and maximum levels need to be specified. The requirements for the other essential lipids: cholesterol, phospholipids and fatty acids, also need to be specified.

Fiber is relatively undigestible by shrimp. Undigestible nutrients are degraded in the aquatic environment but excessive levels decrease water quality. High fiber levels also affect the water stability of feeds. A maximum level of fiber is usually specified. Although the nutritional quality of a shrimp

feed usually improves with the lowering of the fiber content, severely restricted fiber levels would significantly increase the cost of the feed.

Shrimp require a high level of available phosphorous which can be absorbed directly from the water. However, phosphorous is usually found in limited quantities in water and is one of the most limiting nutrients of shrimp feeds. On the other hand, calcium levels in brackishwater are usually high and shrimp will absorb a considerable amount. Calcium is specified as a restriction primarily to maintain a calcium:phosphorous ratio ranging from 1:1 to 1.5:1.

Vitamins and trace minerals are usually not considered in least-cost formulations for shrimp because they are usually added at fixed levels.

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CHAPTER 26

Don V. Lightner and R.M. Redman

PENAEID VIRUS DISEASES OF THE SHRIMP CULTURE INDUSTRY OF THE AMERICAS

26.1 INTRODUCTION

Six virus diseases are presently recognized in the penaeid shrimp (Table 1). These six viruses are: BP = Baculovirus penaei (Couch 1974); MBV = P. monodon-type baculovirus (Lightner and Redman 1981); BMN = baculoviral midgut gland necrosis (Sano et al. 1981); IHHNV = infectious hypodermal and hematopoietic necrosis virus (Lightner et al. 1983a); HPV = hepatopancreatic parvo-like virus (Lightner and Redman 1985); and REO = reo-like virus (also known as RLV) of the hepatopancreas (Tsing and Bonami 1987). Each virus may actually be comprised by a multitude of individual strains, some of which are highly pathogenic to some penaeids, while being of little importance to others (Table 2).

The host geographic range of the known penaeid viruses has been updated several times recently (Couch 1981; Johnson 1983; Brock et al. 1983; Lightner 1983; Lightner et al. 1985; Lightner 1988). Since then, surveys and investigations of mortality problems undertaken by the senior author and colleagues in various shrimp growing areas have provided new data on several of the virus diseases that affect cultured penaeid shrimp. This review of the penaeid viruses emphasizes the current diagnostic procedures, their natural hosts, and their natural and introduced geographic distributions.

26.2 DIAGNOSTIC PROCEDURES

Three basic diagnostic procedures are used in screening penaeid shrimp for virus infections: 1) direct samples for microscopic (wet-mount) examination and/or histopathology or electron microscopy; 2) enhancement of infection followed by sampling and histopathology and electron microscopy; and 3) bioassay of a suspect shrimp population with a sensitive indicator species combined with direct sampling and examination of the indicator shrimp for signs of infection using wet-mounts or histopathology.

Table 1. The known penaeid viruses.

Virus	Approximate Virion Size	Nucleic Acid	Classification
IHHNV	21 nm	ssDNA	Parvovirus
HPV	22 nm	ssDNA ?	Parvovirus
REO	60 nm	dsRNA	Reo-like virus
BP	~ 75 x 300 nm	dsDNA	Baculovirus; occluded
MBV	~ 75 x 300 nm	dsDNA	Baculovirus; occluded
BMN	~ 75 x 300 nm	dsDNA	Baculovirus; non-occluded

26.2.1 Direct Diagnostic Procedures

Random or (preferably) nonrandom samples of shrimp, or shrimp feces, are selected in the direct sampling procedure from culture tanks, ponds, or cages and examined directly for signs of BP or MBV in wet-mounts, or they may be preserved in Davidson's AFA or in 10% buffered formalin (Humason 1967) for histological evaluation. The sensitivity of this procedure is limited, and it will only demonstrate shrimp with viral infections that are acute or subacute in a population with a high incidence rate. All six types of penaeid virus infections (IHHN, REO, BP, MBV, BMN, and HPV) may be diagnosed successfully with direct samples, but such samples have also produced false negative diagnoses on populations later shown by electron microscopy, enhancement, or bioassay diagnostic procedures to be positive for one of these virus diseases.

26.2.2 Enhancement Diagnostic Procedures

In the enhancement procedure, a quarantined population is reared under relatively crowded and stressful conditions. PLs are best suited for this test, which normally requires 30 to 60 days. Random samples are taken at intervals throughout the test period, or moribund animals are nonrandomly sampled when they are observed. Samples may be prepared for direct wet-mount microscopic examination for occlusion bodies diagnostic of BP and MBV-caused diseases, or for histology for diagnosis of IHHN disease in P. stylirostris, P. vannamei, and P. monodon. Demonstration of inapparent infections due to HPV and REO may also be possible by the enhancement procedure. Enhancement has at best only limited usefulness as a diagnostic procedure for demonstration of IHHNV in asymptomatic carriers (i.e.

Table 2. The penaeid viruses and their known natural and experimentally infected hosts.

Host Subgenus	Species**	VIRUS*					
		BP	MBV	BMN	IHHNV	HPV	REO
<u>Litopenaeus</u> :	<u>P. vannamei</u>	+++	+	-	++	+	-
	<u>P. stylirostris</u>	++	-	-	+++	-	-
	<u>P. setiferus</u>	+	-	-	+(e)	-	-
	<u>P. schmitti</u>	++	-	-	-	-	-
<u>Penaeus</u> :	<u>P. monodon</u>	-	++	-	++	++	++
	<u>P. esculentus</u>	-	+	-	-	++	-
	<u>P. semisulcatus</u>	-	+	-	+	+++	-
<u>Fenneropenaeus</u> :	<u>P. merguensis</u>	-	++	-	-	+++	-
	<u>P. indicus</u>	-	-	-	-	++	-
	<u>P. chinensis</u> (=orientalis)	-	-	-	-	++	-
	<u>P. penicillatus</u>	++	++	-	-	++	-
<u>Marsupenaeus</u> :	<u>P. japonicus</u>	-	-	+++	++(e)	-	+++
<u>Farfantepenaeus</u> :	<u>P. aztecus</u>	+++	-	-	+(e)	-	-
	<u>P. duorarum</u>	+++	-	-	+(e)	-	-
	<u>P. brasiliensis</u>	++	-	-	-	-	-
	<u>P. paulensis</u>	++	-	-	-	-	-
	<u>P. subtilis</u>	++	-	-	-	-	-
<u>Melicertus</u> :	<u>P. kerathurus</u>	-	+	-	-	-	-
	<u>P. marginatus</u>	+++	-	-	-	-	-
	<u>P. plebejus</u>	-	++	-	-	-	-

* Abbreviations:

BP = Baculovirus penaeiMBV = P. monodon-type baculovirus

BMN = Baculoviral midgut gland necrosis

IHHNV = Infectious hypodermal and hematopoietic necrosis virus

HPV = Hepatopancreatic parvo-like virus

REO = Reo-like virus

+ = Infection observed, but without signs of disease

++ = Infection may result in moderate disease and mortality

+++ = Infection usually results in serious disease in one or more life stages

e = Experimentally infected; natural infections not yet observed

** Classification according to Holthuis 1980, FAO Species Catalog.

subadult or adult P. stylirostris IHHN epizootic survivors, or in species such as P. vannamei which are readily infected by the virus, but seldom show diagnosable infection after the early juvenile stages).

26.2.3 Bioassay Diagnostic Procedures

Carriers of IHHNV may be detected by bioassay with sensitive "indicator" shrimp. Indicator shrimp in this procedure (juvenile P. stylirostris of 0.05 to 4 g body weight) may be exposed to samples of suspect carrier shrimp by one or more of three methods: 1) injection with a cell-free filtrate prepared from a homogenate of suspect carrier shrimp (the indicator shrimp will show signs of IHHN disease within 5 to 15 days if the suspect shrimp were infected with IHHNV); 2) rearing in the same tank suspect carrier shrimp with indicator shrimp (the indicator shrimp will show signs of IHHN disease within 30 to 60 days); and 3) feeding minced carcasses of suspect carrier shrimp to indicator shrimp (the indicator shrimp will show signs of IHHN within 15 to 30 days). In actual bioassay tests, the latter technique of exposure (i.e., feeding carcass fragments to the indicator shrimp) has become the method of choice.

26.2.4 Current Disease Specific Procedures

Actual diagnosis of infection by BP, MBV, HPV, IHHNV, and REO is dependent on microscopic or histologic demonstration of the particular cytopathology that is unique to each disease. Gross signs and behavior are usually not sufficiently specific in shrimp with infection by these penaeid viruses to be used reliably in diagnosing these diseases.

26.2.4.1 BP and MBV

Patent acute BP and MBV infections may be readily diagnosed by demonstration of their characteristic occlusion bodies in either wet-mounts of feces, hepatopancreas, or midgut, or in histological preparations of the latter two organs. BP occlusions are distinctive tetrahedral bodies (Couch 1974 and 1981) easily detected by bright field or phase microscopy in unstained wet-mounts of feces or tissue squashes (Fig. 1a & b), while MBV occlusions are spherical (Fig. 2a & b) and therefore difficult to distinguish from normal nuclei, lipid droplets, and secretory granules. The use of a stain, like 0.05% aqueous malachite green, in preparing wet mounts for MBV diagnosis aids in demonstration of the occlusion bodies (Lightner et al. 1983c). Apparently, the protein making up the occlusion absorbs the stain more rapidly than does most other material in the feces or in host tissues, contrasting them relative to other materials present within a few minutes (Fig. 2a).

BP and MBV occlusion bodies in histological preparations appear as prominent eosinophilic (with hematoxylin and eosin stain, H&E) single or more often multiple inclusion bodies within the hypertrophied nuclei of

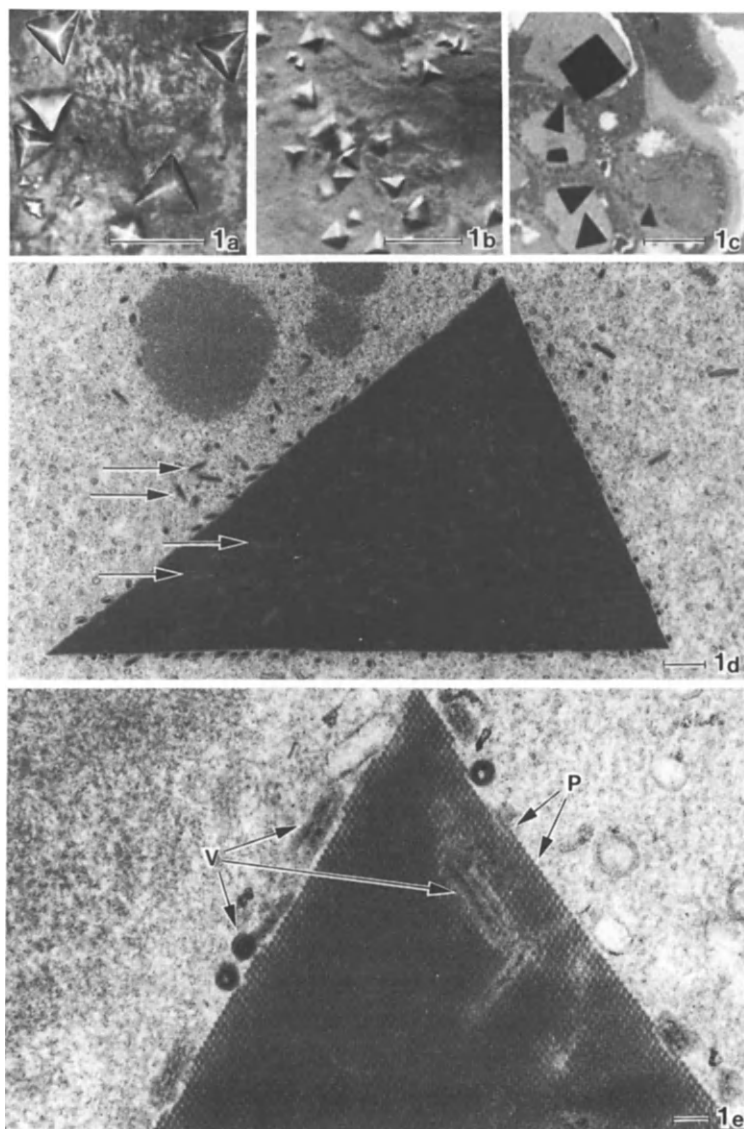


Figure 1. Baculovirus penaei (BP):

- 1a) & 1b) BP tetrahedral occlusion bodies as they appear in feces and tissue squashes from Penaeus vannamei; no stain. a) bright-field microscopy, X1,520; bar is 10 μ m; b) Hoffman interference contrast, X660; bar = 20 μ m.
- 1c) BP occlusions in a histological section of P. aztecus hepatopancreas. O-toluidine blue, X530; bar = 20 μ m.
- 1d) TEM of a BP-infected hepatopancreatocyte from P. marginatus. Rod-shaped BP virions (arrows) are present free in the karyoplasm and occluded within the tetrahedral occlusion body. X14,400; bar = 0.5 μ m.
- 1e) High magnification view of a BP occlusion body in the hepatopancreas of P. aztecus. Virions (V) are being occluded by proteinaceous polyhedrin (P) subunits of the occlusion body. X61,200; bar = 100 nm.

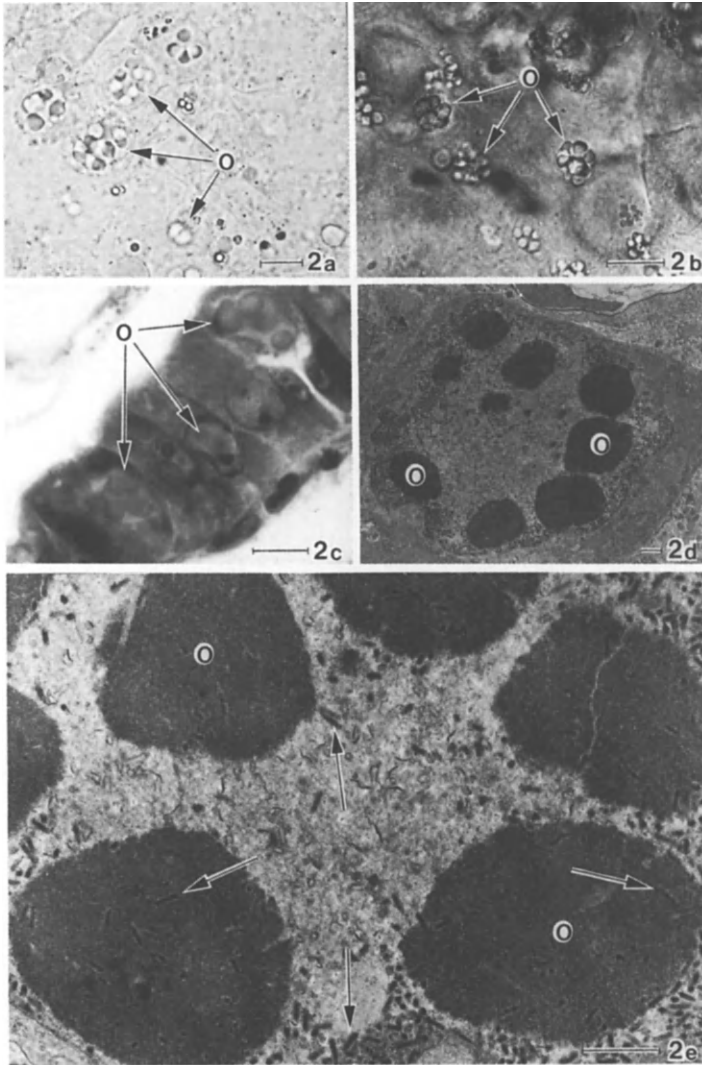


Figure 2. *P. monodon*-type baculovirus (MBV) in *P. monodon*, showing diagnostic spherical occlusion bodies (O) in:

- 2a) A wet-mount of an MBV-infected hepatopancreas cells. Malachite green stain, X660; bar = 10 μ m.
- 2b) In feces from an infected adult. No stain, X250; bar = 10 μ m.
- 2c) In hypertrophied nuclei of MBV-infected hepatopancreas. Histological section, H&E stain, X950; bar = 10 μ m.
- 2d) & 2e) By TEM in MBV-infected hepatopancreatocytes. Rod-shaped MBV virions (arrows) are apparent free and within the occlusion (O) bodies. d) X3,630; e) X13,300. Bars = 1 μ m.

hepatopancreatic tubule or midgut epithelial cells (Fig. 1c & 2c). The affected nuclei usually have a peripherally displaced compressed nucleolus and margined chromatin, giving affected nuclei a "signet ring" appearance even before occlusion bodies become well developed. Brown and Brenn histologic Gram stain (Luna 1968), although not specific for baculovirus occlusion bodies, tends to stain occlusions more intensely (either red or purple, depending upon section thickness, time of decolorization, etc.) than the surrounding tissue, aiding in demonstrating their presence in low-grade infections.

Transmission electron microscopy of BP and MBV infected cells show large numbers of rod-shaped baculovirus particles both free and occluded within the proteinogenous crystalline matrix of the occlusion body (Fig. 1d & e and 2d & e).

26.2.4.2 BMN

BMN affects the same target organs as does BP and MBV, but unlike BP and MBV it does not produce an occlusion body. Hence, its diagnosis is dependent upon history, clinical signs, and wet-mounts and histopathology of the hepatopancreas. Sano and coworkers (1984) in Japan have also reported development of a fluorescent antibody diagnostic technique for BMN. By wet-mount microscopy or histology the principal diagnostic feature of BMN is hypertrophied nuclei within infected hepatopancreatocytes (Sano et al. 1981; Momoyama 1983). These enlarged nuclei have margined chromatin, a laterally displaced or disassociated nucleolus, but lack occlusion bodies (Fig. 3).

26.2.4.3 HPV

Diagnosis of HPV is dependent upon the histological demonstration of single prominent basophilic (with H&E), Feulgen positive (Luna 1968) intranuclear inclusion bodies in the hypertrophied nuclei of infected hepatopancreatic tubule epithelial cells (Fig. 4a & b). Consequent lateral displacement and compression of the nucleolus and chromatin margination are also prominent features of such infected cell nuclei (Fig. 4a & 4c). Early in their development, HPV inclusions are small eosinophilic bodies centrally located within the nucleus and closely associated with the nucleolus.

TEM of HPV-infected hepatopancreatocytes shows the inclusion body to contain virus-like particles of 22 to 24 nm in diameter (Fig. 4d). HPV particle size, along with the features of host cell cytopathology, are quite similar to the reported characteristics of the parvovirus group (Kurstak et al. 1977; Longworth 1978; and Paradiso et al. 1982).

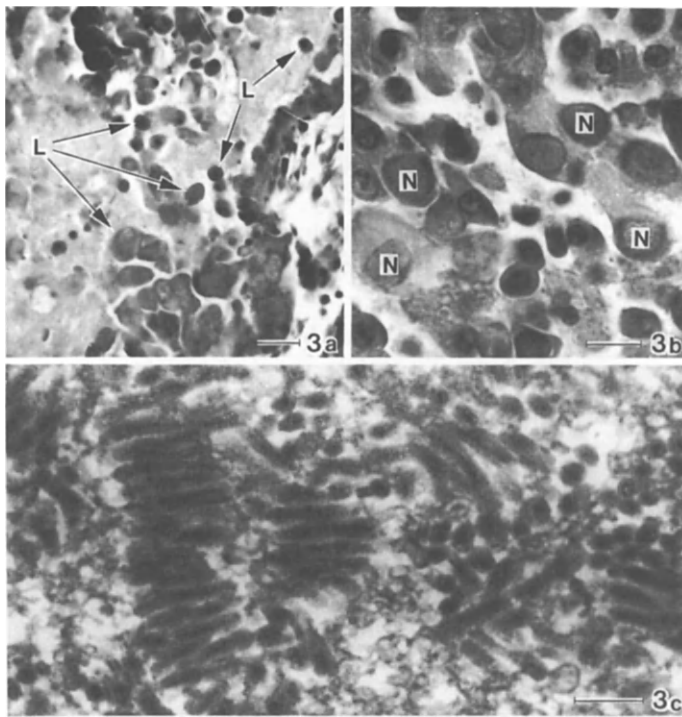


Figure 3. Baculoviral midgut gland necrosis virus (BMN) in *P. japonicus*: 3a) Histological section of necrotic hepatopancreas tubules from a postlarva. Tubule lumens (L) are filled with cell debris and necrotic cells (arrows). H&E stain, X380; bar = 20 μm . 3b) Hepatopancreatocytes with diagnostic hypertrophied nuclei (N) that do not contain occlusion bodies. H&E stain, X960; bar = 10 μm . 3c) TEM of a BMN-infected nucleus that contains masses of rod-shaped virions. X60,000; bar = 0.2 μm .

26.2.4.4 IHHNV

Diagnosis of infection by IHHNV is dependent upon histological demonstration of prominent eosinophilic (with H&E), Feulgen negative intranuclear inclusion bodies (Fig. 5a & b) within chromatin margined, hypertrophied nuclei of cells in tissues of ectodermal (epidermis, hypodermal epithelium of fore and hindgut, nerve cord, and nerve ganglia) and mesodermal origin (hematopoietic organs, antennal gland tubule epithelium, connective tissue, and striated muscle). Usually the midgut, midgut ceca, and the hepatopancreas (endoderm-derived tissues) are unaffected, except in severe cases where hepatopancreatic involvement has been observed (Lightner et al. 1985). These inclusions match closely the characteristics of the type A intranuclear inclusion body class described by Cowdry (1934). Basophilic chromatin strands are occasionally visible by light microscopy

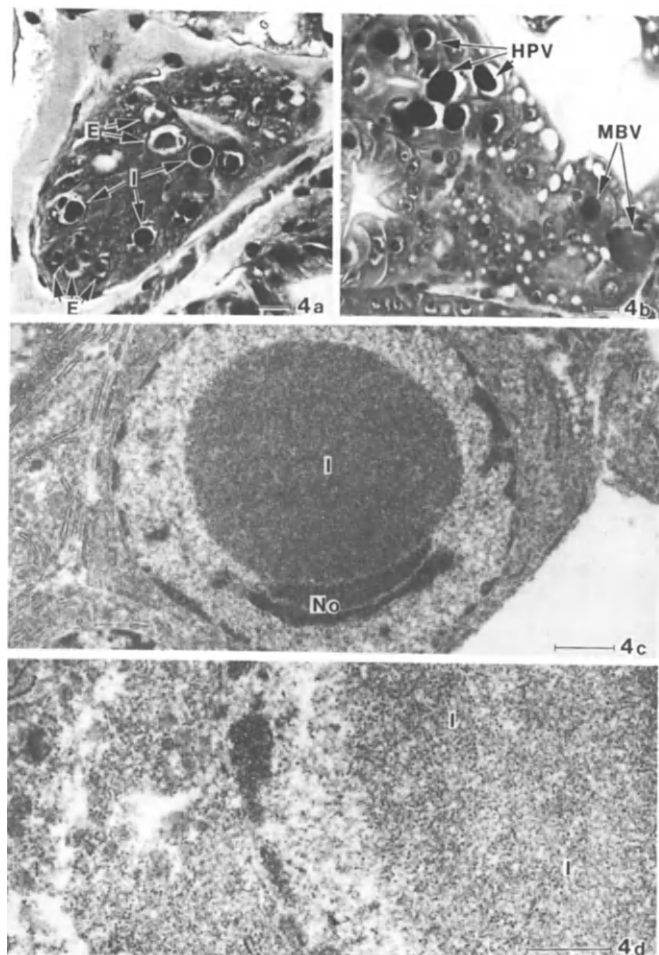


Figure 4. Hepatopancreatic parvo-like virus (HPV):

- 4a) Histological section of an HPV-infected hepatopancreas from a juvenile *P. monodon*. Infected cells nuclei contain prominent intranuclear inclusion bodies, which are relatively small and eosinophilic early in development (E), but are larger and basophilic when fully developed (I). H&E stain, X660; bar = 10 μ m.
- 4b) A dual infection of the hepatopancreas of a juvenile *P. monodon* by HPV and MBV. H&E, X530; bar = 10 μ m.
- 4c) TEM of a hepatopancreatocyte from *P. orientalis* showing an HPV intranuclear inclusion body (I), which is developing in close association with the laterally displaced host cell nucleolus (No). X11,900; bar = 1 μ m.
- 4d) A higher magnification TEM of an HPV-infected hepatopancreatocyte that shows unorganized masses of 22 nm diameter virions developing within the virogenic stroma of the inclusion body (I). X33,600; bar = 0.5 μ m.

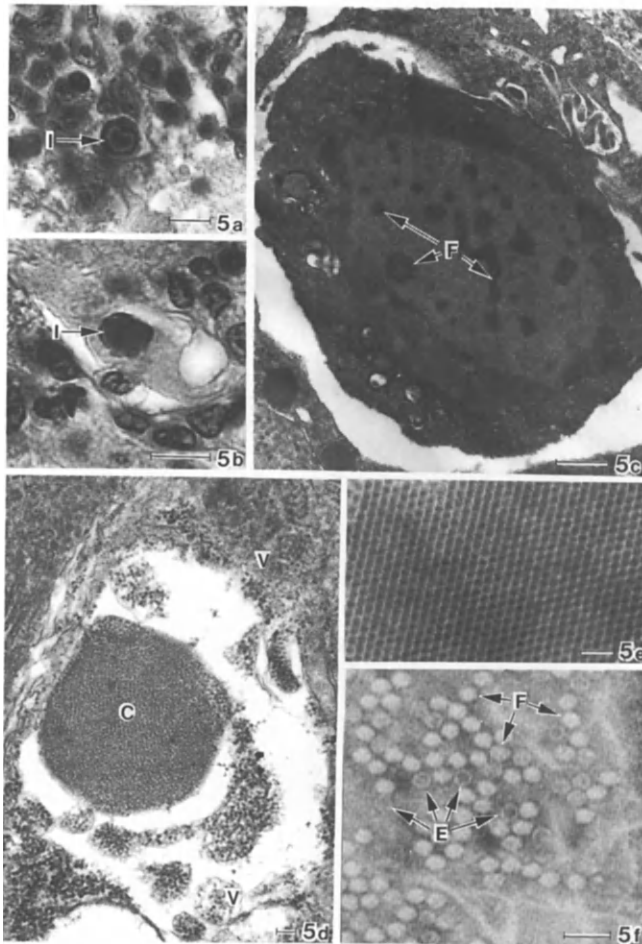


Figure 5. Infectious hypodermal and hematopoietic necrosis virus (IHHNV) in Penaeus stylirostris:

- 5a & 5b) Histological sections of intranuclear eosinophilic inclusion bodies (I), diagnostic of IHHN, 5a in a hematopoietic cell, X825, and 5b in a gill epidermal cell, X1,220; H&E stain; bars = 10 μ m.
- 5c) TEM of a gill podocyte with an IHHN intranuclear inclusion body. The dense fibrillar strands (F) are presumed to be regions of virus-induced nucleic acid embedded in a less dense granular material primarily of ribosomes and protein. No virus particles are evident in this cell's nucleus or cytoplasm; X10,600; bar = 100 nm.
- 5d) TEM of IHHNV present in loose aggregates (V) and condensed paracrystalline arrays (C) in the cytoplasm of an infected cell in the gills of a juvenile; X37,800; bar = 0.1 μ m.
- 5e) High magnification TEM of 20 nm average diameter virions of IHHN in a paracrystalline array; X130,000; bar = 50 nm.
- 5f) IHHN virus from density gradient centrifugation. Full (F) and empty (E) capsids are present; 2% PTA stain; X190,000; bar = 50 nm.

within IHHN intranuclear inclusion bodies. These chromatin strands are a prominent feature of IHHN intranuclear inclusion bodies by TEM (Fig. 5c).

IHHN intranuclear inclusion bodies are common early in acute infections, later decreasing in number, and are followed by necrosis and inflammation of target tissues. Affected cells may also have highly vacuolated cytoplasm with cytoplasmic bodies that range from eosinophilic to basophilic. Although the prominent intranuclear inclusions present in shrimp infected with IHHNV are evidence of nuclear involvement, assembly of the virus occurs in the cytoplasm of affected cells (Fig. 5d). The size and morphology of the virus, 17 to 26 nm in sections (Fig. 5e) and 20 to 22 nm in purified preparations (Fig. 5f), and its replication within the cytoplasm have been interpreted as evidence that IHHNV should be classified with the picornaviruses. However, recent data on the physiochemical properties of purified IHHNV indicate that the virus may be related to the Parvoviridae (Bonami et al. 1991).

26.2.4.5 REO

REO is the newest of the penaeid viruses and it was discovered by Tsing and Bonami (1987) in juvenile P. japonicus in France using electron microscopy, and subsequently, in the same species in Hawaii using the same technique (Lightner et al. 1985). Most recently REO, or a closely related form, has been found associated with a serious disease syndrome in pond-cultured P. monodon in Southeast Asia (Nash et al. 1988). In both species, other lesions were more apparent by light microscopy, and signs of REO infection were overlooked until found by electron microscopy. The virus was located in the cytoplasm of F-cells and R-cells of the hepatopancreatic tubule epithelium, where it formed large cytoplasmic viral inclusions (Fig. 6a). The non-enveloped, icosahedral virions of REO measured about 60 nm and 50 to 70 nm in diameter, respectively, in purified preparations and in tissue sections (Fig. 6b & c).

Tsing and Bonami (1987) experimentally transferred the disease in juvenile P. japonicus by inoculation of new host shrimp with purified virus or by feeding new host shrimp pieces of REO-infected hepatopancreas. Development of the infection was slow, requiring about 45 days to develop. Secondary infections by Fusarium solani were common in REO-infected shrimp. Some data (Tsing et al. 1985) suggested a probable link between infection by REO and "gut and nerve syndrome" (GNS), an idiopathic condition found in chronically ill populations of P. japonicus cultured in Hawaii (Lightner et al. 1984).

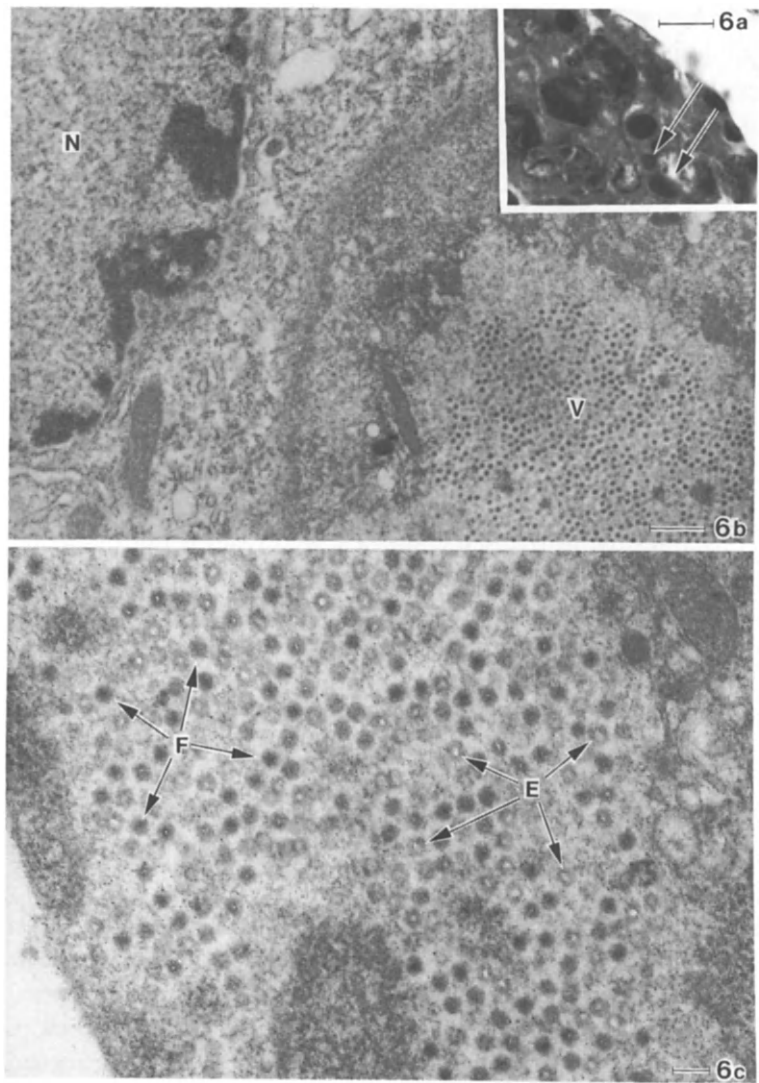


Figure 6. Reo-like virus (REO) in *P. japonicus*:

- 6a) Histological section of a REO-infected hepatopancreas of a juvenile. Magenta-staining cytoplasmic inclusion bodies (arrows) may represent virus masses. H&E stain; X960; bar = 10 μm.
- 6b) TEM of a REO virus mass (V) in the cytoplasm of a hepatopancreatocyte. The nucleus (N) of the cell appears unaffected. X18,900; bar = 0.5 μm.
- 6c) High magnification view of a cytoplasmic mass of REO showing both full (F) and empty (E) 55 nm average diameter virus particles. X190,000; bar = 100 nm.

26.3 HOSTS AND GEOGRAPHIC DISTRIBUTION

26.3.1 BP

BP is widespread in distribution in cultured and wild penaeids in the Americas (Table 3), ranging from the Northern Gulf of Mexico south through the Caribbean and reaching at least as far as the State of Bahia in central Brazil. On the Pacific Coast, BP ranges from Peru to Mexico, and it has been observed in wild penaeid shrimp in Hawaii. BP has not yet been observed outside of the Americas in penaeid shrimp which were wild, cultured or imported from the Americas. Recent new information on the host and geographic distribution of BP has come from Brazil and Mexico. In South America, BP was found to infect larvae and PL of five penaeid species: imported Penaeus vannamei and P. penicillatus; native P. schmitti, P. paulensis, and P. subtilis. Four of these represent new host species for the virus (Table 2).

BP was found for the first time in Mexico in cultured larval and post larval P. stylirostris at a facility near Guaymas, Sonora on the West Coast of Mexico (Lightner et al. 1989). Because the affected facility at that time had no history of stock importations, BP must be assumed to be enzootic in wild penaeids in the region.

26.3.2 MBV

MBV-type baculoviruses are analogous to BP in their diverse host range and in their wide distribution on the IndoPacific coasts of Asia, Australia, and Africa, and in Southern Europe (Table 3). However unlike BP, MBV has been observed in the Americas in imported stocks and in an American penaeid exposed to the virus. Although MBV was first discovered in a quarantined population of P. monodon that had originated from Taiwan (Lightner and Redman 1981 and Lightner et al. 1983c), it had not actually been demonstrated in Taiwan until it was found to be widely distributed in Taiwanese shrimp farms in a 1986 survey of the country (Lightner et al. 1987). Later studies have linked MBV to serious disease losses in many Taiwanese farms (Chen et al. 1989).

Since the information on MBV was last summarized, MBV has been found in Texas, South Carolina, Ecuador, and Brazil in imported stocks of P. monodon. Of possible significance was the presence of a low grade MBV infection found in the hepatopancreas of a juvenile P. vannamei that also had a heavy BP infection. In this instance both P. vannamei and MBV infected P. monodon were being cultured at the same Ecuadorian farm.

A similar agent, found first in P. plebejus and thus called Plebejus Baculovirus (PBV), was found in cultured penaeids in Australia (Lester et al. 1987). Other than its presence in a new host species, the agent of PBV

Table 3. Observed and reported occurrences of the penaeid viruses in wild and cultured penaeids indicating their probable natural and introduced geographic distributions.

Virus	Region/site where found	Host Status*	Virus Status
IHHNV	Atlantic: SE U.S., Caribbean, & Brazil	Cul	introduced
	Eastern Pacific: Ecuador, Peru, & Central America	Cul, CW, W	introduced?
	Central Pacific: Hawaii, Guam, French Polynesia	Cul	introduced
	Asia: Taiwan, Singapore, Malaysia & Philippines	Cul CW	introduced enzootic?
	Middle East: Israel	Cul	introduced
HPV	IndoPacific: P.R. China, Taiwan Philippines, Malaysia, Singapore & Australia	Cul, CW, W	enzootic
	Africa: Kenya	W	enzootic
	Middle East: Israel & Kuwait	Cul, CW	enzootic
	Americas: Brazil	Cul	introduced
BP	Atlantic: SE U.S., Caribbean & Brazil	Cul, CW, W	enzootic
	Eastern Pacific: Ecuador, Peru & Central America	Cul, CW, W	enzootic
	Mexico	Cul	enzootic?
	Hawaii	W	enzootic
MBV	IndoPacific: P.R. China, Taiwan, Philippines, Malaysia, Singapore & Australia	Cul, CW, W	enzootic
	Africa: S. Africa	W	enzootic
	Middle East: Israel & Kuwait	Cul, CW, W	enzootic
	Mediterranean: Italy	Cul, CW, W	enzootic
	Pacific: Tahiti, Hawaii	Cul	introduced
	Americas: Mexico, Ecuador Texas, and Brazil	Cul Cul	introduced introduced
BMN	Japan	Cul, CW, W	enzootic
REO	Japan, Malaysia	Cul	enzootic
	Hawaii & France	Cul	introduced

* Cul = "cultured"; from cultured or captive-wild broodstock.

CW = "captive-wild"; from wild-caught seed or from single-spawn wild broodstock.

W = "wild"; from natural sources or commercial fishery.

differs little from MBV in host cell cytopathology and in the morphology of the virus, and it probably represents a strain of the MBV-type viruses rather than a separate distinct virus type (Doubrovsky et al. 1988).

26.3.3 BMN

BMN has been reported only in P. japonicus cultured in Japan (Table 3), where it is considered a major problem in the larval and early postlarval stages of that species (Sano et al. 1984 and 1985; and Sano and Fukuda 1987). Despite numerous introductions of P. japonicus stocks (larvae, PL, and broodstock) to Hawaii, France, Brazil, and other locations during the past two decades, BMN has not been reported in that species or in other penaeids cultured outside of Japan, in the Americas, or elsewhere.

26.3.4 HPV

HPV has a geographic range similar to that of MBV in Asia and Australia (Table 3), and like MBV it has been introduced to the Americas with imported penaeids. More recently, HPV was found for the first time in Taiwan in dual infections with MBV in postlarval and juvenile P. monodon sampled from farms in the Pingtung area of Southern Taiwan (Fig. 4b). This region in 1987 and most of the shrimp growing areas in 1988 had experienced serious disease losses in its farms due, at least in part, to MBV. The severity of HPV infections in some of the shrimp sampled suggests that HPV, while unrecognized, may have contributed to the 1987 and 1988 epizootics.

Reports of HPV in captive-wild P. esculentus in Australia (Paynter et al. 1985), in P. monodon imported to Israel from Kenya (Colorni et al. 1987), and in captive-wild and hatchery reared P. indicus and P. merguensis in Singapore (Chong and Loh 1984) have expanded the known host and geographic distribution of this virus (Tables 2 and 3). In the Singapore study, of four shrimp farms surveyed, HPV incidence was highest (>50%) in the two farms that reared hatchery-derived post-larvae, and lower (<15%) in the two farms which cultured only feral shrimp collected by tidal entrapment (Chong and Loh 1984). This suggests that HPV is transmitted either vertically from parent broodstock, or horizontally from shrimp to shrimp with efficiency only during the larval stages.

HPV has been observed in the Americas. In Brazil in 1987, HPV was found in stocks of P. penicillatus imported from Taiwan. At the same culture facility, HPV was found in light infections in juvenile P. vannamei, which had been exposed to infected P. penicillatus indirectly as a result of normal farming practices. The discovery of HPV in cultured shrimp in Brazil represents the first time this pathogen has been documented in the Americas and in an American penaeid (S. Bueno, R. Meyer Nascimento, and D. Lightner, unpublished observations).

26.3.5 IHHNV

IHHNV has a world-wide distribution in cultured penaeid shrimp (Table 3), but its distribution in wild penaeids remains unknown. Infection by the virus causes serious disease in *P. stylirostris*, and acute catastrophic epizootics in intensively cultured juveniles of that species. In other penaeids, IHHNV has been reported to cause infection and disease (Brock et al. 1983; Lightner et al. 1985; and Lightner 1988), but disease severity does not approach that observed in *P. stylirostris*. The natural host(s) and geographic distribution of IHHNV is unknown. However, the occurrence in Southeast Asia (Singapore, Malaysia, and the Philippines) of IHHNV (or a similar agent) in shrimp culture facilities using only captive-wild *P. monodon* broodstock suggests that the region is within the virus' geographic range, and that *P. monodon* may be among its natural host species.

Since 1985, no new hosts for IHHNV have been demonstrated. However, the geographic distribution of the virus in culture facilities has continued to expand. In Mexico in 1987, IHHNV was found in an imported population of post-larval *P. vannamei* at a facility in Baja California (Lightner, unpublished data). Likewise, IHHNV was found to be present in imported quarantined stocks of *P. vannamei* in a 1986 survey of Taiwanese shrimp culture facilities, but not in cultured stocks of other penaeid species, including *P. monodon*, at the farms surveyed (Lightner et al. 1987).

26.4 DISCUSSION AND CONCLUSIONS

The present diagnostic procedures for the penaeid virus diseases are largely dependent upon history, clinical signs, and histopathology. Electron microscopy is also of importance in some diagnostic applications. Techniques like enhancement and animal bioassays when coupled to histopathology add sensitivity to these diagnostic procedures.

These procedures, however, are very limited. Examination of relatively small samples is one important limitation; the length of time required to carry out routine histopathology and/or electron microscopy is another factor limiting their practical usefulness. Also, the cost of histopathology, electron microscopy, of maintaining enhancement and bioassay areas, and the limited availability of specific pathogen-free indicator shrimp for bioassays, all add to the list of reasons why better, more rapid, more sensitive diagnostic procedures are needed.

Methods using tissue culture, serologic methods, and gene probe diagnostic techniques that have become state-of-the-art in human and veterinary medicine, are being developed for penaeid shrimp. For example, the first documented success at producing primary cell cultures from shrimp was recently reported (Chen et al. 1986). However, while development of

Table 4. Penaeid viruses in the Americas and their status.

Virus	Status in the Americas and Hawaii
IHHNV	Widely distributed in cultured <u>P. vannamei</u> and <u>P. stylirostris</u> ; not recognized in wild American penaeids except possibly in Ecuador; enzootic in Southeast Asian wild penaeids; recently introduced into Western Mexico.
HPV	Enzootic in Asia, Australia, and Africa; introduced to one or more sites in South America from Taiwan; will infect the American penaeid <u>P. vannamei</u> .
BP	Widely distributed in American penaeids; enzootic in wild penaeids on both Atlantic and Pacific sides of tropical and subtropical America.
MBV	Enzootic in Asia, Australia, Africa, and Mediterranean; introduced to several sites in Hawaii, North, Central, and South America; will infect <u>P. vannamei</u> ; contaminated stocks eradicated from Hawaii, Mexico, and Texas.
BMN	Enzootic in Japan; not reported outside of Japan.
REO	Enzootic in Japan; introduced to Hawaii from Japan; contaminated stocks eradicated in Hawaii.

these techniques for use with shrimp is underway, none are yet routinely available to the diagnostic labs of the industry. As the new diagnostic methods do become available, they should provide more rapid diagnoses than do current methods; they should be very sensitive and easily standardized among various labs that use them; and they should be inexpensive and simple to run.

The practice of transporting penaeids stocks between facilities and between different geographic regions has resulted in the introduction of five of the six known penaeid shrimp viruses to regions where they may not have previously existed. Five of the six known types of penaeid viruses are apparently not native to the Americas, but of these five, four (IHHNV, MBV, HPV, and REO) have been introduced with shrimp intended for aquaculture (Table 4). Whether or not these introduced viruses have escaped the culture facilities to which they have been introduced and have become established in local wild penaeid stocks is not known.

While evaluation of non-native penaeids by the emerging shrimp culture industry is an essential component to the growth and development of that industry, introduction of pathogens like IHHNV to regions where it previously did not occur can have catastrophic consequences to the industry (Lightner et al. 1983a; 1983b; and Lightner 1988). Prevention of such introductions of exotic pathogens is dependent upon the use of quarantine,

certification and inspection policies, and procedures that are supported by reliable diagnostic procedures. Sindermann (1988) provided a copy of the "Revised Code of Practice to Reduce the Risks of Adverse Effects Arising from Introduction of Non-indigenous Marine Species" as adopted in 1979 by the member countries of the International Council for the Exploration of the Sea. The practices outlined in this code, if practiced, are effective for their intended purpose. Adoption and implementation of such a policy by the penaeid shrimp aquaculture industry of the Americas may be in the best interest of that emerging industry.

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CHAPTER 27

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PENAEID MARKETS AND ECONOMICS

27.1 INTRODUCTION

Success of a shrimp culture system depends primarily, if not exclusively on its profitability. Profit can be simply defined as the difference between total gross income and total production cost. Gross income, in turn, depends on production level and farm price. Therefore, three major factors affect shrimp culture profitability; production level, production cost, and farm price.

The first two factors are related to production economics, while the third factor is related to marketing economics. Both production and marketing economics of shrimp culture will be reviewed and discussed here.

27.2 PRODUCTION ECONOMICS

Yield level and production cost for a shrimp farm depend on many technical and economic elements. Before reviewing some of these elements, let us identify the major cost items in shrimp culture. As with any business, shrimp farming expenses can be grouped into two categories: fixed and variable costs. Fixed costs include facility and equipment depreciations, interests on loans, land lease, fixed wages, etc. These usually do not change with total production level; however, as production increases, fixed cost per kg of shrimp output decreases. Variable costs, which include costs of seed, feed, hired labor, energy, etc., increase with production level and intensity.

Case studies indicate that seed and feed are the most important cost items for shrimp farming (Table 1). Their combined costs range from 41 to 83 % of total annual operating cost. Labor, depreciation and energy are the other important cost items.

The following section reviews the major factors affecting production economics of shrimp farming, including farming intensity, stocking and harvesting strategies, polyculture, multi-cropping, economies of scale, tidal vs. pumped water systems, and water quality. Lastly, methods of production economic analysis are presented.

27.2.1 Farming Intensity

Farming intensity affects relative costs of major inputs. Extensive culture is often practiced in the areas with ample wild seed supplies, inexpensive land, water and labor, and high cost of borrowed capital; while intensive culture is

TABLE 1. Major cost items (%) of shrimp culture in semi-intensive or intensive operations.

Major Cost Item	Ecuador ¹	China ²	Japan ³	Indonesia ⁴	Philippines ⁵	Taiwan ⁶	Texas ⁷	Thailand ⁸
PL (Seed)	27	6	5	30	9	15	27	20
Feed and Fertilizer	25	77	43	45	32	43	30	29
Electricity and Fuel	4	--	12	--	--	5	3	7
Labor	3	12	9	13	11	7	10	9
Maintenance	4	--	11	--	--	2	2	3
Interest	24	--	--	--	--	7	6	8
Depreciation	9	--	3	--	--	3	9	18
Miscellaneous	4	5	17	12	48	18	13	6

¹ Liu, (1989) (semi-intensive operation).⁵ IFC (1984).² Shang (1989).⁶ Chiang and Liao (1985; *P. monodon*).³ Hirasawa (1984) (Kuruma shrimp, intensive).⁷ Griffin, et al. (1985; semi-intensive operation).⁴ Hung, et al. (1988) (*P. monodon*, intensive culture)⁸ Hanvivatankit (1988; *P. monodon*, semi-intensive).

usually practiced in areas with relatively high cost of land, water and labor, and with low cost of borrowed capital. For example, in Japan and Taiwan, intensive culture is prevalent, while in Ecuador, Indonesia, the Philippines and Thailand, extensive and semi-intensive culture systems are more popular. When culture intensity increases, stocking rate, aeration intensity, and feeding rate all increase. Therefore, the higher the culture intensity, the higher the operating capital required and the higher the risks involved. Many farmers, especially small-scale operators in developing countries, often cannot afford to adopt more intensive culture. A study in the Philippines (Israel et al. 1985) found that extensive shrimp culture is preferred over semi-intensive culture by traditional shrimp farmers, mainly due to high costs of feed, fuel and risk of the latter culture system.

As culture intensity increases from low level extensive, total yield and total production cost per unit of area increase, but production cost per unit (kg) of shrimp output may decrease first and then increase after a certain

TABLE 2. Cost of *P. monodon* culture in Thailand (per ha).

	Extensive		Semi-intensive		Intensive	
Variable Costs						
Seed	\$350	17%	\$1,842	22%	\$2,708	15%
Feed	288	14	2,612	32	6,316	34
Hired labor	50	2	135	2	1,848	10
Electricity and fuel	221	11	658	8	2,355	13
Maintenance	170	8	290	4	401	2
Opportunity cost of family labor	293	14	631	8	511	3
Sub-total	<u>\$1,372</u>		<u>\$6,168</u>		<u>\$14,139</u>	
Fixed Costs						
Depreciation	254	12%	766	9%	1,968	10%
Interest	202	10	773	9	1,724	9
Land lease	235	11	514	6	514	3
Sub-total	<u>\$691</u>		<u>\$2,053</u>		<u>\$4,206</u>	
Total Cost	<u>2,063</u>		<u>8,221</u>		<u>18,345</u>	
Total Revenue	<u>1,763</u>		<u>15,915</u>		<u>33,434</u>	
Profit before tax	<u>-300</u>		<u>7,694</u>		<u>15,089</u>	
Average production/ha/yr ^a	188 kg		2,135 kg		4,487 kg	
Cost of production (\$/kg)	10.97		3.85		4.09	
Ratio between profit and total cost(%)	-15%		94%		82%	

^a Average crops/year: extensive= 1.77, semi-intensive= 1.93, intensive= 1.93.

Source: Hanvivatanakit, 1988.

level of yield (Hirasawa 1985). This principle was clearly shown in a recent economic analysis of *P. monodon* farming in Thailand (Table 2). Total production cost increased first when culture method changed from extensive to semi-intensive. Production costs increased again following further intensification from semi-intensive to intensive. Based on unit production cost and the ratio between profit and total production cost at a given farm gate price, semi-intensive culture in this case was more profitable than the other two systems.

A comparative economic study of extensive, semi-extensive and semi-intensive shrimp farming systems in Ecuador (Griffin et al. 1985) revealed that internal rate of return for semi-intensive culture was much higher than for the other two systems. Another study surveyed extensive and semi-intensive shrimp farms in Ecuador (Table 3) and found that (1)

fertilization plus feeding increased production dramatically, (2) stocking with large size postlarvae (PL), although more costly, reduced the rearing period and increased the possible number of crops per year, and (3) as stocking density increased, production per unit area improved, but the growth rate and size of the shrimp decreased. Shrimp were harvested either at a small size, or the rearing period was extended to produce larger shrimp. Smaller size shrimp command a relatively low price, and a longer rearing period would mean higher production costs and risks. Individual shrimp size significantly affects farm income. Johns et al. (1986) found that production per ha with two crops per year in Texas is greater than one crop, but that a farm with two crops per year received less income due to smaller shrimp and lower price per unit production.

A Taiwan study (Chiang and Liao 1985) found that production cost per kg of shrimp decreased, and rate of return on investment increased, as stocking density increased. This study concluded, however, that higher stocking without proper management does not necessarily guarantee higher profit. A recent study in Hawaii (Leung et al. 1988) indicated that intensive P. vannamei culture is more profitable there than extensive and semi-intensive systems, due to relatively high costs of land and labor.

The economic trade-offs of production intensity through high or low stocking density, feeding or no feeding, stocking small or large PL, and one or two crops a year should be evaluated in each case based on existing environmental and economic conditions.

27.2.2 Stocking and Harvesting Strategies

Stocking and harvesting strategies are important factors affecting shrimp farm profitability. Extensive and semi-intensive culture methods can be greatly improved by using the "progressive system", and "continuing system" of pond management (Hirasawa 1985). The progressive culture system uses a series of nursery and grow-out ponds of various sizes. The shrimp stock is moved from densely stocked small ponds to progressively larger ponds. The smaller ponds are then cleaned and re-stocked. Using this method, it is possible to double the number of harvests within a year. The continuing culture system is the stocking of different shrimp cohorts in a given pond, with staggered harvests. Using this system, pond production can almost double.

Given variable growth rates under different conditions, prices of different sized shrimp, and costs of production at different culture stages, a management tool is needed to guide stocking and harvesting schedules in order to maximize farm profit. A dynamic decision model for shrimp farms has been developed in Hawaii to determine optimal stocking and harvesting schedules (Leung et al. 1989). This model provides a simple set of

Table 3. Survey of shrimp farms in Ecuador

	Intensity of Culture		
	Extensive ^a	Semi-intensive A ^b	Semi-intensive B ^c
	Rearing Period (days)		
<u>Stocking Size</u>			
PL 20	150-160	130-145	130-145
Juveniles	110-130	90-120	90-120
	Avg. Weight Harvested		
<u>Stocking density (#/m²)</u>			
1.5	23 g	-	-
2.0	17 g	30 g	-
4.0		19 g	-
8.0			17.7 g
	Kg/ha/crop		
	136-318	273-682	546-1590

^a no feeding^b fertilization and supplemental feeding^c continuous feeding

optimization policies for each calendar week, and for each given age of crop. Application of this model to a hypothetical shrimp farm in Hawaii indicates that net return can increase three times by applying these policies, compared with a conventional fixed scheduling scheme.

27.2.3 Polyculture

Polyculture of shrimp with suitable species may be economically feasible in some cases. Polyculture of shrimp with oyster was explored by a private shrimp farm in Texas. Integrated shrimp and oyster culture, using shrimp pond waste waters for oyster culture is being evaluated at the University of Hawaii. Preliminary data indicate that these culture systems are promising, but not yet ready for commercialization.

When shrimp, the primary species, is polycultured with a low value species, net income may be reduced if shrimp stocking rate is reduced. A survey of Taiwan shrimp farms (Chen 1980) indicated that net income from monoculture farms is about double that of polyculture farms (e.g. polyculture with milkfish). The ratio between net revenue and operating cost is also higher for monoculture farms, even though of production costs are relatively high.

27.2.4 Extended Season

A recent economic study of shrimp farming in Texas concluded that by far the most cost efficient method to increase profit margins is to increase the growing season by introducing a cold tolerant species, such as *P. chinensis* or *P. penicillatus*. In addition to obvious benefit to farmers in places with a limited growing season, producing a second crop would greatly benefit the auxiliary shrimp seed production industry. Currently, with only one crop/year, hatcheries and trained personnel are under utilized on an annual basis. Economic feasibility of such a multi-species culture system, however, awaits evaluation.

27.2.5 Economies of Scale

There are definite economies of scale in both hatchery and pond rearing operations. Simon (1983) estimated that price per thousand of hatchery produced PL should be \$12 for a hatchery sized to supply a 42 ha (100-acre) farm, and \$34 for a hatchery sized to supply a 8 ha (20-acre) farm.

Griffin et. al (1985) analyzed construction cost sensitivities of farm size and pond size. Their study revealed that total investment decreased as pond size increased for a given farm size. There was a sharp reduction in construction cost when a farm exceeded 100 ha, and pond size increased from 2 to 4 ha. Total operating cost per kg of shrimp production declined as the farm and pond sizes increased.

Hirasawa (1985) found that, with white shrimp culture in Thailand, productivity (kg/ha) decreased with increased farm size, while production costs per kg of shrimp (\$/kg) decreased first and then increased as farm size increased. A farm having 4.8 to 9.4 ha was most profitable, based on net profit per kg.

Optimal farm or pond size depends on many bio-technical and socio-economic factors. It would be difficult to determine the best or most profitable operation size without a more comprehensive, site specific study.

A systems approach integrating all the relevant factors is being developed at the University of Hawaii (Leung et al. 1989).

27.2.6 Tidal vs. Pumped Water

Many shrimp farms in Southeast Asia rely on tidal water exchange for ponds. This has resulted in inefficient management and low yield. With water pumping systems, pond filling, draining, and harvesting can be done at almost any time without need to wait for high or low tide. More frequent filling and draining is likely to improve pond water quality, with resultant higher shrimp stocking rates, better growth and survival, and higher production rates. With pumped water systems, labor management is much easier, and harvesting does not have to be done during the limited time of

low tide, nor is a large temporary labor force needed for harvesting. Pumped water systems allow farms to be built behind the mangrove zone, and require relatively narrow dikes compared with tidal-operated systems. Therefore, pond area for a given size farm would be larger. Small dikes also reduce surface area for acid-sulfate runoff. This is likely to improve pond water quality, and consequently increase the productivity. A comparative economic study in Malaysia indicated that a pump-operated system is more economical than a tidal-operated system (Gedney et. al. 1982).

27.2.7 Water Quality

Water quality is an important factor affecting shrimp pond productivity. The biomass cultured within a given space depends on dissolved oxygen concentration and other water quality values. Data from Taiwan and Japan show close positive relationship between shrimp productivity and daily water exchange rate (Hirasawa 1985). Dissolved oxygen can be improved by aeration. In addition, salinity requirements change with shrimp size, especially in P. monodon culture. In Taiwan, sea water and fresh water (from wells) are pumped and blended in order to create the most suitable salinity for any stage of shrimp growth. These methods for water quality improvement are economically feasible when added benefits exceed additional costs.

27.2.8 Social Benefit and Cost

The previous sections reviewed economics of shrimp production at the farm level only. Economic feasibility assessment of shrimp development projects should not be based exclusively on business criteria, i.e. profit making, but on social benefits and costs as well. Social benefits and costs have a broader scope than private sector revenues and costs, because the former include both direct and indirect effects on society as a whole. For instance, ground water over-draft of shrimp culture in Taiwan has caused a serious land subsidence problem in coastal areas, and damages to other uses and activities. Shrimp culture development in mangrove areas of several Asian countries conflicts with commercial fisheries development and other uses. These impacts are often difficult to quantify, but they should at least be qualitatively assessed since they are important for decision making.

27.3 METHODS OF ANALYSIS

Production economic analysis is essential to evaluate investments in shrimp farming, to determine the efficiency of resource allocation, to improve existing management practices, and to evaluate new culture technologies. Analytical methods for shrimp farming can be summarized into five categories.

27.3.1 Cost-Return Analysis

This is the most common method used to evaluate economic feasibility (e.g. Table 2). It answers questions such as, "How much will it cost to start the business?", "How much does it cost to operate the farm annually?", "What are the major cost items?", "Is it profitable to invest in this venture?", "What is the average rate of return to capital, land, and labor?", "What is the break-even production and price level?", "How many years does it take to recover the initial investment?". This method has also been used to compare economic feasibility of different systems and practices, such as extensive versus intensive, monoculture versus polyculture, etc., and to evaluate the economics of different size operations or different facility designs.

27.3.2 Partial Budget Analysis

This method is usually used to re-evaluate economic feasibility of a minor change in a production technique resulting in partial change in the cost-return structure. For example, economic feasibility of adding nursery ponds to production ponds, adding aerators or pumps to production ponds, using automatic feeders, making minor changes in pond design, etc. can be evaluated by partial budget analysis.

27.3.3 Production Function

This method is used to estimate physical input-output relationship, followed by marginal analysis to evaluate the producer's farming efficiency. Results of this analysis can be used to answer such questions as, "Which inputs are significant in explaining variation in output?", "Are there economies of scale in production?", "Are producers making optimal use of inputs?". A production function analysis of marine shrimp farming in Thailand was done by Tokrisna (1979).

27.3.4 Bio-economic Modeling

This analysis takes into account bio-technical, environmental and economic elements, and their inter-relationships throughout the entire production process. It is one of the most promising approaches for improving shrimp farm management efficiency (Leung et al. 1989).

27.3.5 Discounting Method

Economic feasibilities of private or public shrimp investment projects are often analyzed by the discounting method where annual benefit and cost streams are converted into present values. Net present value, benefit-cost ratio, and internal rate of return can then be calculated. For private shrimp investments, annual revenues and costs at farm level are the base for calculation; while with public shrimp investment projects, the usual concern

is with benefits and costs to society as a whole. A financial analysis (private investment) of shrimp production using an electronic spreadsheet model is a good example of this approach (Leung and Rowland 1989).

27.4 SHRIMP MARKETING

World demand for shrimp has grown very rapidly during the past decade. In view of stagnant production from the world's ocean, shrimp aquaculture has emerged as an important industry to fill the gap between future supply and demand. As a percentage of world shrimp production, cultured shrimp increased from about 2% in 1980 to 26% in 1989 (Aquaculture Digest 1989). Most farmed shrimp entered international trade. The United States, Japan, and Europe are the major shrimp importers. The following sections will review supply and demand, market structures, and prices of shrimp in these three major markets.

27.4.1 U.S. Market

Total U.S. market supply of shrimp has increased from 231 to 349 million metric tons (MT, head off weight) between 1980 and 1988, a 51% increase. These shrimp supplies come from two sources: domestic catch and imports. Decreased and unstable domestic shrimp supply was counterbalanced by higher imports. Shrimp import share, as a percentage of total domestic supply, increased from 51% in 1980 to 78% in 1988 (Table 4).

Traditionally, Latin America, primarily Mexico and Ecuador, have been the major source of imported shrimp for the U.S. market. In 1988, however, China became the most important source of imports. Shrimp imports from other Asian countries such as India, Philippines, Thailand, and Taiwan (up to 1987) have also increased (Table 5). Market demand and lure of lower prices finally interested more U.S. importers in Asian shrimp.

Major product forms of imported shrimp are raw headless shell-on (about 50%) and raw peeled products (about 37%). Eating satisfaction, ease of preparation, and quality are important factors determining product preference. Demand for prepared convenience foods is expected to rise. For shell-on shrimp, certain U.S. regional purchase patterns are evident; premium white shrimp is generally desired on the west coast and the northeast, brown in the midwest, and pink in the southeast. In the U.S. market, the size "count" usually refers to the number of shell-on, headless (frozen) shrimp tails per pound. Large shell-on shrimp (size 21/25) are consumed primarily by the better restaurants. Supplies of large size shrimp are usually from Mexico, U.S. domestic catch and Panama. Medium size shrimp (size 26/30s through 41/50s) are mainly imported. Dramatic increases in imports of these sizes in recent years resulted in a sharp price decline. The large price difference

TABLE 4. Tonnage from all sources of U.S. shrimp supplies, 1980 - 87.

	1980	1981	1982	1983	1984	1985	1986	1987	1988
	(x1000 M.T., heads-off weight)								
Domestic catch	94.5	99.5	79.8	70.7	85.5	94.2	111.1	101.6	92.4
Imports	117.3	117.8	145.3	191.5	192.0	205.6	223.6	265.0	272.0
Exports	18.7	19.9	16.9	16.3	12.1	12.3	13.8	15.4	15.9
Net supply	230.5	237.2	242.0	278.5	289.6	312.1	348.5	351.2	348.5

Source: Fisheries of the United States, 1987-1988.

between this size and larger sizes has made medium size shrimp very attractive to restaurants. Small size shrimp (51/60s through 80/over) are very versatile. They can be used by processors, by supermarkets as "attention-getters" because of their lower price, by restaurants as low cost shrimp items, and by fast-food chains (Filose 1988).

U.S. shrimp consumption is primarily determined by the condition of the domestic economy. Fluctuations in disposable personal income have a dramatic impact on shrimp consumption. Income elasticity of demand for imported shrimp in the United States is estimated at 2.04 (Prochaska et al. 1983). This means a 1% increase in income will cause a 2.04% increase in shrimp consumption when shrimp prices remain stable. Decreased personal income will decrease shrimp consumption by the same ratio. Steady growth of the U.S. economy has led to a sustained growth in per capita and total shrimp consumption. Other factors contributing to the growth in U.S. shrimp consumption include improved quality and availability of shrimp, and relatively higher prices of other seafood products competing in the same market category. Real (constant) shrimp prices for most sizes, have a flat to downward trend since 1979 (Vondruska 1989). Price elasticity of demand for shrimp in the U.S. is about 0.29; which means a 1% increase in shrimp price will result in a 0.29% decrease in shrimp consumption, when income remains stable (Prochaska et. al. 1983).

About 80 percent of all shrimp is currently consumed in restaurants. Shrimp has become the leading seafood menu item in more food outlets. Home consumption of shrimps is likely to increase.

U.S. shrimp prices depend upon size, species, quality, and source. Larger shrimp command higher prices. White shrimp generally commands a premium over other colors. Price for peeled and deveined shrimp is usually higher than headless shell-on to the extent of weight loss caused by removing the shell, and the additional labor cost. In practice, this relationship is often over-ridden by supply and demand factors. Quality is another factor affecting shrimp prices. The same shrimp species and size from different sources may

TABLE 5. U.S. shrimp imports by major countries, 1980-88.

Country	1980	1981	1982	1983	1984	1985	1986	1987	1988
(1000 M.T., product weight)									
China	0.4	2.3	1.3	0.9	1.5	3.1	9.4	19.3	47.4
Ecuador	9.2	11.2	16.4	23.4	21.2	20.0	28.2	46.1	47.3
Mexico	34.6	32.2	36.5	38.5	19.0	30.7	33.8	39.1	28.9
India	5.9	8.6	12.2	13.7	10.5	10.9	11.1	12.9	14.6
Thailand	4.0	3.0	3.6	8.8	8.3	11.1	11.0	11.0	10.8
Brazil	4.0	5.0	5.8	6.6	9.0	11.5	9.1	7.6	9.1
Taiwan	2.5	2.5	4.2	9.1	8.3	13.5	15.7	16.9	7.9
Panama	6.2	7.2	8.0	7.4	7.4	9.0	9.9	7.6	6.7
Other	32.9	29.3	36.6	47.0	52.4	53.9	53.7	57.2	56.4
Total	99.7	101.3	124.5	155.2	155.7	163.6	181.9	217.4	229.1

Source: Globefish, Mar. 15, 1989.

command different prices due to the producer's reputation for good quality and weight, accurate counts and uniformity of size and color.

Shrimp prices in the U.S. tend to follow a seasonal pattern. The price of each size tends to drop as domestic production of that size increases. The domestic Gulf of Mexico season starts in May-June, and shrimp size increases as the season advances.

Shrimp price variation in the U.S. became more sophisticated recently. World shrimp production, the world economy, and market situations in other major shrimp markets, especially Japan, are important factors affecting shrimp price in the U.S.

27.4.2 Japanese Market

Total shrimp supply in Japan increased from 196 to 306 thousand MT between 1980 and 1988, a 56% increase (Table 6). The growing demand for shrimp in Japan has been met mostly by imports since domestic production is small and declining. Shrimp imports have provided over 80% of total supply since 1986. Indonesia and China were the top suppliers in 1988 (Table 7). Taiwan declined from the top position since 1987 to fifth place in 1989, as epidemic mortality on Taiwan shrimp farms severely cut production and exports. Thailand, with rapidly expanding cultured shrimp production, emerged as an important supplier to Japan in 1988.

Increased demand for shrimp in Japan is mainly due to the substantial increase in personal disposable income, traditional values associated with eating shrimp, population increase, and urbanization (Eys 1987). Income elasticity of demand for imported shrimp in Japan is estimated at 1.03

TABLE 6. Shrimp supplies in Japan.

Year	Domestic landings	Imports (1000 MT)	Total supply	Imports as % of total supply
1980	52.4	144	196	73
1983	64.4	149	213	70
1985	55.0	183	238	77
1986	47.9	213	261	82
1987	48.3	246	294	84
1988	47.8	258	306	84

Source: FAO Yearbook of Fishery Statistics; Globefish, March 15, 1989.

(Hirasawa 1988), where a 1% increase in income will result in a 1.03% increase in shrimp demand when shrimp prices remain stable. Another factor contributing to increased supply and demand for shrimp, is the recent rise in value of Japanese Yen against the U.S. dollar. Also, shrimp prices (in Yen) had a downward trend since 1982. Price elasticity of demand for imported shrimp in Japan is about 0.68 (Hirasawa 1988), which means a 1% change in price will result in a 0.68% change in demand in the opposite direction.

Regional preferences exist within Japan. Consumers in southern Honshu Island prefer white shrimp, especially from India due to its low price. Osaka and Kyoto are important consumption centers for black tiger shrimp, while all species are used in the Tokyo area (Eys 1987). Live kuruma shrimp (*P. japonicus*) is traditionally preferred, and there is no substitute for it thus far.

Shrimp demand normally peaks during the first quarter of the year. Prices for all grades tend to rise during this period. Other peak periods are April/May and August/September (Eys 1987). About 70% of shrimp is consumed in restaurants, 25% in homes, and 5% by institutions. The most popular product form of imported shrimp is raw headless, shell-on; accounting for about 70% of total imports. Head-on shrimp accounts for about 10%, and peeled shrimp about 10 to 15%.

Large shrimp are mostly served in luxury hotels and restaurants, while medium-size shrimp, which constitute the bulk of imports, are mostly used for "tempura" and "sushi" in ordinary restaurants and noodle shops. Small size shrimp are commonly repacked or peeled, and sold through seafood retail stores and supermarkets.

Major factors affecting shrimp prices are import volume, prices of competing products (like salmon, tuna, beef and chicken), seasonality, and exchange rate of the Yen. Other factors are shrimp size, quality, species, color, and origin. Large size shrimp command a very high price. The Japanese place considerable importance on freshness and quality.

TABLE 7. Japanese shrimp imports by major countries.

	1984	1985	1986 (x1000 M.T.)	1987	1988
Indonesia	24.1	24.2	27.2	30.8	38.6
China	10.3	10.7	18.7	27.9	38.0
India	38.5	36.3	36.7	36.5	32.0
Thailand	6.7	7.4	9.4	11.6	21.9
Taiwan	16.5	21.8	37.8	49.2	20.6
Others	62.8	71.9	73.0	89.9	107.1
Total	169.1	182.9	212.8	245.9	258.2

Source: Globefish, Mar.15, 1989.

Consequently, large, live shrimp command the highest price, especially P. japonicus. A bright red color after cooking is considered ideal, and species possessing this characteristic generally command higher prices. Shrimp producers with reputations for excellent quality get higher prices.

When the value of the Yen is rising compared with the U.S. dollar, it increases the volume of shrimp imports, which will tend to depress shrimp prices, and further increase demand. In this case, both shrimp exporters and Japanese consumers enjoy more favorable conditions in selling and buying shrimp. The situation is different, however, when the value of the Yen is weak compared with U.S. dollar.

Rapid increase in supplies of P. monodon from Asian countries has substantially depressed its price in Japan, which in turn, is a serious threat to survival of many shrimp producers. The price of P. monodon may continue to decline if Asian shrimp producing countries do not diversify their species of production and their export markets.

27.4.3 Western Europe Market

Total shrimp imports in the seven major Western European countries (Belgium, Spain, France, U.K., the Netherlands, Germany, and Italy) increased from about 102 MT in 1981 to 175 MT in 1987, a 72% increase (Table 8). Total domestic shrimp production in these countries accounted for only about 29% of their total supply. The demand gap is filled by shrimp imports. About 53% of present shrimp consumption is coldwater shrimp species. Major suppliers of coldwater shrimp are Greenland and the Faeroe Islands, traded mainly through Denmark, Iceland and Norway. Imports of tropical shrimp from Asia and West Africa have increased. Latin American countries such as Argentina and Cuba are also import sources.

TABLE 8. Shrimp imports (in MT) of 7 major EEC countries.

Country	1981	1983	1985	1986	1987
Belgium	8.8	10.5	9.6	12.0	14.2
France	27.7	31.1	31.3	35.6	38.2
Germany F.R.	9.2	11.6	11.7	12.4	12.9
Italy	6.5	12.2	17.9	20.1	19.9
Spain	12.0	14.6	8.2	18.4	39.2
The Netherlands	15.1	12.2	13.1	13.3	10.0
U.K.	23.0	30.8	36.4	41.0	40.9
Total	102.3	123.0	129.2	152.8	175.3

Source: Nierentz and Josupeit, 1988.

Each country has its own preferences for shrimp products. In Spain and southern France, species and size preferences are still very much in line with traditional available products. Whole head-on shrimp are the most popular. Italy usually imports headless shell-on shrimp of small size, mostly pink or red. In recent years, shell-on products have gained importance in the U.K., Spain and Belgium, while the share of cooked and peeled shrimp increased in Italy and Germany.

The European countries are very price-conscious. Traders are always ready to take advantage of the lowest shrimp price. Although consumers generally prefer coldwater species because of their flavor and firm flesh, price considerations often attract consumers to tropical shrimp.

The upward consumption trend and greater receptiveness to new products in Europe provide a large potential market for tropical, cultured shrimp. Increased shrimp production from farms in tropical countries, decreased coldwater supplies, and price differences between the two sources may increase overall tropical shrimp consumption in Europe.

27.5 CONCLUSION

Increased availability of shrimp in the major consuming countries will result in lower prices and higher demand. Imbalances between supply and demand will inevitably occur if the current growth rate of cultured shrimp production continues. Competition among shrimp producing countries will become intense in the international market. Only the most efficient producers will survive. Efficiency here means diversified, high quality products, with low production and marketing cost, selling to a diverse market.

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CHAPTER 28

**SUPPLY RELATIONS AND COSTS OF SHRIMP
MARICULTURE AND SHRIMP FISHERIES**

28.1 INTRODUCTION

Until the last two decades all shrimp supplied to the world markets was harvested from wild stock in bays and open seas. In fisheries, such as the Gulf of Mexico, major capital inputs are vessel and gear. In the early 1900's, shrimping vessels were constructed of wood and used drag seines, cast nets and traps to harvest shrimp. Today shrimping vessels are built of wood, steel, or fiberglass and use double and twin otter trawl rigs, as well as sophisticated electronic equipment. Also, the number of vessels has increased steadily into the early 1980's (Tettey and Griffin 1984).

Because of the open-access, common-property nature of the shrimp resource, fishermen will increase the number of vessels (increasing effort) in a fishery as long as excess profits exist (Crutchfield and Zellner 1982; Smith 1969; Turvey 1964). This imposes extra cost burden on other fishermen and gives rise to over-capitalization (Tettey and Griffin 1984). Although the number of vessels and boats continued to increase from the 1950's through the 1970's, shrimp production has not increased in the Gulf of Mexico (Figure 1). Production has become rather unstable from year to year and, for some states in the Gulf, has actually declined.

Shrimp farming has become a major source of shrimp within the last decade. Estimates of cultured shrimp production are difficult to obtain, but latest estimates by Rosenberry (1989) indicate that in 1981 cultured shrimp were only 2.1% of world production. He estimates cultured shrimp production in 1989 to be 26% of total world supply at 2.2 million metric tons.

Shrimp farming is primarily confined to the tropical and subtropical areas of the world. In terms of production area in 1982, Ecuador was the leading country in commercial shrimp farming, with approximately 38,000 ha in production, followed by Thailand with approximately 12,000 ha, and Taiwan with 3,200 ha. Indonesia, the Philippines, and India used a method of rotational shrimp farming - alternating mariculture with a crop such as rice. Other countries developing their shrimp farming capabilities in 1982 were Malaysia, Panama, Costa Rica, and Brazil (Shang 1982).

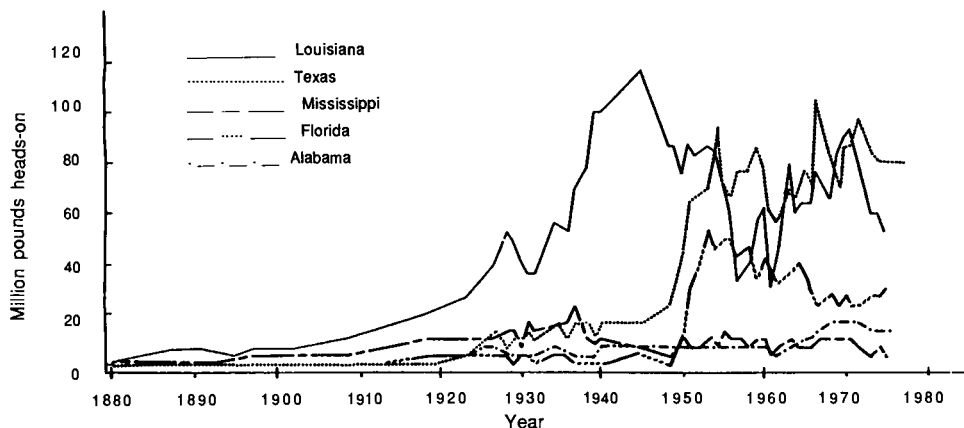


Figure 1. Annual report of commercial landings of shrimp (heads-on) by Gulf state. (Gulf of Mexico Management Council 1981)

By 1989, the center of shrimp farming in the world had shifted to the Orient. Presently, China leads the world in cultured shrimp production with 145,000 ha of production, and 29% of total world supply of cultured shrimp. Indonesia and Thailand each have 16% of total world culture production. Other countries included are The Philippines, Ecuador, Vietnam, India, and Taiwan. *P. chinensis* is cultured primarily in China. *Penaeus monodon* is the popular species cultured in most of the other Asian countries while *P. vannamei* is the principal species grown in Latin American countries.

Shrimp farming can be broken into three broad categories which are based on management intensity: extensive, semi-intensive and intensive. The main characteristics of the extensive method of shrimp culture is that the production depends entirely on natural conditions. Cast nets and bamboo traps produce harvests of 50 to 500 kilograms (heads on) per hectare per year. Production costs range from \$1.00 to \$3.00 per kilogram of live shrimp. The semi-intensive farming method utilizes a nursery phase, carefully laid out ponds, feeding and diesel pumping. The harvest yields can range from 500 to 5000 kilograms (heads-on) per hectare per year. Production costs range from \$3.00 to \$5.00 per kilogram of live shrimp. The intensive culture system introduces smaller ponds, high stocking densities, and continuous management of feeding, waste removal and aeration. Yields of 5,000 to 10,000 kilograms (heads-on) per hectare per year are common and production costs range from \$5.00 to \$7.00 per kilogram of live shrimp (Rosenberry 1989). For a more complete description of these systems, see Chapters 14, 15, 16, and 17.

The total world production of farm raised shrimp has increased and this impact has been felt in the U.S. market. Figure 2 shows a 4 year price cycle from 1977 through 1984 with a slight upward trend in nominal prices. Since

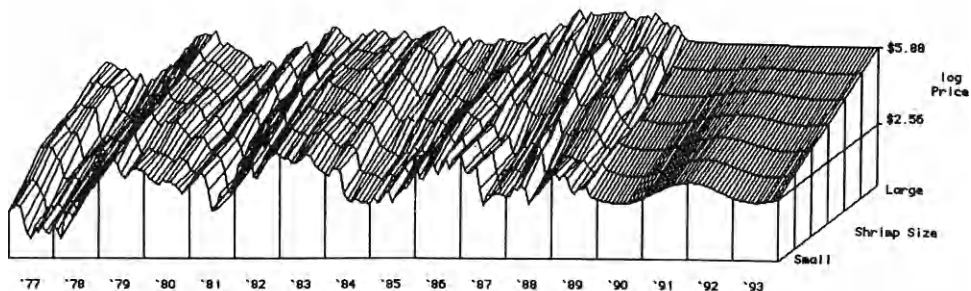


Figure 2. Actual (1977 to Oct. 1989) and predicted (Nov. 1989 to 1993) Western Gulf of Mexico Shrimp Prices (nominal dollars).

1984, when shrimp mariculture became a significant part of world production, the price cycle seems erratic. We would suggest the following explanation. In 1986, following El Nino, we see a significant increase in the price of small shrimp, but not in the price of large shrimp. This is partly due to a severe lack of PL in 1985 in Ecuador, which forced producers to extend their growout periods. In 1986, with the availability of hatchery raised shrimp and the abundance of wild PL, the price of PL was as low as one dollar per thousand and producers harvested large crops of small shrimp (personal communication with Mr. Mark Hardin). This large supply of small shrimp forced the price of small shrimp to fall radically in 1987, while the price of large shrimp increased. The increased presence of *P. monodon* in the U.S. market is thought to have caused the large shrimp price to decline, and 1989 ended with the same price level and structure as in 1985.

Since supplies of farm raised shrimp are expected to increase over the next two years, Rosenberry (1989) suggests that prices will re-stabilize at even lower levels, as shown in the predicted portion of Figure 2. He suggests this new lower price will cause a shake-up in the whole shrimp industry (wild stock harvesting and mariculture production). According to Rosenberry, those countries utilizing the extensive or semi-intensive methods, the low cost producers, will be able to compete while those with higher costs will not be able to survive. Commercial fishermen will be in trouble as well. Rosenberry (1989) states that "As shrimp farmers around the world increase their production and as shrimp prices stabilize at lower levels, fishermen will not be able to compete. At the end of the day, the fisherman will be gone, and an expanding market will belong to the farmer." Given the importance of the shrimp fishery in many countries, such a radical change, as suggested, would have a nearly catastrophic impact on the coastal economies of several countries.

Table 1. The 1982 Cost of Farming Shrimp for Several Countries in 1982 U.S. Dollars.*

Item	Semi-Extensive		Semi-Intensive		Intensive
	Ecuador	Thailand	Texas	Malaysia	Taiwan
Production					
Kg/ha/yr	1,818	2,000	1,571	5,000	15,000
Crops/yr	2	2	1	3	2.5
Kg/ha/crop	909	1,000	1,571	1,667	6,000
Revenue (\$/KG)	5.00	7.00	6.00	6.00	8.00
Cost					
Post Larvae	0.32	1.63	0.71	0.55	1.33
Feed	1.56	0.40	1.18	1.64	3.73
Labor	0.30	0.56	0.41	0.65	0.60
Fuel and Electricity	0.05	0.11	0.12	0.11	0.34
Capital	0.35	0.40	0.73	0.86	0.90
Other	0.33	0.10	0.14	0.17	0.12
Total	2.91	3.21	3.28	3.98	7.03

* Adapted from Shang (1982)

The purpose of this paper is to (1) examine the costs of culturing shrimp in various parts of the world and at different intensity levels, (2) examine the costs of wild stock harvesting, and (3) determine the impact of decreased shrimp prices due to increased culture of shrimp on the fate of shrimp fisherman.

28.2 COST OF SHRIMP FARMING

Producing shrimp on a farm can be accomplished with a variety of different husbandry methods. The costs of shrimp farming vary with the method of farming used, the intensity of the system and the environmental and cost constraints faced within the individual country. Some countries, such as Ecuador, have abundant land and water resources, as well as a natural supply of PL. Others, such as Texas, face individual constraints such as climate and a lack of PL.

A comparison of the costs by Shang (1982) of shrimp farming in different countries is listed in Table 1. It shows that, for all countries except Thailand, feed is the most important cost item. It ranks almost 2 to 5 times higher than any other cost item. PL cost varies considerably between countries depending on its source of supply. For Thailand it is the most important cost; however,

Table 2. Production costs for 200 Ha Shrimp Farms in Ecuador in 1984 U.S. Dollars.

Item	U.S.	Ecuador		
	Semi-Intensive	Semi-Intensive	Semi-Extensive	Extensive
Production				
Kg/ha/yr	1159	1323	554	232
Crops/yr	1	2.4	1.8	1.3
Kg/ha/crop	1159	551	308	178
Revenue (kg/\$)	8.47	9.00	10.00	11.00
Cost				
Post larvae	1.55	0.36	0.32	0.26
Fertilizer	0.05	0.20	0.49	0.00
Feed	1.76	1.51	0.60	0.00
Labor	0.57	0.24	0.34	0.34
Fuels and Electricity	0.19	0.08	0.14	0.17
Capital	1.02	0.47	0.72	1.48
Other	0.69	0.82	1.14	1.67
Total	5.83	3.69	3.75	3.92

* Adapted from Griffin, et al.(1985)

it is one of the lesser costs for Ecuador and Malaysia. Capital ranks very important in many countries, and is the second most important item in Ecuador, Texas and Malaysia. Labor cost is of less importance in most countries except Thailand, where it ranks second. Finally, fuels and electricity are relatively unimportant, but increase in importance with culture intensity due to higher flow-through rates and aeration; fuel is almost three times higher for the intensive system in Taiwan than for all other systems.

Table 1 compares costs between countries. Unfortunately, these costs are difficult to compare due to differences in government policies, labor supply, PL supply, exchange rates and land availability, which inherently distort a comparison between countries. The internal cost structures of countries dictate the relative importance of any given cost item in a given shrimp farming budget.

Griffin et al. (1985), however, compare the costs of systems within Ecuador in 1984 (Table 2). Within the systems in Ecuador, feed cost ranges from 0 for the extensive system to \$1.51 per kg for the semi-intensive system. In opposition, capital becomes less important when intensity increases, due to the decrease in the land area needed. For example, the capital cost for the semi-intensive system is only \$0.47 per kg, but increases to \$1.48 for the

extensive systems. The category "other costs", which includes repairs, packing and miscellaneous, exhibits the same pattern, and is as high as \$1.67 for the extensive system. Labor is relatively less expensive for the semi-intensive system than the two less intensive systems. Fuel and electricity are again the least expensive items in all budgets with the exception of the extensive system which has no feed or fertilizer costs. Finally, the overall cost of production decreases slightly as production intensity increases.

Griffin et al. (1985) also compare two semi-intensive systems for Ecuador and the U.S. The U.S. incurs a substantially higher cost for PL, since they must be imported or produced in climate controlled environments. As with Ecuador, fuel and labor are less important costs. Overall, the cost of producing in the U.S. is substantially higher because the U.S. is limited to a single crop per year, whereas the Ecuadorean system produces 2.4 crops per year.

Recent budget estimates at Texas A&M University are shown in Table 3, and are calculated from actual production of shrimp farmers along the Texas coast. Table 3 shows that, for intensive and semi-intensive systems, feed remains the most important cost item, at nearly \$ 3.00 per kg. Likewise, PL are still a very important cost item, which is lower for the less intensive system. Labor, in these budgets, ranks third and costs more than \$1.00 per kg. Fuel and electricity are much more important for intensive systems because they operate with 1.6 hp per ha aeration capacity. Surprisingly, the capital requirement is less for the intensive system. This is due to the reduced land and construction requirement per kg produced. Finally, the intensive system produces shrimp for \$ 0.45 less than the semi-intensive system when considering all costs.

As noted in the introduction, the recent drop in prices may lead to a reversal in the trend toward shrimp farms with higher intensities. However, it is not correct to automatically infer that high intensity producers will be the first to leave the industry. From Table 1, it is clear that the countries with less intensive production systems clearly have lower costs of production. If the same comparison is made within a country, however, such a sweeping statement does not hold. Comparison between systems in Ecuador are given in Table 2, and in Texas in Table 3. It is clear that within a country there is less variation in cost, and that the more intensive systems have a lower production costs per kg produced.

It is short sighted, however, to imply that the low cost producer will always dominate the high cost producer. There are at least four reasons why the low cost producer is not necessarily better off. The first is market conditions. For years there has been a small but healthy shrimp farming industry in Hawaii, yet studies consistently show Hawaii to be the high cost producer. The reason for the success of shrimp culture in such an

Table 3. Production Cost for a 78 Ha Intensive Shrimp Farm and a 155 Ha Semi-Intensive Shrimp Farm in Texas during 1989 in 1989 U.S. Dollars.

Item	Intensive 78 ha.	Semi-Intensive 155 ha.
Production		
Kg/ha/yr	3447	1323
Corps/yr	1	1
Kg/ha/crop	3447	1323
Revenue (\$/kg)	8.17	7.74
Cost		
Post larvae	1.19	1.54
Fertilizer	0.00	0.07
Feed	2.99	2.87
Labor	1.05	1.06
Fuels and Electricity	0.96	0.27
Capital	0.55	0.61
Other	0.62	0.45
Total	6.42	6.87

*Calculated by the shrimp farming simulation model MARSIM (Hanson et al. 1985)

environment of high costs can in part be explained by market situations. If the producer finds a niche for his product that cannot be filled by low cost suppliers, the high cost producer will prevail despite the cost disadvantage.

The second mitigating factor on the farm cost approach is the narrow scope of the cost definition. Some producers may have lower production cost, but are severely disadvantaged in other areas, such as infrastructure or government regulations. For example, if cold storage facilities are expensive, quality control is scarce, or other disadvantages in processing and distribution are present, the low cost of production may be more than offset. Many developing countries are facing this hurdle.

The third major deficiency of the cost approach is the differentiation of the product. For example, the intensive farm in Table 3 not only has a lower cost of production, but it also sells a larger size shrimp, on average, resulting in a larger revenue per kg sold. Other factors contributing to the value of the shrimp are their general condition, species, size variation, availability and continuity of the supply. If cost of production were the only consideration, certain species would not be cultured at all.

The fourth consideration that must be taken into account is risk. When properly implemented, higher intensity husbandry systems allow for certain risk reducing practices such as aeration and water flow. The risks of algal

blooms crashing, introduction of natural predators and oxygen deprivation can be lowered for properly developed and managed intensive systems through the use of capital investment. By considering these four factors, the impact of market conditions, additional cost structures, product characteristics and risk, the low cost producers may not always have the advantage, particularly when the producers are in different countries.

28.3 COST OF SHRIMP FISHING

In their natural environment, shrimp migrate between bays and estuaries and the open ocean during their life cycle. The life cycle for native Gulf of Mexico species begins in the open Gulf where the adults spawn and the larvae complete their development (Lawrence et al. ?). After metamorphosing into PL, they migrate into the bays and estuaries where they develop into juveniles that later return to the open ocean. The life cycle is described in more detail in Chapter 2.

Traditionally the shrimp fishery has been separated into bay and offshore vessels. Bay vessels are typically smaller and make trips of less than 24 hours. As the name suggests, their primary fishing grounds are the bays, and the average size of shrimp landed is small. Offshore vessels, on the other hand, fish deeper waters off the coast, are larger and more seaworthy, and make trips of longer duration. Some freezer vessels stay out for as long as several weeks. These vessels catch a larger size shrimp than the bay fishermen. Naturally, the offshore vessels are more expensive and sophisticated and thus require more capital investment.

Table 4 contains the costs of shrimp vessels for the Texas coast. The data for bay vessels are from Warren (1980), and Swartz and Adams (1979). For offshore vessels, data are from Clark and Griffin (1983). The data was adjusted to 1985 U.S. dollars. Fuel prices were adjusted by the Price Index for Fuel. Revenue and crew share were adjusted by landings and prices actually received in the appropriate years. All other costs were adjusted by the Producer Price Index. Table 4 shows there is a pronounced difference between the costs incurred by the two vessel classes. The largest single difference between the two categories can be found in the use of fuel. The cost of fuel for the offshore vessel is the most important cost item at \$2.65 per kg, whereas, for bay vessels, it ranks fourth in importance at only \$0.22 per kg.

The cost of labor (crew shares) is dependent on the size of the catch and the price per kg received, as crew members do not receive a fixed wage, but rather a share of the catch. For both bay and offshore vessels the labor cost is very important. Operating costs such as repair and maintenance are slightly more important than labor for both offshore and bay vessels. The total cost

Table 4. Cost of Wild Stock Harvesting in Texas in 1985 U.S. dollars. ¹

	Offshore Vessels ²	Bay Vessels ³
Revenue		
Value (\$/kg)	10.53	2.45
Cost		
Fuel	2.65	0.22
Repair and maintenance	2.38	0.60
Ice	0.25	0.03
Crew Shares	2.11	0.49
Capital	1.40	0.43
Total	8.78	1.77

¹ Revenue and shares were adjusted from actual price and landings in the Western Gulf of Mexico, repair and maintenance, ice and capital were adjusted to 1985 \$ using the PPI, and fuel was adjusted by the fuel price index.

² Non-typical, modern vessels. An average of all offshore vessels will have a smaller average catch size and lower revenue per kg. Adapted from Clark and Griffin(1983).

³ Adapted from Swartz and Adams(1979), and from Warren(1980)

of shrimping by the offshore vessel is nearly five times higher than the bay vessel, but offshore vessels also land larger, more valuable shrimp.

28.4 COST COMPARISONS OF SHRIMP FARMING AND FISHING

Relative to the total cost of production, fuel and labor are much more important for the Texas offshore vessel than for any of the culture systems examined. In shrimp mariculture, the important cost items are generally feed and PL. It is difficult to compare the different tables (1 through 4) because they are not all adjusted for inflation, but it is clear that the Texas offshore vessel incurs the highest cost per kg, while the Texas bay vessels have the lowest cost per kg of production, but also produces the lowest value shrimp.

If the increase in world mariculture production causes the price of shrimp on the world market to settle to a lower level, what will the impact be on wild stock harvesting? This question will be addressed from a theoretical and practical point of view in the following sections.

28.4.1 Theoretical Considerations

As stated above, the increase in production by shrimp farmers will have an effect on the market throughout the world. The shrimp market obeys the law of demand, meaning that an increase in quantity will lead to a reduction in price. The question to be answered is then: how will this increase in

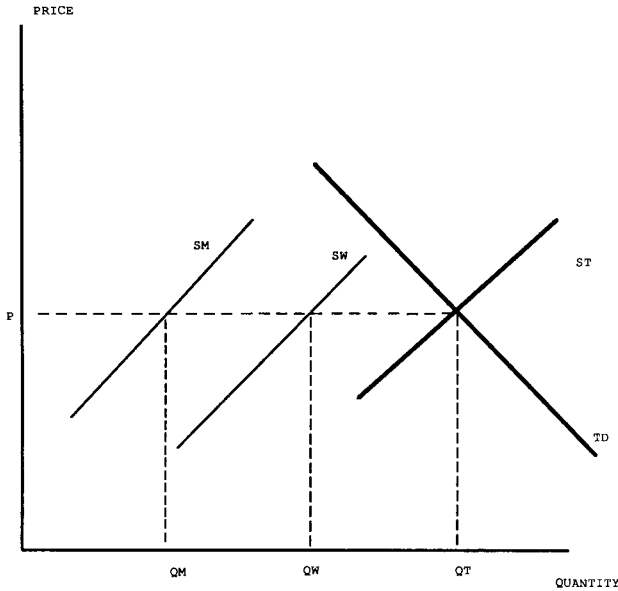


Figure 3. Graphical representation of the world shrimp market with a supply curve for wild stock (SW), a supply curve for shrimp mariculture (SM), a total supply curve ($ST = SW + SM$), a total demand curve (TD), and equilibrium price (P).

quantity of shrimp produced by farmers influence the price of shrimp and the quantity of shrimp produced by wild stock harvesters? To answer this question we will set up an theoretical framework representing the shrimp market.

Figure 3 is a graphical representation of the shrimp market. The vertical axis represents the price of shrimp and the horizontal axis represents the quantity of shrimp. The curves SM, SW and ST are the supply curves for the shrimp mariculture sector, the wild stock harvesting sector, and the total shrimp sector, respectively. Supply curves show the relationship between the price of the product and the quantity supplied to the market, holding all other economic factors constant. Other factors would include the cost of inputs and technology. Hence, a price or quantity change will cause a movement along the curves, but a change in any other factor will cause a shift of the curve itself. The curves SM and SW together represent the total supply to the market, and thus their horizontal addition is the curve ST; the total supply curve.

The curve TD represents the total demand for shrimp by consumers. As with supply curves, a change in price (or quantity) will cause a movement along the curve, but any other change, such as a change in consumer taste,

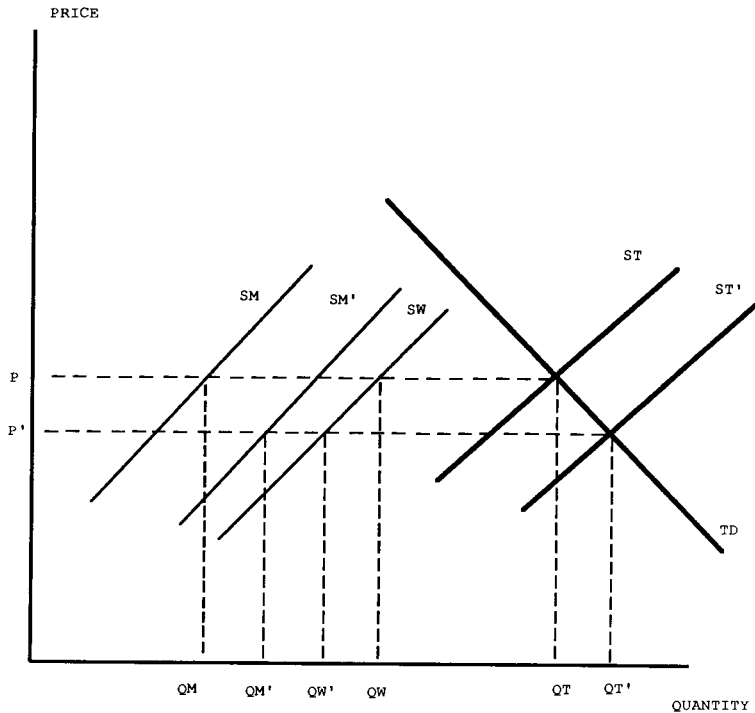


Figure 4. Graphical representation of the world shrimp market with an increase in supply of cultured shrimp (from SM to SM'), resulting in a new lower equilibrium price (P').

prices of competing products, consumer income, etc, will result in a shift of the curve itself. Holding all other factors constant, we can find the equilibrium price and quantity from Figure 3 by observing the intersection of the TD and ST curves. The equilibrium price will be P and the equilibrium total quantity supplied and consumed QT .

Once the equilibrium price of the system, P , is known, we can also find the distribution of the production between the farming and fishing sectors. The intersection between the price line and each of two individual supply curves will give the quantities supplied by each. Thus, in Figure 3 the quantity supplied by the mariculture industry will be QM and the quantity supplied by their competitors, the wild stock industry, will be QW .

To determine the effect of an increase in the quantity of shrimp supplied by farmers, it must be fit into the framework introduced above. By realizing the increase in production was not caused by an increase in price, but rather by an improvement in technology, increased government support and other external factors, it becomes clear that this change in production must be represented by a shift in the supply curve for shrimp farming. In Figure 4 this

shift of the supply curve SM is reflected by the curve SM'. The next step is to shift the total supply curve for the shrimp market by horizontally adding the supply curve for wild stock harvesting, SW to the new supply curve of mariculture, SM'. This addition results in the total supply curve ST'.

From this point the interpretation of the Figure 4 becomes clear. The total demand curve TD and the new total supply curve intersect at the point P'/QT', indicating the new price and the new total quantity supplied to the market. The quantity supplied by the fishermen and the farmers can be found by observing where the price line, P', intersects their respective supply curves. Thus, farmers will produce QM' and fishermen will produce QW'.

The answer to the question "What will happen to the fishermen?" is now clear. The quantity of shrimp supplied to the world market will increase from QT to QT', the quantity supplied by the mariculture sector increases from QM to QM' and the quantity supplied by the fishermen will decrease from QW to QW'. There is no reason, however, to assume that the increase in mariculture will cause the wild catch fisheries to disappear. The wild stock fisheries sector will become smaller, however, in both a relative and absolute sense.

28.4.2 Practical Considerations

To estimate the relationships described above and the supply relationships in the Gulf of Mexico, the shrimp fisheries simulation model GBFSM (Blomo et al. 1978) was used. The model is able to assess total harvest, total revenue, fishing cost and rent in the fishery, as well as distribution of revenue, cost, and rent among different classes of fishing vessels. Recruitment, natural mortality and the growth rate of shrimp are accounted for in the model, as well as movement between depths and areas. The model represents fishing effort exerted on each species by vessel class, depth zone, area and time frame. An economic sub-model translates these effects into monetary values.

The theoretical implications of the increase in shrimp farming are clear with the exception of one factor, the slope of the supply curve for the fishermen in Figures 3 and 4. If the supply curve is nearly horizontal, a small decrease in price will mean a very large decrease in production, making the statement that fishermen will be eliminated by fishermen realistic, in principle.

There are two factors that suggest that the supply curve of wild-stock harvesting is not horizontal. The first is the universal economic principal of decreasing marginal returns. Simply stated, decreasing marginal returns mean that as production increases, the production of additional quantities becomes increasingly more costly. This concept may be illustrated by considering the production of grain, where additional production of grain in a nation requires the use of marginal land, increased rates of fertilizer, or both. By using less

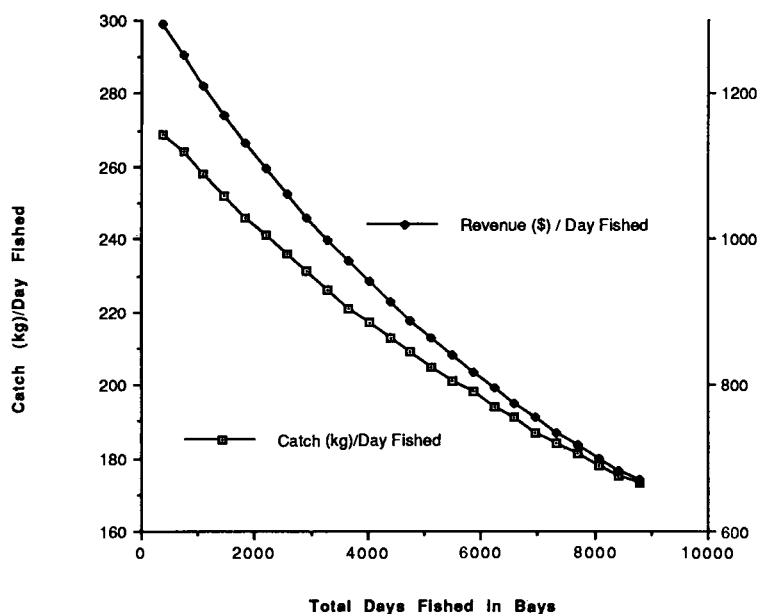


Figure 5. Daily catch and daily revenue for bay vessels and fishing effort in days in 1985 U.S. \$. Calculated by GBGSM (Blomo et. al. 1978) gulf shrimp fisheries simulation model.

than optimal resources or less than optimal combinations of resources, the cost of producing the additional grain becomes larger.

The second reason is the nature of fisheries. Since fishermen use the common resource of the ocean as their means of production, if one fisherman reduces his fishing effort, all others directly benefit. Not only do they gain in the market but also in their production process because there is an increase in their catch per unit of effort. In addition, the average size of the catch of the other fishermen increases because shrimp will grow to a larger size with less fishing pressure. This is illustrated in Figures 5 and 6. In these figures, the catch per day fished and the revenue per day fished is graphed against the total days fished for bay and offshore vessels, respectively. It is important to note that all other economic factors are held constant in these figures, e.g. the price of shrimp and the cost of inputs. As can be observed, the catch per day fished in the bays and offshore increases as the fishing pressure falls. Because shrimp now live longer, the average size caught increases, and the average price the fishermen receive for their catch increases. The line representing the average revenue per day fished, therefore, has a steeper slope than the line representing average catch per

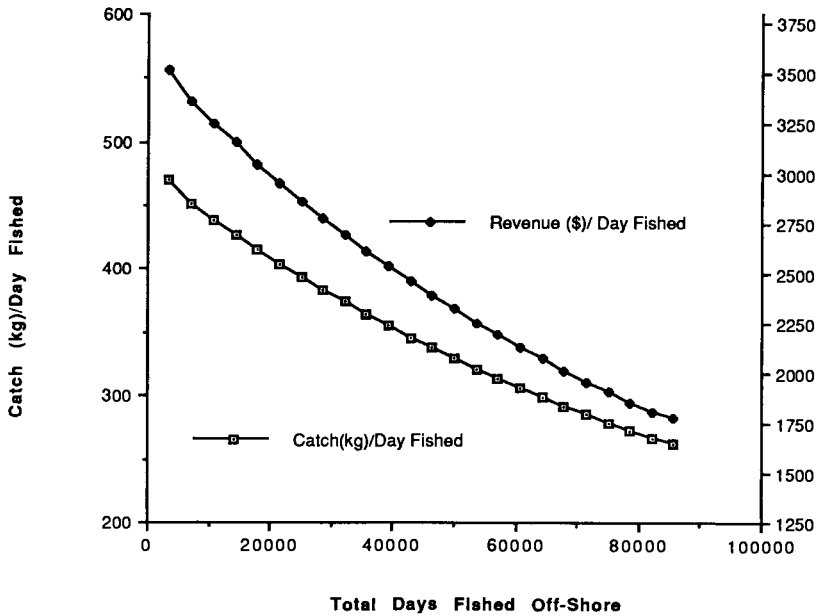


Figure 6. Daily catch and daily revenue for offshore vessels and fishing effort in days in 1985 U.S. \$. Calculated by GBGSM (Blomo et. al. 1978) gulf shrimp fisheries simulated model.

day. Thus, if one fisherman cannot compete and leaves the industry, the cost of production decreases on a per pound basis for all remaining fishermen, while the revenue per pound increases. Therefore, although the volume of shrimp caught decreases, the net benefit to the industry increases.

The relationship between landings in Texas and prices are shown in Figures 7 and 8. Of course, these graphs are no more than the supply curves for the Texas wild catch shrimp fishery. The average price for shrimp landed in 1985 was \$6.82/KG for offshore vessels and \$3.98/KG for bay vessels. As can be seen, these prices can drop 30 % without eliminating the shrimping industry. Indeed, the shape of the curves suggests that the price of shrimp can decrease quite substantially without jeopardizing the entire industry. Evaluation of effects beyond the historical record on prices becomes conjectural due to the origin of the values used. Simulation modeling of the Texas shrimp fisheries has been shown to be rather accurate within the range of historical data, but values which require extrapolation may or may not have the same accuracy. Nonetheless, Figures 7 and 8 show clearly that shrimp farmers will not put the shrimp fishermen out of business. Obviously, the wild stock harvesting industry will be affected by the increase in shrimp farmers.

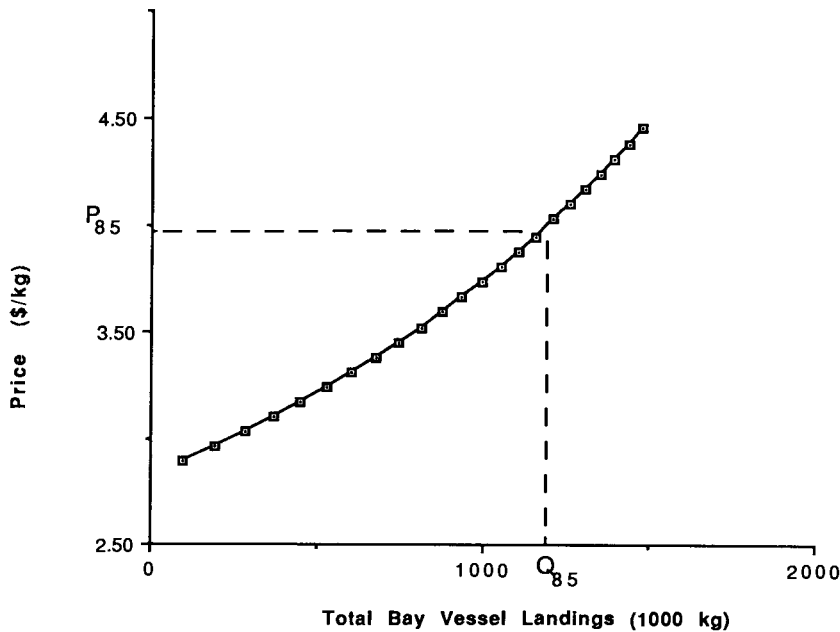


Figure 7. Long run supply of shrimp by Texas bay vessels in the Gulf of Mexico and average price received in 1985 U.S. \$. Calculated by GBGSM (Blomo et. al. 1978) gulf shrimp fisheries simulated model.

There are few doubts and many indications that this will cause great instability in the market. But there is no evidence to suggest that the wild-stock harvesting of shrimp will soon be displaced by farmers.

28.7 CONCLUSIONS

The shrimp producing industry is in a period of rapid change caused by the phenomenal increase in the production of farm raised shrimp. This increase in production is likely to cause a decrease in prices, which will reduce the landings by the shrimp fishing industry. However, the shrimp farmer will not eliminate the fisherman.

The costs of shrimp farming and wild-stock harvesting are distributed among different production factors. In general, it can be stated that wild-caught shrimp require higher expenditures of labor and fuel than farmed shrimp (in \$/kg). Thus, increases in fuel costs will reduce the production level of fisheries more than the production on farms, and likewise with an increase in the labor cost. It is important to caution the reader about application of such conclusions. Much of the production of shrimp now takes place in countries with strong price controls (India) or even centrally planned

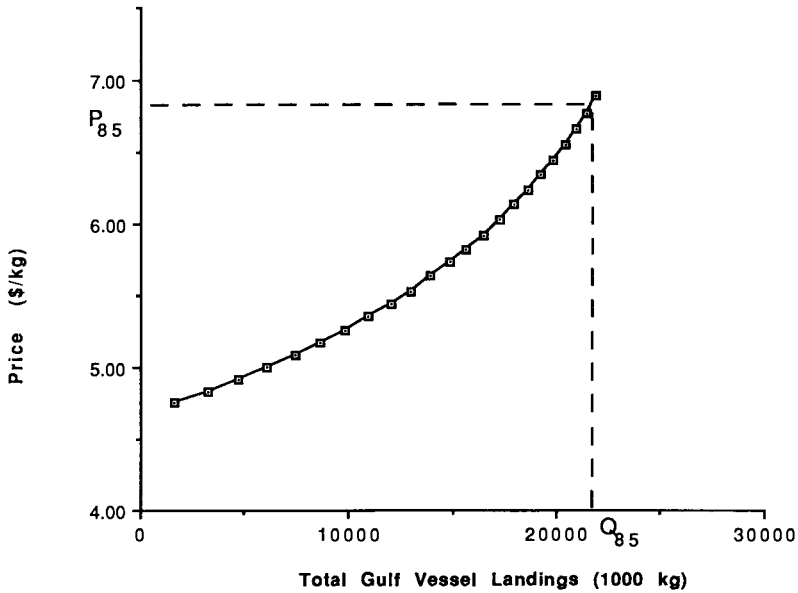


Figure 8. Long run supply of shrimp by Texas offshore vessels in the Gulf of Mexico and average price received in 1985 U.S. \$. Calculated by GBGSM (Blomo et al 1978) gulf shrimp simulated model.

economies (China), with foreign exchange revenue as the prime reason for production. Such countries may not pass their cost of energy or labor down to the producer; this will leave them unaffected by price changes of their resources.

Finally, there are several factors other than cost which determine the viability of shrimp farming in certain areas or by certain husbandry methods. To evaluate the viability of a producer, factors in addition to the cost of production must be considered, such as market demands, costs other than production, risk, and product characteristics.

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CHAPTER 29

Arlo W. Fast

AN OVERVIEW OF ASIAN MARINE SHRIMP CULTURE

29.1 INTRODUCTION

Development of marine shrimp culture has its deepest roots in Asia. Extensive pond growout systems for fish and shrimp were well developed in Indonesia, the Philippines and other Asian countries centuries ago (Ling 1977). Penaeid larviculture had its beginning in Japan during the first half of this century (Hudinaga 1935, 1942). With practical larviculture techniques came mass production of postlarvae (PL) to stock growout ponds, and to provide the basis for marine shrimp culture intensification.

Environmental, political and economic factors all favored rapid commercialization of marine shrimp culture in Asia. By 1989, Asian cultured shrimp production accounted for 89% of the world's total culture production and more than 90% of total culture area (Table 1; Fig. 1). Only 11% of total culture production, and less than 9% of total culture area was in the Western Hemisphere. The world's marine shrimp culturists now produce 26% of the world's total supply of shrimp, fishermen produce 74% (Rosenberry 1990). Exact production figures are hard to obtain, but there is no doubt that Asia leads the world in cultured shrimp production. This trend should continue for the foreseeable future.

In this chapter, I will give a brief overview of some aspects of Asian marine shrimp culture, while the following chapters will present detailed descriptions of important shrimp culture industries in several Asian countries.

Throughout this volume, references are made to important contributions made by Asian shrimp culturists and researchers to development of shrimp culture technology. I will not try to repeat these here, although I would emphasize that shrimp culture would not be where it is today without these contributions.

29.2 CULTURED SPECIES

During 1985, Penaeus monodon was the most commonly cultured marine shrimp in Asia, with 41% of total crustacean culture production (Table 2). Penaeus monodon captured first place because of its rapid growth to large

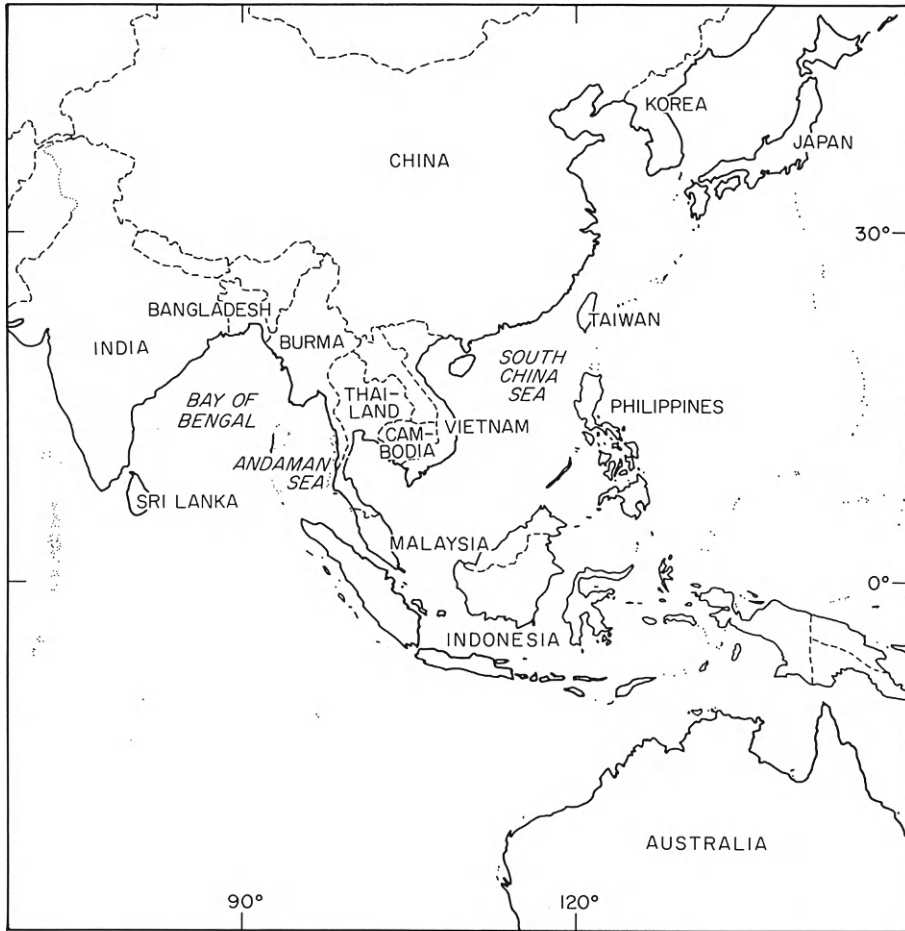


Figure 1. Map of Asia showing principal shrimp culture countries.

size, and its other desirable qualities (Chapter 31; SEAFDEC 1988; Motoh 1985). Its large size and high value per kg are important export qualities. Penaeus merguensis and P. indicus were the next most commonly cultured Asian shrimp species during 1985, accounting for 23% of the total. While these species do not commonly grow larger than 10 to 15 g in pond culture, and are therefore relatively low value, their seed are locally abundant and they have a long history of pond cultivation in Asia. Penaeus chinensis was third in production volume during 1985, with 17%.

By 1989, changes had occurred in species production compositions. World-wide, P. monodon was still the most commonly cultured shrimp at 33%

Table 1. Summary of world cultured shrimp production during 1989. Production values are in thousand MT live weight. (Rosenberry 1990)

Country	Cultured Production (1,000 MT)	Share of World Production (%)	Culture Area (1,000 ha)	Productivity (kg/ha/yr)
China	165	29	145	1,138
Indonesia	90	16	250	360
Thailand	90	16	80	1,125
Philippines	50	9	200	250
Vietnam	30	5	160	187
India	25	4	60	416
Taiwan	20	4	4	5,000
Ecuador	45	8	70	643
Central America & Caribbean	12	2	12	1,000
South America	7	1	8	875
Other	31	5	103	298
Total	565	100	1,092	
Average				517
Eastern Hemisphere	500	89	1,002	499
Western Hemisphere	65	11	90	717

(Table 3), with virtually all its production in Asia. During 1989, *P. chinensis* moved to number two in production volume with almost all production from the Peoples Republic of China. *Penaeus vannamei* accounted for 10% of total world culture production, while *P. merguensis/indicus* were collectively 16%. These trends are likely to continue, with *P. chinensis* increasing its share as production increases continue in China.

29.3 STATUS OF SHRIMP CULTURE BY COUNTRY

29.3.1 Peoples Republic of China

The most dramatic shrimp culture news during the past few years was the phenomenal increase in cultured shrimp production from China. During 1985, China produced only 5,000 MT of cultured crustaceans (Csavas 1988). This was less than 2% of total Asian cultured production. By 1989, however, China increased production to 165,000 MT, or 35% and 29% of cultured Asian and world shrimp production respectively (Table 1). The principal species cultured in China was *P. chinensis*, a temperate species that grows well below 20 C. In south China, smaller quantities of the warmer water species *P. monodon*, *P. merguensis*, and *P. penicillatus* were cultured.

Table 2. Asian cultured crustacean species composition during 1985 (Csavas 1988).

Species	Percent of Total	Major Producing Countries
Marine Shrimp		
<u>Penaeus monodon</u>	41%	TWN, PHI, INS, IND, BGD, VIE
<u>P. merguensis</u> , <u>P. indicus</u>	23%	INS, VIE, THA, IND, CPR, PHI
<u>P. orientalis (chinensis)</u>	17	CPR, ROK,
<u>P. japonicus</u>	1	JPN, TWN, ROK
Other penaeids	4	CPR, THA, BGD, IND
<u>Metapenaeus</u> spp.	10	INS, THA, IND, BGD
Subtotal	96%	
Other Crustaceans		
<u>Scylla serrata</u> , and <u>Portunus</u> spp.	1	PHI, TWN, INS, SIN, THA
<u>Macrobrachium</u> spp.	3	THA, VIE, BGD, MAL
Subtotal	4%	

Country legends: BGD: Bangladesh; CPR: People's Republic of China; IND: India; INS: Indonesia; JPN: Japan; MAL: Malaysia; PHI: Philippines; ROK: Republic of Korea; SIN: Singapore; THA: Thailand; TWN: Taiwan; VIE: Vietnam.

China's 32,000 km coastline, 1.2 billion population, low land and labor costs, abundant source of broodstock shrimp, and political dedication provide ideal conditions for even further expansion of their shrimp culture industry. Most shrimp in China are cultured in semi-intensive earthen ponds, although private investment favors more intensive culture systems. Overall productivity during 1989 was 1,138 kg/ha (Table 1), an impressive figure considering that China is largely limited to one crop per year. Perhaps the principal constraints are feed quality and availability, and infrastructure support. These constraints notwithstanding, we can expect further shrimp production increases from China. Chen and Yang (Chapter 32) provide a more detailed description and history of shrimp culture in China.

29.3.2 Indonesia

Indonesia has one of the longest shrimp culture histories in Asia, primarily as a result of extensive polyculture of shrimp with milkfish. By 1989, Indonesia produced 16% of the world's supply of cultured shrimp (Table 1). Shrimp exports ranked second only to petroleum in export value, and during 1988 were valued at more than \$450 million (Aquatic Farms 1989).

Wild caught shrimp production between 1979 and 1987 ranged from 112 to 145 thousand MT for marine and freshwater capture (Aquatic Farms 1989). The lower values occurred between 1982 and 1985, corresponding to

Table 3. Species composition of the world's total cultured shrimp production during 1989 (Rosenberry 1990).

Shrimp Species		Share of World Culture Production (%)
<u>Penaeus monodon</u>	Black Tiger Prawn	33%
<u>Penaeus chinensis</u>	Fleshy Prawn	28%
<u>Penaeus vannamei</u>	Whiteleg Prawn	10%
<u>Penaeus merguensis</u>	Banana Prawn	8%
<u>Penaeus indicus</u>	Indian White Shrimp	6%
<u>Metapenaeus ensis</u>	Greasy Back Shrimp	2%
<u>Penaeus stylirostris</u>	Blue Shrimp	1%
Other species (>20)		12%

bans on shrimp trawling during those years. Partial lifting of the bans in 1985 resulted in increased shrimp production. During 1986, the capture fishery produced 119,600 MT of shrimp, compared with 41,000 MT from culture (Table 4). Cultured shrimp production is now approaching that of the capture fishery, and could exceed it in the near future.

Prior to 1986, most Indonesian shrimp culture occurred in traditional, brackishwater "tambak" ponds, polycultured with milkfish. During 1987, there were 249,000 ha of these ponds; some were many centuries old. Tambak ponds typically have shallow water depths (average <50 cm), tidal water exchange, do not receive formulated feed applications, and rely mostly on benthic algal mats for food production for the cultured crop. Fish and shrimp seed are either stocked by flooding or purchased from fry collectors and stocked in the ponds at low densities (1 shrimp PL/m²). Typical annual yields range from 400 to 700 kg/ha, with about 80% fish (mostly milkfish and mullet), and 20% crustaceans (shrimp, mangrove crab and swimming crab,; Csavas 1988).

Increased shrimp prices, and potential profits during the early 1980's led to greater interest in shrimp culture. Farmers began to intensify production from existing ponds, and new semi-intensive and intensive shrimp farms were constructed by corporate investors. Traditional family owned and operated tambak ponds were intensified by pond deepening, increased stocking densities, shift from polyculture to shrimp monoculture, formulated feed applications, increased water exchange and aeration. Seed supply, originally from wild caught sources, increased through hatchery production starting in 1984. During 1986, hatchery produced P. monodon PL on Java sold for as much as \$40/1,000. By 1987 PL prices dropped to \$11.50/1,000 with even lower prices today. During 1987, 120 hatcheries produced >2 billion PL.

Table 4. Asian shrimp production (in MT) from wild capture and from cultivation by country during 1986 (U.S. Dept. Commerce 1988).

Country	Shrimp Production (MT)			Cultured Share (%)
	Captured	Cultured	Total	
China	188,486	79,054	267,540	30%
Taiwan	87,702	51,003	138,705	37%
Indonesia	119,600	41,000	160,600	26%
India	179,100	20,000	199,100	9%
Thailand*	111,803	18,296	130,099	14%
Philippines*	44,540	29,040	73,580	39%
Japan*	57,151	2,184	59,335	4%
Malaysia	57,982	269	58,251	<1%
Bangladesh*	34,820	14,658	49,478	30%
ROK	45,354	133	45,487	<1%
Pakistan	27,000	8	27,008	<1%
Australia	20,520	15	20,535	<1%
Burma	9,744	506	10,250	5%
Sri Lanka*	4,731	300	5,031	6%
Singapore	1,925	95	2,020	5%
Fiji	N/A	20	N/A	-
New Caledonia*	N/A	40	N/A	-
TOTAL	990,458	256,621	1,247,019	21%

* Data for 1986 were not available. Data for 1985 were used instead.

N/A = no data available

Unlike the Philippines which has some large land holdings, 65% of Indonesian's tambaks are privately owned farms of less than 2 ha, 25% are 2 to 5 ha, and only 10% are >5 ha (Csavas 1988). During 1980, 100,000 people were engaged in brackishwater aquaculture, with a much higher number today. About 1984, the Indonesian government began a massive program to increase brackishwater aquaculture production, including extension services, hatchery construction, infrastructure support, and direct assistance. An important feature of this development was that serious efforts were and are made to assist not only large corporate ventures, but the small farmer as well. On Java, for example, new farms of >30 ha must integrate small local farmers into their plans. Outside Java 40% to 60% of the large farm developments should include small farmers as part of a "nuclear estate" principal (Csavas 1988).

Shrimp production in Indonesia up to 1986 did not show the explosive increases that occurred in China, Taiwan and some other countries. Instead, production increased more steadily, with a slight down turn in 1983 (Fig. 2). Average annual production is still low at 360 kg/ha (Table 1), which indicates

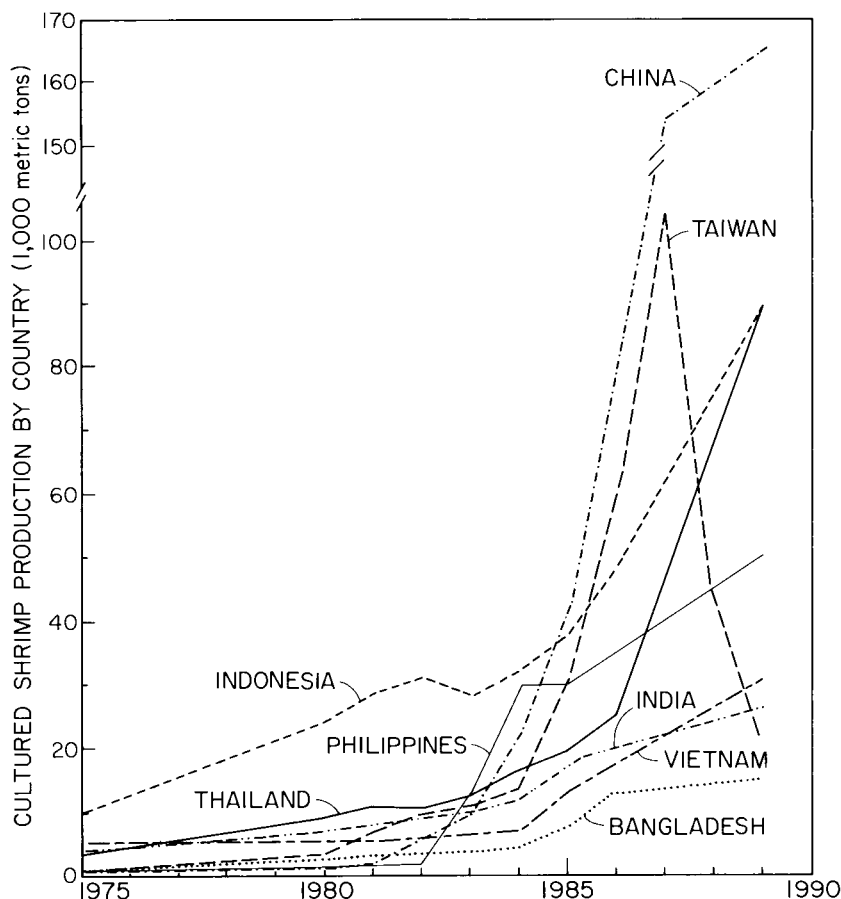


Figure 2. Cultured shrimp production in Asia from 1975 through 1989. Data through 1986 from Csavas (1988), and after 1986 from country reviews in Chapters 30 to 36.

that productivity and profit can further increase even with future shrimp price declines (Hirasawa 1985). We can expect this to occur because shrimp production costs from improved tambaks were about \$3.00/kg during 1988 at production levels of 300 to 800 kg/ha/crop (Aquatic Farms 1989). Traditional, extensive systems produce shrimp for \$2.00/kg, but cannot satisfy the demand.

Land, soil, climate, labor costs and a good supply of *P. monodon* broodstock all favor continued expansion of shrimp culture in Indonesia. Perhaps the principal constraints are feed availability and costs, and traditionally poor handling of product by the processors.

29.3.3 Thailand

During 1989, Thailand ranked third in total world shrimp culture production with 90,000 MT from 80,000 ha of ponds (Table 1). There is a long tradition of both freshwater and marine fisheries and aquaculture in Thailand, with annual seafood consumption of 39 kg per capita (22.5 kg/capita direct and 16.5 kg/capita indirect consumption; TDRI 1987). Thailand also has a large shrimp capture fishery in the Gulf of Thailand, which developed during the 1960's. Traditional shrimp culture in Thailand was in large ponds where seed were stocked through pond flooding (tidal exchange and/or pumps), and minimal feed was applied. The banana prawn, *P. merguensis* was the principal species cultured. More recently, especially since 1986, substantial intensification has occurred with most production increases coming from *P. monodon* culture. Taiwanese intensive culture technology, along with Taiwanese personnel and capital, were imported to Thailand and account for a large portion of the production increase. These intensive farms suffered serious financial difficulties during 1989 when shrimp prices fell. This has been partly remedied by strong government support, reduced feed prices, construction of cold storage facilities, and attempts to diversify the market. Thailand's ideal climate, low labor costs, developed feed industry, broodstock and seed supplies, and strong business sense should result in continued growth of its shrimp culture industry. Menasveta (Chapter 33) describes shrimp culture in Thailand more fully.

29.3.4 The Philippines

Philippine shrimp culture traditions and developments are similar in many ways to Indonesia. The Philippines also has more than 200,000 ha of shallow, brackishwater ponds in which milkfish and shrimp have been cultured for centuries (New and Rabanal 1985). In the Philippines, however, these ponds tend to be larger (2 to 20 ha) and belong to large estates or corporations (50 to 300 ha; Csavas 1988). Nevertheless, by 1983 there were 60 private and public hatcheries producing 500 million PL. One of the largest corporations in the Philippines, San Miguel Corporation, began a large demonstration project on Negros Island including a cooperative program with farmers. SEAFDEC's Aquaculture Department contributed to technology development and extension, all of which has helped lead to increased shrimp production. By 1989, the Philippines produced 50,000 MT or 9% of the world's cultured shrimp production (Table 1). While this lagged behind Indonesia's development, it is still significant considering some of the difficulties. In the Philippines, political turmoil, reluctance to invest capital, and the threat of land reform have all had a somewhat dampening effect on shrimp culture expansion. Even so, production has increased and will continue to do so. This could be accelerated even more if potential problems are resolved.

Honculada-Primavera (Chapter 34) describes shrimp culture in the Philippines more fully.

29.3.5 Vietnam

Despite a relatively long history of brackishwater pond culture of fish and shrimp in Vietnam, not much has been written about it. Vietnam has a long coastline (Fig. 1) with perhaps 300,000 to 600,000 ha of land suitable for pond construction. Traditional ponds were often very large and relied on tidal exchange for pond stocking. These "catch and hold" ponds are still operational, although production is among the lowest of the major producers (Table 1). Despite economic problems and a poorly developed infrastructure, Vietnam produced 30,000 MT of cultured shrimp during 1989, or 5% of the world's total cultured production. Vietnam is now building hatcheries and attempting to create economic incentives for shrimp culture. Given these priorities, a good climate, and low land and labor costs, shrimp culture production should continue its expansion. Quynh (Chapter 35) describes Vietnam's shrimp culture history and potential in more detail.

29.3.6 India

India has long been one of the world's largest exporters of shrimp, now ranking only second to China. During 1986, India produced 199,100 MT of shrimp, only 9% (20,000 MT) of which was from culture (Table 4). By 1989, cultured shrimp production had increased to 25,000 MT, or 4% of the world's total, but cultured production has not increased as rapidly as in other major shrimp producing nations of Asia. India has a long coastline (Fig. 1), and large population (>1 billion people). There are perhaps 1 million ha of land potentially suitable for pond culture, but only about 50,000 ha are pond cultivated (Csavas 1988). Most pond cultivation is with extensive, trap and hold operations. The ponds tend to be very large (20 to 50 ha), use tidal water exchange, culture both fish and shrimp without much effort to exclude predators or competitors, and have relatively low yields. Most of the ponds alternate between rice production during the rainy season and shrimp/fish culture during the remaining 8 or 9 months. More than 60% of these ponds are located on the east coast in West Bengal on the diffuse Ganges River delta shared with Bangladesh. Penaeus monodon PL are abundant in West Bengal, and country wide P. monodon accounts for more than 50% of cultured production. On the west coast of India, P. monodon is rare and farms there culture mainly P. indicus and Metapenaeus dobsoni (Aquatic Farms 1989).

The principal constraints to increased shrimp production in India include, lack of strong government support, ineffective extension of appropriate technology, land use problems, seed shortages, poor soil, low tidal amplitude,

and feed shortages (Csavas 1988, U.S. Dept. Commerce 1988, Aquatic Farms 1989). The government has plans to facilitate release of lands for pond aquaculture, but these have been in the planning stages since 1984 with very little progress. This is now considered the principal constraint to expansion of shrimp culture area. Programs have been initiated, however, to increase PL supply through wild seed collection, establishment of "seed banks", and distribution of PL to farmers. Shrimp hatcheries are also under development, but progress has been slow with 1989 hatchery production potentials of <200 million PL.

Many of India's coastal soils are either too acid or too sandy for good pond construction. This, coupled with low tidal amplitude, limits the land area potentially suitable for shrimp pond construction. Use of more efficient and more cost effective pumping methods could, however, greatly expand the areas available for pond culture. Better predator/competition control and increased availability of low cost feeds would also lead to greater intensification, more efficient culture techniques, and greater total production.

India almost certainly will continue its expansion of cultured shrimp production, but at a slower rate than some other Asian countries. The rate could accelerate very quickly if government policies and support improve.

29.3.7 Taiwan

In aquaculture lore, the name Taiwan is almost synonymous with intensive shrimp culture. Taiwanese pond growout and hatchery culture technologies are legend. The rapid development of shrimp culture on this small, subtropical island was truly remarkable. In the mid-1980's, Taiwan led the world in cultured shrimp production. There were, however, problems which arose that decimated Taiwan's shrimp culture industry beginning in 1988. The first major problem was disease that caused total production to decrease from 95,000 MT in 1987 to only 30,000 MT in 1988 (see Chapter 31). Estimated production in 1989 was only 20,000 MT (Table 1). Efforts are now underway to identify and correct the problems that led to this collapse. Proposed solutions include culturing a greater diversity of shrimp species, improving culture techniques, establishing disease-free stocks, concentrating on development of high-technology but appropriate aquaculture approaches, and transferring technology (and capital investments) to other countries.

It now appears that world shrimp supplies will exceed demands and shrimp prices will fall. This does not bode well for intensive culture systems wherever they may be. Production costs from intensive culture typically exceed \$5.00/kg. With extensive and semi-intensive culture, production costs range from about \$2.00 to \$3.50/kg. Intensive culture systems, for which Taiwan is famous, will most likely remain with us for a long time, but their

application may be more for specialized production of shrimp species and product forms that command premium prices. Liao (Chapter 31) describes Taiwan's shrimp culture more fully.

29.3.8 Bangladesh

In many ways, Bangladesh is blessed with conditions for shrimp culture which are only now starting to be realized. Bangladesh is also unique in that its fisheries production from freshwater capture fisheries and aquaculture (freshwater and marine) far outweighs production from its marine capture fisheries. In 1986/87 for example, total shrimp production from all sources was 73,000 MT, of which 43,000 MT was captured in freshwater (Aquatic Farms 1989). About 95% of these 43,000 MT were "small shrimp and prawns" which were consumed locally. Of the remaining 30,000 MT, about half were from aquaculture pond production, and half from artisanal and industrial marine fishermen. Another source estimated total production at 49,478 MT for 1986 (Table 4), and 14,658 MT from culture. The discrepancy could be due to estimates of local consumption, which are difficult to obtain. Whatever the case, shrimp production potential from Bangladesh's more than 80,000 ha of shrimp culture area is large.

Traditional culture methods in southwest Bangladesh, like in West Bengal, India, involve rice/shrimp-fish crop rotation. During the rainy season, rice is cultured in low salinity waters, while, during the dry season, the fields are flooded with brackishwater and shrimp and fish are cultured in large ponds. In southeast Bangladesh, shrimp-fish culture rotates with salt production. The wet season crop here is shrimp-fish, while in the dry season, salt is produced. Overall during 1985, 60% of shrimp pond area was rotated with rice, 35% with salt, and 5% was under shrimp monoculture (Csavas 1988).

The broad Ganges River delta covers a large part of coastal Bangladesh. This estuarine environment is very productive biologically and is one of the world's largest sources of wild P. monodon PL. During 1985, 20 to 25 thousand fry collectors produced between 1 and 2 billion P. monodon PL. Other species collected and cultured include P. indicus/merguiensis, P. semisulcatus, Metapenaeus brevicornis, M. monoceras, and Macrobrachium rosenbergii.

Production is very low from the traditional ponds which average <150 kg/ha/yr. Improved culture methods such as selective stocking and fertilization increase yields to between 200 and 500 kg/ha/yr.

The principal constraints to increased shrimp culture production include; infrastructure development (roads, ice, electricity, etc.), poor pond management methods, PL shortages and distribution problems, feed shortages, and weather. A large percentage of Bangladesh lies only a few meters above

sea level. Tropical typhoons strike the country once or twice a year with substantial losses of life and property. Although wild PL are often abundant and inexpensive (<\$3.00/1,000), they are at times inadequate to meet the needs. Programs are now in place through loans from the Asian Development Bank and World Bank to solve some of these problems. With large potentials for shrimp culture production, and adequate profit motive, shrimp production will almost certainly increase soon. Production levels approaching 100,000 MT by the year 2000 are not unrealistic.

29.3.9 Japan

Japan is rightly considered a pioneer of modern shrimp culture, but cultured shrimp volume has always been small. During 1986, cultured production was only 2,184 MT compared with 57,151 MT from ocean capture (Table 4). Farmed shrimp production increased to about 3,000 MT during 1988 (see Chapter 30), but it is not likely to experience production increases anything like those which occurred in other Asian countries. Almost all cultured shrimp production is for karuma prawn, *P. japonicus*, one of the most thoroughly researched marine shrimp species. Live karuma prawn sell for very high prices in Japan, but dead their price is not much greater than for other species. Principal constraints for shrimp culture in Japan are cold climate, scarcity of suitable and available land for culture, and high labor costs. Other than for the high priced live market, it is more economically feasible for Japan to import shrimp than to culture it domestically. Shigueno (Chapter 30) and Fast (Chapter 17 and 18) describe Japanese shrimp culture in more detail.

29.3.10 Malaysia

For its size and coastline length (3,400 km), Malaysia is one of the least densely populated countries in coastal Asia with only 16 million people. While the Malaysians have a long tradition of fish capture, they have very little history of aquaculture. These trends are evident in the 1986 shrimp production statistics which show 57,982 MT were captured from the wild, but only 269 MT were cultured (Table 4). The shrimp capture fishery has now reached or exceeded maximum sustainable yield and any production increase must now come from cultured production. Government policy now favors use of public lands for shrimp culture. Many farms, especially those built in mangrove areas, have failed because of acid sulfate soil problems. High construction costs, and labor shortages have also contributed to a sluggish shrimp culture industry. Shifts in government policy could result in substantial production increases. Favorable climate, a well educated population, large land area and abundant *P. monodon* broodstock could contribute to this expansion.

29.3.11 Republic of Korea (ROK)

During 1986, the Republic of Korea produced 133 MT of marine shrimp (mostly *P. chinensis*) from 430 ha of ponds, compared with 45,354 MT captured from the wild. Shrimp production in ROK is severely limited by cold climate, scarcity of suitable pond sites, and high development costs. There are no plans to substantially increase production (U.S. Dept. Commerce 1988).

29.3.12 Burma

While Burma lacks an aquaculture tradition, it has a long history of fish and shrimp capture from both marine and freshwater. During 1986, Burma produced 9,744 MT from its capture fishery, and 506 MT from cultured production (Table 4). Although climate, coastline length (Fig. 1), labor costs and other factors could favor expansion of shrimp culture, political unrest, government policies, and economic constraints are likely to severely dampen shrimp culture developments in Burma.

29.3.13 Singapore

Although Singapore has a small land area, it has high per capita income, a tradition of seafood consumption, and high prices for live shrimp. These conditions have resulted in a small, but prosperous shrimp culture industry. During 1985, 95 MT were produced from 300 ha of ponds and floating cages (U.S. Dept. Commerce 1988). Production may increase slightly, mostly for domestic consumption.

29.3.14 Sri Lanka

Shrimp culture began in Sri Lanka during 1985, and because of political unrest has developed slowly. Cultured shrimp production during 1986 was 300 MT, compared with 4,731 MT captured from the wild (Table 4). A modest increase in shrimp culture production is expected, but is at least partly dependent on socio-political conditions.

29.3.15 Pakistan

Captured shrimp production was 27,000 MT during 1986 compared with only 8 MT from culture (Table 4). Lack of brackishwater culture tradition, suitable pond sites, and critical mass of culturists is likely to greatly limit shrimp culture in Pakistan, despite governmental interest in its development.

29.3.16 Hong Kong

Hong Kong, like Singapore, has limited land area suitable for shrimp culture, although during 1988 there were 210 ha of shrimp/fish ponds in

production (U.S. Dept. Commerce 1988). There are no shrimp hatcheries and a limited growing season. Production is not likely to increase much.

29.3.17 Cambodia

Cambodia (Kampuchea) has a small coastal area which could be used for brackishwater culture (Fig. 1), but not much information exists about its use. Whatever production exists should be small. Political unrest during the past 20 years almost certainly preclude near-term realization of shrimp culture potential.

29.3.18 Australia

Australia produced only 15 MT of cultured shrimp during 1986, and 20,520 MT of captured shrimp (Table 4). There is strong interest in shrimp culture, but few successes. The principal cultured species differ from most other shrimp culture areas, and include Metapenaeus macleayi and P. latisulcatus. High labor costs (New and Rabanal 1985), land use restrictions, and lack of an aquaculture infrastructure are some constraints. Maguire and Allen (Chapter 36) describe Australian shrimp culture more fully.

29.4 MANGROVE FOREST CONVERSIONS

In Asia, as elsewhere, a realization has developed that mangrove forests are not wastelands, but instead are valuable resources. While their exact value is still difficult to quantify, they do provide an important nursery area for many fishes and crustaceans. They are also valuable sources of human food, detritus for marine food-webs, firewood, building materials, and other products. Until recently, their perceived low value and typical lack of ownership made them prime targets for extensive shrimp pond construction. While pond construction in dense mangroves is difficult, it was economically feasible where labor was cheap and land free. Mangrove ponds are often well suited for tidal water exchange, while shrimp and fish seed are typically abundant. Pond stocking is through water exchange.

Mangrove ponds exhibit some problems for aquaculture production, the greatest one of which is acidification. Soils in mangrove areas are often acid-sulfate. Disturbances caused by pond construction and renovation often create severe acid problems, particularly when attempts are made to intensify production through pond deepening. Mangrove ponds also have leakage problems from mangrove roots embedded in the dikes, and from crabs that bore into the dikes. Shrimp farms built deep in mangrove forests often have water quality problems, particularly from recycled pond effluents both from their ponds and from ponds closer to slough entrances. These problems did not stop mangrove conversions to shrimp and fish culture ponds.

By the time people came to realize the greater good of mangrove forests, many countries had lost large portions of these valuable resources. By 1985, Java had lost 70% of its mangroves, the Philippines 45%, Thailand 27%, Malaysia 20% and so on (Csavas 1988). Laws were enacted in many countries to limit further destruction, but these are often ineffectual and not consistently applied.

An alternative to pond construction in mangroves is to build either behind the mangroves or in non-mangrove areas and use pumped water exchange. This approach can avoid the acid soil problems which have doomed many farms to economic failure. It can result in better water quality. Furthermore, pump-fed ponds (as opposed to tidal-fed) have been shown to provide better economic returns (Gedney et al. 1983).

The mangrove forest destruction rate has slowed. As we get better information on their value, better management plans will evolve. Awareness of a problem is the first step towards a solution. That first step has been taken.

29.5 SEED PRODUCTION

Shrimp seed production from hatcheries made possible the large expansion of shrimp culture production. Still, a sizable portion of total seed comes from the wild. In some ponds, this means passive stocking of ponds through water exchange, while in other cases it involves shrimp seed collection and transport to the pond for stocking. With passive stocking, the pond must be located where seed are abundant in source waters, often in mangrove areas. Stocking rates are usually low (<1 PL/m²), seed species are not controlled, predators and prey often enter ponds with shrimp seed, and shrimp seed are not always present. Seed collection is also a very destructive process since, "...usually not more than 10% of the collected seed belongs to the preferred species (the rest is destroyed) and a similar low percentage of the selected seed reach the growout ponds and have a chance of survival" (Csavas 1988). For every one PL stocked in the pond from wild seed collection, more than 100 other shrimp and fish seed have died. Improved collection and distribution of shrimp seed could thus not only prevent needless waste of unwanted seed species, but it could also increase seed availability from this source by a factor of 10. This ten-fold increase could be realized without greatly increasing the number of people collecting and distributing wild shrimp seed. Only handling procedures and techniques need improvement.

Seed shortages exist in some countries at all time, and in other countries at some times. Increased seed availability of the right species, at the right time, and at the right price will lead to further major increases in shrimp

production. The increases due to seed availability alone might result in production increases equivalent to what we have seen during the past 20 years.

Countries with the greatest shrimp seed shortages include India, Vietnam and Australia. All three countries lack adequate hatchery facilities and do not collect sufficient wild seed of the desired species to meet their needs. Taiwan, Thailand and the Philippines have the least problems with shrimp PL supplies. An interesting phenomenon occurred in the latter three countries to supply shrimp, namely the evolution of a small-scale hatchery sub-industry. These hatcheries as described by Forbes (Chapter 8) are typically family run, low overhead operations that have substantial flexibility. Their internal rate of return, return on investment and cost/benefit ratios were all superior to larger hatcheries, especially large corporate ones (Csavas 1988). In Thailand, many of these hatcheries were originally developed for freshwater prawn seed production, but can and will produce penaeid seed depending on nauplii and/or broodstock availabilities and the current price/demand situation. Large hatcheries are typically designed for continuous production. Shut-downs from disease or nauplii shortages greatly disrupts production schedules and negatively impact break-even prices of PL sales. Small-scale hatcheries, on-the-otherhand, take these shut-downs in stride. It is unlikely that large hatcheries, as presently designed and operated, can compete with a well developed network of small-scale hatcheries. If this conclusion is correct, it will eventually result in either the demise of large hatcheries, or their redesign.

Seed availability and price are still constraints for shrimp culture, but they are less important than they once were. Existing technology and profit motives will surely eliminate seed shortage constraints, increase production levels, and, in so doing, make some other condition the limiting factor for shrimp culture profitability.

29.6 PRICE STABILITIES AND MARKETS

Talk of possible shrimp over supplies has existed for years, but was not taken too seriously by most people until recently. Conceptually, when supply exceeds demand, prices should fall in order to increase consumption. This concept became reality in Asia during 1989.

Thailand was one of the first countries to suffer from the 1989 price drops. This occurred during early 1989 and precipitated a march on the Thai legislature by irate Thai shrimp farmers during April 1989. The crisis was caused by a number of factors including import reductions by the Japanese, a shortage of other outlets for Thai shrimp, and insufficient cold storage where Thai shrimp could be stockpiled until market conditions improved.

Reductions in Japanese imports were attributed to reduced shrimp consumption by Japanese, related to Emperor Hirohito's failing health, and to increased imports to Japan of lower priced Indonesian shrimp. This created a bottleneck for Thai shrimp exports. They then had to be sold elsewhere at reduced prices. Within a very short time, Thai shrimp prices pond-side for 30 to 40 g *P. monodon* dropped from \$9/kg to less than \$4/kg. The lower price was below break-even costs for intensive farms which have proliferated in Thailand. High feed costs (>\$1.25/kg) contributed to the problem. Thailand responded by lowering taxes on imported feed ingredients, lowering feed prices, construction of more cold storage facilities, and market diversification.

Although Thailand suffered first during 1989, the Philippines, Indonesia and other countries were also affected later. The wave effect in each case progressed from exporter to processor to farmer to seed and feed suppliers. Prices have since recovered almost to their former levels, but apprehension exists that the cycle will repeat.

An interesting footnote is that the 1989 price swing was mostly confined to Asia. Shrimp producers in Central and South America were largely unaffected. The reason for this is apparently related to integration of production with exporters and importers in the Americas. This integration prevented panic bidding at dock-side that occurred with Asian shrimp.

A recent market assessment commissioned by the World Bank indicated that world cultured shrimp production is expected to increase by 17% annually through 1993, compared with 41% annual growth for the period 1985-1988 (Aquatic Farms 1989). A 17% annual cultured production increase and a stable catch fishery will result in an overall increase in shrimp supplies of 6% annually. At the same time, if real prices remain constant, world demand for shrimp is expected to grow at 3.5% annually. Given this excess supply relative to demand, shrimp prices are expected to drop in order to increase demand. Assuming an average price elasticity of demand for shrimp of -0.30, shrimp prices are expected to drop by 6% to 10% annually through 1993. This means that by 1993, real shrimp prices could decline by 30% to 40% compared with 1988 prices. For shrimp farmers this could mean a pond-side price for 30 g *P. monodon* of \$4.00/kg, and for 20 g *P. chinensis* pond-side prices of only \$2.10/kg. Even integration of production with consumption will not alter an oversupply if this situation continues. One solution is to increase the market demand through creative marketing and diversification of the market and product forms. Europe perhaps offers the greatest potential for market development.

Other partial solutions to potential shrimp price drops are to diversify the species cultured and, more importantly, to use culture systems that produce

shrimp at less cost. Today, semi-intensive culture systems are the most cost effective.

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CHAPTER 30

K. Shigueno

SHRIMP CULTURE INDUSTRY IN JAPAN

30.1 INTRODUCTION

Japanese people, with a long and close association with the sea, naturally enjoy the taste of many seafoods. Among seafoods, very fresh kuruma ebi (*Penaeus japonicus*) is one of the most popular items, not only because of its wonderful taste, but also because of its beautiful color and elegant shape that provide a feast for the eyes. The shrimp, wild or cultured, are shipped live to markets where they usually command premium prices. They are served raw, as Odori, or cooked, as Tempura, before gourmet diners at super A class restaurants. Kuruma ebi is rarely bought by housewives for home use. By contrast, as much as 260,000 MT per year of imported frozen shrimp is consumed by the general public.

Modern shrimp culture in Japan began in 1963 when the late Dr. M. Fujinaga (Hudinaga) established a pioneer shrimp farm at a remote town in western Japan, after 30 years of research on larval rearing techniques for *P. japonicus*. His mariculture venture was applauded by many people, and soon triggered a shrimp culture boom in many parts of the world. Despite success with larval rearing, however, many problems with pond management and nutrition remained unsolved and caused many difficulties for his farm, and other farms that followed his example.

In 1975, I published a paper, 'Shrimp Culture in Japan,' in which I described how the culturists could overcome some of these difficulties. Now, 14 years later, new advances in production have made the paper outdated. Having continued my interests in shrimp culture, and still owner of a shrimp farm, I would like to take this opportunity to comment on current shrimp culture practices in Japan.

30.2 SHRIMP CULTURE OVERVIEW

30.2.1 Species cultivated

In Japan, *P. japonicus* is the only penaeid shrimp that is cultivated in significant quantities. According to government statistics, annual production of cultured shrimp from 157 farms amounted to 2,882 MT in 1987, with estimated production of 3,000 MT in 1988. Production during the past ten

Table 1. Yield of cultured and ocean caught P. japonicus in Japan from 1976 to 1988.

Year	Number of Farms	Cultured Yield	Pond Area	Ocean Yield
1976	105	1,042 MT	360 ha	2,579 MT
1977	104	1,124	-	2,440
1978	119	1,184	455	2,673
1979	120	1,480	397	2,468
1980	117	1,546	403	2,307
1981	128	1,666	-	2,864
1982	129	2,000	474	3,068
1983	134	2,302	476	3,578
1984	142	2,037	497	3,356
1985	148	2,151	531	3,741
1986	154	2,434	-	3,357
1987	157	2,882	-	2,904
1988	-	(3,000)		

years has increased steadily (Table 1). During that period, shrimp farm number increased 50%, and annual yield almost trebled.

Cultured shrimp production is now comparable to catch from the wild. Most existing shrimp ponds are constructed by impounding a sandy area in the intertidal zone, 0 to 50 cm above mean low tide. Pond water is changed through water gates, taking advantage of the tidal flood twice daily. Total active pond area in Japan is presently about 550 ha. Productivity at successful farms may reach 6 MT/ha/yr. One can ignore production from net enclosure and concrete tanks built on land. These culture systems have not proven economically successful, and are not used much.

Shrimp production in Japan is expected to level off soon because of limited tidal area available for further development. Because of climate, land and economic factors, shrimp farming in Japan cannot compete with some other countries. Japan has, however, developed a unique technology specific to P. japonicus. Cultivating this indigenous species is advantageous for Japanese farmers since there is a strong market demand for live product. It is still one of the most sought after seafoods.

Japanese shrimp farm locations are illustrated in Figure 1. Most shrimp farms are located in the southwestern part of mainland Japan, where the principal shrimp fishing grounds are located. Recently, new shrimp farms have been established in the southwestern archipelago, where P. japonicus is not abundant in the wild.

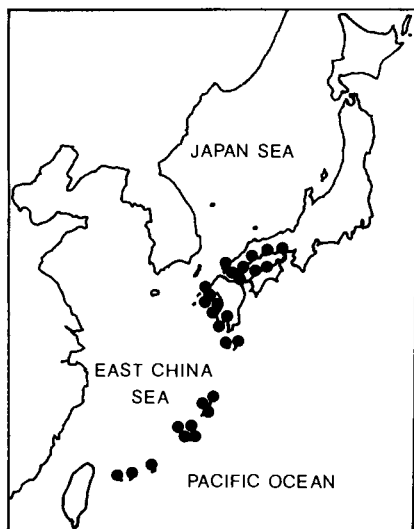


Figure 1. Location of shrimp farms in Japan in 1988.

30.2.2 Unique features of *P. japonicus* culture

Among seafood delicacies, *P. japonicus* about 22 cm long served as Odori or Tempura has always been highly prized among gourmet diners. The well-defined brown, yellow, and blue stripes on its body, soft meat and mild sweet taste are all exceedingly appealing. Live shrimp marketed each month and auction price of 20 and 30 g shrimp at the Tokyo Central Fish Market during 1988 are shown in Figure 2. Symbols I, W, and C denote imported, domestic wild and domestic cultured shrimp, respectively. Imported *P. japonicus* came mostly from Taiwan, Japan's neighboring competitor. Taiwanese shrimp imports amounted to 30%, compared with 55% for domestic cultured production. The auction price of shrimp weighing 20 to 30 g, the most popular size, was as high as \$50/kg.

Middlemen purchase shrimp at auction for this price and then sell the shrimp to restaurants with added commission. With additional profit to the restaurant, imagine how much a single dish costs a gourmet. Housewives cannot afford to buy such an incredibly expensive item for home use.

The premium on live shrimp encourages local fishermen who operate gill-nets or baby trawls to catch and keep the shrimp alive. Once the shrimp die, the price falls to one third or one fourth the live price. Middlemen at local fish harbors compete at auction. Every middlemen who specializes in this trade has his own aquarium where he stores live shrimp before shipment. This practice facilitates the selection and acquisition of gravid female shrimp by culturists for hatchery work. During the spawning season, it is sometimes

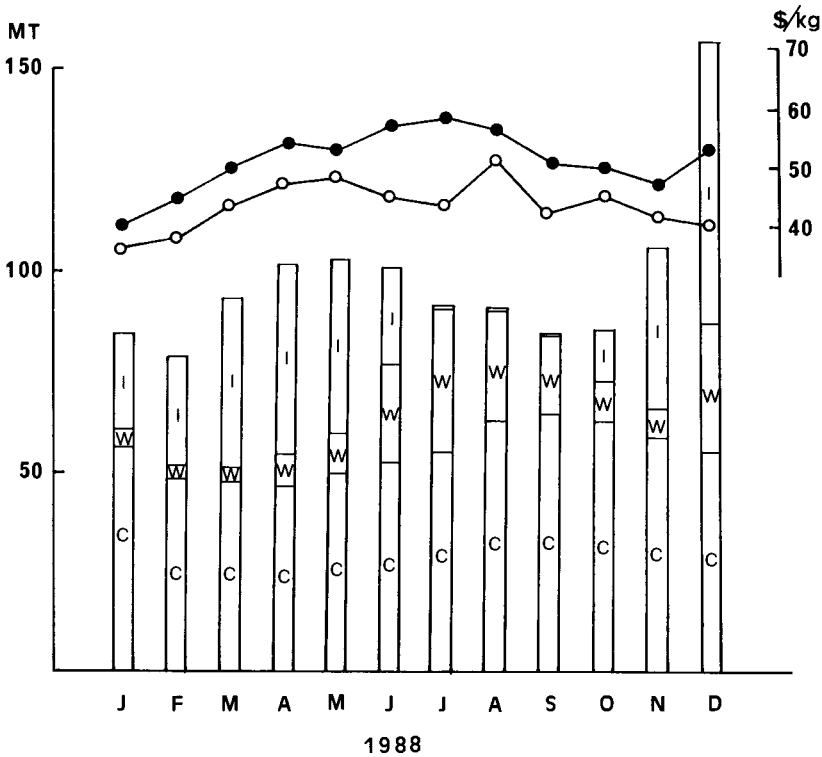


Figure 2. Live shrimp prices and volume at the Tokyo Central Fish Market during 1988. Top line is price of 30g and bottom line 20g shrimp. Bars are tonnage; I= imported, W= domestic wild caught, C= domestic cultured.

possible to buy more than a hundred wild spawners at a time. This situation has motivated culturists to set up huge larval rearing tanks. A 100 to 400 m₃ capacity tank is not unusual.

Wild spawners obtained from the local market are shipped to the hatchery in an aerated tank on a truck, or in chilled sawdust for air shipment. The former method gives slightly better spawning efficiency. The second method makes greater demand on the remarkable ability of this species to survive out of water. The closed thelycum of the female holds the spermatophore firmly and makes captive mating and maturation unnecessary.

Table 2. Composition of SH medium (Shigueno 1985).

Component	Amount	Component	Amount
Filtered sea water	700 l	H ₃ BO ₃	3.4 g
Fresh water	300 l	Na ₂ MoO ₄ ·2H ₂ O	0.13g
NaHCO ₃	60 g	Na ₂ SiO ₃ ·9H ₂ O	28 g
KNO ₃	21 g	FeCl ₃ ·6H ₂ O	0.39 g
EDTA-2Na	6 g	Na ₂ HPO ₄	3.6 g
Vitamin B ₁₂	0.02mg		

30.3 CULTURE TECHNIQUE

30.3.1 Larval rearing

Larval rearing in large concrete tanks has evolved through repeated trials over the past two decades. This technique is well suited to the physiology and ecology of *P. japonicus*. Details of technique vary among culturists, reflecting personal attitude and preference. The following method is one currently used on a farm, which is believed to be using progressive techniques.

First, the larval rearing tanks are built outdoors. Experience indicates that outdoor tanks are more productive. This is thought due to sterilization of the dry tanks by sunlight between cultures and to the favorable rearing environment created by flourishing diatoms during larviculture. There is no need to control light intensity, nor rainfall, since the larvae are resistant to these, as well as to chemical fertilizers applied directly to the tank for diatom growth. Water pH should not exceed 8.7 which is associated with excessive diatom blooms.

Careful attention to the hatchery water supply ensures consistent larval production. Water is filtered through a tank equipped with layers of gravel, sand and activated charcoal or anthracite. The filtration system should be well maintained to ensure adequate nitrification.

A few days before placing gravid spawners in the tank, diatom cultures are started in 1 m³ semi-transparent containers. These are placed outdoors, filled with SH medium (Table 2) and heavily aerated. In four to five days, the water turns dark brown reflecting the growth of diatoms such as *Chaetoceras*, *Skeletonema*, *Melosira*, *Rhizosolenia*, *Nitzschia* and so forth. The culture is added to the larval rearing tanks when shrimp are nauplii. This causes water in the rearing tanks to turn slightly brown. Diatoms are maintained by daily applications of SH chemicals to the tanks. Application can be done safely at twice the dose of chemicals in Table 2 for each 50 m³ of water. Addition of mixed culture diatoms, followed by direct application of SH fertilizer, results in favorable rearing conditions in terms of food and water quality. These

Table 3. An example of larval rearing operation making use of an experimental tank (56 m³) during 1988.

Date	Stage of larvae	Number of larvae (x 10 ³)	Depth	Application of SH chemicals	Diatoms added	Artemia cysts	Artificial diet	Temperature
April 24	*		105 cm					25.0 C
25	E,N	1,900	109					25.3
26	N	2,187	120	yes	yes			24.5
27	Z	2,130	130				17 g	25.8
28	Z	1,788	150	yes	yes		30	25.8
29	Z	1,905	150				35	26.2
30	Z	1,605	170	yes	yes		50	25.3
May 1	Z	1,664	177				80	26.0
2	M	2,087	180	yes		140g	100	25.8
3	M	1,599	195			410	125	25.2
4	M	1,599	210	yes		530	130	
5	PL	1,790	210			520	150	26.0
6	PL	1,473	210			520	180	26.1
7	PL		210	yes		520	250	25.8
8	PL		210	yes		470	270	26.1
9	PL		210			470	290	25.8
10	PL		210	yes		605	310	25.5
11	PL		210			205	320	25.1
12	PL		210	yes			350	25.0
13	PL		210				400	25.4
14	PL		210	yes			560	25.1
15	PL		210				640	26.0
16	PL		210	yes			700	25.2
17	PL		210				720	26.2
18	PL		210	yes			800	25.9
19	PL		210				840	25.8
20	PL		210	yes			900	26.3
21	PL		210				968	25.7
22	PL		210				1,040	25.8
23	PL		210				1,172	26.0
24	PL		210				1,240	
25	PL		210					
Harvest		1,302			Total	4,435 g	12,667 g	

*: 38 Spawners

E: Egg, N: Nauplius, Z: Zoea, M: Mysis, PL: Postlarvae.

Number of larvae estimated by random sampling.

steps minimize the occasional larval rearing failures seen in the past. This technique also eliminates the need to maintain a large stock of food organisms.

Table 3 gives an example of larval rearing using large tank culture techniques. It shows the production of 1,300,000 postlarvae (PL) in a 56 m³ tank. At first, zoea larvae feed on cultured diatoms. After a few days, feeding of finely divided artificial diet, four times a day, begins. The amount and size of the diet is increased throughout four weeks of larval development. Diatoms and artificial food are supplemented with brine shrimp nauplii during late mysis and early PL stages. In summary, three food items, mixed diatoms supported by SH medium, brine shrimp nauplii, and refined artificial diet are the key ingredients in this larval rearing scheme, which in the example yielded 25 PL/l. Average farm production ranges from 5 to 10 PL20/l. Costs of PL20, including capital depreciation, is estimated at less than \$3.50/1,000. Most farms produce PL for themselves, but occasionally sell to another farm for \$7.00/1,000 PL20.

Postlarval production of *P. japonicus* is done extensively throughout Japan by both private and public organizations. Nowadays, about 200 million PL are produced by shrimp farmers for commercial culture and 500 million PL are produced by government organizations for marine ranching every year.

Diseases have hampered larval production, and PL mass mortality of 60 to 100% has been reported by many farms. Especially during 1971/73, heavily infected PL, mostly 6 to 9 mm in length, could be easily distinguished as they floated inactively on the water surface and exhibited white intestinal lines. Cells of the infected midgut were largely destroyed by gram-negative bacteria. It was also observed, in rare cases, that blotches of brownish black pigment developed in the midgut. Later, investigations by pathologists identified the cause as BMN one of the viral diseases of cultured penaeids (Lightner 1988). No effective countermeasures are known, but fortunately, no such serious infections have been reported subsequently.

30.3.2 Nursery procedures

PL are usually transferred to a nursery pond at 130 to 150/m² where they are grown to 0.5 g juveniles. This takes 40 to 45 days in southern Japan. Nursing serves two purposes. First, it allows good stock inventory control as juveniles start their pond growout. Secondly, it minimizes predation on shrimp by fish. Transfer from nursery to growout ponds is facilitated by electrical shockers which stun the juveniles. During transfer, the number of juveniles allocated to each pond is confirmed. Experience shows that PL survival in nursery ponds is about 70%, while nearly 100% survival can be anticipated thereafter in well managed growout ponds. This enables the culturists to know production costs at any time.

30.3.3 Management of growout ponds

It is most desirable to construct nursery and growout ponds by making embankments in the sandy tidal zone, 0 to 50 cm above low tide. The embankment should be equipped with a water gate so that water can be exchanged by the tide. Some farms install low head, high volume pumps to allow water exchange even during neap tides. A screen should be installed in each water gate. Water aerators at 2.2 kwh/3,000 m³ serve to mix and aerate the water. Several trenches dug in the bottom trap dirty organic sludge produced during growout. It is thought desirable to maintain at least 2 m water depth in the pond. It is also desirable to maintain adequate algal densities, preferably diatoms, through appropriate water exchange.

Juvenile stocking densities in the growout ponds differ from one farm to another, but range from 25/m² to more than 50/m². In order to increase production and lengthen the harvest period, some influential farms have recently introduced the practice of two pond stockings so that two age groups of shrimp are simultaneously raised in the same growout pond. Figure 3 shows an example of shrimp growth curves for two age groups in the same growout pond. It also shows the contribution of each age group to standing crop during the year. In this case, harvesting and shipment began during late November and lasted until early June.

Baited traps covered with a large mesh net were used to selectively harvest large individuals. Selective harvest serves two purposes. First, it yields large shrimp which command high market prices. Secondly, it enhances the growth rate of smaller shrimp which remain in the pond. As shown in Figure 3, population density reached a peak of 350 g/m² in late November, when harvest began. Densities remained just below this level for about three months, before falling off until harvest ceased in early June.

Total yield from this pond was 634 g/m². Stocking densities for this method are about 25 juveniles/m², which on average yields about 550 g/m². The best locations for farms using this method are in southern Japan where the climate is mild in winter. Minimum total pond area for farms to successfully use this refined method may be about 10 ha. Most family owned shrimp farms are smaller than 10 ha, and, consequently, this method is inappropriate for them. Instead, they often stock at greater densities of PL in an attempt to increase yield without adopting nursing procedures. This tends to result in unpredictable yields, smaller shrimp, reduced growth rates, and increased susceptibility to disease.

Some time ago, an ultra-intensive culture system, which made use of double bottomed round tanks was pioneered in Japan. This culture system has now been abandoned because of the excessively high construction and operation costs that occurred after the mid-1970's oil crisis. In addition, this design led to reduced growth rates and higher susceptibility to fungal and

Vibrio infection, probably due to unmeasured stress. These problems caused pessimism among the scientists and practitioners involved.

30.4 PACKING AND MARKETING

Pond harvested shrimp are transferred immediately to net-trays, at proper densities. The net-trays are stacked in the water of cooling tanks. Each cooling tank is made of insulated concrete with refrigeration coils on its inner surface. A 10 m³ tank can hold 300 kg of shrimp, and can reduce temperatures 10 C below pond temperature within several hours. As the water cools, shrimp become inactive, moving only their walking legs and swimmerets. Body color darkens to a reddish tinge, especially the walking legs and connecting body parts which develop a brilliant red. Proper harvesting, handling and packing of live shrimp is very important since it affects the condition of shrimp at the market, and therefore, price at auction.

After the live shrimp are adequately cooled, they become tame and easily handled. They are then sorted in baskets by size, and moisture is shaken off. Shrimp are next packed in cartons with dry, cool sawdust using alternate layers of sawdust and shrimp. The full and tightly packed cartons are then sealed with adhesive tape. Six small cartons, each containing 1 kg of shrimp and sawdust are placed in one large carton. On both the small and large cartons are marked the contents, weight, number of shrimp and farm name. Shrimp are quickly moved to market by cold storage trucks and air freight. Upon arrival, the shrimp are kept in a cool place until early the following morning when the market opens. Receiving agents at large fish markets sell

Table 4. Production and costs for first five years of start-up and operation of a successful shrimp farm in southern Japan (Amami Prawn Inc.). Monetary exchange, US \$1.00/Y140.

	1984	1985	1986	1987	1988
Yield (MT)		33.411	41.507	58.606	72.894
Total pond area (ha)		7.5	7.5	12.5	12.5
(Avg. yield, MT/ha)		(4.45)	(5.53)	(4.68)	(5.83)
(Feed conversion ratio)		(2.89)	(2.58)	(2.32)	(2.47)
Gross income		\$1,465,604	\$2,073,992	\$2,403,583	\$3,608,676
(Avg. price per kg)		(\$43.86)	(\$49.96)	(\$41.01)	(\$49.50)
Total cost	\$108,701	\$1,324,755	\$1,610,604	\$1,764,148	\$2,590,270
Profit		\$ 139,849	\$ 463,388	\$ 639,435	\$1,018,406
Profit/Gross income		9.5%	22.3%	26.6%	28.2%

shrimp on consignment for the farms. The shrimp are sold at auction to middlemen, who are accredited by the market, especially as concerns financial reliability. The middlemen bid based on shrimp quality, quantity, and the needs of their customers, the hotels and restaurants. Vitality, muscularity and well-defined coloration of the shrimp are important criteria of quality. Receiving agencies handle sales for farms very responsibly, and receive a 5.5% commission on sales.

30.5 COST ANALYSIS

Table 4 shows production and costs for the first five years of start-up and operation of a successful shrimp farm, established in 1984 in southern Japan. During the first year, one nursery pond (1.5 ha) and two growout ponds (2.5 ha and 3.5 ha) were constructed. The next year, cultivation began in the 7.5 ha of ponds. In 1987, one more growout pond (5.0 ha) was constructed and put into operation during the later part of the season, but too late to yield a full crop that year. In 1988, the farm eventually realized its expected productivity, with a high profitability (28%). Shrimp were fed exclusively with an artificial feed, that had feed conversion ratios (FCR) ranging from 2.32 to 2.89. These FCR reflect lower feed efficiency during winterfeeding on this farm where the main shipment was scheduled in March, April, and May. By December, FCR was lower than 2.0. According to technicians on this farm, their target yield was 5.5 MT/ha/year. This sounds reasonable in view of experience elsewhere with P. japonicus given normal growth and survival, and adequate nutrition and environmental control. The high price of \$50/kg represents a unique feature of this industry. The benefits of operational scale, and the stabilized high profit rate can be seen in Table 4. Cost analysis for this farm during 1988 is shown in Table 5. Three items, feed (33.8%), remuneration and wage (14.4%), and packing and shipping (12.3%) account for 60% of total costs.

In Japan, there are six feed manufacturers that produce about 4,000 MT of P. japonicus feed annually. In addition, a fairly large amount of frozen materials such as mysids, trash shrimp, and trash fish are still used as shrimp food by more traditional farmers who prefer them to manufactured feed.

30.6 MARKET TREND AND PROSPECT

Some successful culturists, and others, think shrimp culture is a promising and lucrative business because of the high market price and increasing shrimp consumption in Japan. Japanese farmers, however, face competition from imports. Live imports of P. japonicus from Taiwan in the last three years have had a strong psychological impact on Japanese shrimp farmers. Imported Taiwanese shrimp, which are comparatively small in size, actually

Table 5. Cost analysis, calculated from a record of culture operation in 1988 (see Table 4).

Gross income (72.894 MT)		\$ 3,608,676
Total cost		\$ 2,590,270
Feed	33.8%	
Spawner	0.4%	
Balance of inventory	0.5%	
Officers' remuneration	6.3%	
Wage	8.1%	
Legal welfare expenditure	1.0%	
Welfare expenditure	0.0%	
Wear & tear expenses	2.5%	
Packing & shipping	12.3%	
Traveling expenses	0.6%	
Communication expenses	0.1%	
Social expenses	0.3%	
Sales commission	7.5%	
Land rent	1.0%	
Facilities rent	1.6%	
Fuel & power	5.4%	
Advertising expenses	0.2%	
Repair expenses	4.1%	
Insurance	0.1%	
Tax	3.5%	
Depreciation	7.2%	
Depreciation of deferred assets	0.0%	
Allowance for bad debts	0.0%	
Allowance for bonus	0.1%	
Balance of goods in progress	1.0%	
Balance of interest & miscellaneous receipts	2.2%	
Abandonment cost	0.2%	
Miscellaneous expenses	0.4%	
Profit		\$1,018,406
Profit/Gross income		28.22%

depressed the price of that size shrimp from time to time. On the other hand, the increased supply and lower price stimulated greater consumption. As demand increased, the relative shortage of larger shrimp became conspicuous, and the price increased. A few years ago, market trade of live *P. japonicus* which sustained a reasonable price level in Tokyo, was about 1 MT/day. Today, this has grown to more than 3 MT/day, including imported shrimp. At the same time, differences of shrimp quality between farms became conspicuous. Cultured shrimp from the leading farms usually command higher prices because of their quality. Consequently, these farms

keep achieving good business results. It is believed that the key to success in the hardening competition, is not merely to produce in quantity, but to grow really gorgeous shrimp comparable to ocean caught shrimp.

30.7 SUMMARY

Penaeus japonicus is the only shrimp species cultured in quantity in Japan. Total production of cultured shrimp in 1988 was 3,000 MT from 160 farms. Shrimp mariculture in Japan is characterized by the production of an incredibly expensive, live sea food to supply the needs of a limited number of rich gourmets. Housewives cannot afford to buy such an expensive item for home use. In contrast, the amount of imported frozen shrimp consumed annually by the general public is large. The two shrimp types are consumed in such different ways that they are essentially different market products.

Larval rearing techniques are well known among culturists. Fortunately, culturists can easily obtain gravid spawners from middlemen at local fish markets since shrimp are kept alive until final consumption. Wild spawners are available for more than seven months a year. Larvae are resistant to direct sunlight and rainfall, as well as to chemical fertilizers applied directly to the tank water to support diatom growth. Although slight differences exist in larval rearing technique among farms, three food items, namely, mixed diatoms supported by SH medium, brine shrimp nauplii, and a refined artificial diet, are the key essentials. These foods eliminate the need to maintain a stock of food organisms. PL nursing to juveniles has been successfully introduced at many farms. This enables the culturists to know shrimp costs throughout the culture cycle. Harvested shrimp are cooled in special tanks, reducing their basal metabolism. They are then packed in cooled, dry sawdust in cartons and transported by air to markets in big cities. The high price of P. japonicus allows feed manufacturers to use expensive materials in producing a reliable compound feed. The limited availability of additional tidal zone for new shrimp ponds, and the development of refined culture techniques, indicate the Japanese shrimp culture industry has reached maturity. It is believed among Japanese culturists that improved yields from existing ponds and production of high quality shrimp are the only ways to survive the hardening competition in the open market.

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CHAPTER 31

I-Chiu Liao

MARINE PRAWN CULTURE INDUSTRY OF TAIWAN

31.1 INTRODUCTION

Taiwan's marine prawn culture industry is a popular, well-organized industry characterized by many small, mostly family-owned farms. There are about 3,000 of these farms with total culture area of 16,400 ha. Almost 90% use monoculture systems, with about 85% intensive and 15% semi-intensive. Land for prawn culture is limited in Taiwan. This encouraged high stocking densities and high productivity of 6 tons/ha average for Penaeus monodon during the past few years.

Various sub-industries with highly specialized operations have evolved within the industry over its 20-year history, an originally unique feature of the Taiwanese industry. Each specialized sub-industry operates to serve specific needs of the industry. In 1987 this network included 2,000 hatcheries, with a combined production volume of 15 billion postlarvae (PL) and a feed sub-industry that marketed over 140,000 tons of some 70 brands of formulated feed. Other operations within the industry include professional services for harvesting, pond cleaning and prawn processing.

The main culture species are P. monodon (grass prawn or black tiger prawn), P. japonicus (kuruma prawn), P. penicillatus (redtail prawn) and Metapenaeus ensis (sand shrimp). Culture of several candidate species, such as P. semisulcatus (bear prawn), and P. chinensis (fleshy prawn) are currently under development to diversify production. Other local and imported species are also being considered.

31.2 COMMERCIALY CULTURED SPECIES

In 1987, the 95,000 tons of P. monodon harvested set a world record for Taiwan, and accounted for 83% of Taiwan's total prawn production that year (Table 1). Other marine prawns include P. penicillatus, 7,000 tons (6.1%); P. japonicus, 1,500 tons (1.3%); and M. ensis, 1,000 tons (0.9%), with various other species accounting for 10,000 tons (8.7%). Taiwan's total prawn culture production in 1987 was 114,500 tons. Prawn production plummeted in 1988 due to mass mortality of P. monodon (Table 1). Although P. monodon still

Table 1. Production volume tons and percent share in total production (in parenthesis) of grass prawn, Penaeus monodon; kuruma prawn, P. japonicus; redbait prawn, P. penicillatus; and sand shrimp, Metapenaeus ensis, in Taiwan from 1981 to 1988 (Liao and Chien 1990).

Year	<u>Penaeus monodon</u>	<u>Penaeus japonicus</u>	<u>Penaeus penicillatus</u>	<u>Metapenaeus ensis</u>	Others	Total
1981	6,000 (72.3)	100 (1.2)	–	1,200 (14.5)	1,000	8,300
1982	8,000 (73.1)	50 (0.5)	–	1,600 (14.6)	1,300	10,950
1983	15,000 (89.3)	50 (0.3)	–	850 (5.4)	900	16,800
1984	18,000 (89.0)	200 (1.0)	–	900 (4.3)	1,600	20,700
1985	30,000 (91.7)	500 (1.5)	–	1,200 (3.7)	1,000	32,700
1986	60,000 (85.7)	800 (1.1)	3,000 (4.3)	1,200 (1.7)	5,000	70,000
1987	95,000 (83.0)	1,500 (1.3)	7,000 (6.1)	1,000 (0.9)	10,000	114,500
1988	30,000 (68.7)	4,000 (9.2)	3,500 (8.0)	1,200 (2.7)	5,000	43,700

occupied the top place, its percentage share dropped to 68.7% (30,000 MT), while the other species increased their percentage contribution.

31.2.1 Biology of Penaeus monodon

In the wild, P. monodon inhabits nearshore littoral areas to depths of about 160 m, and are non-burrowing. They spawn at sea and their planktonic stages migrate to inshore estuaries and mangrove areas. Their spawning season in SW Taiwan is from September to November at depths of 10 to 40m (Su et al. 1990). They migrate into deeper water as sub-adults. Their life-span is about 3 years. Penaeus monodon's natural range is the Indo-West Pacific, south, east and southeast Africa including Mozambique; India; Pakistan; southern Japan; the Malay Archipelago; Indonesia; New Guinea; and northern Australia.

Penaeus monodon is the largest penaeid and exhibits the highest growth rate among the cultured penaeids. In intensive culture, they can grow to 30 g in 14 weeks, to 44 g in 19 weeks, much faster than other cultured penaeid prawns (Liao and Chao 1983; Fig. 1). Females grow larger and faster than males as sexual maturity approaches.

Many biological characteristics of P. monodon make it ideal for culture. Favorable culture temperatures range from 21 to 32 C, but it tolerates temperatures as low as 12 C and as high as 36 C. Penaeus monodon's

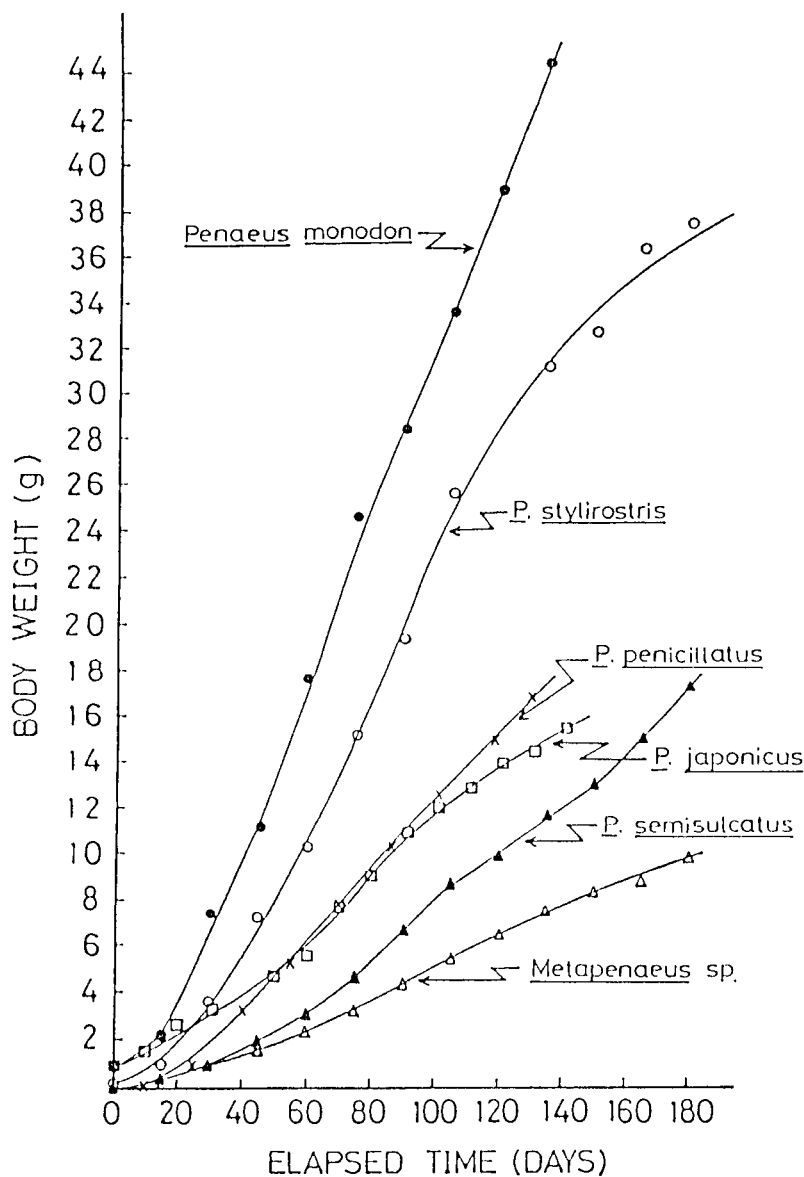


Figure 1. Comparison of growth curves of five penaeid and one metapenaeid prawn cultured at Tungkan Marine Laboratory, Taiwan (Liao and Chao 1983).

optimum salinity ranges from 10 to 25ppt although salinities <10ppt do not retard growth. It tolerates salinities as low as 1ppt and as high as 57ppt. This tolerance range is much greater than those of *P. semisulcatus*, *P. merguensis*, and *P. japonicus* (Motoh 1981). Its respiration rate remains

constant at dissolved oxygen (DO) levels 3.0 to 4.0 mg/l; below which respiration gradually decreases. They become moribund at DO levels of 0.4 to 0.7 mg/l (Liao and Murai 1986). The limiting DO level for P. monodon culture is 4.0 to 4.3 mg/l, which can be easily maintained with paddlewheel aerators.

Penaeus monodon is omnivorous. Natural food items include crustaceans, organic detritus, radiolarians and mollusks (Su and Liao 1984). These food habits and its low protein requirements help reduce production costs. Relatively simple facilities are adequate for its culture. Low cost clay or earthen pond bottoms are suitable for growout, and even give better results than cement bottoms. Investment costs are therefore lower, especially those for pond construction and maintenance.

Another advantageous feature of P. monodon is its hardiness. Typical survival rates are 80 to 95%. With a survival rate of 95%, production costs are merely half those of similar species with 50% survival (Liao 1988a).

Penaeus monodon has several distinct external features. In Taiwan it is called "grass prawn" because of its dull green color, and less conspicuous bands. Dark pigmentation from telson to antenna scales gives PL a somewhat different appearance from most other penaeids. In prawn fisheries, on the other hand, P. monodon is better known as "black tiger prawn" because its body is strongly pigmented with a mud-yellow abdomen and dark brown cross bands. Its postrostral ridge is without a distinct top groove. When cooked, it turns brilliant red. This color is highly desirable, particularly in the important Japanese market, which prefers reddish cooked prawn.

31.2.2 Biology of Penaeus japonicus

Currently, P. japonicus production in Taiwan ranks second to P. monodon. Production almost tripled between 1987 and 1988 (Table 1), mainly due to the mass mortality of P. monodon during 1988. Many P. monodon farmers shifted to P. japonicus, which has a ready market in Japan where it commands a much higher price than P. monodon. Penaeus japonicus is, in fact, the most expensive prawn species in the world. Almost 50% of P. japonicus production in Taiwan is shipped to Japan, accounting for about 30% of Japanese consumption of this species. If current trends continue, it is likely that more Taiwanese P. monodon farmers will convert to P. japonicus culture, resulting in increased competition for Japanese growers of P. japonicus, and lower prices.

The main Taiwan culture areas for P. japonicus are Changhwa, Ilan, Kaoshiung and Pingtung Counties (Fig. 2). Ilan increased its P. japonicus culture area from 100 ha in 1987 to almost 450 ha in 1988. In 1989, P. japonicus culture production was 3,500 tons in Ilan County alone.

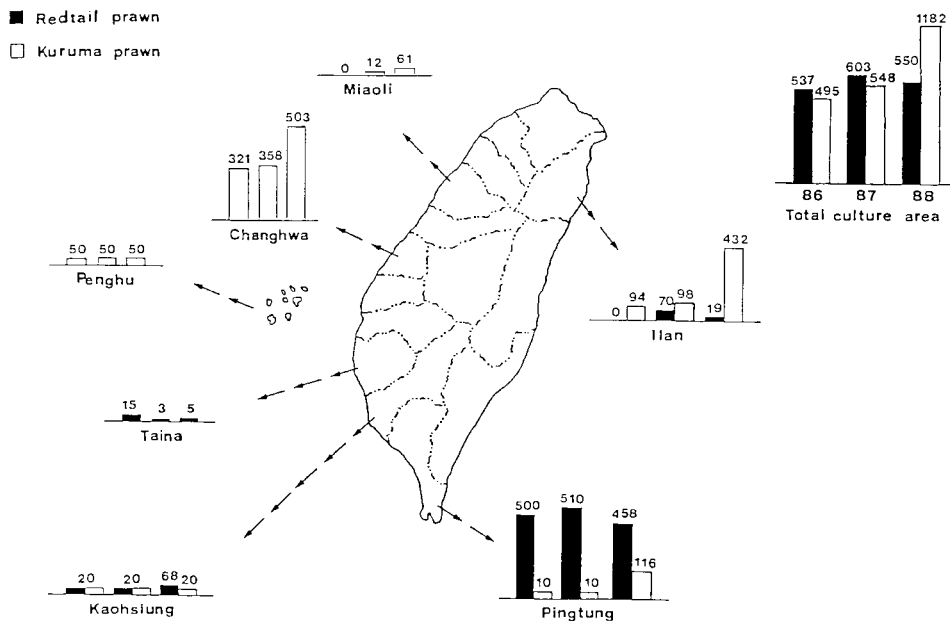


Figure 2. The culture area of *P. japonicus* and *P. penicillatus* in Taiwan from 1986 to 1988 (Liao and Chien 1990).

Penaeus japonicus has a bright, colorful pattern of cross bands on the body. It closely resembles another prawn species, *P. canaliculatus*. The two can be distinguished by adult body weights. *Penaeus canaliculatus* seldom exceeds 50 g, while *P. japonicus* commonly grows larger. *P. japonicus* has a wide subtropical distribution. It has the distinction of being the first prawn successfully propagated under controlled conditions, and the species for which the most advanced culture techniques have been developed (Hudinaga 1942; Hudinaga and Kittaka 1967).

One unique feature of *P. japonicus* is its ability to withstand low temperatures, and to survive transit for as long as 30 hr, packed with chilled sawdust in an insulated styrofoam box.

Penaeus japonicus has a number of disadvantages in culture, but these can be offset by its high price. One disadvantage is its slow growth. Another is that it burrows and needs a sand bottom which is easily polluted by feces and residual feed. The resulting deterioration of its culture habitat can cause stunting, or even mass mortality, as will high temperatures 33 C. Also, *P. japonicus* is more carnivorous and thus requires greater dietary animal

protein. Formulated feed costs are high for this species, costing US\$2.70 to 3.00/kg.

Penaeus japonicus has a relatively brief culture history in Taiwan. Although wild fry were stocked incidentally with P. monodon and P. semisulcatus in milkfish ponds, they seldom survived because pond conditions were not suitable. In the early 1970s, some farmers attempted to culture this species, but failed because they lacked proper understanding of its biological requirements. They employed erroneous culture practices such as feeding trash fish, which caused pollution of the pond bottom, and using poor aeration equipment, which could not provide adequate DO. Then, in the mid-1970s, prawn farmers in central Taiwan began polyculture of P. japonicus with hard clam, Meretrix lusoria, as a winter crop. Although prawn yield was a meager 0.5 tons/ha/crop, it sold for a high price and gave a good profit.

It is easy to obtain locally large numbers of P. japonicus spawners from the wild, several hundreds at a time. Using 100 to 250 m³ concrete tanks, hatcheries can produce 10,000 to 15,000 PL/m³ in 30 to 40 days. Optimal larviculture temperature range is 25 to 30 C, and optimal salinity is 27 to 32ppt. Ideal stocking time is early in September. The prawn can then be harvested from December through April. Thereafter, temperatures are too high for live transport. Under ideal conditions, the prawn can reach 5 to 6 g in December, and 20 to 25 g in March or April. Recently, larger juveniles (5 g) were stocked, producing larger prawns at harvest.

Taiwanese prawn farmers call P. japonicus (as well as P. semisulcatus) "thunder prawn" because they tend to die after heavy thunder and lightning during summer. Actually, their death is due to sudden dilution of culture water after heavy rains. P. japonicus cannot tolerate low salinities, especially a sudden change in salinity.

31.2.3 Biology of Penaeus penicillatus and Metapenaeus ensis

While Taiwanese production of P. monodon and P. japonicus is largely geared for export, cultured P. penicillatus and M. ensis are almost entirely for the domestic market. Taiwanese consumers like the taste and texture of these two species, especially the latter.

31.2.3.1 Penaeus penicillatus

For some years, P. penicillatus was the most popular cultured prawn in Taiwan, after P. monodon. In 1987, its total production was 7,000 tons, or 6.1% of total prawn production (Table 1). Its production dropped by almost half during 1988, along with P. monodon. It is possible that MBV and some common P. monodon diseases also affected P. penicillatus.

Penaeus penicillatus is a medium-size species which looks very much like the Indian white prawn, P. indicus, and banana prawn, P. merguensis. It can

grow to 100 g (Liao and Chao 1983). It is distributed in Southeast Asia, Pakistan and India. It occurs naturally in central Taiwan, where it is commonly called "pei-chee" (white prawn) because of its color and rostrum length. The ideal culture area for it is Northern Taiwan, however, where it is used as an alternate crop in the winter months. This species grows even at 20 C.

Both P. penicillatus broodstock and fry are locally abundant and gravid females are caught in nearshore waters almost year-round. They can be caught in large numbers because they school (Liao 1988b). Hatcheries buy gravid females for about US\$10 each. They spawn them once and then induce them, through unilateral eyestalk ablation, to spawn several times more at 5 to 10 day intervals.

Nauplii are then sold to hatcheries for about US\$0.04/1,000 where they are reared to early PL. These PL sell for about \$1.00/1,000 to nurseries, where they are stocked at a density of about 19,000/m², with water exchange of 20% to 50%/day. Juveniles are sold to growout farms, where they are cultured for 2 to 3 months.

This species has very simple nutritional requirements and does not need high dietary protein in its diet (Liao 1973). Pond bottoms are of earthen, organic clay. Penaeus penicillatus are usually sold at 10 to 15 g because after this size their growth declines (Liao 1977). Although P. penicillatus is smaller and lower priced than P. monodon, profits for the two are comparable because the shorter culture period of the former reduces production cost, and because it can be stocked at higher densities. Growout survival is about 60%. Average production for P. penicillatus was 11,203 kg/ha/year in 1987, with two crops (Liao and Chien 1990).

Unlike P. japonicus, P. penicillatus does not easily survive outside water, and therefore is not suitable for live transport. Soon after it dies, melanosis occurs and the head detaches.

31.2.3.2 Metapenaeus ensis

There are actually two or three Metapenaeids species cultured in Taiwan, but the most important of these is M. ensis. Metapenaeid species, including M. ensis, are naturally abundant in Southeast Asia. Metapenaeus ensis is smaller than P. penicillatus, but is still medium sized. Mass larviaculture is easy. Gravid spawners are easy to obtain, as with P. japonicus and P. penicillatus. In fact, hatchery production of this species earns even higher profits than with penaeids. It has high tolerance to low salinities and, like P. penicillatus, also tolerates low temperatures. Furthermore, it can survive for rather long periods out of water and is easily transported live, like P. japonicus. This last feature makes it ideal not only for human consumption, but also for game fishing bait.

Table 2. Production volume, in tons, and percent share of total prawn culture and prawn capture production in Taiwan from 1986-1988.

Year	Prawn Culture		Prawn Capture		Total tons
	tons	%	tons	%	
1986	70,000	44.5	87,400	55.5	157,400
1987	114,500	56.7	87,400	43.3	201,900
1988	43,700	37.8	71,900	62.2	115,600

Culture of M. ensis has been practiced in Taiwan for many years. This species was originally polycultured with P. monodon, milkfish, and seaweed. Wild PL were collected from estuaries, tidal canals, and lagoons. When pollution began to affect the natural supply of PL, however, artificial propagation techniques were used. In 1982, total PL production exceeded 150 million, and annual production of marketable prawn exceeded 1,500 tons (Table 1). Culture of this species has eventually shifted to more intensive monoculture methods. Despite the relatively long time that M. ensis has been cultured, it still has low survival. This needs further investigation.

31.2.4 Prawn Fishing

In Taiwan, prawn production from capture fisheries has been rapidly augmented by prawn culture. The prawn fishery is mostly for Metapenaeopsis barbata (thick-shell shrimp; 7 to 8%), P. penicillatus (7 to 8%) and P. japonicus (6%). Penaeus monodon, M. ensis, and M. affinis (Lu shrimp) account for, <1% each, while 75% is accounted for by miscellaneous species such as Parapenaeus fissurus (sharp prawn), P. cornuta (sword prawn), P. hardwickii (sword prawn), Metapenaeopsis andamensis (small prawn), M. dalei (small prawn), Trachypenaeus curvirostris (white whisker prawn), Solenocera choprai (bighead prawn), and several others.

In 1987, total prawn culture production (114,500 tons) surpassed prawn fishery production (87,433 tons); but in 1988, the prawn culture share of total production was slashed from 56.7% to merely 37.8% (Table 2). The capture fisheries share increased to 62.2%, despite a considerable (15,500 tons) decrease in fishery production.

31.3 CULTURE AREA

Taiwan prawn culture has very little flexibility. Land is scarce and expensive. Pond construction costs in 1987-88 ranged from US\$60,000 to US\$180,000/ha. In such a situation, the most feasible way to increase output has not been by building more farms or ponds, but by increasing production

Table 3. Total prawn culture area by region in Taiwan during 1988.

Location	Estimated area (ha)	Share (%)
Tainan County	3,500	21
Chiayi County	2,400	15
Tainan City	2,100	13
Pingtung County	2,100	13
Yunlin County	1,900	12
Kaohsiung County	1,700	10
Ilan County	1,200	7
Changhwa County	1,000	6
Others	500	3
Total	16,400	100

per unit area. Space limitation has, in fact, been a significant factor behind the strong move toward culture system intensification.

Prawn ponds are concentrated along Taiwan's west coast where most of the flat coastal lands are located (Fig.2). Prawn culture originated in the southwestern coast and then spread towards the midwest and southeast. Recently, many farms can also be found in the northeast.

The 3,000 prawn farms account for about half of the entire brackishwater culture area for all species. Today, a little less than 25%, or 16,400 ha. of total aquaculture area (freshwater and marine) in Taiwan is devoted to prawn culture. In 1988, the most important culture areas were in Tainan County (21% of total area), Chiayi County (15%), Tainan City (13%), and Pingtung County (13%) (Table 3). In 1987, 88% (14,500 ha) of total was used to culture P. monodon; 7% for P. japonicus, 3% for P. penicillatus, and about 1% for M. ensis (Table 4). Interesting shifts occurred in distributions of culture area have been taking place since the 1988 P. monodon production crash. Most noticeable of these was the decrease in P. monodon culture area especially in Ilan and Pingtung Counties which were the most seriously affected areas during 1988. Culture area for P. monodon shrank by 50% in Ilan and by 23% in Pingtung. At the same time, P. japonicus culture area expanded considerably, especially in Changhwa (by 40%), Ilan (340%) and Pingtung (1060%). There were also significant increases in total prawn culture areas of Changhwa and Yunlin Counties and Tainan City, mostly for new P. monodon farms. It is possible that farmers in these areas took advantage of the crash in other areas and jumped in to fill the production void.

Table 4. Total prawn culture pond operation by species in Taiwan in 1988.

Species	Estimated area (ha)	Share (%)
<u>Penaeus monodon</u>	14,500	88
<u>P. japonicus</u>	1,200	7
<u>P. penicillatus</u>	500	3
<u>Metapenaeus ensis</u>	100	1
Others	100	1
Total	16,400	100

31.4 HISTORY AND STATUS OF HATCHERIES

The year 1968 marked a turning point in the history of prawn culture in Taiwan. Breakthroughs with artificial propagation of P. monodon and Metapenaeus monoceros (sand shrimp), laid the groundwork for commercial prawn culture in Taiwan (Liao et al. 1969a; 1969b). Propagation techniques were also successively established for some other important species, such as P. semisulcatus (bear prawn), P. teraoi (white beard prawn), and P. penicillatus.

The decade that followed (1968-1977) did not see any dramatic increase in the number of prawn hatcheries. Farmers stubbornly preferred wild fry, since they doubted the quality of hatchery produced fry (e.g., health and growth performance). By the end of 1977, there were 150 hatcheries producing 100 million PL. As prawn farmers gained confidence in hatchery produced fry, and as techniques for mass larviculture were refined, more and more hatcheries began operation.

In 1977, formulated feeds were marketed, which encouraged more and more farmers to venture into prawn culture. Growout farm areas expanded and the demand for fry increased above what could be supplied from the wild. The period 1978 to 1982 was characterized by a slow but steady increase in hatchery production. PL production rose from 150 million in 1978 to 600 million in 1982, while the hatchery number increased from 200 to 500 (Table 5). The concurrent shift from semi-intensive to intensive culture systems and Taiwan's success in penetrating the Japanese P. monodon market beginning in 1981 caused hatchery production to soar to record levels. In 1987, 2,000 hatcheries were operating with a combined larval production volume of 15 billion.

These hatcheries have now evolved into efficient, highly specialized operations. Concentrating on certain stages of hatchery production enables the hatcheries to shorten their turnover time and to respond quickly to certain problems such as disease outbreaks. It now appears, however, that

Table 5. Number of hatcheries and postlarval production of grass prawn, *P. monodon*, in Taiwan from 1968 to 1988 (Liao 1989).

Year	No. of hatcheries	PL production (x 10 ⁶)
1968	1	-
1969	1	1.2
1970	3	2
1971	3	5
1972	5	8
1973	10	10
1974	30	15
1975	50	40
1976	70	60
1977	150	100
1978	200	150
1979	300	300
1980	350	350
1981	400	500
1982	500	600
1983	1,200	1,000
1984	1,200	1,300
1985	1,500	3,000
1986	2,000	7,500
1987	2,000	15,000
1988	2,000	13,000

such specialization can have some deleterious effect on the industry. The isolation of each sub-business makes integration of the industry more difficult (Liao 1989).

31.4.1 Spawning/Broodstock

The earlier hatcheries relied entirely on wild caught gravid spawners. During the period 1976-1981, when hatcheries proliferated and the strong demand for spawners created supply shortages at exorbitant prices, Taiwan began importing gravid prawn from Southeast Asian countries. At that time, imported spawners made up 20% to 40% of the total supply, but by 1984 they accounted for 90%. A single spawner reportedly fetched US\$2,000 in 1977 (Liao 1984), but in the early 1980s the average price dropped to only US\$125 to 150. Since 1983, after adoption of unilateral eyestalk ablation only non-gravid females were imported. With this technique, a non-gravid female could be induced to mature and spawn two or three times, and sometimes as much as ten times. One spawning can produce up to several million eggs. Today, ablation is still widely used .

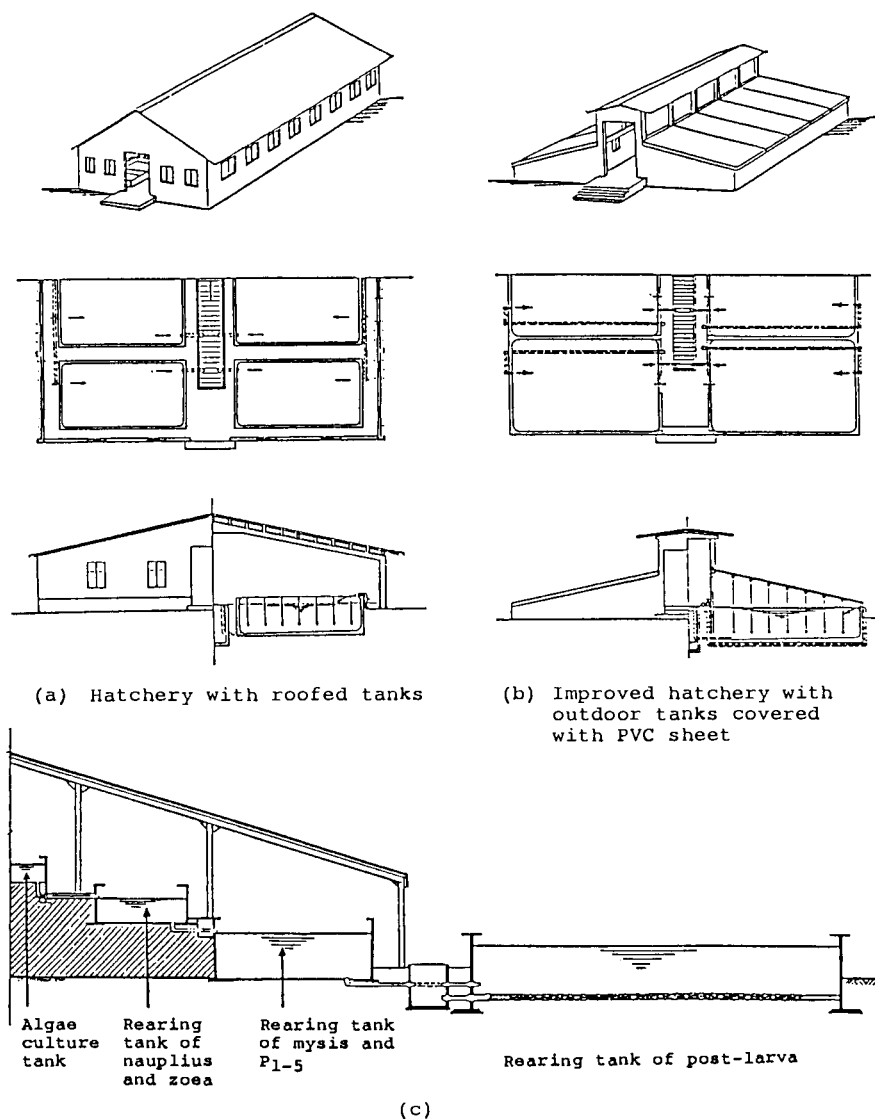


Figure 3. Schematic diagrams of hatcheries: a) with roofed tanks, b) with outdoor tanks covered with PVC sheets, c) ladder-style hatchery and nursery (Liao 1986).

31.4.2 Development of Hatchery Designs

Before the development of larval rearing techniques, special hatchery equipment was not available. Round plastic tanks (0.5 to 1.0 m³) with flat bottom were adapted to hatchery and nursery operations. In late 1968

concrete tanks were constructed inside a well-insulated building as a preliminary hatchery for P. monodon. A more refined hatchery facility equipped with heating apparatus was built at the Tungking Marine Laboratory (TML) of the Taiwan Fisheries Research Institute (TFRI) in 1969, which later served as the basic model for commercial hatcheries (Fig. 3). Basically, a hatchery comprises one or two rows of concrete tanks with a capacity of about 50 m³ each (Fig. 3a). Some hatcheries have separate outdoor tanks covered with PVC sheets, which are generally easier to manage, disinfect and clean (Fig. 3b). More advanced types, known as "ladder style" hatchery take advantage of the slope of the ground and different water levels in tanks for sequential larval stages (Fig. 3c). This latter type is more functional and saves on labor costs. See Chapter 7 for more discussion of Taiwanese hatcheries.

31.5 HISTORY AND STATUS OF FEED DEVELOPMENT

Prior to 1968, P. monodon was only polycultured with milkfish and fed on what was given to the fish, including live feeds, rice bran, peanut cake and bean cake. Between 1968 and 1977, with the advent of prawn monoculture, trash fish was provided as the main prawn feed. The next key event was the development of formulated feeds which accelerated growth of the prawn industry during the late 1970s, Taiwan's prawn industry could not have

Table 6. Production, in tons, and number of brands of formulated feed for grass prawn, P. monodon, in Taiwan from 1977 to 1988 (Liao 1989).

Year	Production	No. of brands
1977	110	3
1978	820	3
1979	3,600	4
1980	6,400	7
1981	9,000	7
1982	16,000	12
1983	30,000	20
1984	36,000	30
1985	51,000	40
1986	120,000	62
1987	140,000	70
1988	80,000 *	87

* Note the sharp decline in feed production, attributed mainly to the P. monodon mass mortality in 1988. In that year, a small portion of the feed produced was consumed locally; the bulk of production was exported to Southeast Asian countries.

developed to the level it did without these formulated feeds. To produce 1 kg of prawn, about 8 to 10 kg of trash fish are needed. Therefore, to produce 95,000 tons of *P. monodon* in 1987 would have required some 760,000 tons of trash fish, an unlikely condition.

As early as 1972, research and development efforts on nutritional requirements of *P. monodon* and on formulation of appropriate feeds were already in progress. TML and a local private company launched a joint research project on formulated feeds specifically for *P. monodon*, while the Tainan Fish Culture Station collaborated with another private company.

Five years of experimentation bore fruit in 1977 when 110 tons of formulated feeds in pellet form were manufactured and marketed (Liao 1984). Five years later, production soared to 16,000 tons, and the number of prawn feed brands increased from 3 to 12 (Table 6). After another five years (1987), production was 140,000 tons. At that time, there were 70 brands of formulated feed. The fast and steady rise in feed production was only broken by the 1988 mass mortality crisis that hit *P. monodon* farms. Even then, a relatively large amount of feed was still produced (80,000 tons), including exports to other Asian countries.

The prawn feed sub-industry in Taiwan is highly competitive, although the most popular brands have more or less the same formulations. Formulations probably differ more according to stage of prawn growth, than between brands (Hopkins 1986; Table 7). The usual protein content is 30 to 40%, up to 50%.

Taiwanese prawn feeds are characterized by superior quality. Their ingredients are finely ground, and they are more tightly bound and richer in fish protein. A special binding technique is used whereby heat is applied to activate natural starches. Water immersion for as long as 6 hr will soften but not dissolve the pellets.

Defatted soybean meal is used in prawn feeds, mainly for its protein. However, Taiwanese aquaculturists have found that greater use of protein derived mainly from fish meal, supplemented by unprocessed fish flesh, provides much faster prawn growth rates. Fish protein is, however, costlier

Table 7. Typical protein levels in Taiwanese formulated prawn feed according to various sizes of prawn.

Average body weight (g)	Protein level (%)
less than 1	38
1-10	37
10-25	36
35 and up	35

and contributes to the higher price for the ration. At present, these feeds cost US\$0.43/kg in Taiwan (Fast et al. 1989). Feed costs account for 50 to 55% of total prawn production costs.

Unlike growout feeds there has been little progress in Taiwan with formulated feeds for prawn larvae. The reason for this is that diatoms, rotifers and other live feeds are easily cultured locally. Taiwan's climate is ideal for mass culture of these live feeds organisms. Brine shrimp cysts, although imported, are readily available. A recent study of artificial microbound diets has shown favorable results, possibly due to the feed formulation which had a high content of polar lipids, n -3 HUFA and vitamins (Liao et al. 1990).

31.6 CULTURE TECHNIQUES

31.6.1 Extensive Growout Systems

Traditionally, polyculture and extensive or low-density monoculture were predominant in Taiwan especially where the tidal flat is wide and a steady supply of seawater is very hard to obtain. The culture methods required minimal water exchange. There are still farms of this type found in the central-west and central-southwest of Taiwan. In this system, prawn is polycultured either as a main or secondary crop with the hard clam, milkfish, mud crab (*Scylla serrata*), or seaweed (*Gracilaria* spp.).

31.6.1.1 Milkfish-prawn-crab polyculture

Polyculture of prawn and milkfish had been practiced in Taiwan for centuries, although prawns were then merely a fortuitous benefit derived from milkfish culture. Prawn larvae were either carried by seawater or brackishwater into coastal impoundments for milkfish, or caught by chance in nets collecting milkfish fry. Euryhaline prawn species thrived in such ponds, feeding on natural food organisms.

During the early 1970s, prawn polyculture with milkfish and mud crab was still common in southwestern Taiwan. *P. monodon* were stocked 10,000 PL/ha, *M. ensis* at 60,000 PL/ha, milkfish fingerlings at 2,000/ha, and milkfish fry at 2,500/ha. *Penaeus monodon* fry were usually stocked in spring, and reached 35 to 40 g during summer. *Metapenaeus ensis* fry were stocked next, and harvested two months later at 5 to 8 g, a size preferred in the domestic market. Stocking of milkfish fingerlings was done in June shortly after the *M. ensis* were completely harvested. In July or August, milkfish fry were stocked for overwintering, and were restocked the following year. After stocking milkfish fry, medium-sized mud crabs (50 to 60 g) were stocked and cultured until they became gravid. They were harvested in December (Chien et al. 1988).

Table 8. The percentage of area monoculturing grass prawn, *P. monodon*, to total farming area and average unit area production (monoculture and polyculture together) in Taiwan from 1977-1988 (Chien et al. 1988).

Year	Monoculture Area (%)	Unit Area Production (tons/ha)
1977	26.71	0.68
1978	23.28	1.03
1979	23.05	1.63
1980	42.45	1.01
1981	43.20	1.28
1982	49.20	2.22
1983	56.66	2.54
1984	61.38	3.42
1985	70.87	4.46
1986	89.00	5.74
1987	89.40	5.92*
1988	88.77	2.11*

* Added after Chien et al. 1988

31.6.1.2 Clam-prawn polyculture

The clam-prawn polyculture areas include the counties of Changhwa, Yunlin, Chiayi, Hsinchu and Tainan. The more sandy coasts in these counties are suitable for clam culture. Prawn is only polycultured with clam because the climate is not warm enough for two crops of prawn. Stocking is done at 10,000 to 40,000 PL/ha during April or May and harvested in September or October. Harvest size ranges from 30 to 40 g; yield is 280 to 1,280 kg/ha. Supplemental feeding is given in the form of rice bran and soybean cake, which also fertilizes the ponds.

Culturing clam together with prawn is mutually beneficial. The clams feed on the rich plankton, thereby controlling algal blooms and maintaining adequate DO levels. The prawns, in turn, mix and expose the sediments through their crawling and feeding activities.

31.6.2 **Semi-Intensive and Intensive Growout Systems**

Intensification of prawn culture systems in Taiwan is clearly evident in the upward trend in percentage of monoculture area devoted to *P. monodon* from the early 1980s to the present (Table 8). In 1979, only 23% of the total prawn culture area was in monoculture, but by 1987 about 90% was in monoculture. Formulated feed developments in the late 1970s had much to do with this trend towards monoculture and intensification.

While monoculture includes both semi-intensive and intensive growout systems, practically all monoculture farms in Taiwan now use intensive culture

Table 9. Prawn culture systems used in Taiwan (Liao and Chao 1983; Chiang and Liao 1985; Chien et al. 1988).

	Types of Culture Systems		
	Extensive	Semi-intensive	Intensive
Culture method	Polyculture	Monoculture	Monoculture
Stocking density (PL/m ²)	Under 10	10-30	30 and up
Pond size (ha)	1-3	0.5-1.0	0.1-0.5
Water depth (m)	0.3-0.6	0.6-1.5	1.0 up
Pond bottom	Earthen/sand	Earthen or Gravel dash	Earthen/sand
Pond dike	Earthen	Earthen	Concrete
Dike slope	1:2	1:1-2:1	Vertical-1:1
Water source	Tidal	Pump	Pump
Water supply	Canals	Canals and pipes	Ditches and pipes
Drainage system	Not controlled	Mainly controlled	Controlled
Aeration	Natural	Water exchange or mechanical	Continuous mechanical and flushing
Paddle wheels (no./ha)	-	2 - 4	8 and up
Salinity	30-35	20-30	10-25
Water exchange (%/day)	For evaporation and seepage replacement	1-5	10 or more
Food	Natural	Natural and formulated feeds	Formulated feed
Crops/year	1	1.5	2-2.25

systems. Table 9 describes some features of these and extensive culture system. This section will refer mainly to intensive culture, since about 85% of Taiwan's ponds now use this method.

The primary goal of intensification is to increase productivity through high stocking densities (30 to 80 PL/m²), use of formulated feed, disease prevention, and stringent water quality management. Maintaining an ideal culture environment is quite critical, since water quality and sediment are affected by the build-up of metabolites and wastes from both prawn and feed.

31.6.3 Pond design

Most intensive growout ponds are small, ranging from 0.1 to 0.5 ha. They come in a variety of shapes, but the long, narrow, rectangular shape is most common. Small size and elongated shape facilitates intensive management. The wide bottom ditch is ideal for frequent feeding and for efficient habitat utilization (as prawns tend to aggregate along the ditch). Pond corners are

rounded to facilitate uniform dispersal and water circulation (Chien et al. 1988).

Pond depth ranges from 1.0 to 2.0 m. There is a trend toward deeper ponds because greater depth allows more flexibility in manipulating water quality parameters. It also cushions the pond against sudden changes in water temperature.

Pond bottoms are usually sand or gravel with little organic matter and few food organisms. Reliance of prawns on bottom food organisms is unnecessary because of formulated feed applications.

A distinct feature of Taiwanese intensive ponds is their narrow and steep dikes. Dikes are built that way because it helps maximize land use, and because a gradual incline is not necessary for access by heavy machinery. Highly compacted materials are used for dike construction, such as full concrete, pebbles and bricks. Concrete dikes minimize the land area not in pond production. Most ponds, though, have earthen bottoms, which are less expensive (Fast et al. 1989).

31.6.4 Water supply, distribution and drainage

31.6.4.1 Water supply

There are four possible ways to provide water for intensive ponds (Liao 1986; Chien et al. 1988). (1) Ponds located close to rivers or estuaries can take advantage of high tide for obtaining water. Sometimes, the supply is supplemented by a small pump. Although this method minimizes pumping cost, water supply consistency is difficult to control. (2) In some ponds, pumps deliver seawater via pipes directly from ocean intakes. A filter system is built into the distribution canal, or at the pond entrance to screen out harmful organisms. (3) Water may be drawn from pipes buried in the coastal sand layer, which acts as a natural filter. (4) In places where underground brackishwater is available, a well is drilled and the water aerated before use. Generally, most intensive farms have a two well systems; one freshwater, and the other, saltwater.

31.6.4.2 Water gate

Water gates are used to let in or discharge water, whether at the pond bottom or at the surface. Flows can be regulated by adjusting the arrangement of boards in the gate. Filter screens are also installed at the gates to keep out undesirable organisms, and to prevent prawn escape.

31.6.4.3 Water distribution and drainage

Canals or pipes are used to channel water to ponds. Canals are more expensive to construct, and may require additional pumps if the water needs to be elevated, but can supply larger amounts of water and provide some

natural aeration. Three practices of draining pond water are by pumping, by gravity-flow pipes, and/or by gravity-flow through a water gate. As standard practice, average water exchange rate is 10% per day with Taiwan's intensive culture method (Fast et al. 1989).

31.6.4.4 Aeration and mixing

Water quality management in intensive Taiwanese farms relies greatly on water aeration and mixing. Mixing brings oxygen-rich water down to the bottom where DO level is low. The bottom water is brought to the surface and is aerated through atmospheric exposure, photosynthesis and by mechanical aerators. Mixing also creates horizontal currents which form a spiral at the center, pulling the organic waste material to this area and keeping the rest of the bottom clean. Without this mechanism, the entire pond bottom could become anaerobic. An additional benefit of mixing is that salinity and temperature are kept uniform.

Aeration and mixing are achieved with electric paddlewheel aerators, the most commonly used aeration equipment in Taiwan. The basic parts of a paddlewheel aerator are an electric motor, a speed control gear box, two or four impellers, a frame and floats of fiberglass, or plastic or PVC pipes. Back-up generators are needed in case of power failure.

Paddlewheel number and operating schedule of each unit varies according to the pond biomass, water quality, and to the operator's personal preference. Intensive ponds generally use 6 to 8 paddlewheel aerators/ha. Aerators are seldom operated during the early growout. Operation occurs first at night time, increases to cover the period from dusk to dawn, and eventually is continuous during the final phase of growout (Fast et al. 1989).

31.6.4.5 Bottom disposal

After the pond is drained, soft mud must be removed. In small ponds, the slime is usually flushed through the drain with a "pressurized water hose". Sometimes, the pond is partially flooded and the slime is removed with a floating suction dredge (Chien et al. 1988). Bottom slime of large ponds, on the other hand, is usually bulldozed and dumped on top of the dike. The bottom is then sundried and tilled. When the bottom is dry, fresh sediment is applied.

Lime application in Taiwan varies, but it usually is applied only in specific areas, such as around the drain or in other "dark soil" areas (Fast et al. 1989).

31.6.5 Umbrella net

Umbrella nets (0.5 to 1.0 m²) are used to check feed consumption by prawns 1 to 2 hr after feeding. Feeding rate is adjusted based on this measure of consumption.

Umbrella nets are also used to check prawn health and pond bottom conditions. With abnormal or undesirable conditions, soil sticks to the net. Energetic, healthy prawns tend to jump out of the net as it is raised, while weak ones remain in the net. Another sign of prawn health is their position in the net. When their heads are turned upwards towards the net edge, they are healthy. If their heads are turned downward towards the net center, their health is not good.

The net pole can also be used as a pH indicator. When the pole is rough with carbonate deposits, it means the acidity is high. The net can also be used to check prawn feces. Normal feces are soggy and even. Uneven appearance of the feces may indicate a digestion problem.

31.6.6 Harvesting

The old method of harvesting prawn was by a cast net with crushed sea snails as an attractant. This was popular in the 1960s, but now it is used only for partial harvests or for catching a few prawn at a time.

Presently, the most common method is by electrical trawl. The trawl is equipped with electrodes which transmit a low-level (8 to 12 volts) shock to make the prawn jump. Prawns are then easier to catch in the net. This method is efficient and cost-effective. It can harvest 85 to 90% of the prawn. The remainder are captured when the pond is drained by a funnel net attached to the drain pipe or water gate. Professional harvesters offer this service, using their own equipment, for a reasonable fee. Thus, pond owners seldom do the harvesting. Polyculture ponds use a set net, instead of an electrical trawl because the latter may be harmful to the other crops. Six to eight set nets are used per ha.

Most farms harvest two crops/pond/yr of prawns averaging 32 g. Yields on well-run farms may average 16,000 kg/ha annually (Fast et al. 1989).

After the crop is harvested, professional cleaners are hired to clean the pond and treat the pond bottom. Pond cleaners provide their own tools and materials, such as plows, tillers and chemicals, another example of specialized sub-businesses in the Taiwan prawn industry.

31.7 FUTURE DIRECTIONS FOR THE TAIWAN PRAWN INDUSTRY

For most of the past 20 years, Taiwan's prawn culture industry grew steadily, and at certain times dramatically. This growth climaxed during 1987 when Taiwan became the world's leader in cultured prawn production. The industry tried to surpass its own record, but in the process realized that such growth has many dimensions. This was a painful, but meaningful, lesson learned from the crisis which gripped the industry in 1988.

Today, the industry views growth not in terms of limitless production but more in terms of limitless opportunities for improvement and export of technology as well as prawns. Land scarcity was the factor which forced development of advanced technology for the industry. The coming years will likely witness expansion in two areas where few other countries have the capacity to compete. The industry's emerging role is that of a joint-venture partner and R&D center. It can provide investment capital and progressive technology for other prawn-producing countries which may largely lack these two conditions but have an abundance of other valuable resources, such as land, climate and labor. In these countries, Taiwan's new programs can play a vital role in technology transfer to their prawn farmers. In Taiwan, however, emphasis should be on development of more sophisticated, appropriate technology. The objective is not to merely increase the quantity of prawns produced, but instead to improve quality, consistency and long-term profitability. (Liao 1989).

Another direction in which the Taiwan prawn industry is moving is towards systematic diversification of culture species. The search for alternative species actually began many years ago, precisely with the foresight that it is not wise nor healthy for farmers to be too dependent on just one species. If problems specific to that species arise, or if market situations shift, the farmers lose everything. The 1988 production crash accelerated this species diversification and drew well-deserved attention to the great promise that it offers.

While Taiwan pursues leadership in prawn technology, aspects of prawn culture R&D which need attention include stock enhancement, nutrition and feeds, and disease prevention and cure. Feed formulations for P. japonicus have to date been the most well established, but the same or better is needed for other prawn species. At present, Taiwan is gearing its efforts for development of improved formulations for other prawns.

With intensive and semi-intensive systems, disease problems are inevitable. Taiwanese aquaculturists are now devoting more attention to disease research for both prevention and cure, including establishment of quarantine and health certification procedures. Cell culture techniques must be developed to boost disease diagnosis and to produce vaccines. On the other hand, careful study and planning are needed before a quarantine and a health certification procedures can be implemented. These should facilitate the needs of the industry rather than create bottlenecks, and they must be effective in preventing and curing pathogens (Liao 1990).

Furthermore, it is hoped that through genetic improvement and manipulation, Taiwan will be able to produce transgenic prawn which can produce strains or hybrids that are pathogen-free, disease-resistant, cold-tolerant, fast-growing, and more delectable.

With its newly identified role as a supplier of progressive technology and investment capital through joint-venture partnerships, Taiwan aims to promote international cooperation and exchange of information through conferences, symposia, training programs, and the like. It is hoped those industries with high development potential may learn from the Taiwanese experience.

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CHAPTER 32

Chen Jia Xin and Yang Ning Sheng

SHRIMP CULTURE INDUSTRY IN CHINA

32.1 INTRODUCTION

China has rich species diversity and abundance of marine shrimp. China has more than 100 shrimp species, 40 of which have high commercial value (Liu 1955, 1959; Pong 1959; Liu and Zhong 1988, Sheng and Liu 1976). This abundance and diversity has led to a sizable fishery for wild shrimp, and it has made shrimp culture in ponds possible. While the wild catch fishery is valuable, it cannot meet market demands due to maximum sustainable yield limitations and to large yearly fluctuations in yield. For example, the fleshy prawn (also called Chinese prawn, Penaeus chinensis Osbeck) catch decreased from 32,896 MT in 1980 to only 7,374 MT in 1982. In order to overcome these limitations, and to meet market opportunities, the Chinese government has enthusiastically encouraged and supported shrimp culture development in all of China's coastal provinces since 1978. In only ten years, these efforts have resulted in shrimp culture production increases from 240 MT in 1978 to 153,200 MT in 1987 (Table 1). This production level has clearly elevated China to world leadership in marine shrimp culture. It has also resulted in an 80% increase in shrimp exports from China between 1980 and 1986, and a 44% increase in foreign exchange earnings from shrimp (Table 2).

32.2 SHRIMP SPECIES CULTURED

There are presently seven shrimp species cultured in China, either on a large scale or experimentally (Table 3). These species all belong either to the genus Penaeus or the genus Metapenaeus, both of the Family Penaeidae, Superfamily Penaeoidea, Order Decapoda. The main distinction between the two genera is that Penaeus has rostral teeth on the upper and lower edge of the rostrum, and a longitudinal suture on the top of the antennal spine of the carapace, while Metapenaeus lacks teeth on the lower edge of the rostrum and lacks the suture.

Table 1. Marine shrimp culture production, culture area and productivity in the People's Republic of China between 1980 and 1987.

	YEAR							
	1980	1981	1982	1983	1984	1985	1986	1987
Culture Production (x1,000 MT)	2.6	3.7	7.1	9.0	19.3	40.7	82.8	153.2
Culture Area (x1,000 ha)	9.34	13.7	16.5	19.5	33.4	59.6	85.1	131.3
Productivity (MT/ha)	0.278	0.270	0.430	0.452	0.578	0.683	0.873	1.167

32.2.1 *Penaeus chinensis* (*P. orientalis*)

This is the most widely cultured species, and the most abundant captured species from the wild. It makes up 97% of the culture production (Table 3). *P. chinensis* is mainly found in the Bohai Sea and Yellow Sea, but smaller numbers are also found in the East China Sea and Guangdong coastal area along with *P. merguensis* (Fig. 1). *P. chinensis* are found along the west coast of Korea during their spawning migration.

In pond culture, *P. chinensis* has rapid growth and high tolerance to many important environmental conditions. *P. chinensis* can grow from postlarvae (PL) to 12 cm length, or more than 20 g, during 100 to 120 days.

Protein content requirement of prepared feeds is moderate at 40%. *P. chinensis* is not an obligate burrower, and mud bottoms are entirely suitable for culture. It will also swim readily with the water flow during pond draining, making harvest simple and efficient. Spawners for hatchery broodstock are

Table 2. Volume and value of marine shrimp exports from the People's Republic of China from 1980 to 1986.

	YEAR						
	1980	1981	1982	1983	1984	1985	1986
Export Volume (x1,000 MT)	22.6	23.5	14.8	10.8	17.0	19.4	40.9
Export Value (US\$ million)	178.9	183.6	122.4	88.9	113.3	110.7	258.4

easily captured from the ocean seasonally, but this species also readily matures in ponds, even without eyestalk ablation. Future culture is expected to rely entirely on pond reared broodstock in order to conserve wild populations. Perhaps the main problem with culture of this species is its thin exoskeleton which is easily damaged by handling. Disease or death soon follow mechanical injury. Consequently, transport and sale of live *P. chinensis* is difficult. Most production is, therefore, marketed fresh killed or as frozen tails.

32.2.2 *Penaeus penicillatus*

This species is found from the Indian Ocean and Pakistan in the west, through Indonesia, and into Fujian, Guangdong and Taiwan. It is the main culture species in Fujian, Guangdong and Guangxi provinces. In culture, *P. penicillatus* can grow to 11 cm and 17 g in slightly more than 100 days. It can also grow well at cooler temperatures, but not as well as *P. chinensis*. It also

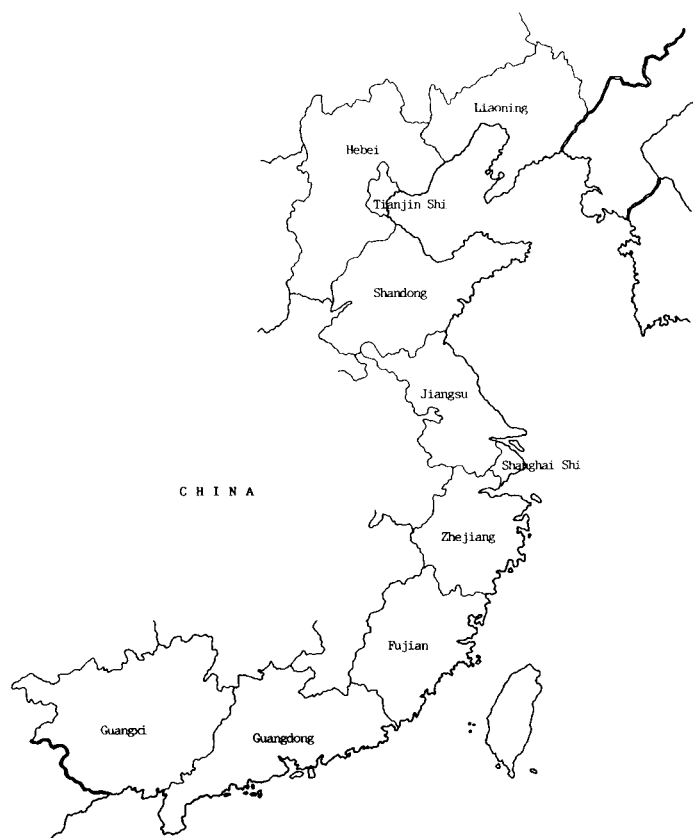


Figure 1. Map of the coastal provinces of China.

Table 3. Name, percentage of culture production, and distribution of the most commonly cultured marine shrimp species in the People's Republic of China.

Scientific name	Chinese or common name	Percentage of Culture Production	Principal Culture Areas
<u>P. orientalis</u>	couple shrimp	97%	All maritime provinces
<u>P. penicillatus</u>	long hair shrimp	1%	Fu Jian, Guangdong, Guangxi
<u>P. merguensis</u>	mergui shrimp	1.5%	Guangdong, Hainan, Guangxi
<u>P. japonicus</u>	Japanese shrimp	---	Zhejiang
<u>P. monodon</u>	grass shrimp	0.5%	Hainan, Guangdong
<u>M. ensis</u>	sand shrimp	---	Guangdong, Guangxi
<u>M. affinis</u>	sand shrimp	---	Guangdong

matures readily under captive conditions, and PL production is not a problem. The main culture problems with this species include its requirements for high dissolved oxygen and high salinity, and its thin exoskeleton which, like P. chinensis, is easily damaged by handling.

32.2.3 Penaeus merguensis

This species is most common in warm tropical waters of the western Pacific to India. It often appears in the western Guangdong and Guangxi provinces and along the Hainan coast. It is the principal cultured species in Guangdong province. In 160 days of pond culture, it can grow to 12 cm and 28 g. Its fresh quality and appearance are good, and it commands a high price. Broodstock are readily available, and PL production is easy. Optimum salinity is 20 to 30 ‰, with high mortality at greater than 40 ‰ or less than 5 ‰. It requires warmer water than P. chinensis and P. penicillatus, and does not do well in turbid waters. It also has a thin exoskeleton.

32.2.4 Penaeus monodon

This species is widely distributed throughout Asia and the western Pacific, including India, Red Sea, east Africa, Australia, Philippines, Indonesia, Japan and Fujian, Taiwan, Guangdong and Hainan Provinces. It is cultured in small quantities in the People's Republic of China, but may become more important in some southern coastal areas. P. monodon is one of the largest and fastest growing shrimp. It can grow to 600 g in the wild, while specimens of 100 g or more are common in extensive culture. P. monodon has a wide salinity tolerance of 0.2 to 70 ‰, with an optimum between 1 and 25 ‰. It can tolerate low dissolved oxygen of 0.2 mg/l for short periods. It has a thick exoskeleton which is resistant to mechanical damage, a characteristic that allows it to survive out of water and makes it a good candidate for live sale.

It is omnivorous, and can grow well on feed with 35% protein. Its main drawbacks for culture are the availability of spawners, and its tendency to burrow in the pond bottom during drain harvest.

32.2.5 *Penaeus japonicus*

This species is widely distributed in the western Pacific to India, the Red Sea, east Africa, Korea, Japan, East China Sea, South China Sea, especially in Guangdong Province. *P. japonicus* grows slowly in culture, 20 to 25 g in 160 days. Optimum water temperature is 20 to 30 C, but it can grow at 18 C. It requires high salinity, in the range of 15 to 30 ‰ with mortality at less than 7 ‰. It is also easy to mature and spawn, and PL production is not a problem. It also has a thick exoskeleton and is a good species for live sale. Its main problems for intensive culture are its requirement for a high protein (60%) and expensive feed, and its preference to burrow in clean sand.

32.2.6 *Metapenaeus affinis* and *Metapenaeus ensis*

Both species are widely distributed throughout coastal southeast Asia, and are important in the offshore shrimp fisheries in Fujian, Guangdong, Guangxi and Hainan provinces. They can grow to 7.5 cm after 40 days in pond culture, but seldom grown larger than 10 g. They have high tolerance to low dissolved oxygen, high temperatures, and a wide range of salinities. Their exoskeleton is thick, and they are often sold live. They also have a long spawning season. Their PL are often abundant in places where traditional extensive fish culture is practiced. In these places, PL enter the pond during flooding and a crop of shrimp is typically obtained in polyculture with fish without PL cost or feed purchased for the shrimp.

32.3 SHRIMP CULTURE HISTORY IN CHINA

Chinese shrimp culture began more than 300 years ago. It was then called "port culture" and was accomplished by passively stocking extensive culture bays or ponds with tidal water. Flooding of these impoundments brought in shrimp PL which then mostly fed on natural food production. Small quantities of fresh feeds were applied in some cases. The shrimp were then harvested by draining the impoundment at low tide. This was the typical method of shrimp culture in China until the early 1970's. Total production, as well as production per unit area, were very low with only a few dozen kg of shrimp produced per hectare.

During the 1950's, the Chinese government began investigating improvements of traditional shrimp culture methods. These investigations aimed to improve both shrimp culture and management of wild shrimp populations. Studies included research on natural resources, ecology and

Table 4. Postlarval (PL) shrimp production from hatcheries in the People's Republic of China from 1980 through 1987.

	YEAR							
	1980	1981	1982	1983	1984	1985	1986	1987
Total PL Production (millions)	337	1,646	2,789	4,242	7,770	18,947	34,465	72,443
Total Hatchery Capacity (x 10 ³ m ³)	58	62	75	81	98	137	221	348
PL Production Rate (#PL/l of capacity)	5.8	26.5	37.1	52.5	79.0	138.0	155.7	208.1

classification (Liu 1955, Dong 1959, Sheng and Liu 1976); larval rearing (Yellow Sea Fisheries Research Institute 1960; Zhao 1965; Qingdao Institute of Oceanography 1977; Wang 1982); and culture techniques (Qingdao Marine Fisheries Institute 1972, 1973; Yellow Sea Fisheries Research Institute 1979). For the first time, during 1959, China produced PL of *P. chinensis*. Then followed the "Cultural Revolution", a period when aquatic research, like other sciences, developed slowly or was simply forced to stop. The early success did not, therefore, lead to rapid development of China's shrimp culture industry until the late 1970's. Under China's reform and open-door spirit starting in 1978, a policy for aquaculture development was established at the National Fish and Shrimp Culture Conference presided over by the Fishery Bureau of the Ministry of Agriculture. To meet the urgent demand for shrimp PL, the government in 1980 called on this organization to organize and coordinate cooperation among the scientific, educational and production work units. Technological breakthroughs in large-scale PL production were made during the next two years. This resulted in a larviculture methodology unlike those in Japan or the United States. This allowed China to advance shrimp culture production to a level for international trade. In 1980, China's PL production was 337 million. By 1987, seven years later, PL production exceeded 72 billion. PL production density increased from 26/l in 1980 to 208/l in 1987 (Table 4). Now, hatchery produced PL not only satisfy all culture needs, but they are also used to stock 3 cm juvenile shrimp into the Bohai Sea, Yellow Sea, East China Sea, and South China Sea for wild stock enhancement.

32.4 PENAEUS CHINENSIS REPRODUCTION AND LARVICULTURE

As mentioned earlier, China has several cultured shrimp species, but P. chinensis is by far the most important. For that reason, the following account describes the culture techniques for this species.

32.4.1 Migration and Reproduction

P. chinensis leave their wintering grounds in the south of Yellow Sea each year in February and March, and migrate north (Figure 2). They reach the open sea near Shidao Island, south of the Shandong Peninsula in early March and concentrate near the eastern end of the peninsula during mid to late March. They then proceed west to spawning grounds in the shallow waters of Laizhou Gulf, Bohai Gulf, and Haizhou Gulf. Small populations also spawn along the south shore of the Liaodong Peninsula, the south coast of Shandong Peninsula, and the west coast of Korea. Movement to the spawning grounds is called spawning or reproductive migration. Spawning occurs in April and May. The new year class of shrimp then develops in the gulf and estuarine areas until autumn. When water temperatures decrease to 10 C or less, the shrimp migrate to deeper waters of the Yellow Sea on their wintering migration.

32.4.2 Sourcing Broodstock

Broodstock shrimp are available from three sources. The first source is from the spawning grounds soon after their spawning migration (Fig. 2). These shrimp are presently the main source of broodstock in northern China, and they can be spawned soon after capture. They are also the least expensive. There is concern, however, that continued use of these broodstock will threaten the wild resource, and negatively impact the ocean fishery. The second source of broodstock includes either collecting prospective broodstock from culture ponds at the end of the summer, or collecting from the sea during the wintering migrations. These shrimp are then overwintered in tanks or ponds, and spawned the following spring when they become sexually mature. This method is widely used in Zhejiang, Fujian, Guangdong and Guangxi provinces because winter temperatures are higher and it is not necessary to heat the water. The third means of broodstock procurement is by capturing shrimp during their reproductive migration before they are sexually mature. They are then held in nursery ponds until ready to spawn. The second source is considered ecologically most desirable because it impacts the wild stock the least.

32.4.3 Spawning

P. chinensis typically spawn several times. In the hatchery under good conditions, one female can spawn 4 to 5 times. The highest number of multiple spawns from one female was 7. The average interval between successive spawns is 15 days, but can range from 5 to 20 days. Spawning from females captured from the spawning grounds typically begins within 2 to 5 days, but depends on technique and quality of the broodstock. Between 30 and 50% of these females spawn in captivity. Average egg production per spawning is between 400,000 and 500,000. One 15 cm female produced 1,700,000 eggs.

Since spawning usually occurs at night, gravid females are selected and placed in tanks during the afternoon or at dusk. They are then examined the next morning.

32.4.4 Hatching

Water quality and condition are especially important for ensuring normal embryo development, high hatch rate, and healthy nauplii. Water temperature and salinity have great influence on success. There are many other factors that affect hatching and subsequent development, including substances such as mercury, copper, zinc and pesticides. Great care needs to be taken in hatchery siting to avoid these contaminants.

32.4.5 Larval Development

After hatching, P. chinensis, like all other penaeid shrimp, goes through four development stages during its larval (and postlarval) development (see Chapter 2; Zhao 1965). This includes 26 molts before becoming a juvenile similar in form to adult shrimp. Along with changes in shape and form during this development, the larvae undergoes changes in environmental needs and selection as well.

32.4.5.1 Nauplius stage

Although the nauplius does not feed, unicellular algae must be provided at least by the second naupliar stage to ensure significant algae are present when the nauplii metamorphose to zoea. Algae are provided by inoculating the larviculture tanks with stock cultures and providing sufficient sunlight. The nauplius stage takes 3 to 4 days.

32.4.5.2 Zoea culture

Zoea feed mainly on unicellular algae. The most commonly used algae in China are Phaedactylum spp., Tricornutum spp., Nitzschia spp., Chaetoceros spp., and Skeletonema spp. Additionally, soybean milk, egg yolk,

fertilized shellfish eggs, rotifers and artemia nauplii are also fed. Zooplankton food is indispensable at zoea stage III and later.

32.4.5.3 Mysis culture

Mysis larvae feed on zooplankton, and secondly on algae. Water exchange and aeration should be increased in response to higher biomass and metabolic waste.

32.4.5.4 PL culture

PL feed almost entirely on zooplankton and animal feed. At the PL stage, minced clam is often substituted for Artemia to reduce costs, and to prevent cannibalism, especially at PL densities greater than 50/l. Daily water exchange should exceed 50%.

32.4.6 PL Sale and Transport

Depending on water quality and temperature, PL are ready for pond stocking and growout within 20 days of hatching. They are typically 7 mm in length at this time. Transfer of PL from the hatchery to the farm without high mortality is of utmost importance. (See Chapter 12 for techniques developed with P. vannamei.) Stocking density in the transportation container, water aeration, shipping time, water temperature and water quality are the key factors. In China, transfer is typically accomplished in canvas barrels on trucks. A barrel of 1 m diameter with 20 C aerated water can transport 300,000 to 400,000 PL of 7 to 10 mm in length for 6 to 8 hours without excessive mortality. PVC plastic bags filled with oxygen over the water are also used. A 10-l bag can hold 10,000 to 20,000 PL for 10 hours or more.

32.5 PENAEUS CHINENSIS POND GROWOUT

Successful pond culture of P. chinensis depends on good site selection and pond construction, PL transport and stocking methods, predator control, water quality management, feeding, disease control, and harvesting. Older ponds need yearly maintenance.

There are several methods of shrimp culture in China, including; fish pond polyculture, shrimp monoculture without feeding, shrimp monoculture with feeding, and pen culture in open water. The first two methods are extensive systems with low yields and economic inefficiencies. They are seldom used now, but were formerly the principal means. The last two methods are usually semi-intensive now, although production was only 278 kg/ha during 1980. This increased to 1,167 kg/ha by 1987. Production levels of 7 to 15 MT/ha are also possible with P. chinensis under intensive culture.

Rapid development of shrimp farms in China has created impediments which reduce yields. In 1980, there were only 9,340 ha of shrimp ponds in China. By 1987, there were 131,300 ha (Table 1). This rapid expansion created a series of problems which negatively impacted yield. These problems have included, (a) insufficient funds which resulted in construction of ponds not resistant to wind and wave action, and (b) building too many ponds in some areas making it difficult to obtain high quality source water and to dispose of waste waters, (c) food quality is not adequate. Problem (b) is pronounced in Shandong and Hebei provinces. The goal now is to correct these deficiencies, increase production level, and improve economic benefits.

32.5.1 Shrimp Farm Construction

Site selection is most important, especially with respect to land elevation and topography, soil conditions, and water quality. With P. chinensis, water pH in the range of 7.8 to 8.6, and salinities of 5 to 35 ‰ are best. Metal ions should not exceed the following maxima in mg/l: Hg^{2+} , 0.0002; Cu^{2+} , 0.017; Zn^{2+} , 0.03; and Pb^{2+} , 0.16. Sandy mud, which is solid, sticky without leakage, and does not crack excessively when dried, makes the best bottom. Acid sulfate soils are not suitable because oxidation of these soils forms sulfuric acid, decreases pH and solubilizes iron and aluminium. The latter are not only toxic themselves, but they also bind phosphorus and lower pond productivity. Other factors to consider when siting a farm include available labor force, PL source, vehicle access, precipitation, temperatures, and post-harvest processing.

32.5.2 Predator and Disease Control

Precautions should be taken to minimize shrimp losses due to disease and predation. Thorough drying of the pond bottom between crops will help reduce pathogens and solubilize nutrients in non-acid soils. Filamentous algae should be eliminated with herbicides. When re-filling the pond, waters should be filtered to prevent fish and fish eggs from entering. Teaseed cake should be used later to kill fish intruders.

32.5.3 Feed Organism Culture

Promotion of natural food production in ponds will result in better shrimp growth and lower production costs. In China, Corophium spp. is stocked in ponds to promote food production. Experience indicates that, at stocking densities up to 7.5 PL/m² with 150 to 300 kg of Corophium stocked after pond filling, prepared feed applications may not be necessary until the shrimp exceed 8 cm. Other food organisms sometimes stocked include Unciola spp, Gammarus and polychaete worms.

32.5.4 PL Stocking

This activity involves the transition from the hatchery to the growout ponds, and can bring great economic loss if not done properly. The key is to avoid large differences in water quality between the hatchery situation and the pond. With respect to *P. chinensis* and salinity, for example, the differences between hatchery and pond salinities should not exceed 10 ‰. A difference of 5 ‰ or less is even better. Regarding temperature, shrimp transferred from 18 C to 15 C become immobile, while a transfer from 18 C to 10 C causes rapid mortality. Ponds should not be stocked with *P. chinensis* at temperatures less than 14 C.

32.5.5 Feeds

Feed costs are of considerable importance in shrimp culture economics. Efforts are now underway to improve feed quality while keeping feed costs within acceptable limits. Studies are underway to determine the necessary protein level, composition and percentage of amino acids, and composition of necessary fatty acids. Other considerations include growth stimulants, and binders. (See Chapter 25 for a thorough treatment of feed composition.)

Feed is one of the main problems facing shrimp culture in China. China's shrimp aquaculture industry is actively developing protein sources needed to sustain the shrimp culture industry. China has a large agricultural sector with substantial quantities of by-products such as peanut cake, bean cake, cotton seed cake, rape seed cake, etc. China is also a major fishing country. In 1988, China's fishery sector produced more than 10 million MT of fish, the third largest production in the world. At the same time, however, China has a large population resulting in a relatively small average per capita consumption of resources and products. Taken together, protein shortage is still a problem for the development of shrimp feeds. One response of the government has been to promote some industries that provide new, low cost protein sources for shrimp feed.

32.6 HARVESTING AND PROCESSING

Harvest timing depends on growth rates, location and market demands. In the north, shrimp growth ceases when pond temperatures drop to 10 C. High mortalities occur when temperatures reach 4 C. Harvesting in this area starts, therefore, in September or October in Liaoning and Shandong Provinces of northern China, respectively. In southern China, in areas like Guangdong and Hainan Provinces, shrimp culture is year around and harvesting can depend more on market demand, prices, and processing availability.

P. chinensis is processed primarily into a frozen or iced, headless product. Some are sold whole. Only a few are sold alive.

After years of development, a complete trade system has now been formed in China for larval production, pond culture, processing, and marketing. China's "AAA" brand of frozen prawn is very popular with customers around the world.

32.7 SUMMARY

In conclusion, China's shrimp culture industry has undergone rapid development and expansion over a 10 year period, and now ranks first in terms of country production worldwide. China also has the largest land area under shrimp cultivation. While these achievements are impressive, additional improvements are needed in order to maintain and further increase production, and to improve profits, including the following.

(a) Strengthen shrimp genetics research. To date, shrimp culture has used wild stocks only. Substantial improvements in such things as disease resistance, feed conversion, low oxygen tolerance and growth rate should be realized through captive reproduction and genetic selection. This has been the history of agriculture with other plant and animal crops.

(b) Improve feeds. The need is for a low cost, quality feed that will not substantially impact human food sources.

(c) Pond construction. There is a need for better pond designs and construction, as well as operating procedures. This should result in higher yields and better profits.

(d) Diseases. Disease identification and control is an important factor. This will require more research on the nature of disease transmittal, vaccines, and medications.

(e) Information exchange. China needs to develop strong technological cooperation with other shrimp culture researchers and practitioners. Solutions to many of the shrimp culture problems will require a diversity of talents and resource bases.

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CHAPTER 33

Piamsak Menasveta

SHRIMP CULTURE INDUSTRY IN THAILAND

33.1 INTRODUCTION

Since 1960 the Thai fishery industry has developed tremendously. Fishery production increased from 200,000 metric tons (MT) in 1960, to the present level of 2,200,000 MT. In 1986, Thai fishery production ranked tenth in world record with 2,119,000 MT. Fishery products ranked 7th of export values from Thailand, and included items such as; canned tuna, frozen shrimp, frozen squid, frozen fish, and fish meal.

Due to increasing interests in shrimp industries world wide, this article presents and analyses facts and figures about the shrimp industry in Thailand. Contents include; present shrimp production, future trends, and economic considerations.

33.2 PRESENT SHRIMP PRODUCTION AND FUTURE TREND

Thailand shrimp production ranks fifth in the world after China, the United States, India and Indonesia. Production comes from two principal sources, ocean capture fishery and culture in ponds. In the past, ocean capture contributed the greatest share. Today, production from pond culture in Thailand has increased and nearly equals capture production (Table 1).

Shrimp production by capture includes several species: Penaeus merguensis, P. indicus, P. semisulcatus, P. latisulcatus, P. monodon, and Metapenaeus spp. Of these, P. merguensis and Metapenaeus species are common in the catch and account for the largest portion of yearly production. Catch of P. monodon is usually the least, contributing 500 to 1000 MT yearly.

The most important shrimp fishing grounds in Thailand are the Gulf of Thailand and the Andaman Sea. In the past, Thai fishing boats also used to fish at sea beyond the 12 miles territorial sea limit of neighbouring countries. After Thailand ratified the 200 miles exclusive economic zone in 1981, however, she lost about 50% of her previous fishing grounds. This is the main reason why shrimp production from the Thai capture fishery has not increased since 1981. This limitation on fishing grounds led Thailand to put

Table 1. Shrimp production from ocean capture fishery and pond culture in Thailand.

Year	Production by Capture (MT)	Production by Culture (MT)	Total Production (MT)
1981	122,706	10,729	133,435
1982	156,523	10,091	166,614
1983	127,584	11,550	139,134
1984	104,394	13,007	117,401
1985	91,632	15,840	107,472
1986	102,227	17,886	120,113
1987*	100,000	40,000	140,000
1988*	100,000	70,000	170,000
1989**	100,000	100,000	200,000

Source: Royal Thai Department of Fisheries

* Estimation

** Expectation

special emphasis on shrimp culture development in coastal areas. Thailand's 2,600 km coastline has many areas which are suitable for shrimp culture.

Coastal areas of Thailand have several conditions that are very favorable for shrimp culture. Thailand is seldom affected by typhoon and cyclone. Water temperatures are ideal with small seasonal variation, and soils and terrain are often ideal for pond construction. These unique features give Thailand advantage over some other countries in Southeast Asia.

In fact, Thailand has been culturing marine shrimp for several decades. Early shrimp culture was mostly by extensive culture methods. Shrimp ponds were comparatively large, ranging from 5 to 10 ha each with a peripheral canal around the inner dike (see Extensive Ponds, this volume). Farmers used water elevators powered by wind mills for inundating the ponds. Shrimp seed entrained by the influent water grew in the ponds for 2 to 3 months before the ponds were drained and the shrimps, usually small size, were harvested. During the culture period, some fertilizers were added to the pond, but feed was not provided. Shrimp production by this extensive methods was rather low, with an average of only 180 kg/ha/year or less. These methods are still used by many Thai shrimp culturists even today.

About a decade ago, some shrimp culturists began developing a higher technology for both semi-intensive and intensive culture systems. Thai intensive culture is very similar to the Taiwanese method. With these new technologies, shrimp production rate increased to 3.6 to 6.0 MT/ha/crop, with 4 months per crop. The shrimp species used almost exclusively with this type of culture is Penaeus monodon, or giant tiger prawn.

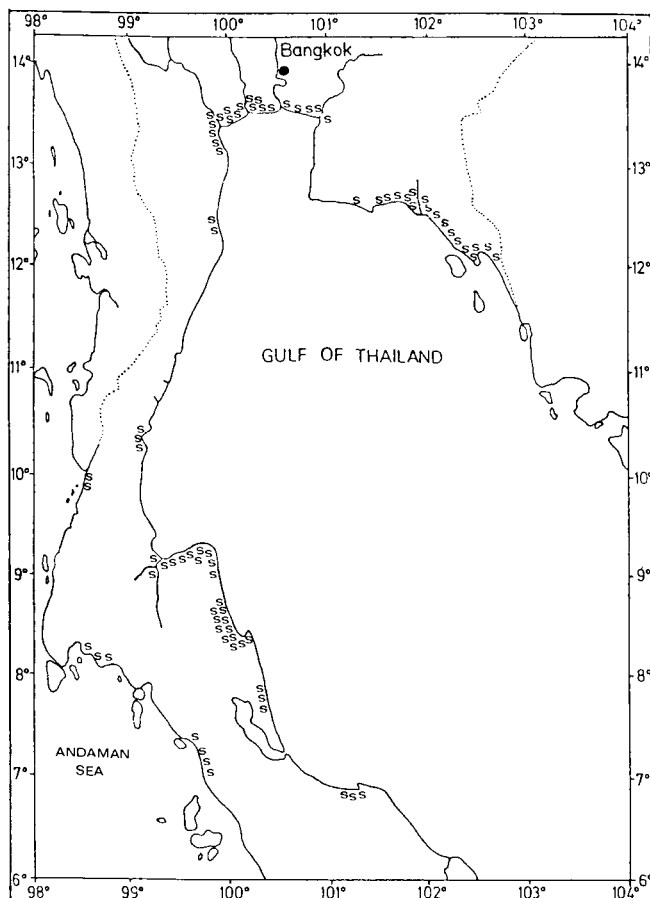


Figure 1. Map of marine shrimp culture areas (shown with s) in Thailand.

Shrimp culture area in Thailand increased steadily since 1980, with a very rapid increase during the past four years (Fig. 1). Using satellite imagery, we can see that Thailand presently has about 80,000 ha of shrimp culture area; or twice the shrimp culture area of four years ago (Table 2). This area can be categorized as; 56,000 ha of extensive (conventional) ponds, 16,000 ha of semi-intensive ponds, and 8,000 ha of intensive ponds.

Shrimp culture in Thailand created several related activities, such as hatchery, feed production, processing plants, and cold storage. At present, there are about 30 large hatcheries and not less than 1,000 backyard (small-scale) hatcheries. Postlarval (PL) production from hatcheries is about 2 billion/year, and is still increasing steadily. Shrimp feed production is estimated at not less than 100,000 MT/year. Shrimp processing plants have the present capacity to produce block frozen shrimp at 40,000 MT/year from 70 processing plants and cold storage facilities. Nevertheless, the Thai

Table 2. Shrimp culture area, farm number, production, value and yield in Thailand.

Year	Number of Farms	Culture Area (ha)	Production (MT)	Value (US\$ x 10 ⁶)	Yield (kg/ha)
1980	3,572	26,036	8,063	17.6	309
1981	3,657	27,459	10,727	25.3	390
1982	3,943	30,792	10,090	29.4	327
1983	4,327	35,537	11,549	36.5	325
1984	4,519	36,791	13,006	39.4	353
1985	4,939	40,768	15,840	51.8	388
1986	5,534	45,367	17,885	66.8	393
1987*	-	64,000	40,000	149.2	625
1988*	-	80,000	70,000	215.4	875
1989**	-	80,000	100,000	270.0	1250

Source: Royal Thai Department of Fisheries

* Estimation

** Expectation

government is trying to promote this type of business, because it is still inadequate for processing the present level of shrimp production.

The future trend for Thai shrimp industry will continue to put special emphasis on shrimp culture. In large part this is because shrimp production from the ocean capture fishery cannot expand due to a limited resource. Shrimp culture methods are likely to continue intensification to semi-intensive and intensive levels. For the sake of mangrove forest conservation, total culture area may not much above present levels. Future expansion in culture area, should it occur, most likely will be into non-mangrove areas.

If half of the present shrimp culture area in Thailand is converted to intensive culture, this will increase result shrimp production to not less than 150,000 MT/year, valued at \$(U.S.)800 million. This production level can be expected within the next five years, depending on the market situation.

33.3 PRESENT SHRIMP EXPORT AND FUTURE TREND

Export of frozen shrimp from Thailand has increased tremendously since 1984 (Table 3). In 1988, Thailand exported 42,000 MT of frozen shrimp, valued at \$280 million. The important markets for Thai shrimp exports are Japan and the United States (Table 4). Shrimp exports to these two countries account for 60% of the total shrimp exports each year.

Thai exports of frozen shrimp to Japan did not increase much during 1982 to 1987. These exports fluctuated within the range of 7,000 to 10,000

Table 3. Volumes and values of frozen shrimp exported from Thailand.

Year	Volume (MT)	Value (US\$ x 10 ⁶)
1981	18,761	85.4
1982	22,647	110.5
1983	20,150	126.5
1984	19,428	111.9
1985	24,041	137.5
1986	28,717	175.6
1987	35,000	224.6
1988	42,000	280.0

Source : Royal Thai Department of Customs

MT per year (Table 5). During 1988, however, exports to Japan jumped to 17,000 MT, with estimates of 25,000 MT for 1989. Unlike Japan, Thai frozen shrimp exports to the U.S. increased steadily from 2,475 MT in 1981 to 10,955 MT in 1987 (Tables 4 and 6).

Other countries who are also increasing imports of Thai shrimp are Singapore and the United Kingdom (U.K.). It is interesting to note that shrimp imports by Singapore increased sharply since 1987, especially for small sizes. Singapore may be processing small size shrimp exporting the value-added products to other countries.

Review of frozen shrimp imports to Japan (Table 5), shows that India and Indonesia once had the largest market shares. Later (1985 to 1987), Taiwan's success with Penaeus monodon culture put Taiwan first by 1987 with import volume to Japan of 49,230 MT. Taiwan's success did not last long. In 1988, Taiwan experienced serious shrimp disease problems, which significantly reduced their export volumes.

The People's Republic of China is now the largest importer of shrimp to Japan. Their market share of the Japanese market rose from 4.8% in 1982, to 10.8% in 1987 (Table 5), and further increased during 1989. Shrimp culture production by P.R. of China increased 10 folds during 1982 to 1986; from 7,079 MT to 79,054 MT (Shang 1989).

Frozen shrimp imports to the U.S. are still dominated by Ecuador and Mexico, due mostly to proximity and established marketing and trade connections. Thailand's share of the U.S. market could be increased through greater marketing effort and provision of consistent supplies of quality products.

Thailand's frozen shrimp exports during the next 2 to 3 years may slow down, however, due to large production increases and keen competition among the countries in Asia. Although, Japan may increase its shrimp

Table 4. Countries that imported frozen shrimp from Thailand.

Countries	1982		1983		1984		1985		1986		1987(Jan-June)	
	Volume	Value	Volume	Value	Volume	Value	Volume	Value	Volume	Value	Volume	Value
Japan	12,312	74.1	7,662	61.4	5,053	48.5	7,650	58.2	9,385	83.7	4,965	42.8
U.S.A.	3,458	14.0	6,149	34.9	5,941	38.4	7,097	44.0	7,964	48.4	3,938	24.8
Singapore	388	2.1	459	1.7	1,010	3.6	3,362	13.6	3,357	13.5	2,207	9.2
U.K.	718	3.5	894	4.6	1,116	4.0	1,347	4.6	1,994	8.6	1,294	6.7
Hong Kong	3,431	7.5	2,503	5.6	1,862	4.4	1,907	4.6	1,882	4.4	1,044	3.0
Germany	394	3.0	479	4.4	267	2.2	272	2.5	366	4.0	148	1.7
Italy	740	2.0	157	0.5	58	0.1	116	0.5	555	3.6	911	6.2
Australia	418	2.1	1,002	8.7	1,062	7.5	852	6.5	1,202	2.6	690	4.8
Others	788	2.3	845	4.8	3,059	3.4	1,438	3.0	2,012	6.8	1,567	6.6
Total	22,647	110.6	20,150	126.5	19,428	112.0	24,041	137.5	28,717	175.6	16,764	105.8

Source : Department of Customs

Volume : tons

Value : million U.S.\$

Table 5. Frozen shrimp imports in Japan (volume in tons).

Countries	1982		1983		1984		1985		1986		1987	
	Volume	%	Volume	%	Volume	%	Volume	%	Volume	%	Volume	%
Taiwan	7,759	5.1	11,052	7.4	16,494	9.8	21,771	11.9	37,825	17.8	49,230	19.1
India	39,833	26.3	36,912	24.8	28,298	16.8	36,235	19.8	36,727	17.3	37,759	14.7
Indonesia	23,600	15.6	21,767	14.6	24,051	14.2	24,357	13.3	27,742	13.0	30,311	12.0
P.R.of China	7,253	4.8	5,778	3.9	10,307	6.1	10,664	5.8	18,718	8.8	27,898	10.8
Australia	11,822	7.8	11,096	7.5	12,206	6.0	10,544	5.8	9,457	4.4	12,016	4.6
Vietnam	2,885	1.9	5,104	2.4	5,104	3.0	6,974	4.4	9,361	4.4	N.A.	N.A.
Thailand	9,188	6.1	7,541	5.1	6,747	4.0	7,371	4.0	8,945	4.2	11,560	4.5
Philippines	3,694	2.4	4,282	2.9	5,096	3.0	5,986	3.3	8,402	3.9	N.A.	N.A.
Bangladesh	3,354	2.2	3,725	2.5	5,943	3.5	7,428	4.1	7,250	3.4	N.A.	N.A.
Malaysia	5,151	3.4	6,168	4.1	5,060	3.0	4,731	2.6	4,698	2.2	N.A.	N.A.
Others	36,857	24.4	36,768	24.8	51,675	30.6	46,850	25.7	43,681	20.6	87,255	34.3
Total	151,396		148,627		169,081		182,911		212,806		256,629	

Source: INFOFISH 4/1987

N.A. = not available

imports by another 50,000 MT in 1989 (increase from 250,000 MT in 1988 to 300,000 MT in 1989), profits to the producer countries may be less than in the past. During the second half of 1988, the farm price of shrimp in Thailand decreased sharply from \$12/kg to only \$4.8/kg. This particularly affected farms using intensive culture, where production cost at these farms is about \$5/kg.

Price depreciation of Thai shrimp during 1988/89 is from several factors. First, is the rapid expansion of farming area and production without a strong marketing plan. Second, is insufficient processing facilities (contact freezer and cold storage) to cope with the large shrimp production volume. Unprocessed shrimp then have to be sold locally, which brought down shrimp prices sharply. Third, is higher production cost, mainly caused by the feed cost increases.

Thai imports to the U.S. market, may increase, but at a slow rate. Thailand is at some disadvantage due to long shipping distance, when compared with Ecuador and Mexico. Besides, the U.S. market prefers white shrimp rather than the dark or striped shrimp. Therefore, if Thailand wishes to increase its U.S. market share, it may profit greatly by farming more banana shrimp (*Penaeus merguensis*).

It is very interesting to study the European shrimp market. This market is still small, and can expand. At present, per capita shrimp consumption is only 0.5 kg/person in Europe, comparing with Japan and the U.S. at more than 2 kg/person and 1 kg/person respectively (Nierentz and Josupeit 1988). Nevertheless, shrimp imports to the European Economic Community (EEC) did increase from 130,000 MT in 1980 to 227,000 MT in 1986 (Nierentz and Josupeit 1988). Thailand has a good market share of shrimp

Table 6. Frozen shrimp import by the U.S. in 1987.

Countries	Volume in	
	tons	%
Ecuador	46,045	21.18
Mexico	39,136	18.00
P.R. of China	19,273	8.86
Taiwan	16,864	7.76
India	12,909	5.94
Thailand	10,955	5.04
Panama	7,545	3.47
Brazil	7,545	3.47
Others	57,137	26.28
Total	217,409	100

imports to the EEC, but mostly as small shrimp in cans. Therefore, increased marketing of frozen shrimp to EEC is desirable.

33.4 CONCLUSIONS

In general, there are major impediments for marine shrimp culture in Thailand. We have both technical knowledge together with a large natural resource. The problem is with the market, which is very competitive at this moment. Thailand must adjust and prepare for these events. We must find ways and means to reduce production cost in order to make our products more competitive on the world market. Processing shrimp for value-added products is one such example of things to try.

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CHAPTER 34

J. Honculada Primavera

PRAWN/SHRIMP CULTURE INDUSTRY IN THE PHILIPPINES

34.1 HISTORICAL BACKGROUND

The Philippines is an archipelago of more than 7,100 islands with 17,460 km of coastline (Fig. 1), including mangrove forests which covered about 450,000 ha in the 1920s. Coastal aquaculture began a few centuries ago when earthen ponds for the culture of milkfish (Chanos chanos) were first converted from mangrove swamps. For a long time, coastal aquaculture was synonymous with milkfish pond culture; while prawns and shrimps were incidental byproducts resulting from wild fry that entered the ponds during tidal water exchange.

In 1943, studies on low density monoculture of the giant tiger prawn (Penaeus monodon) using wild fry were initiated at the Dagat-dagatan Experimental Station of the Bureau of Fisheries in Malabon, Rizal Province (Delmendo and Rabanal 1956). Information on the ecology and early life history of P. monodon generated by the Institute of Fisheries Research Development of the Mindanao State University (MSU-IFRD) in the early 1970s (Villaluz et al. 1972) was used in setting up the first experimental prawn hatchery at IFRD.

This was followed by the establishment of big-tank and small-tank hatcheries at the Aquaculture Department of the Southeast Asian Fisheries Development Center (SEAFDEC/AQD) in Iloilo Province (Mochizuki 1978). An active technology transfer program that included short-term, hands-on training courses on small-scale hatchery starting in 1977, contributed to a dramatic hatchery production of 15 million prawn PL in 1978 (Primavera 1983).

Based on the earlier Dagat-dagatan studies, SEAFDEC/AQD started higher-density (semi-intensive) growout pond experiments with P. monodon in the mid-1970's. At that time, farmers started stocking more than 10,000 PL/ha using hatchery fry. Soon after, the first intensive culture trials, using imported Taiwanese technology and feed formulations were undertaken by a Philippine food conglomerate (Liu and Mancebo 1983).

The availability of both seed and feed, and the attraction of lucrative export market prices contributed to the take-off of the prawn industry. In

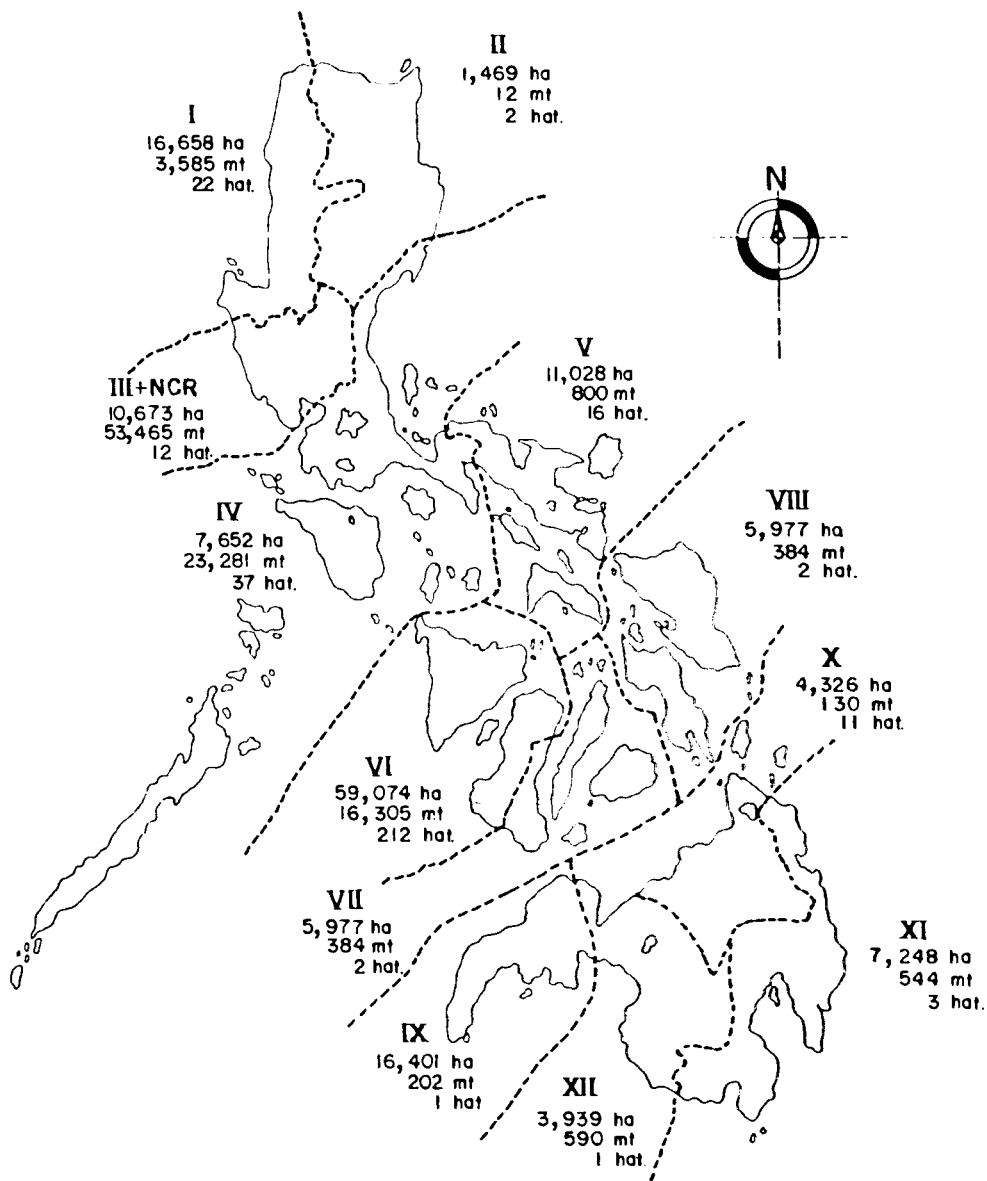


Figure 1. Philippine regional profile of 1987 milkfish and prawn pond area (ha), 1987 prawn production (MT) and 1988 prawn hatcheries. (Bureau of Agricultural Statistics 1989; Philippine Federation of Aquaculturists Annual Convention 1989)

1983, when the country's 56 hatcheries produced 85 million PL's, and commercial pellets for intensive culture first appeared in the market, pond production totalled 12,100 MT, a quantum leap from a harvest of only 1,800 MT the previous year.

Since then production of PL, adults and exports have steadily increased to a peak of 20,000 MT of exports from 40,000 MT of pond harvests in 1988 (Fig. 2). The following year the bubble burst. From a high of P200/kg (US\$1=P21) in 1988, farm gate prices plummeted to as low as P70/kg in mid-1989 due to Southeast Asian excess production of black tiger prawn, and to prawn exports from China glutting the Japanese market.

This chapter discusses the various components of the Philippine prawn industry with a focus on growout, problems of the farming sector, and problems of the industry as a whole. Lastly, recommendations are offered for long-term viability.

34.2 COUNTRY PROFILE

34.2.1 Total fisheries production

Total Philippine fisheries production in 1987 was 2.14 million MT with 1.06 million MT (49.4%) from municipal or small-scale fisheries, 585,600 MT (27.4%) from commercial or large-scale fisheries, and 497,600 MT (23.2%)

Table 1. Comparison of species composition of prawns and shrimps from catches and culture ponds in the Philippines during 1987.

	Capture			Culture	
	Quantity (MT)	% of Penaeids	% of Total	Quantity (MT)	% of Penaeids
White shrimp ^a	13,616	77.27	42.16	2,690	7.53
Tiger prawn ^b	2,370	13.45	7.34	32,380	90.60
Endeavour prawn ^c (Greasyback shrimp)	1,636	9.28	5.07	670	1.87
Acetes, mysids. etc.	14,670	---	45.43	---	---
Total	32,292	100.00	100.00	35,740	100.00

Source: Bureau of Agricultural Statistics.

a/ *Penaeus indicus*, *P. merguensis*

b/ *P. monodon*, *P. semisulcatus*, *P. japonicus*

c/ *Metapenaeus* spp.

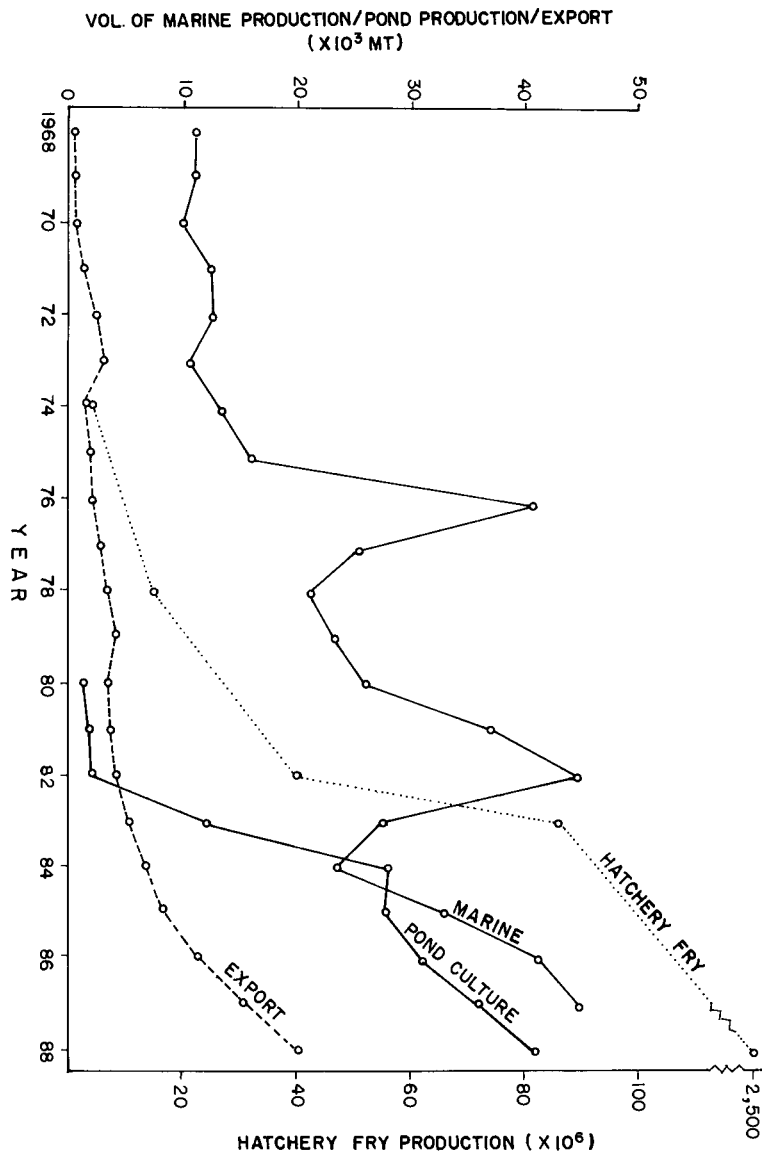


Figure 2. Prawn production from hatcheries, culture ponds and marine fisheries (includes penaeids and non-penaeids) and exports from the Philippines (BFAR 1987; BAS 1989; Primavera 1984; Primavera 1989)

from aquaculture (BFAR 1987). The contribution of aquaculture has steadily increased from 8.6% in 1967 and 10.8% in 1977, to almost a quarter of total fisheries production at present.

34.2.2 Prawn/shrimp production

Prawns and shrimps contributed 68,000 MT or 3.2% of total 1987 fisheries production of 2.14 million MT. Marine landings have fluctuated between 4,000 and 40,000 MT in contrast to pond culture which has consistently increased from a mere 1,400 MT in 1980, to approximately 40,000 MT in 1988 (Fig. 2).

A second difference between culture and capture is species composition. Whereas the black or giant tiger prawn (*P. monodon*) made up 90.6% of pond harvests, it contributed only 13.4% (together with other tiger prawns) of marine landings in 1987 (Table 1). In contrast, the white shrimp made up 77.3% of all marine catches (excluding non-penaeids), and only 7.5% of cultured prawns.

Municipal fisheries (using vessels of 3 gross tons or less that operate within 7 km of shoreline) contributed 26,764 MT or 83% of total 1987 landings with baby trawl (motorized pumpboat), push net, filter net and gill net as the main fishing gears. Commercial fisheries brought in 5,528 MT (17%), mostly from trawls.

Pond production of prawns from the different regions of the country roughly follows the distribution of culture pond hectareage (Fig. 3). Among the 12 regions, Western Visayas (VI) leads in both production (39.6%) and area (28%), followed by a combined Central Luzon-National Capital Region (III + NCR) with 26% of production and 25.7% of total area.

34.2.3 Prawn/shrimp exports

Prawn and shrimp exports (fresh, frozen, cooked, preserved, etc.) have steadily increased from 179 MT valued at \$149,000 in 1968, to more than 20,000 MT worth \$251.6 million in 1988. This increase comes mainly from cultured products rather than capture, as can be seen from the parallel trends of pond culture and exports (Fig. 2).

Approximately 80% of 1987 Philippine prawn and shrimp exports went to Japan, with exports to the U.S. trailing far behind with only 13.6%. The very first black tiger prawns imported by Japan consisted of a 450-kg shipment sent from the Philippines in October 1975 (Lim 1988). Prior to this, Japanese consumers had an aversion to this species because of its black color when uncooked. An aggressive promotional blitz by a Philippine company paved the way for the introduction of the black tiger prawn to the Japanese market (Lim 1988). Promotions included cooking demonstrations (to show off the bright red color) to visiting distributors in the Philippines as

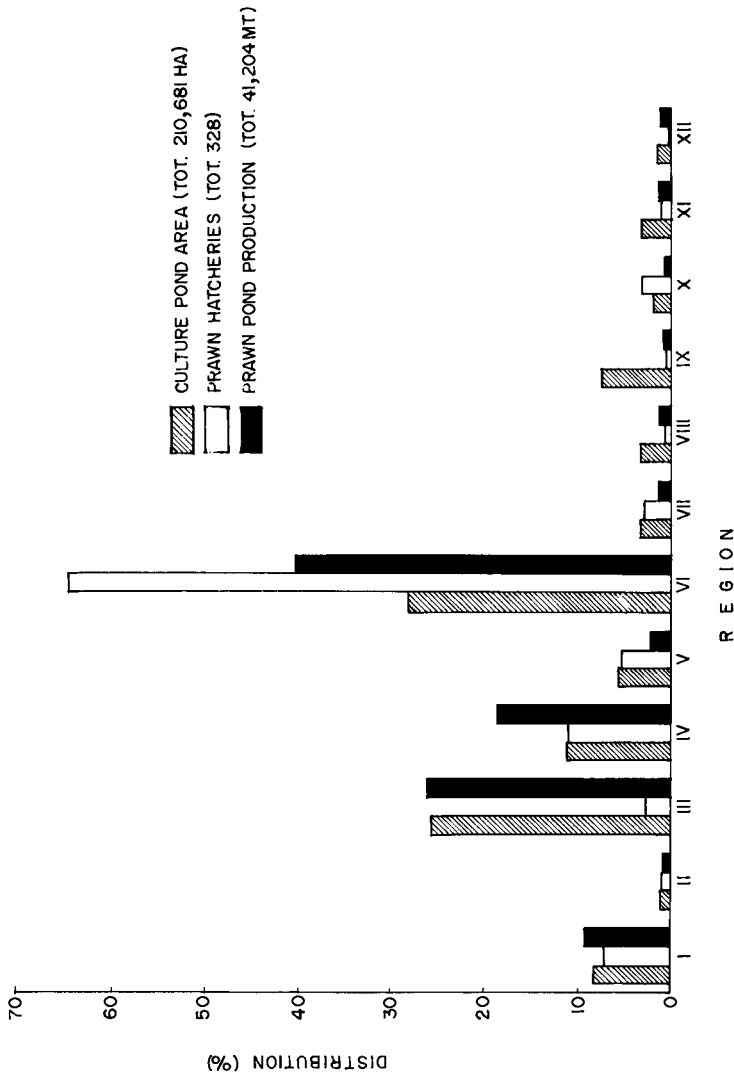


Figure 3. Regional distribution of 1988 milkfish/prawn culture pond area, prawn hatcheries and prawn pond production in the Philippines. Region I = N.W. Luzon; II = N. E. Luzon; III = Central Luzon + National Capital Region; IV = S. Luzon + adjacent islands; V = Bicol Region; VI = Western Visayas; VII = Central Visayas; VIII = Eastern Visayas; IX = W. Mindanao + Sulu + Tawi-tawi; X = N. Mindanao; XI = S.E. Mindanao; XII = Central Mindanao. (Data from Bureau of Agricultural Economics Dept.; Dept. of Agriculture; Proceedings of the Annual Convention, Philippine Federation of Aquaculturists, 2-5 May 1989.)

well as to consumers in Japanese restaurants and hotels, and extensive advertising.

At present there are 18 processing plants and 44 exporters in the Philippines, with 7 companies accounting for at least 60% of total yearly exports (Gomes and Cruz 1989).

34.3 SEED SUPPLY

Seed (PL) supply of P. monodon has evolved from the accidental entry of wild prawn seed during tidal water exchange in milkfish ponds, to the intentional stocking of fry procured from wild collectors, to the rearing of hatchery PL obtained from wild spawners or broodstock matured in captivity by eyestalk ablation. Until the early 1980s, most of the seed stocked in ponds came from wild seed collectors. At present, hatchery seed constitute about 80% of total supply.

34.3.1 Wild seed sources

Wild seed are caught by different gears adapted to different habitats: lures made of grass and twigs for mangrove areas, set raft and filter nets, seine and scissors nets for shore waters, etc. (Motoh 1980; Bagarinao et al. 1986). Compared to other species, P. monodon seed are not so abundant in coastal and estuarine waters. In a two-year survey, P. monodon seed constituted only 5.5% of all penaeid seed compared to 85% for white shrimps (P. indicus and P. merguensis; Motoh 1981).

34.3.2 Hatcheries

Most of the commercial hatcheries in the Philippines were established after 1975, when SEAFDEC/AQD first operated its big-tank hatchery, and when a P. monodon spawner cost only P5 compared to at least P300 at present. Production of PL's has since increased to 15 million in 1978, 40 million (from 50 hatcheries) in 1982, and an estimated 3 billion (from more than 300 hatcheries) in 1988 (Fig. 2). Pond operators started buying hatchery-reared seed instead of wild seed because of availability, more uniform sizes and absence of contaminating predators (Apud et al. 1983).

A majority of the prawn hatcheries are found in Western Visayas (Figs. 1 and 3) where SEAFDEC/AQD, a source of information and training courses on prawn broodstock, larval rearing and hatchery operation is located. Region III and the National Capital Region with only 3.6% of total pond area, ranks second in number of hatcheries (26%) and produced the next highest level of farmed prawns. Philippine hatcheries have been classified according to volume of rearing water and capitalization (Primavera 1983; Israel et al. 1986).

34.3.3 Economic analysis

Using both undiscounted (income ratio and payback period) and discounted (net present value, etc.) economic indicators, Israel et al (1986) compared various prawn hatchery sizes: backyard (<50 t), small-scale (51-100 t), medium-scale (101-500 t), and large-scale (>500 t). Results, that included sensitivity analysis to evaluate effects of risk factors, showed that all hatchery systems are highly profitable with the smaller hatcheries, particularly the backyard hatchery, giving the best performance (Fig. 4).

Among the earlier problems that beset the hatchery industry were massive export of spawners and broodstock to Taiwan (Chiang and Liao 1985), lack of well-trained technicians, improper siting/location, and lack of reliable marketing information, and financing (Primavera 1983; Israel et al. 1986).

34.4 GROWOUT

Prawn farming in the Philippines has progressed from low-density polyculture with milkfish using wild seed, to ever increasing intensities of monoculture using wild or hatchery-reared PL. A number of papers give comprehensive reviews of prawn growout technology in the Philippines (Apud et al. 1983; Apud. 1985; Corre. 1988; Gomes and Cruz 1989).

34.4.1 Culture systems

Prawn growout systems may be classified into four categories; traditional, extensive, semi-intensive and intensive (Table 2). Traditional culture is totally dependent on natural food and tidal water exchange that can support densities of not more than 10,000/ha with yields of up to 500 kg/ha annually. Prawns may be cultured alone or with milkfish. In polyculture, the recommended densities are 4,000-6,000 prawn juveniles + 2,000 milkfish fingerlings/ha (Eldani and Primavera 1981).

Extensive culture uses densities of 10,000 to 30,000 PL/ha and yearly production of 0.6-1.5 MT/ha. It requires occasional supplemental feed in the form of wet, unprocessed materials such as trash fish, bivalves, snails, rice bran, etc.

Semi-intensive culture uses both natural and artificial feed inputs of unprocessed or formulated feed to supplement natural food, and a combination of tidal exchange and pumping. Paddlewheels are used towards harvest time to provide aeration for the high biomass. Stocking rates of 30,000 to 100,000 PL/ha produce 2-6 MT/ha/yr.

Intensive culture uses formulated feeds in the form of dry pellets and brackishwater salinity levels of 15 to 20 ppt. Dissolved oxygen levels above 4 ppm are maintained by regular water pumping and aeration. Stocking ranges

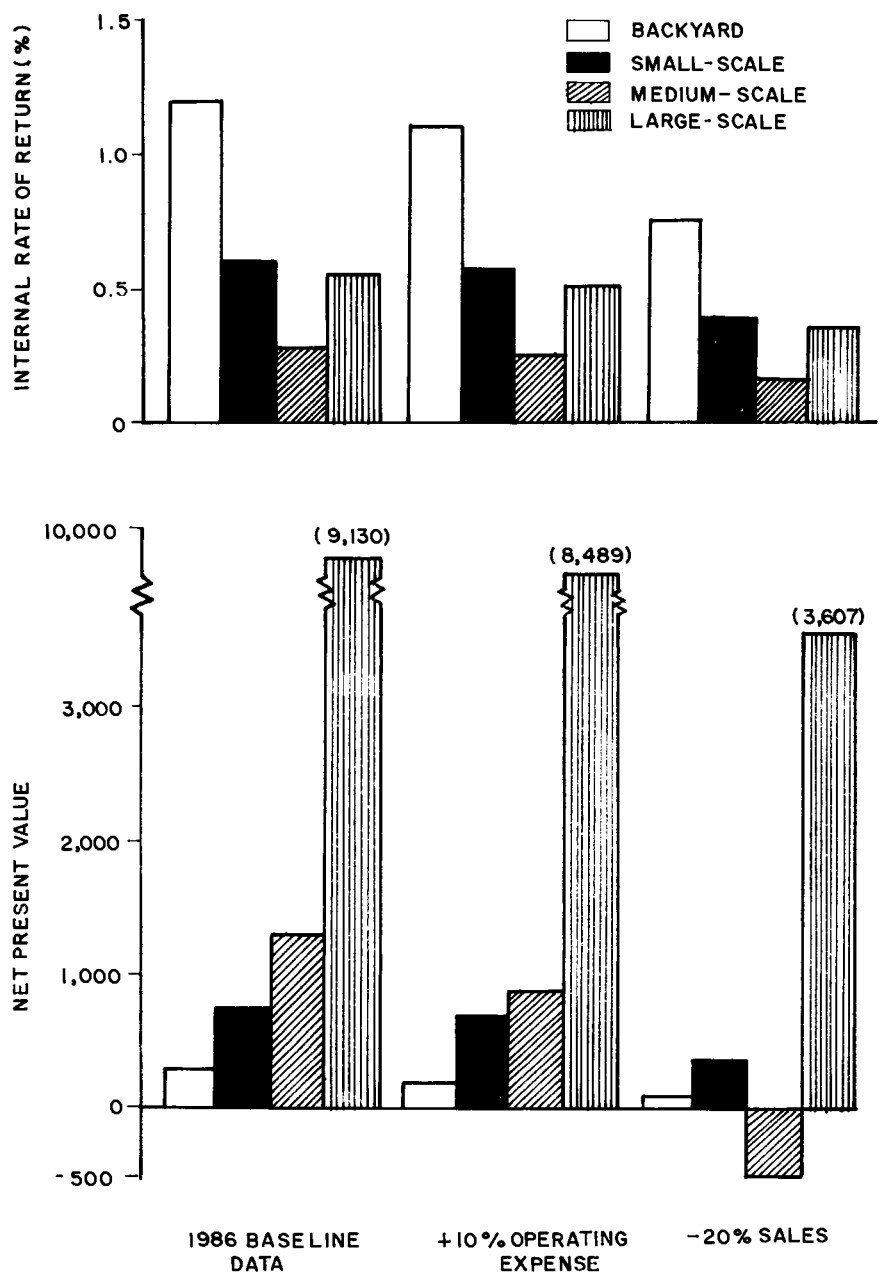


Figure 4. Net present value and internal rate of return for different scales of prawn hatcheries using sensitivity analysis (data from Israel et al. 1986).

Table 2. Different pond farming systems for giant tiger prawn (*Penaeus monodon*) in the Philippines (after Apud et al. 1983; Rabanal 1986; Primavera 1989).

	Traditional	Extensive	Semi-intensive	Intensive
Pond size (ha)	1 - 20	1 - 10	1 - 2	0.1 - 1
Pond depth (m)	0.5 - 1.0	0.5 - 1.0	1.0 - 1.2	1.0 - 1.5
Pond elevation	intertidal	intertidal	intertidal	above high tide
Water management	tidal	tidal, pumping optional	tidal & pumping; aeration	pumping & aeration
Dikes	earthen	earthen	earthen or concrete riprap	concrete riprap or concrete
Stocking density	<1/m ² (milkfish polyculture)	>1-3/m ² (monoculture or polyculture)	>3-10/m ²	10-30/m ²
Fry source	wild	wild or hatchery	hatchery	hatchery
Feed	natural food	natural food & occasional supplemental (unprocessed)	natural food & supplemental (unprocessed or formulated)	artificial feed
Culture period (mo)	4 - 6	4 - 5	3.5 - 4	3.5 - 4
No. crops/year	1.5 - 2	2	2 - 2.5	2 - 2.5
Survival rate (%)	50 - 60	60 - 80	70 - 90	70 - 90
Harvest wt. (g)	40	40	31 - 40	30 - 35
Production (MT/ha/yr)	0.1 - 0.5	0.6 - 1.5	2 - 6	7 - 15

from 100,000 to 300,000 PL/ha, and gives annual yields of 7-15 MT/ha/yr. Some super-intensive farms stock above 300,000 PL/ha.

Of the country's 210,00 ha of brackishwater ponds in 1988, roughly 50,000 ha were stocked with prawns (Primavera 1989). The best estimates available for areas devoted to different categories of culture are; 40,000 ha for traditional and extensive, 6,000 ha for semi-intensive, and 4,000 ha for intensive farms (P. F. Cruz pers. comm.).

34.4.2 Pond design and construction

Because tidal water exchange is commonly used with all but the highest intensity culture systems, low density prawn (and milkfish) culture ponds are constructed within the intertidal zone where bottom elevations are compatible with ordinary tides (see extensive pond chapter this volume).

Intensive ponds require frequent draining and water change because water quality becomes more critical as pond biomass increases. Hence, the prime areas for intensive farms are elevated lands to facilitate draining and drying of pond bottoms, continuous water exchange and complete drain harvests. Other advantages offered by elevated agricultural lands over traditional coastal mangrove areas are a shorter pre-conditioning time due to minimal clearing and less acid-sulfate soil problems, and fewer predators because water can be filtered when pumped (Yap 1989).

Traditional and extensive prawn ponds, which were initially built for milkfish, have irregular outlines and large areas of up to 20 ha (Table 2). For prawn culture, the shallow depth of milkfish ponds (required to grow lablab, a natural food) has to be increased by digging peripheral or diagonal trenches on the pond bottom. For effective pond management at intensive and semi-intensive stocking rates, ponds must be smaller, 0.1 to 2 ha in size.

Other changes in design of milkfish ponds renovated for prawn culture include adoption of a double gate and canal system for separate water entry and drainage, and improved water filtration by installing screens in the water supply gate. Intensive ponds have ferro-concrete or concrete gates, concrete or reinforced dikes, and a central drain.

34.4.3 Pond management

34.4.3.1 Pond preparation

Before stocking a pond with shrimp PL, the pond is prepared to eliminate pests and predators, condition the soil, and propagate natural food. Pests that commonly enter the pond as larvae or eggs during tidal flushing of extensive and semi-intensive ponds include the ten pounder (Elops hawaiiensis), tarpon (Megalops cyprinoides), seabass (Lates calcarifer), Tilapia spp. and gobies (Apud et al. 1983). Pond preparation is also the time for maintenance work; repair of dikes, gates and canals, and reshaping of the pond bottom.

Ponds are completely drained and sun-dried between crops. For intensive and some semi-intensive ponds, the pond bottom may be scraped to remove organic wastes and metabolites, and then tilled to loosen the soil (Young 1987). Teaseed cake is applied at 15 to 25 ppm to kill fish pests. For undrainable portions of traditional and extensive ponds, a combination of lime at 500 to 1,000 kg/ha and ammonium sulfate at 100 to 200 kg/ha is

applied to kill unwanted species (Norfolk et al. 1981). Agricultural lime is applied at 1 MT/ha or more, to adjust soil pH.

Fertilization of intensive ponds, with organic fertilizer at 50 to 100 kg/ha and inorganic fertilizer at 20 to 30 kg/ha is mainly to induce plankton growth for maintenance of good water quality. Low density culture systems that are more dependent on natural food, such as plankton, filamentous algae, aquatic macrophytes Ruppia maritima and Najas graminea; (Primavera and Gacutan 1989), use higher fertilization rates. Organic fertilizer (usually chicken dung) is applied at 1 to 2 MT/ha, while inorganic fertilizer, such as monoammonium phosphate (16-20-0), is applied at 75 to 100 kg/ha, or urea (45-0-0) at 25 to 50 kg/ha. The first application of inorganic fertilizer may be followed up by lower supplemental doses.

Various chemicals and antibiotics may be added to further sterilize intensive ponds (Gomes and Cruz 1989).

34.4.3.2 Stocking

Postlarvae (PL15 to PL25) are stocked in intensive ponds, whereas older juveniles (0.1 to 2 g) are preferred for traditional, extensive and even semi-intensive ponds. Because they are bigger and hardier, juveniles may give a shorter crop cycle time, and higher survival rate in extensive ponds.

This preference for prawn juveniles stimulated a number of nursery studies in tanks (Gabasa 1982), ponds (Cholik 1978; Apud 1979), and net cages (Primavera 1976; dela Pena and Prospero 1985). Ranges of volume/area and stocking rate are 1 to 20 m³ at 1,000 to 5,000 PL/m³ for nursery tanks; 200 to 2,000 m² at 50 to 100 PL/m² for earthen ponds; and 5 to 10 m³ at 2,500 PL/m³ for net cages or hapas. The latter may be installed inside the growout pond or in marine coves. Nursery systems normally use substrates, such as dried palm leaves, bamboo slats, and give supplemental feeding in the form of trash fish, mussel meat or artificial feeds. Body weight of juveniles after 2 to 4 weeks is 0.1 to 0.3 g in tanks, and 0.5 to 2.0 g in ponds and hapas.

Because of the quantities required, intensive and semi-intensive ponds use mainly hatchery-reared seed, whereas traditional and extensive ponds stock seed procured from either hatcheries or wild seed collectors.

If PL are nursed in hapas inside the pond or in adjacent nursery ponds, transfer to growout ponds is direct without any packing or acclimation. Seed from hatcheries or tank nurseries need to be packed, transported and acclimated prior to stocking in the ponds. Counting of fry and salinity adjustment of transport water may be undertaken in the hatchery before packing to minimize stress during stocking.

Some farmers' cooperatives have diagnostic laboratories that check seed quality using morphological and behavioral criteria. Other farmers patronize only "tried-and-true" hatcheries with a track record for producing healthy PL.

34.4.3.3 Water management

Traditional and extensive ponds depend on tidal fluctuation for regular water exchange every two weeks during spring tides. In addition to tidal water exchange, semi-intensive ponds pump water from rivers and other sources during neap tide. With increasing densities and biomass, maintenance of good water quality becomes more critical in intensive ponds. Hence, the need for more frequent pumping, especially during the last two months of rearing.

The salinity range of 15 to 20 ppt preferred for intensive culture is related to the higher potential oxygen absorption rate of brackishwater compared to full strength seawater. *P. monodon*, a euryhaline species, can tolerate a wide salinity range (Ferraris et al. 1986), but does not require low salinity for survival and growth (see Chapter 24). Dilution of pond water to achieve salinities in the range of 15 to 20 ppt is an established practice, although it is not necessarily recommended. When this practice is followed, it is best to decrease salinity by diluting seawater with groundwater pumped from deep wells, rather than river water which may be contaminated by domestic, agricultural or industrial pollution.

Paddlewheel aerators, the most popular type of aerator in the Philippines, are operated in intensive ponds, and some semi-intensive ponds (above 60,000 PL/ha) to increase oxygen levels and prevent thermal and salinity stratification.

34.4.3.4 Feeding

When stocking exceeds 10,000 PL/ha, supplemental feeding is required during growout. Extensive and some semi-intensive ponds use wet, unprocessed feeds such as trash fish, mussel, snails, frogs, chicken entrails, etc. Most semi-intensive and all intensive ponds use formulated feeds in the form of dry pellets because of less pollution, availability, and better handling/storage properties.

Once natural food in the pond is depleted, feeding begins; usually at 1 to 2 weeks after stocking in intensive ponds, and 1 to 2 months in semi-intensive ponds. Feed is given 2 to 5 times/day in semi-intensive and intensive ponds, and less frequently in extensive ponds.

The amount fed daily follows a theoretical feeding regime starting at 15% and declining to 10% of prawn biomass for wet feeds and 10 to 4% for pellets. The theoretical rate is refined by considering actual feed consumption,

physical condition of stock, and prawn biomass. The latter is determined by sampling with a cast net.

Feed consumption and prawn health are monitored by means of feeding trays. These 1 x 1 m bamboo-nylon trays are distributed along the pond periphery at 6 to 10 trays/ha. About 10 to 15% of the daily feeding ration is placed in the trays, with the remainder broadcast directly into the pond.

Monitoring of feed ration is very important, especially for intensive ponds where feeds constitute 60% of operating costs. An acceptable feed conversion ratio is 3:1 to 5:1 for wet feeds and 1.5:1 to 2.0:1 for dry feeds.

Total 1988 supply of prawn growout feeds was 27,390 MT, of which 24,873 MT was produced locally (BAI 1988) by 17 feedmills. However, 80 to 90% of ingredients used in local feeds were imported. Nutritional quality and product consistency vary among brands. More than 20 commercial brands are represented.

A number of studies at SEAFDEC/AQD (Alava and Lim 1983; Bautista 1986; Pascual 1988) have determined optimum levels for growth and survival of *P. monodon* juveniles as 40 to 45% protein, 20 to 25% carbohydrates and 5-10% lipid.

34.4.3.5 Diseases

Diseases are more common in intensive and semi-intensive ponds stocked at >60,000 PL/ha because of crowding, excess feeds and other wastes. Many pond diseases are caused by nutritional and environmental factors, such as soft-shell (low Ca and P, pesticide contamination), blue shrimp (low dietary astaxanthin, poor soil-water quality), cramped tails (temperature shock), red disease (dietary and detrital mycotoxins), and tail rot (see Baticados 1989). Other diseases such as black gill and shell disease are caused by viral, fungal or bacterial pathogens, but may be associated with nutritional and environmental factors.

Among the chemicals used for disease prevention and control in intensive ponds are hydrated lime, teaseed cake, zeolite, formalin, ammonium and copper compounds, microbial inoculants and antibiotics (Gomes and Cruz 1989). Farmers often undertake water change upon detection of disease to induce molting and improve water quality.

34.4.3.6 Harvest and postharvest practices

Harvest is total in intensive and most semi-intensive ponds. Traditional, extensive and some semi-intensive ponds may be harvested partially due to low local demand and/or a wide range in prawn sizes. Partial harvest may be done by bamboo trap, cast net or seine net; total harvest uses a bagnet. After completely draining the pond, about 15 to 20% of prawns remain in the pond bottom and are collected by hand.

In traditional, extensive and semi-intensive ponds, harvest is done 2 to 3 days after spring tide, or 5 days after the last water change to allow time for shells to harden following molting induced by the water change. Similarly, intensive ponds are harvested 4 to 5 days after a sudden water change. For more efficient harvest, the prawns are first stimulated to move around by introducing new water into the pond prior to seining or completely draining the pond.

Harvested prawns are washed, chilled at 10 to 15 C, and packed with alternate layers of crushed ice inside styrofoam boxes for immediate transport to processing plants.

Pricing is either by straight-buy method which uses a single price based on average size of the harvest, or by composite-buy method which takes into account the proportion of different size groupings (Gomes and Cruz 1989).

Undersized, soft-shelled and diseased prawns are bought at lower rates, or rejected outright. Marketable prawn sizes, 25 to 60 g may be attained in 3 to 5 months of growout.

34.4.4 Economics

Comparative economic analyses of giant or black tiger prawn culture in Southeast Asia used both theoretical assumptions (Hirasawa 1985, 1988) and actual data (Israel and Agbayani 1987; Posadas 1988). According to Hirasawa (1988), intensive farming, evaluated on a per kilogram basis, is characterized by low fixed cost because of high productivity per area, but high variable cost mainly for feeds and water quality maintenance. If market prices are favorable, intensive farming remains profitable simply from the sheer production volume of 10 to 17 MT/ha/yr. When prices drop, so does profitability because of the high production or variable cost (Fig. 5). Neither intensive nor extensive systems (less than 300 kg/ha/yr) are profitable when prices drop 20% or more. Only semi-intensive culture will survive because of relatively higher profit margins per unit of production.

Using 1985 data, however, Israel and Agbayani (1987) found that extensive systems (4,000 to 5,000 PL/ha) are more viable than semi-intensive culture of 30,000/ha, when operating costs increase or sales decrease (Table 3). Such economic indicators as net present value and internal rate of return remain higher for the low density systems.

Based on 1987 data, Posadas (1988) found intensive culture (300,000 PL/ha) gave a higher per ha (P537,000), but a lower per kg (P34.12) profit compared to semi-intensive ponds (100,000 PL/ha stocking) with P240,000/ha and P39.72/kg respectively. Moreover, both these systems are more profitable during static market conditions than lower intensity culture systems (10,000 PL/ha and 30,000 PL/ha) in terms of both undiscounted (payback period and average rate of return), and discounted (net present value, internal rate of

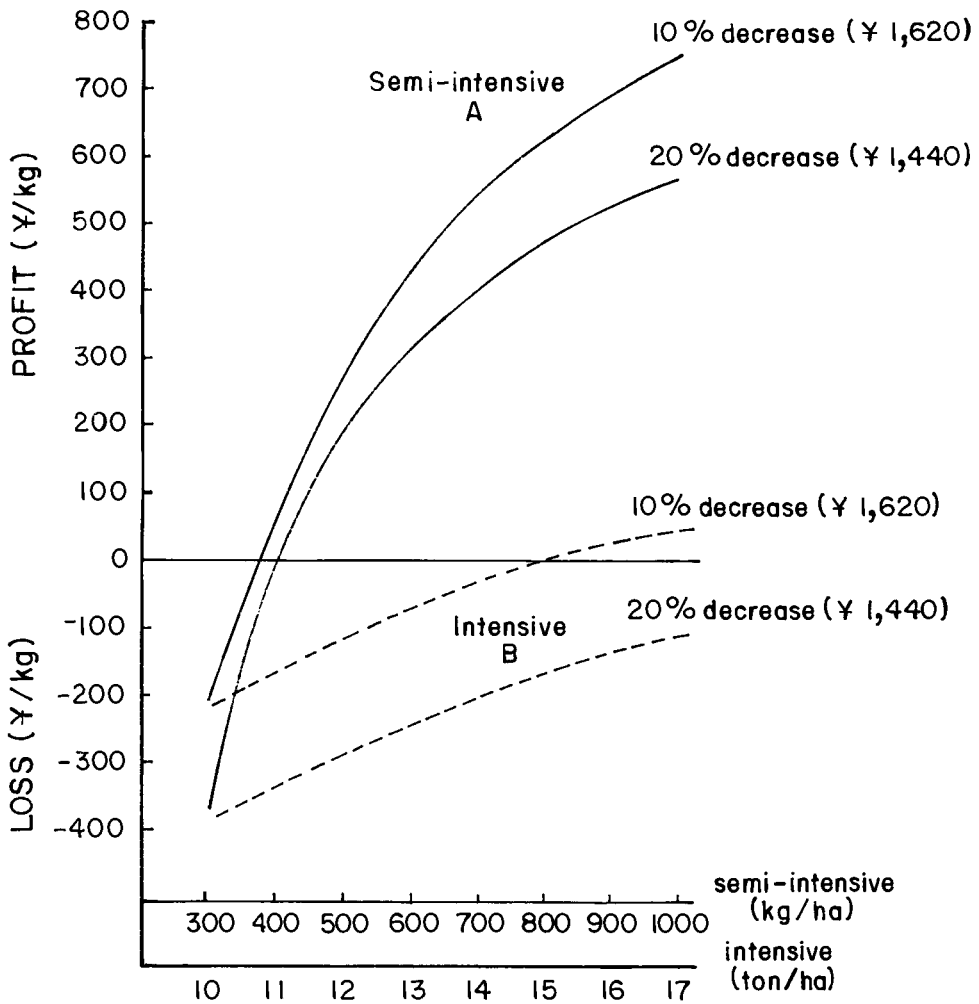


Figure 5. Profit and loss per kilogram given a decrease (by 10% and 20% of present levels) in selling price of black tiger shrimp (Hirasawa 1985).

return) indicators (Table 4). According to this study, only 100,000 PL/ha stocking will remain viable with a 20% fluctuation in sales or costs; higher and lower densities become unprofitable.

Both the studies of Hirasawa (1985, 1988) and Israel and Agbayani (1987) conclude that lower densities (4,000 PL/ha to above 10,000 PL/ha) are more viable than high densities. This contradicts the finding of Posadas (1988) that a 100,000 PL/ha level performs better than lower densities. The seeming contradiction may be traced to Posadas' (1988) assumption that

extensive and modified extensive ponds are built from scratch or are fully depreciated.

In the Philippine setting, these low-density ponds are renovated from existing milkfish ponds so that actual development costs are much less. Observers point out that while traditional and extensive farmers managed to survive the 1989 *P. monodon* price collapse, newly-constructed intensive ponds are unprofitable because of interest payments on development loans in addition to high operating costs. Nevertheless, all the studies agree that systems stocked at densities greater than 100,000 PL/ha are not viable given the fluctuations and risks attendant to the export market.

34.5 PROBLEMS

Prawn farming in the Philippines has produced some ecological and social problems. The industry also has some inherent flaws, brought more sharply into focus by the 1989 price collapse.

34.5.1 Ecological

Most of the country's 210,000 ha of brackishwater ponds were constructed from mangrove swamps. About 60% of the decrease in Philippine mangroves, from about 450,000 ha in 1918 (Brown and Fischer 1920) to only 140,000 ha in 1987 (BFD 1987), can be attributed to pond conversion at the rate of 4,000 ha/yr through the 1950s and 1960s (Fig. 6). A slowdown in pond construction followed the issuance of the 1975 Fisheries Code which placed mangrove areas under public trust.

Table 3. Comparative economic analysis of different *Penaeus monodon* farming systems in 1985 (from Israel and Agbayani 1987).

Stocking density	Net income	<u>Net present value</u>		<u>Internal rate of return</u>	
		+20% oper. costs	-20% sales	+20% oper. costs	-20% sales
5,000/ha	P18,118	<u>Extensive monoculture</u>		0.20	0.04
		9,005	-197,060		
		<u>Extensive polyculture</u>			
4,000/ha + 2,000 milkfish/ha	27,612	200,406	86,063	0.37	0.27
		<u>Semi-intensive monoculture</u>			
30,000/ha	46,620	-261,076	-475,469	0.08	-0.04

US \$1 = P20 (1985)

Table 4. Comparative economic analysis of different Penaeus monodon farming systems in 1987 (from Posadas 1988).

Stocking density	Payback period (yrs.)	Avg. rate of return	<u>Net present value</u> static + 20% sales (P150/kg)costs	<u>Internal Rate of return</u> static + 20% sales (P150/kg)costs
Extensive 10,000/ha	4.59	12.70	186	-376*
Modified Extensive 30,000/ha	2.65	30.17	264	-272*
Semi-intensive 100,000/ha	1.65	56.09	2,340	292
Intensive 300,000/ha	1.95	46.92	4,281	-985*

*Not profitable

But, prawn farming expansion in the 1980s stimulated new pond construction, totalling over 34,000 ha, mostly in mangrove areas. Intensive ponds are excavated on agricultural lands that have the required elevation. Sugar-lands have been particularly vulnerable because of the earlier decline in world prices for sugar, another export crop.

34.5.1.1 Mangrove conversion

The ecological importance of mangroves as a primary energy and nutrient source for adjacent marine ecosystems, as a breeding and nursery ground for many finfish and shellfish species, as a physical buffer providing coastal protection from typhoons and storms, as a soil stabilizer through sediment accumulation, and as a source of food, fuel and a variety of products for local communities is well-documented (Odum and Heald 1975; Saenger et al. 1984). The contribution of mangroves to nearshore and offshore fisheries is supported by studies that show a relationship between mangrove area and marine fishery landings (Martosubroto and Naamin 1977). A positive correlation between Philippine municipal fishery catches and existing mangroves has been documented by Camacho and Bagarinao (1987).

34.5.1.2 Pond wastes

Effluents from intensive ponds and hatcheries, including organic wastes, excess lime and feeds, pesticides, toxic chemicals and disease-carrying microorganisms, dumped into neighboring waterways may harm estuarine and

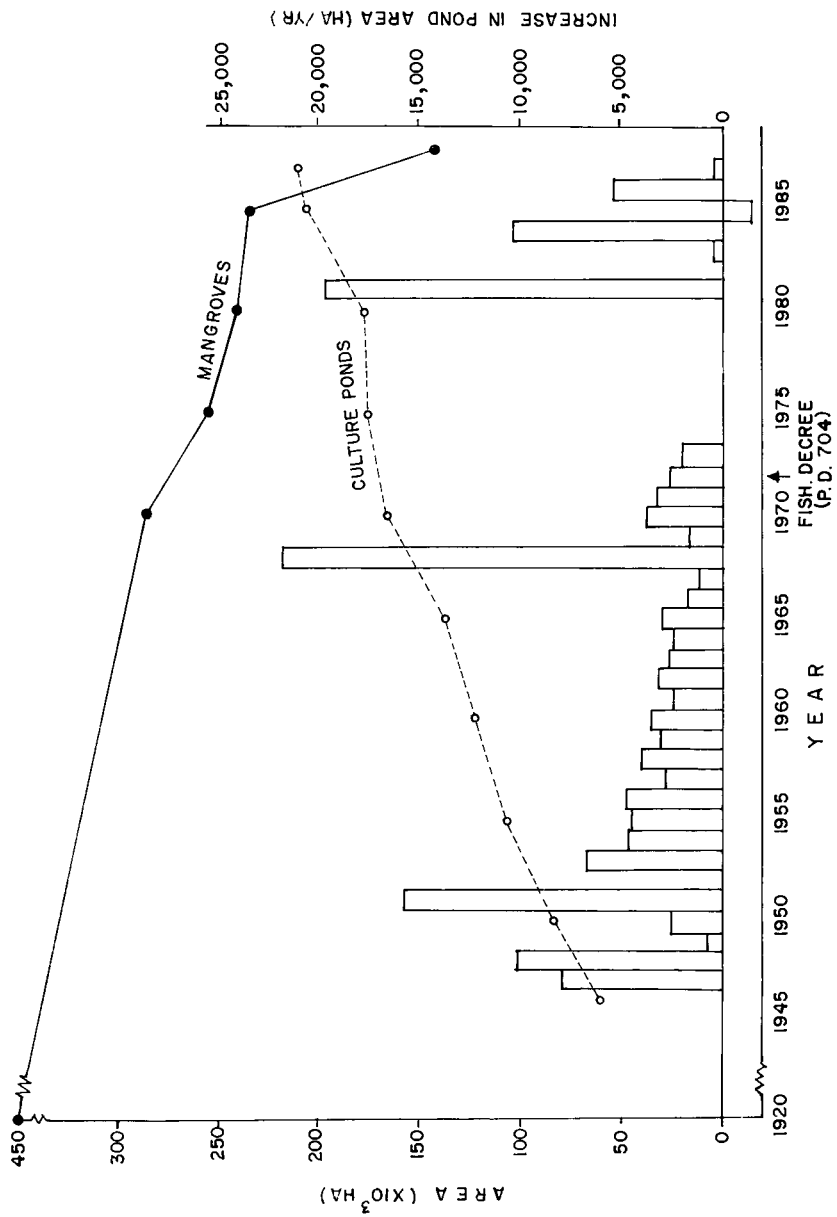


Figure 6. Increase/decrease in mangroves and brackishwater culture ponds in the Philippines. Sources: Brown and Fisher 1970; Bureau of Fisheries and Aquatic Resources; Bureau of Forest Development.

marine organisms. These wastes may also end up in the intake water of adjacent farms and hatcheries. The unmitigated use of antibiotics could produce resistance in bacteria and other pathogens.

34.5.1.3 Groundwater pumping

Massive extractions of groundwater by pumping of aquifers pose a threat to the environment. Subsequent drawdown of the water table may cause drying up, or saltwater contamination of shallow wells and other underground reservoirs. Water level decline and attendant compaction of aquifers may lead to land subsidence. Depressed land becomes more vulnerable to floods.

34.5.1.4 Salinization of water and soil

Rice lands and orchards located near intensive ponds may suffer because of reduced water supply, or from saltwater contamination of groundwater. Agricultural lands converted into intensive farms may undergo irreversible salinization, precluding the future replanting of rice and other land crops.

34.5.2 **Social**

Social costs of prawn farming arise directly from its negative ecological consequences.

34.5.2.1 Marginalization of fishermen

Depletion of coastal fisheries due to mangrove loss and the discharge of prawn culture wastes into adjacent waters marginalizes subsistence fishermen. Moreover, the wide array of economic benefits derived from the mangroves, including food and shoreline erosion control, is no longer available to coastal communities following the decline of mangroves (Mercer and Hamilton 1984).

34.5.2.2 Reduction of water supplies and crops

Shortage of domestic water for household use and the browning of previously green orchards have been reported following the proliferation of intensive farms in Negros Occidental Province (Primavera 1989). Similarly, rice production has been affected by saltwater intrusion into groundwater.

Milkfish production has decreased from a peak of 252,000 MT in 1982, to only 164,000 MT in 1986. Although due mainly to the decline in Laguna Lake pen culture, reduced milkfish production is also attributable to a shift in pond use to the more lucrative prawn crops.

34.5.2.3 Economic benefits

A study of two coastal villages on Panay Island concluded that the economic benefits of prawn farming do not necessarily trickle down to local residents (Amante et al. 1989). On the other hand, data from Region VI

show that 47,183 direct and 363,500 indirect laborers are required at peak operation times in hatcheries, processing plants, feed mills, etc. to support over 8,000 ha of prawn farms (Anon. 1989).

34.5.3 Industry concerns

The crisis besetting the industry in 1989 is mainly related to marketing and financing.

34.5.3.1 Dependence on a single market and species

Because of high prices for black tiger prawn in the Japanese market, Philippine shrimp producers concentrated their attention on this species. During 1988, 90% of cultured shrimp production was P. monodon, while Japan took 80% of the Philippines shrimp exports. The experience of a prawn price collapse in 1979 was forgotten. Warnings from domestic (Primavera 1983) and international (von Eys 1985) experts of an oversupplied Japanese market by 1990 fell on deaf ears. Recommendations on diversification to minimize the impact of these market changes were ignored. Doomsday predictions have come true now that Japanese prawn inventories have reached 125,000 MT in late 1989.

34.5.3.2 High selling price

Philippine export prices are high relative to other countries, as seen from 1986 prices (per kg); Philippines: P188.77, Indonesia: P161.05, Thailand: P188.65, Singapore: P83.79, and Malaysia: P38.94 (FAO 1986). In late 1989, Vietnam was selling to the Japanese market at rock-bottom prices of P60/kg (average for all species) compared to P180/kg for Philippine black tiger prawn.

34.5.3.3 High cost of production

High export prices are needed to support the high production costs, particularly for intensive farms, and high profit margins of some producers. In mid-1989, intensive production cost of Philippine prawns was P100/kg at a time when the farm-gate price Thailand was P80/kg, and P50 to 60/kg in Indonesia. High production costs are related to high feed costs, which constitute 60% of operating costs for intensive farms. In addition, feed costs are increased by high government tariffs and high profit margins of feed companies. Until recently, imported prawn feeds and feed ingredients were taxed 30% and 10% respectively.

34.5.3.4 High interest rates, scarce capital

Financing for prawn ventures belatedly came in the mid-1980s when banks started to open aquaculture "windows." Some government loans were

made available through the Technology Resource Center, the Guarantee Fund for Small and Medium Enterprises, and the Comprehensive Agricultural Loan Fund. But the high cost of money, commercial interest rates of 18 to 22% in the Philippines compared to only 7.5% for Malaysia, encouraged only intensive farmers who planned on high yields to pay off their loans. Even soft loans from foreign-financed projects had rates effectively raised to 16%, because of re-discounting privileges.

Intensive prawn projects with a total loan exposure of P1 billion have been hardest hit by the 1989 slump in prices. Production costs of P85 to 90/kg increase to P105 to 110/kg when the cost of money is added.

34.5.3.5 Technical background

Lured by the promise of great profits, many investors have rushed into prawn culture without knowing the first thing about prawn farming. Sugar planters with their backs to the wall, and with nothing to lose as a result of declining sugar prices in the early 1980s, eagerly converted their haciendas to prawn culture, the so-called "sunshine" industry.

34.6 RECOMENDATIONS

For the Philippine prawn industry to survive the pending downward trend in shrimp prices, both the government and private sector have to take immediate action to improve cost-efficiency, lower feed tariffs, and set up trade missions for market diversification. To sustain the industry, the government should focus on resource management. Target areas for prawn/milkfish culture should be identified, and rational regulations on mangrove use developed. Groundwater and seawater use must be regulated and their pollution prevented. Wild stocks of prawns must be protected. This will require enforcement of existing laws, promulgation of new legislation, and a continued research and technology dissemination effort.

34.6.1 **Shift to lower densities**

For reasons of economic viability and ecological soundness already discussed, low-density and intermediate prawn culture systems are preferred over intensive culture. Intertidal ponds have the flexibility to use extensive or semi-intensive techniques. Because of enormous operating costs, elevated, intensive ponds cannot afford to stock prawns at lower densities nor shift to low-priced milkfish. They can not revert to agricultural crops because of irreversible salinization. Nevertheless, some intensive farms can decrease stocking rates to 100,000 PL/ha and improve cost-efficiency to remain profitable.

34.6.2 Improve cost-effectiveness

Feed cost can be lowered if feed companies reduce profit margins, or government tariffs are decreased. Farmers can also form cooperatives to share construction costs, to obtain bulk discounts from suppliers, to seek government incentives on importation, and to negotiate prices directly with foreign buyers. Once cost-efficiency is attained, local farmers can lower their selling price and become more competitive with other Asian producers.

34.6.3 Government support

The lowering of tariffs for feed ingredients (from 30% to zero) and other materials and equipment imported by the industry will help improve cost-efficiency. Also, the importation of foreign feeds should be carefully regulated because of the risk of aflatoxin and oxidative rancidity during transport and storage.

Government subsidies should be provided through soft loans with low interest rates for low-density prawn culture and small-scale hatcheries to provide badly needed capital. The government could offer other incentives similar to the investment tax allowance, agriculture tax allowance, and export allowance enjoyed by Malaysian prawn growers and exporters.

Construction of roads, power lines and other infrastructure in major prawn culture areas would also help farmers.

34.6.4 Diversification and marketing

The time is overdue for producers to develop new markets, including domestic markets, and to be willing to sacrifice profit margins, in exchange for the long-term stability and viability of the industry. The American market is particularly promising because of the more than one million Filipinos currently residing in the U.S. Prawn exporters should also set their sights on the coming unification of the European market in 1992.

To aid entry to new markets, the prawn industry should develop a data base which would contain the species and product forms, etc. preferred by a given market. The European market, for example, is characterized by a strong retail trade of restaurant and hotel outlets, and has policies that protect European producers of coldwater prawns.

Trade missions composed of industry and government representatives should be fielded with support from agricultural and commercial attaches abroad. Opening new markets will also mean educational campaigns, food fairs and other promotional strategies following the classic example of the 1975 black tiger prawn introduction to Japanese cuisine.

In conjunction with opening of new markets, there should be diversification to other shrimp and seafoods, such as the white shrimps (P. indicus and P. merguensis), and high value finfish like seabass and grouper.

34.6.5 Culture area and mangrove utilization

Since exploited mangroves already represent more than 50% of the original 450,000 ha in the country, there is a need to enforce existing laws to prevent additional conversion. At the same time, research should be undertaken to determine the minimum area of total mangroves (whether 10% or 50%) needed to sustain nearshore and offshore fisheries yields. If the remaining 140,000 ha of mangroves is below this minimum, an active reforestation program should be initiated.

Realistic national prawn production targets, considering both the absorbing capacity of our export markets and the production capacity of other countries, should be established to prevent a repeat of the 1989 price collapse. To the extent it is feasible, the formation of a prawn cartel would protect producing countries against price manipulation. In spite of the decreased 1989 prices to farmers for prawn, Japanese retail prices have reportedly not decreased.

The rationalization of a food (milkfish) crop:cash (prawn) crop ratio for brackishwater pond area in the country should also be considered. Food sufficiency should not be sacrificed in the pursuit of foreign exchange earnings. Area for cultivation required to attain this national prawn production target, could then be determined. For example, to produce 50,000 to 125,000 MT of prawns, only 25,000 ha of semi-intensive farms (12% of total pond area) or a combined 50,000 ha of extensive and semi-intensive farms (50% of total hectareage) is needed.

34.6.6 Groundwater and seawater utilization

Legislation on the use of groundwater and seawater is necessary to minimize the ecological and social effects of intensive farming. Groundwater drawn for commercial purposes should be regulated by limiting the pumped volume, and levying taxes commensurate to the cost of alternative public water supplies to reflect the true economic value of water. Others believe groundwater is too limited and valuable a resource to be used for prawn farming. Full strength seawater can support prawn densities up to 100,000 PL/ha provided oxygen levels are maintained by frequent water exchange and/or mechanical aeration.

Wastewater from intensive ponds should be cleansed of wastes before draining in order to protect nearby estuaries and other prawn farms located downstream. Farmers who undertake measures to cleanse pond water before flushing should be offered tax incentives.

34.6.7 Protection of wild stocks

There is a need to conserve wild stocks of P. monodon because these support hatcheries, through wild spawners or wild broodstock, and wild seed

collectors. Aside from closed fishing seasons for fry and spawners based on the population dynamics of the species, artificial re-seeding of juveniles in the sea can help replenish natural populations. The Japanese have successfully used this approach with a variety of marine species, including prawns.

Another way of protecting wild stocks is to implement a ban on importations of exotic species, and careful monitoring of aquatic animals whose entry is allowed for experimental purposes. The entry of diseases through infected animals or contaminated water could endanger P. monodon and other native species.

34.6.8 Research, training and extension

Although the technology for P. monodon hatchery and growout is already available (BRAIS 1988), it needs further refinement and dissemination so farmers can improve cost-efficiency. Training and extension programs such as those offered by the SEAFDEC/AQD and some private companies should be continued.

It is in the hatchery, and growout of alternative species that research efforts are still needed. SEAFDEC/AQD, MSU-IFRD and other research institutions should continue experimental work on the white shrimps P. indicus and P. merguensis. Already, a few Luzon hatcheries are trying to produce white shrimp fry.

34.7 CONCLUSION

Beyond weathering the present crisis, the Philippine prawn industry should aim for long-term sustainability. The attainment of this goal will require improvements in low-intensity and medium intensity culture systems, and the cooperation of government, private sector and academe.

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CHAPTER 35

Vu Do Quynh

SHRIMP CULTURE INDUSTRY IN VIETNAM

35.1 INTRODUCTION

The word for "country" in Vietnamese is "Dat Nuoc", which literally means earth and water. That illustrates the importance of water and its products in the everyday life of Vietnamese people. Earth and water make up ricefields which produce the cereal without which no meal could taste very good to a Vietnamese palate. The ricefields also constitute small pond ecosystems in which many aquatic organisms can thrive and develop, some with economic value. This may be one reason why aquaculture, at least in its most primitive form, is a traditional practice in Viet Nam and in all Asia.

Freshwater aquaculture was well developed throughout Viet Nam for centuries, especially in the two main opposite deltas where vast plains occur. Coastal aquaculture, and shrimp culture in particular, developed impressively after 1975. This development occurred because fishery yields decreased, and attention focused on the potentials of brackishwater culture in coastal areas. This development also provided a major source of foreign currencies income for Viet Nam.

Geographically, Viet Nam extends more than 1600 km between latitude 8.5° and 23.5° N, with 3200 km of coastline. Figure 1 shows the different coastal provinces of the three regions of Viet Nam and the Mekong Delta. The notations in the figure are as follows: Northern Viet Nam- QN (Quang Ninh), HP (Hai Phong), TB (Thai Binh), HN (Ha Nam Ninh), THO (Thanh Hoa), NT (Nghe Tinh); Central Viet Nam- BTT (Binh Tri Thien), QN-DN (Quang Nam-Da Nang)NB (Nghia Binh), PK (Phu Khanh), THI (Thuan Hai); Southern Viet Nam- DN (Dong Nai), VT-CD (Vung Tau-Con Dao), LA (Long An), TG (Tien Giang), BT (Ben Tre), DT (Dong Thap), CL (Cuu Long), AG (An Giang), HG (Hau Giang), KG (Kien Giang), MH (Minh Hai). Geographical and climatic diversity divide the country into several areas with different aquaculture conditions. Before reviewing Vietnamese shrimp culture; it would be useful to review environmental conditions with respect to aquaculture.

35.2 GEOGRAPHICAL AND PHYSICAL CONDITIONS

The main geographical features of Viet Nam can be summarized as follows :

- Two major deltaic plains; that of the Red and Thai Binh rivers in the North, and that of the Mekong River in the South.
- A mountain chain, The Truong Son Cordillera, extending from Northwest to Southeast somewhat parallel to the coast, but coming closer to the sea in the south. The mountains have several transverse seaward extensions, resulting in a succession of short, and narrow coastal plains along central Viet Nam.

35.2.1 Climate

Viet Nam lies entirely within the intertropical zone, and its climate is governed by a monsoonal regime. The NE monsoonal begins during September in North Viet Nam and during in November-December in South Viet Nam. It lasts until March of the next year (Nguyen Ngoc Thuy 1978). In North Viet Nam, cold, dry continental air masses coming from central Asia

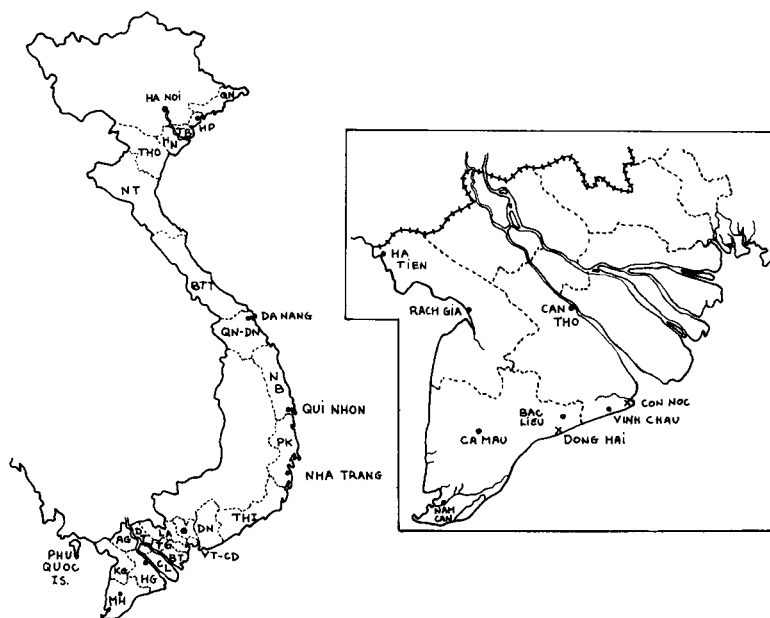


Figure 1. Map of the coastal provinces of the northern, central and southern regions of Vietnam and the Mekong Delta (in box).

with NE monsoons result in cool air temperatures, often less than 10 °C in January and February. Consequently, water temperatures in shallow coastal areas of Thanh Hoa Province are often in the range of 14 to 16 °C in January (Nguyen Anh Tao et al. 1964), while mean temperatures are generally 23 °C during December to February (Tran Huu Phuong 1974 ; Khuc Ngoc Cam 1988). These cold air masses become progressively warmer as they move southward and are interrupted by a transverse mountain ridge north of Da Nang City. South of the 16th parallel, NE winds are more warm and humid from contact with the South China Sea and the Pacific Ocean. The climate is warmer in the south with more limited seasonal temperature fluctuations. At Nha Trang mean water temperature during January-February is about 24 °C (Tran Ngoc Loi 1963). The South China Sea south of 10°N has water temperatures above 27 °C. In shallow coastal ponds and concrete tanks, however, water temperature is influenced more by the diurnal and seasonal changes in air temperature, and may be much colder or warmer than the open sea. Water temperatures increase gradually and reach maximum values by May.

The SW monsoon starts in May-June and lasts until September or December (Nguyen Ngoc Thuy 1978). Water temperatures are usually 28 to 30 °C throughout Viet Nam at that time. In shallow water areas and it can even reach 32 to 33 °C even in North Viet Nam (Nguyen Anh Tao et al. 1964). With the return of the NE monsoon, water temperatures decrease.

35.2.2 Rainfall and Typhoons

The NE and SW monsoons are equivalent to dry and rainy seasons, respectively. In North Viet Nam, the rainy season is from May and through October, with maximum monthly precipitation in August and September and of 300 mm/mo. in coastal areas (Khuc Ngoc Cam 1988). This also coincides with periods of high river run off and of flooding risks. Salinities in some coastal ponds near estuaries can decrease to almost freshwater.

In Southern Viet Nam, rainfall differences between dry and rainy season are more accentuated, with about 90% of the total yearly rainfall occurring during the rainy season (Pham Ngoc Toan 1983). Rain usually starts in late April with a gradual increase in monthly precipitation until a maximum is reached in July to October. During the dry season, evaporation exceeds precipitations and many saltfields are found in coastal areas from Vung Tau to Bac Lieu. There, precipitation is minimal in the Mekong Delta with 1500 mm/year. In other areas of the Delta, especially on the Gulf of Thailand side, precipitation ranges from 2000 to 2500 mm/year.

Typhoons are also a regular feature of Viet Nam's climate and are characterized by strong winds and rain. They originate in the western Pacific Ocean, or from the South China Sea. Their direction is determined by the

low pressure center on land. The center is located in North Viet Nam during June-July, and gradually migrates southward in August. Heavy rainfall accompanying typhoons can cause severe flooding in coastal plains of central Viet Nam. This has to be kept in mind when designing and selecting pond construction sites.

35.2.3 River Systems

The main rivers of Viet Nam are the Red and the Mekong rivers. Their lower basins result in two vast alluvial plains. In the North, the Red and Thai Binh rivers basins combined are of 14,700 km². The Red River flow ranges from 1,000 m³/s in January to 13,000 m³/s in July (Guilcher 1965). The waters are very turbid with 1,000 g/m³ of sediment (Nguyen Viet Pho 1983). About 80,000 m³ or 100 million MT of sediments are carried to the sea by the Red River every year (Nguyen Ngoc Thuy 1984).

On the central Viet Nam coast, with mountainous terrain, rivers have short courses and are often torrential. Here maximum flows coincide with rainfall peaks in October-November.

Southern Viet Nam's lower Mekong basin has 36,000 km², while the whole Mekong River basin has 70,000 km². The Mekong River's annual discharge averages 14,800 m³/s, with a 40,000 to 50,000 m³/s maximum in September (Denecke 1984). Water turbidities are lower than with the Red River, with 50 to 300g/m³; but 70 to 100 million MT of sediment are transported to the sea every year. As a result, land is accruing in the sea at 200 ha/yr.; especially in the extreme south at Cape Ca Mau (Nguyen Viet Pho 1983). The Mekong Delta is very flat and is crossed by an extensive network of canals and rivers of nearly 5,000 km in length. The influence of tides can be observed very far from the sea, up to 200 km inland (Nguyen Ngoc Thuy 1984). Indeed, 80% of the delta can be considered a tidal flat (Denecke 1984).

35.2.4 Tidal Regime

Several types of tides exist in Viet Nam due to the long and varied coastline (Nguyen Ngoc Thuy 1984). In the north, mostly diurnal tides occur with maximal amplitude of 2.6 to 3.9 m, decreasing to 1.2 to 2.5 m south of Thanh Hoa Province. In central Viet Nam, semi-diurnal tides occur in the northern part with limited amplitude of 0.4 to 1.2m. South of Da Nang City, diurnal tides reappear with a 1.2 to 2.0 m range. In South Viet Nam, semi-diurnal tides with 2.0 to 3.5 m ranges occur on the South China Sea side, from Vung Tau to the Cape Ca Mau; while diurnal tides of < 1.0 m predominate on the Gulf of Thailand side.

Table 1. Marine fishery statistics in 1984 for some coastal provinces of Viet Nam and in 1986 for the Red River Delta (includes three provinces, Hai Phong, Thai Binh, Ha Nam Ninh and the Yen Hung district from Quang Ninh Province).

Region	Province	Yield in metric tons	
		Total	Shrimps
North	Red River Delta	23,500	850
Centre	Binh tri Thien	20,000	
	Nghia Binh	32,000	
	Phu Khanh	40,000	
	Thuan Hai	167,000	
South	Minh Hai	90,000	15,000
	Kien Giang	78,000	950

Sources: Ministry of Aquatic Products (1988) for the Red River Delta and Anonymous (1986) for other provinces.

35.2.5 The Mangroves

Environmental and climatic conditions are very favorable for mangrove development. Total mangrove forests area is estimated at 409,000 ha, with 329,000 ha in the South (Le Cong Khanh 1986). During first half of the 20th Century, the Mekong Delta alone had 250,000 ha of mangroves, but war activities, defoliation, and uncontrolled exploitation have drastically reduced this area. Although reforestation has begun mangrove area in the Mekong Delta was estimated at only 98,114 ha in 1986 (State Committee for Science and Technology 1986). Of this, 67,426 ha were found in the Ca Mau Peninsula (Minh Hai Province). The peninsula occupies about 10,000 km², and has a vast network of canals which communicate with both the Gulf of Thailand and the South China Sea. During flood tides, water flows from the South China Sea towards the Gulf of Thailand, while the reverse occurs during ebb tides. Freshwater discharge from large rivers is lacking, and results in relatively high salinity (minimum around 20 ppt), with little seasonal variation. That creates favorable ecological conditions for many marine species and accounts in part Minh Hai Province's privileged place with regards to fishery and shrimp aquaculture yields. Fishery yields are generally much higher in Southern Viet Nam, than in the North. Waters offshore from the Mekong Delta account for 60% of the exploitable stock for Viet Nam. Table 1 shows annual yields from some coastal provinces. Shrimp yields are the highest in waters off the Minh Hai Province, and many shrimp trawlers from the North and centre fish there.

35.3 SHRIMP SPECIES: COMPOSITION AND DISTRIBUTION

About 65 penaeid species are found in Viet Nam waters (Bui Dinh Chung 1988). Three genera are most important for fisheries: Penaeus, Metapenaeus, and Parapenaeopsis. In coastal areas P. merguiensis and M. ensis are particularly common and abundant throughout Viet Nam.

Penaeid shrimps from the Tonkin Gulf and coastal waters of North Viet Nam were studied by Nguyen Van Chung (1971) and Tran Huu Phuong (1973) who found about 50 penaeids species. In brackishwaters, the most common species were P. merguiensis, P. orientalis, P. penicillatus, P. indicus, M. ensis, and M. joyneri. Penaeus japonicus is occasionally caught in coastal ponds. According to Vu Hai Son and Ha Quang Hien (1971), M. ensis represents the bulk of shrimp catches (up to 70%) in brackishwater ponds from Quang Ninh Province, North of Hai Phong City. Some carid shrimps are also abundant, particularly Macrobrachium nipponense and Palaemon carinicauda which constituted 10 to 40% of total shrimp harvests in coastal ponds (Nguyen Anh Tao et al. 1964) (Vu Hai Son and Ha Quang Hien 1971).

In central Viet Nam, besides P. merguiensis and M. ensis, P. monodon is widely distributed but is scarce in brackishwater, coastal lagunas, and bays of Phu Khanh Province. P. semisulcatus is also found, but is more restricted to high salinity waterbodies (Ho The An 1988). Other economical important species include P. latisulcatus.

In South Viet Nam, P. indicus and P. merguiensis account for 20 to 40% of shrimp catches (Pham Ngoc Dang 1987). P. monodon is now seldom caught, but was reportedly quite common at one time (Gruvel 1925). Metapenaeus ensis is more abundant during the dry season than during the wet one when other Metapenaeus species become conspicuous, such as M. affinis, M. brevicornis, M. malaccensis and M. lysianassa (Nguyen Huu Tri 1985, Nguyen Cong Con 1986). Other penaeid species include Parapenaeopsis sculptilis and P. hardwickii (Nguyen Thanh Su 1985). Carid species include many Macrobrachium species, particularly M. lanchesteri which is widely represented in brackishwaters of Ca Mau peninsula (Bui Thi Lang 1987). Exopalaemon styliferus is commonly encountered in reservoir and evaporation ponds of coastal saltfarms (Nguyen Van Thuong, 1987a,b). On the Gulf of Thailand's coast P. monodon and P. semisulcatus are relatively more abundant around Phu Quoc Island (Pham Van Dang 1987).

35.4 TRADITIONAL AND EXTENSIVE AQUACULTURE

Traditional coastal aquaculture in Viet Nam was conducted in a very primitive way, and could be considered more of a fishery. In fact, shrimp

production in Viet Nam was reported with the fishery sector until 1982 (Anonymous 1988). Traditional aquaculture is basically an extensive, polyculture system relying almost entirely on natural sources of seeds and food.

Coastal aquaculture activities were greatly reduced during the periods of the two Indochina wars; although some development occurred during the brief inter-war period of 1954 to 1964. Shrimp aquaculture has mainly developed since 1982. To increase yields, various improvements to traditional and primitive techniques were made, including diversified fish/shrimp/crop systems, and shrimp and prawn culture in ricefield peripheral ditches. Very recently, semi-intensive and intensive culture techniques were used.

35.4.1 Status and Development

Before 1975, brackishwater pond area for growing fish and shrimp was about 15,000 ha in North Viet Nam (Vu Hai Son and Ha Quang Hien 1971) and about 70,000 ha in South Viet Nam (Ling 1973; Rabanal 1974).

Since 1982, brackishwater culture area has steadily increased year by year especially in South Viet Nam (Fig. 2). In 1986, total pond area was 124,600 ha, with 107,400 ha in the South, compared with 8,500 and 6,500 ha in North and centred Viet Nam respectively (Bui Dinh Chung 1988). The above data probably includes areas for giant freshwater prawn (*Macrobrachium rosenbergii*) culture. These areas are mainly located in the Mekong Delta, and are only one-third those under brackish and marine shrimp culture.

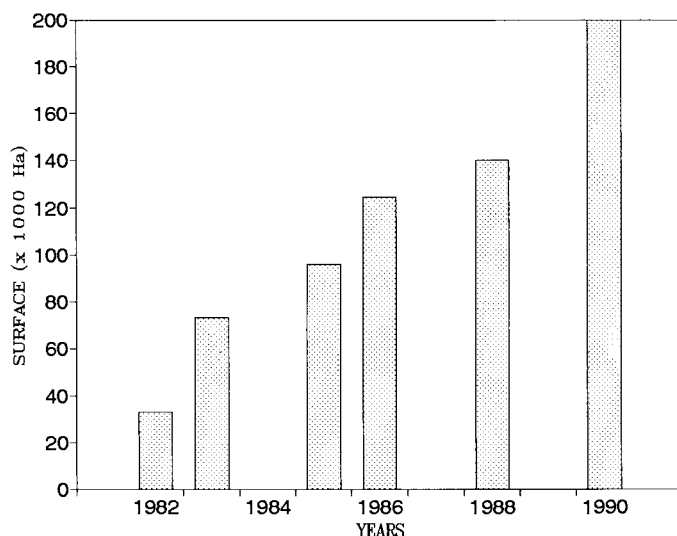


Figure 2. Evolution of aquaculture pond area in Viet Nam from 1982 to 1986. Data for 1988 and 1990 are projections from the Ministry of Aquatic Products (1987).

Table 2. Shrimp and prawn aquaculture production in Vietnam (1986).

Region	Culture area (ha)	Production (MT)	Mean Productivity (kg/ha/year)
North	8,500	540	56-60
Centre	6,700	600	100
South	107,400	22,660	190-200
Total	124,600	23,800	

Source: Bui Dinh Chung, 1988.

Aquaculture is particularly well developed in Minh Hai Province with 40,000 ha of ponds in 1987. Nam Can district (actual name is Ngoc Hien) is famous in all the country for the productivity of its fisheries which annually yield 6 to 8 thousand MT of shrimps, or 20% of the total shrimp landings for all of Viet Nam. This is due to the favorable natural conditions (temperature and salinity), and to mangrove forests abundance. To increase shrimp yields, shrimp pond area was increased from 6,700 ha in 1983, to 15,000 ha in 1986 (Ha Xuan Thong 1988). According to other sources, shrimp pond area increased to 30,000 ha by 1988. There were about 90,000 ha of mangroves in Nam Can in 1975, but uncontrolled wood exploitation and hasty construction of very large extensive ponds decreased mangrove area to 60,000 ha in 1988.

35.4.2 Yields

With primitive techniques, without predator control or stocking, yields are typically low. Productivity, however, increases from north to south as a result of more favorable environments. Bui Dinh Chung (1988) lists mean productivities and shrimp yields by regions (Table 2).

Mean productivities are also negatively correlated with pond size. Mai Van Cu (1988) reported that 5 to 10 ha ponds yielded about 500 kg/ha/yr (in Minh Hai province), while large ponds above 100 ha, had productivities as low as 30 kg/ha/yr. Such low productivities can be imputed to management problems with large ponds, and also to the fact that a significant part of the ponds were seldom covered by water. In fact, except for ditches, most ponds had little water depth. Nguyen Van Be (1988) found in one 35 ha extensive pond in Minh Hai Province only 49% of the pond was covered by 40 cm of water or more. Productivity in that pond still averaged 364 kg shrimps/ha/yr during on 8 year period.

Table 3. Plans for development of different types of coastal marine shrimp and freshwater prawn culture in Viet Nam by 1990.

		Region		
		North	Centre	South
Targeted Species:		Nov.-Mar.:		
		<u>P. orientalis</u>	<u>P. monodon</u>	<u>P. merguensis</u>
		Apr.-Nov.:		<u>P. indicus</u>
		<u>P. merguensis</u>		<u>M. rosenbergii</u>
Type of Aquaculture	Planned Yields (Kg/ha/yr)	Pond Areas (ha)		
Traditional polyculture	50-100	12,500	1,880	85,930
Traditional improved	200	10,000	3,650	66,070
Semi-intensive	500	1,770	2,600	10,615
Intensive	100	730	870	3,385
TOTAL		25,000	9,000	166,000

35.4.3 Potential

Potential brackishwater pond culture area for South Viet Nam only was estimated at about 600,000 ha by Ling (1973) and Rabanal (1974). In the Mekong Delta, there are also extensive saline soils areas of 1 to 1.6 million ha (Akbas and Ponnampuruma 1982; Vo Tong Xuan 1986). These lands necessitate special management for profitable use in agriculture. A majority of them are acid-sulfate soils. Vo Tong Xuan (1987) estimated, however, that about 159,000 ha of these lands could be used for integrated shrimp/fish/crops, such as salt/shrimp, rice/shrimp, coconut/shrimp, forest/shrimp, etc.

More recently, the Ministry of Aquatic Products estimated the total potential area for marine and brackishwater shrimp culture at 300,000 ha (Vo Van Trac 1988; Bui Dinh Chung 1988). According to the characteristics of each region, the Ministry of Aquatic Products (1987) established the guidelines for shrimp culture development until the year 1990 (Table 3). If enough capital is invested, a total of 200,000 ha of aquaculture ponds could be developed in Viet Nam. The above data do not include high-yield, intensive culture ponds recently developed in central Viet Nam.

Traditional polyculture in the South includes mixed/integrated culture systems. Potential development of shrimp and prawn culture in coastal provinces for 1990 are shown in Table 4.

Table 4. Potential areas of shrimp/prawn ponds which could be operating in 1990 for the different coastal provinces of Viet Nam.

North	(ha)	Centre	(ha)	South	(ha)
Quang Ninh	14,000	Phu Khanh	2,500	Minh Hai ^a	40,000
Ha Nam Ninh	6,000	Binh Tri Thien	2,200	Hau Giang	25,000
Hai Phong	2,000	Nghia Binh	2,100	HCM City ^b	21,500
Thai Binh	1,000	QN-Da Nang	1,500	Kien Giang ^a	19,000
Thanh Hoa	1,000	Thuan Hai	700	Cuu Long	17,250
Nghe Tinh	1,000			Ben Tre	12,500
				Dong Thap ^c	10,150
				Long An	5,600
				Tien Giang	5,500
				Dong Nai	5,000
				An Giang ^c	3,000
				Vung Tau-CD	1,300
				Song Be	200
Total	25,000		9,000		166,000

Notes: a: mainly concerned with brackishwater shrimp culture.

b: Ho Chi Minh City includes Duyen Hai District (mangroves).

c: only concerned with freshwater prawn farming.

Source: Ministry of Aquatic Products, 1987.

35.4.4 Mixed-culture Systems

35.4.4.1 Fish/ shrimp polyculture

Fish and shrimp extensive polyculture is obligatory with the existing techniques of trapping wild seed. Mugilid and Tilapia fishes are the most common in brackishwater ponds of Viet Nam. Especially in North Viet Nam, however, supplementary fish stocking is made with Tilapia. Grass carp fingerlings produced from hatcheries are also stocked in ponds of low salinity. Average yields are about 153 kg/ha/yr, of which about 55 kg are shrimps. Productivity is higher in smaller ponds (Mai Van Cu 1980).

In central Viet Nam, milkfish (Chanos chanos) culture is traditional (Ling 1973). People actively collect milkfish fry for culturing. Reservoir ponds and some evaporation ponds on salt farms are often used for extensive polyculture of milkfish and shrimps during the rainy season; but more and more people are switching to shrimp monoculture.

In South Viet Nam, mugilid fishes thrive in mangrove areas and coastal swamps. In extensive ponds, small mud gobies are also a major component of the crop some times of year.

35.4.4.2 Salt-shrimp culture

Salt production occurs during the dry season; with different techniques from north to south. In central and south Viet Nam, classical solar salt production occurs. During the wet season, water in the evaporation ponds becomes diluted and extensive polyculture can take place with tidal waters freely circulating. Such practices are particularly well developed from Vinh Chau to Bac Lieu (Nguyen Van Vien 1980). In that area, there are thousands of ha of mangrove swamps extending from the Mekong estuary southward to Cape Ca Mau. During the 1950's, that area was a tidal flat covered by mangrove trees, mainly Avicennia spp. Traditional polyculture was used but the land elevation gradually increased due to the high sediment deposition from the Mekong River's discharges. In 1967-1968, more salt ponds appeared as an extension of the salt industry which has flourished in the Bac Lieu area since colonial times. People took advantage of the alternate dry and a wet seasons to develop a two-crop system of salt during the dry season and of shrimp/fish during the wet season.

35.4.4.3 Rice-shrimp culture

Large areas of the Mekong Delta can only produce one rice crop a year, during the rainy season. During the dry season, however, the land must not be allowed to dry because of soil acidity problems. Some farmers found that flooding rice fields with saline water during the dry period did not affect rice yields. In addition, they could harvest a substantial amount of shrimp. This practice became popular mainly in Hau Giang and Minh Hai provinces (Vo Tong Xuan et al. 1986).

Trieu Xuan Ut (1988) a rice-shrimp farmer of the Hau Giang Province reported his experience. His farm was 3.4 ha, of which 3 ha was suitable for shrimp culture. It was located on a canal of the My Thanh River, about 30 km from the estuary. Water salinity was about 18 to 20 ppt from January to June, but low enough to allow rice culture during the rainy season. Since 1982-1983, that farmer decided to introduce shrimp culture during the dry season. Mean yields were 170 kg/ha in 1985, and increased to 350 kg/ha in 1986. The shrimp/prawn catch was composed of Macrobrachium (17 to 20% of total), and P. merguensis/P. indicus (20 to 25% of total). His total income was more than double that with rice cropping only.

During the rainy season, a secondary shrimp crop, was also harvested from the ditch surrounding the elevated ground where rice is grown. Annual shrimp yields of 690 kg/ha and 400 kg/ha were reported by Vo Tong Xuan et al. (1986) and Le Ngoc Sen et al. (1987) respectively from farms in Minh Hai Province. Rice field sizes ranged from 2 to 10 ha.

35.5 AQUACULTURE PRACTICES

35.5.1 Shrimp Ponds: Construction, Size and Design

Ponds are often constructed by simply erecting a dam and impounding tidal water. These ponds take advantage of physical features of the land and are usually located in the upper half of the intertidal zone. Construction by collective manual labor is traditional in Viet Nam, especially in the North where man has long fought against nature and the periodic flooding by the Red River. Extensive coastal polyculture of shrimp and fish was also considered a collective task, especially after the establishment of the Revolutionary Power in 1954. Constructing dikes strong enough to resist seasonal typhoons and tides has involved whole villages. A typical example was reported by Vu Hai Son and Ha Quang Hien (1971) where five villages constructed one 1,020 ha pond, northeast of Haiphong, by erecting 43 km of dikes. Large coastal ponds are the rule in North Viet Nam where the same authors reported an average 62 ha for brackishwater ponds during 1965, with 59% of the ponds exceeding 50 ha. Mai Van Cu (1980) surveyed aquaculture practices in six North Viet Nam provinces from 1977-1979 and reported ponds sizes varying from 100 ha for small ponds, 200 ha for intermediate size ponds, and up to 1,000 ha for large ponds. Since then, pond size has decreased. Mai Van Cu (1988) reported that most ponds are now 50 to 100 ha.

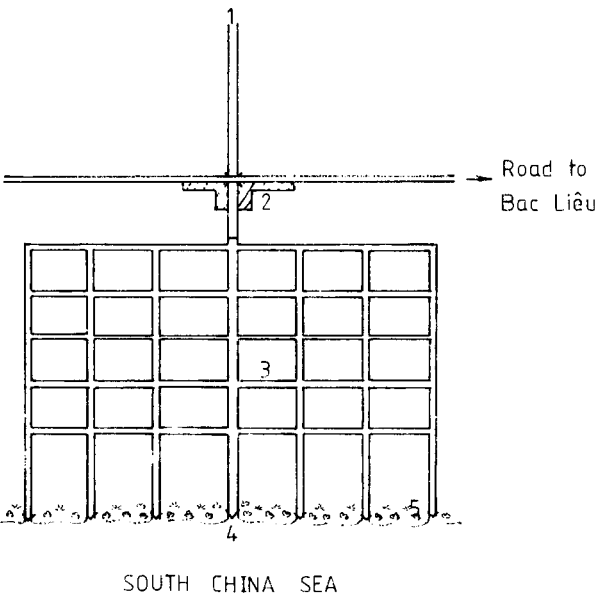


Figure 3. Lay-out of a typical monoculture shrimp farm in Southern Vietnam.

Rapid development of aquaculture ponds resulted in the construction of large, simple ponds which rely on tidal water exchange through sluice gates. Ponds were preferably located in mangrove areas because people were aware of the natural richness of shrimps there. Pond construction seldom included a total clearing of mangrove trees, where perhaps 30% of the pond was covered by mangrove. The reason for this is that people linked the presence of mangrove with shrimp abundance. On Ca Mau Peninsula, shrimp ponds at collective farms were typically 100 to 300 ha, while those of private farmers were 1 to 3 ha (Mai Dinh Yen 1986). Canals are dug inside pond to provide deeper water as shelters against high temperatures. Canals occupy 8 to 10% of ponds area in large coastal ponds (< 100 ha) in Hau Giang Province.

Although information about proper pond design and construction technique exists, it is not widely applied. For example, in many cases earth removed from ponds is only thrown on the dikes and not compacted. One reason may be the lack of capital, and the subsequent temptation to reduce construction costs to the minimum. Another reason could be some reluctance in using non-traditional techniques. In large ponds, especially those in mangrove areas, the natural network of waterways is often turned into culture areas and canals are dug to increase the water area within the ponds.

Another kind of pond lay-out can be found in the Vinh Chau-Bac Lieu where large transverse canals are dug near the coastline. These canals provide seawater for salt and aquaculture uses, as well as waterways for transportation, and rainwater run-off channels. One typical example is the State Farm of Dong Hai (Fig. 3) near the town of Bac Lieu (Minh Hai Province). That farm manages 2,000 ha, of which about one half is suitable for brackishwater culture. The farm includes a rectangular network of seven canals 4 to 6 m wide and 2 m deep and 1.5 km long leading directly to the sea. About 600 ha of swamps is drained by these canals. Farm activities include industrial crops (coconut, fruits, cereals), salt production (80 ha, now abandoned and turned into *Artemia* and shrimp ponds), and extensive marine and brackishwater polyculture. The farm is now introducing shrimp monoculture in small, 1 ha ponds.

Shrimp monoculture trial were conducted during the mid-1980's, but were limited by seed availability. Only recently have some successes been achieved. Monoculture ponds are smaller, only 1 to 2 ha. Poor designs and poor construction were frequent, and the same mistakes were made as with large extensive ponds. Instead of excavating an evenbottom surface, canals are dug and the earth mounded inside the ponds than being placed on the main dikes. Such a typical pond is shown in Figure 4.

The main dike is constructed from the earth excavated from the main peripheral canal, while secondary canals divide the shallower pond bottom. Sometimes the emerging dikes are used to plant coconut trees, but generally

such attempts are economically unsuccessful. As the tidal action is the only way to fill the ponds, the shallower parts are generally covered by a maximum of 30 to 50 cm of water. Not all ponds are alike, however, and companies provided with enough capital and foreign expertise have better designed shrimp ponds; but their total area is still negligible.

Sluice gates are used to control water exchange. Typical ones are 0.8 to 1.0 m wide, and made of wood. Gates are generally equipped with fixed catching devices, or with bagnets for harvest and to keep shrimp and fish from escaping. In large ponds and on state farms, gates are typically made of concrete. The number of gates is variable. In canal-pond systems, there is one gate per canal. In more conventional ponds there is generally one gate for every 10 to 20 ha. In very large mangrove ponds, like the Con Noc Farm, there are 20 gates for a 1,000 ha area.

35.5.2 Pond Preparation

Pond preparation includes repairing the dikes and excavating the canals to accomplish complete drainage. During that process, the pond bottom thoroughly dried. In North Viet Nam, complete drainage and harvest takes place in December-January. The pond bottom is then cleaned. There are generally no attempts to control predators in polyculture ponds. Screens placed in or around gates were mainly for preventing fish and shrimp escaping from the pond. Recent practices include more active control of predators in order to increase shrimp yields. Methods currently used are classic: drainage and drying, use of Derris roots, and fishing with castnets to capture predators. In some coastal areas, like in Hau Giang Province, Derris plantations are quite common and can provide significant income. In small

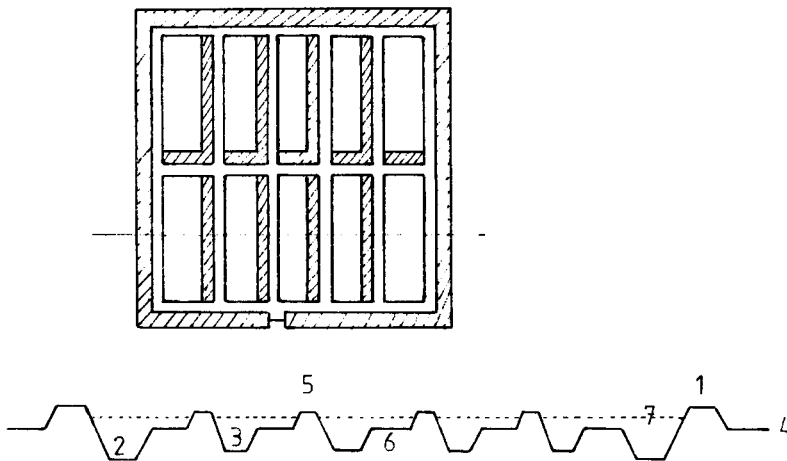


Figure 4. Schematic lay-out of typical monoculture shrimp pond in Southern Viet Nam.

ponds, especially in family-size ponds, organic fertilization is sometimes performed with cattle manure or pig manure.

35.5.3 Trapping the Seed

Shrimp aquaculture in Viet Nam still relies mostly on wild seeds for stocking pond. The most basic trapping technique for fish and shrimp seeds is to fill the pond at periods of high seed abundance. An archaic practice, used in North Viet Nam, consists of breaching the main dikes and letting tidal waters circulate freely for several months, turning the pond bottom into a tidal flat ecosystem. Then, at the peak season for wild seeds in March or April, during spring tide, the dike is closed and water is not exchanged until harvest (Vu Hai Son and Ha Quang Hien 1971). Such practice may have been abandoned by now.

Filling ponds can take several days with large ponds since the size and number of gates is often small relative to pond volume. There after, water is let in only to compensate for water losses and to supplementary seed stock. Water must be taken while the tide is rising. Although water may still enter the pond at high tide, trapping efficiency is lower. Shrimp seeds are more easily trapped at night than during the day, and light is sometimes used to attract shrimp. Water is usually taken in at every spring tide, or whenever possible. Mai Van Cu (1980) reported that gates were operated 90 to 110 times a year, averaging 300 to 500 hours in North Viet Nam. In the central and in South Viet Nam, tidal waters can be exchanged a maximum of 15 to 20 days/mo. More often the exchange period is 4 to 5 days per spring tide, or 10 days/mo.

Favorable periods for trapping wild shrimp seeds are April-June for Penaeus species, and August-November for Metapenaeus species in the north (Do Khac Khoan 1980). In the south, along the South China Sea coast, wild seed occur year-round, but peaks are reported by fishermen in September-October and March-April. Springtime is generally the best time for trapping seed, as it coincides with the start of favorable culturing conditions, such as highest water temperatures. The equinoctial tide on the 23rd day of the third lunar month (around late April) is a traditional date for trapping seed, and many people believe that the abundance of seed at that time will determine the seasons success (Nguyen Van Vien 1980). Table 5 lists shrimp postlarval densities observed at various locations in Viet Nam.

Recently, improvements and reliability in mass production of penaeid PL have made controlled stocking possible. Whenever possible, shrimp farmers buy juveniles from fishermen to stock their ponds. Supplemental stocking is made through water intake for filling the ponds, or through water exchange. In central and South Viet Nam, some people engage in seed collecting as a business. Penaeus merguensis is the main species collected with daily yields

Table 5. Abundance of shrimp postlarvae (Penaeid and Palaemonid) in some brackishwaters of Viet Nam and in waters entering coastal ponds. Values with standard deviation (sd) have been calculated from data sources in references cited - N is the number of data.

LOCATION	PERIOD	DENSITY OF PL	REMARKS
<u>North Viet Nam</u>			
Ha Nam Ninh Prov. ¹	July 1971	Penaeid: 1007/hr. Palaemonid: 371/hr.	Pond's gate (use of a plankton net)
<u>South Viet Nam</u>			
Cuu Long Prov. ²	July 1987	Metapenaeus: 3997 individuals in 2 tows 0.25 m ² Zooplaknton net fishing for 5 mn.	Tidal canal; mangrove waters sampling during the flow, at night
My Thanh River ³	April - July 1985	373/hr. 459/hr.	Mean of 4 months Plankton nets fishing for 10 mn.
Min Hai Prov. Nam Can ⁴	May 1987	Penaeidae:393/hr. 0.25 m ² Zooplankton net	Tidal canal in mangrove waters
Minh Hai Prov. Gai Rai ⁵	February - April	16.8 Pl/liter n=6; sd.= 18.7	Pond's gate 1 km from the river
		35.2 Pl/liter n=6; sd.=17.8	Pond's gate, near the river
Min Hai Prov. ⁶	March - April	11.3 Pl/liter n=6; sd.=3.1	Pond's gate

1. Nguyen Van Chung and Phan Dihn Trong (1979)

2. Nu Do Quynh (unpubl.)

3. Nguyen Van Thong (1987)

4. Vu Do Quynh (unpubl.)

5. Vo Tong Xuan, et al. (1986)

6. Le Ngoc Sen, et al. (1987)

of 2000 to 10,000 juveniles, 3 to 4 cm size. Nevertheless, most extensive shrimp ponds still rely heavily on natural seed trapped inside the ponds through water intake and exchange. Many small-scale fishermen catch Penaeus and Metapenaeus juveniles 0.2 to 0.3 g for direct consumption, instead of using them to stock ponds. Tidal flats around Haiphong provide up to 10,000 kg of this size shrimp (Do Khac Khoan 1980).

35.5.4 Pond Growout

In traditional extensive culture, shrimps feed on natural food only no supplemental feed. Natural food grows in the ponds, and can be enhanced by organic fertilization. This is more generally done in smaller ponds. Because of costs, prepared food is only provided in private family operated farms, or on experimental farms where higher yields are attempted. On a few farms, shrimp pellets produced by frozen food factories are used, but it is still experimental. Much of the prepared shrimp pellets are imported from Thailand.

The growout period is variable and largely determined by environmental conditions such as water temperature, flooding risks, and dry and wet season conditions. Moreover, partial harvesting at spring tides is usually practiced. Partial harvest generally starts 1 to 2 months after pond filling and continues during each water exchange. Complete harvesting is at the end of the season by complete drainage. That occurs during Winter in the North when shrimp seed are scarce and the water temperatures are low. In central Viet Nam, harvest is done before the flooding season (October-November). Semi-intensive P. monodon farms rear shrimp for 4 to 5 mo./crop.

35.5.5 Harvesting

Tran Van Quynh (1980), Vu Hai Son and Ha Quang Hien (1971) describe harvesting techniques used in North Viet Nam. Fixed trapping devices common in South-East Asia are widely used, and are locally called "Do", "Dang", etc... The "Do" is made of bamboo sticks, or similar material, and is composed of two parts; a weir and a trap. The weir is generally 8 to 10 m long and is placed at an angle with the bank. The trap has bamboo sticks, spaced 4 to 5 mm and is oval with 0.6 to 0.8 m width and 0.8 to 1.2 m height. The "Do" is set in the evening, at 5 to 6 P.M. A light is often placed to attract more shrimps and fishes. The "Do" can be used alone, or in a series at 50 to 100 m intervals. Density is usually one "Do" for every 5 ha. The traps are emptied periodically through the night, with peak capture times of 9 PM or 3 to 4 AM.

Other traps are set to filter pond effluent water. The "Don" is a kind of framed bagnet set inside the sluice gate with a length about 10 times its aperture size. Capture efficiency with the "Don" is much greater than for the "Do", but the catch is easily damaged. In Thanh Hoa Province, the "Chuong" is used, consisting of two V-shape weirs, which project about 1.5 m inside a 2.5 m x 2.5 m closed squared bamboo trap. The "Chuong" is set with its mouth opening through the dike. Capture efficiency may be as high as 85% with good quality harvest. Finally, at the end of the culturing season, a complete drain is made and remaining shrimps are hand-caught; sometimes with seining, especially when complete drainage is not possible.

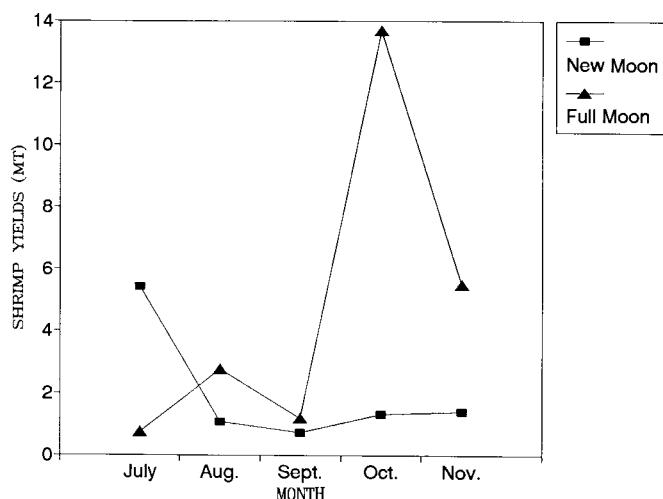


Figure 5. Shrimp harvest during spring tides at the 18 gates of the salt-shrimp farm of Vinh Tien (Vinh Chau district, Hau Giang province) according to lunar phase.

In South Viet Nam, more or less similar methods are used. In salt-shrimp culture, ponds are flooded during the wet season and water circulation is controlled by artisanal gates equipped with trapping devices similar to the Chuong, excepted that the trap is a removable basket. The evaporation and reservoir ponds are connected to the sea through canals which are themselves equipped with sluice gates and trapping devices. Harvests are made during water exchange, generally during spring tides and for 4 to 5 days. Figure 5 shows monthly yields during in 1980, according to lunar phase, at the salt-shrimp Vinh Tien Cooperative Farm, Vinh Chau District, Hau Giang Province (Nguyen Van Vien, 1980). That farm had 18 canals set perpendicular to the shoreline. Annual yields during 1979 to 1984 ranged from 7 to 44.8 MT/yr, averaging 31 MT/yr (Nguyen Thanh Su 1985). Yields varying from 84 kg to 2,154 kg per gate during a 50 day period, in May-June 1985 (average = 611 kg/gate).

Figure 6 shows fish and shrimp composition in monthly catches from the Dong Hai State Farm during 1988. Six gates were used to drain 600 ha of ponds. Most fishes are small gobioid mudfishes (10 to 15 cm long), called "Ca Keo" and represented by several species like *Boleophthalmus boddarti* or *Pseudapocryptes lineolatus* (Mai Dinh Yen 1986).

At the Con Noc Shrimp Farm, shrimp yields from 1987 to 1988 (18 mo.) were about 100 MT, of which 75 MT were exportable. That farm operated 20 gates with yields of 5 to 10 MT of shrimps per gate. Mean productivity

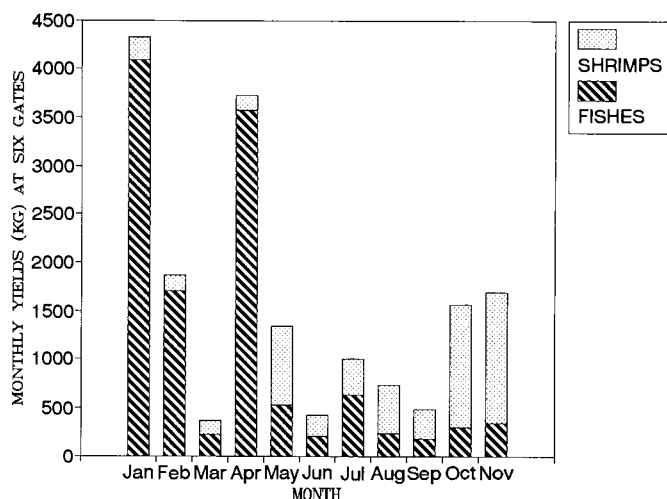


Figure 6. Monthly shrimp harvest at spring tides for 17 gates of the Vinh Tien Salt-shrimp Cooperative Farm (Vinh Chau district).

was 60 kg shrimps/ha/year. In addition, the farm also harvested around 25 tons of mud-crabs, *Scylla serrata*, and tens of tons of "Ca Keo" fish.

35.6 SHRIMP CULTURE INTENSIFICATION

35.6.1 Status

Semi-intensive shrimp culture was closely linked with hatcheries start-up activities in the mid- 1980's. It is still in its experimental phase, and initial goals are to increase yields to 1 MT/ha/year. Most semi-intensive and intensive shrimp culture operations are located near penaeid hatcheries, although some trials are being made in central Viet Nam and the Mekong Delta. Up to now, few trials have been successful. Highest yields of 1.2 MT/ha/yr are reported for *P. merguensis* in Seaprodex's Co May Farm (Dong Nai Province). Recently, that farm stocked 12 ha of semi-intensive ponds with *P. monodon* at 8 PL/m². Several crops during 1988 and 1989 produced yields up to 600 kg/ha/crop (Bui Lai, personal communication). Other companies have also invested in semi-intensive shrimp culture, especially in areas southwest of Ho Chi Minh City, but results are still not reliable. Main causes for failures involve bad pond design and management, lack of suitable shrimp food, and especially a lack of sufficient material incentives to motivate salaried workers.

Recently, in 1988 a joint venture (Vatech) was established between Lobana Investment Company of Australia and Seaprodex-Viet Nam in Da

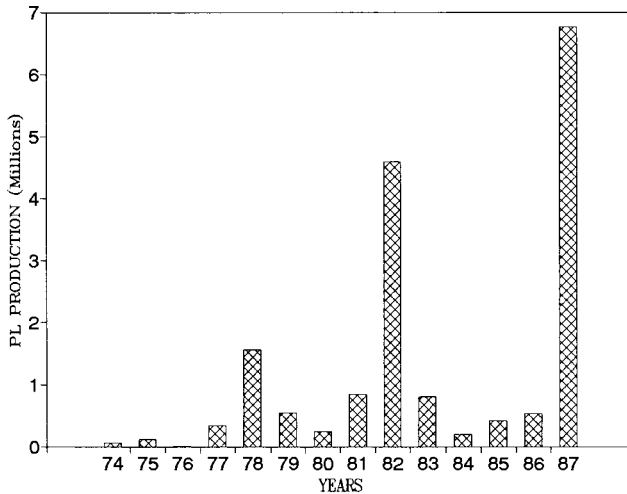


Figure 7. Monthly yields of fish/shrimp in the Dong Hai State farms. Total of six gates draining around 24 Km of canals.

Nang (central Viet Nam). During the experimental phase, modern 1-ha squared earthen ponds were constructed for intensive shrimp culture in several provinces of central Viet Nam, from Da Nang to Phan Rang. The ponds were pump-fed and each equipped with four electrical aerators. Twenty-two ponds were operated in 1989, stocked with hatchery-produced PL at 25 to 30 PL/m². Other ponds are under construction. Vatech's goals are to develop 2,500 ha of intensive shrimp ponds in five years, with 10 MT/ha/yr yields. The first crops were harvested in late- August 1989 with maximum yields of 3 to 4 MT/ha after 4 mo. culture, but most ponds had lower yields of about 1 to 2 MT/ha/crop.

35.6.2 Penaeid Larviculture

35.6.2.1 Hatchery development

Nguyen Khac Do (1976) described the first trials with artificial propagation of penaeid shrimps in North Viet Nam during 1971-1974. Species used were P. merguensis and P. penicillatus. The japanese larviculture technique for mass production of P. japonicus was employed by japanese technicians. One hatchery and several ponds were constructed near Hai Phong with FAO support. Because of the high sedimentation rates, however, the Research Station was gradually surrounded by salinity water and had to convert its activities to freshwater culture. Later, FAO helped again in establishing a penaeid hatchery in central Viet Nam at Qui Nhon. That hatchery focused principally on P. merguensis larviculture. Since 1982,

more scientists became interested in shrimp and prawn larviculture and many institutions started their own research projects, especially in central Viet Nam and Ho Chi Minh City. Species like P. merguensis and P. semisulcatus were spawned using ripe females from the wild with variable success. Postlarval production estimates shown in Figure 7.

First successful mass production of P. monodon PL occurred in 1984-1985 in the Nha Trang area. Since then, most hatcheries have emphasized production on that species. At that time, however, the demand for hatchery-produced PL was low because pond culture techniques were still rather primitive, and it was not possible to stock ponds without facing heavy losses through predation, etc. Recent changes in economic policy has given more incentives to individual enterprises, and many shrimp farmers have begun investing in shrimp more intensive culture ponds. Breakthroughs in mastering basic larviculture techniques for penaeids, linked with rapidly growing demands for P. monodon seeds has resulted in a dramatic increase in hatchery number. This is illustrated by the Nha Trang-Cam Ranh area where the number of hatcheries increased from 13 in late-1988 to 36 by September 1989. Most of these hatcheries are of "backyard", or of small-scale size; with only three of medium-size, and one of large-scale. Typical annual production is currently in the range 1 to 5 million PL/hatchery. Total PL production is increasing quickly, from about 20 million in 1988, to 40 million in 1989. Estimated production capacity and current outputs are given in Table 6.

Hatcheries are concentrated in Phu Khanh Province, around Cam Ranh Bay and Nha Trang City near the main research institutions for fisheries and aquaculture in central Viet Nam. In that area there are about 25 private hatcheries, who hire technical assistance from governmental aquaculturists.

35.6.2.2 Broodstock availability

Gravid female shrimp are collected by small artisanal shrimp trawlers whose fishermen select and transport the females to the hatchery upon request. Prices vary depending on location and demand. Central Viet Nam is well known as a source of P. monodon spawners. Prices are highest in Phu Khanh Province due to the large number of hatcheries there and resulting competition. In early 1989, during periods of high demand, P. monodon stage IV females sold for more than 100,000 dong¹ (US\$ 25 to 30) near Nha Trang and Cam Ranh. At other times the price was as low as 20,000/40,000 dong/spawner. Regulations are under consideration to limit price inflation during high demand periods, and to ensure equitable availability of ripe spawners to every hatchery.

After spawning, the spawners are usually sold to processors. Eyestalk ablation is used to stimulate maturation of stage III females. Research on

Table 6. Development, distribution and estimation of penaeid larviculture production from hatcheries in Viet Nam by September 1989.

Province	Area	Number	Status	Annual Capacity (million)	Current Production (million)
Hau Giang	-Vinh Chau	1	exp.	0.50	.02
CuuLong	-Long Toan	1	exp.	n.d.	n.d.
HCM City	-Duyen Hai	1	prod.	5.0	n.d.
Vung Tau		1	prod.	5.0	n.d.
Dong Nai	-Long Hai	1	prod.	5.0	n.d.
Thuan Hai	-Phan Rang	3	prod.	5.0	n.d.
Phu Khanh	-Cam Ranh	10	prod.	35.0	8.0
	-Nha Trang	25	prod.	104.0	17.6
	-Van Ninh	1	exp.	1.0	n.d.
	-Tuy Hoa	1	prod.	1.0	n.d.
Nghia Binh	-Qui Nhon	3	prod.	10.0	6.0
	-Sa Huynh	1	exp.	n.d.	n.d.
QN-DaNang	-Hoi An	1	prod.	1.0	0.1
	-Non Nuoc	1	prod.	100.0	10.0
Binh Tri Thien	-Thuan An	1	prod.	5.0	n.d.
Hai Phong	-Qui Kim	1	exp.	n.d.	n.d.
Quang Ninh	-Ha Long	1	exp.	n.d.	n.d.
Totals		54	278.5		35.72

Notes: prod. (producing), exp. (experimental phase), n.d. (no data available). Phu Khanh data are from the provincial fisheries; other data are broad estimates.

maturation techniques is still only beginning phase, and most hatcheries do not maintain non-gravid breeders. An exception is the larger hatcheries such as Caratom in Cam Ranh and especially Vatech's hatchery near Da Nang, where about one hundred broodstock are kept and females respawned many times.

35.6.2.3 Hatchery operations

Larviculture techniques are a pot-pourri of the Galveston, Japanese, SEAFDEC and other techniques adapted to local conditions. Seawater is filtrated through plankton gauze to a storage tank. From there, it is distributed by gravity to culture tanks. Larviculture tanks are usually rectangular with 1.5 to 2 m³ capacity. Larger hatcheries, however, have larval tanks of 6 m³ capacity, while Vatech's hatchery near Da Nang has 30 m³ larval rearing tanks.

Phytoplankton is usually cultured outdoor in small, 0.5 m³ concrete cylinders, or in larger concrete tanks. Seawater is filtered through zooplankton net, and enriched with fertilizers. The composition of the

enrichment medium is said to favor development of Chaetoceros algae. In some hatcheries, Chaetoceros strains are used as inoculum. Algal densities are 80 to 130 thousand cells/ml in 3 to 4 days, when fed to zoea larvae (Vu Van Toan 1988; Nguyen Chinh 1988). In many hatcheries, algal are filtered on phytoplankton net with only the algal cells fed to the shrimp larvae. Some hatcheries suppliment algae with baker's yeast and soybean powder for zoea (Vu Van Toan 1988). In Qui Nhon's FAO-supported hatchery, Acetes and crustacean tissue suspension are fed to larval stages (Nguyen Vu Thanh 1988). Although some favorable results were achieved with that feeding method, Artemia nauplii still gave better results.

35.6.2.4 Artemia cysts usage

Artemia cysts were not used until recently in Viet Nam because currency exchange limitations did not allowed their importation. Other live food organisms were used as replacements, mainly rotifers (Brachionus plicatilis) and copepods (Vu Van Toan 1988). Since 1982, however, several research institutions have successfully produced Artemia from salt farms. Cysts are harvested during the dry and beginning of the rainy season (Vu Do Quynh and Nguyen Ngoc Lam 1988; van der Zanden 1988). Presently, Artemia cysts are from two sources, importation through diversified channels, and domestic production. Although imported cysts may be cheaper, locally produced cysts are preferred because of better and less variable hatching quality (70 to 90%). Total current production of Artemia cysts in salt fields of central and South Viet Nam in 1989 was about 250 to 300 kg dry cysts (Vu Do Quynh unpublished). Production continue to increase.

Cysts produced in Viet Nam are used fresh, after processing in saturated brine, but drying and canning are used by Can Tho University for cysts produced in the Vinh Chau area. According to several hatchery managers, cyst consumption is 2 to 3 kg wet weight to produce 100,000 PL10 shrimp postlarvae. Current cyst prices are about 70,000 to 90,000 dong/kg wet weight (approximately US\$ 44 to 56/kg dry weight). During high demand, however, cysts could fetch higher prices.

35.6.2.5 Hatchery economics and nursery operations

Penaeid larviculture has proven it can be very profitable, especially for small-scale private hatcheries where the number of laborers is less than in governmental facilities. Return on investment can be achieved in one successful rearing cycle. For example, in March 1989, one family in Nha Trang invested 13 million dong (US\$ 2,900) in one 16 m³ hatchery, and after two months was able to produce and sell 1 million PL at 10 to 15 dong/PL. That hatchery produced 3 million PL by September 1989. Such success has led to multiplication of hatcheries. Some hatcheries produce only when the

demand and prices are high. Not all hatcheries have been successful, however, since a certain level of expertise is necessary. Diseases and poor sites are also reasons for failures.

Hatcheries usually sell PL when they are at stage PL10-15. Prices vary according to demand, from 7 to 25 or 30 dong a piece (prices in 1989; equivalent to US\$ 1.75 to 7.50/1000 PL10). Non Nuoc-Vatech's hatchery, however, sold its PL's at 60 dong/piece. In periods of low demand (June-July), PL may be kept longer, with some hatcheries holding PL to PL45-PL60 before selling. Typical nursery tanks are of concrete, with 20 m³ capacity (3.5m x 6m x 1m). Since PL45 can fetch prices of 100 to 200 dong/piece, some people have specialized in nursery operations in earthen ponds. In the Nha Trang area, old milkfish ponds have been converted to shrimp nursery ponds of 0.1 ha each. Nursery stocking densities are variable, from 80 to 240 PL15/m². Feeding is with minced fish, steamed fish, or sometimes prepared diet.

35.6.3 Shrimp Feeds

Pelletized shrimp feeds are produced experimentally by various organizations in Viet Nam, and some frozen seafood factories have invested in feedmill equipments to recycle their organic wastes. Most production plants are rather artisanal, and their production capacities are still limited to about 150 to 500 kg/day. Some research and academic institutions, like the Aquaculture Institute II, Can Tho University and Agricultural University IV in Thu Duc (Ho Chi Minh City), are engaged in shrimp feed research. Present prepared feed conversion ratio are from 5:1 to 2.4:1, with prices ranging from 1,800 to 4,000 dong/kg (price during September 1989, equivalent to US\$ 0.45-1.00). State-of-the-art of feeds in Viet Nam is still in its experimental phase, and no large-scale commercialization has occurred.

35.7 MARKETING

Because of their high value on the international market, large shrimp are considered an export product in Viet Nam. Domestic consumption is largely limited to low-quality and small-sized shrimps. In the cities, however, export-quality shrimps are available for the tourist market and in luxury restaurants. Post-harvest processes include; buying, temporary preservation, processing and, freezing, storage, and exporting. Shrimp exporting is a state enterprise reserved to the Central Government, namely to Seaprodex Viet Nam. Since 1986, provincial factories have the right to export their products directly.

Fishermen and farmers can sell their products directly to frozen seafood factories, or to a network of specialized buying stations. That network

includes private people; but most operators belong to provincial and governmental institutions, generally the local fisheries Company. Private intermediaries also buy shrimps directly from the grower, at pond-size, and then sell to the buying stations. That practice is frequent in the Mekong Delta, especially in remote coastal areas where roads are often in bad shape. These people use their personal motorbikes equipped with two rear baskets for shrimp transport. Buying stations are mostly found along the main highways or canals where the shrimp are collected by refrigerated trucks. On buying, shrimps are graded according to size classes, weighed and the payment is made in cash.

With increased aquaculture development, the number of processing plants has also increased gradually. Before 1975, plants were mostly found in harbor cities such as Hai Phong, Saigon, Vung Tau, with total processing capacity of less 100 MT/day (Le Van Phat (1986). Production capacity increased greatly through creation of the governmental Seaprodex Company in 1978, and construction of 12 new processing plants. In 1987, total number of plants was 62, with a total processing capacity of 350 MT/day. According to Seaprodex Company, frozen shrimp exports reached 30,000 MT in 1987, with about 30% from aquaculture. Export markets are mainly Japan, Hong Kong, Singapore, France, Belgium, and Canada.

35.8 CONCLUSION: SOME PROSPECTS FOR THE FUTURE

Shrimp culture was late developing in Viet Nam compared with some other Southeast Asian countries. It has, however, a tremendous potential if modern and wise management techniques are applied. One major breakthrough was the mastering of penaeid larviculture techniques. The resultant boom in shrimp hatchery output has led to greatly increased shrimp yields from existing farms, and experimentation with semi-intensive and intensive shrimp culture. Since semi-intensive culture requires less capital, and has higher returns per unit production, it may be the most appropriate way for shrimp culture development in Viet Nam. It fits better with the existing economical infrastructure of the country. It is also, according to many economists, the best suited to accommodate expected drops in international shrimp market prices. Viet Nam presents many attractive advantages for foreign investors, including land availability, and relatively low land and labor costs. Many problems remain unsolved, such as low technical level, scarcity of technical information, training, etc. Social problems related to salaries insufficient for living, also need attention. New economic regulations and reforms are under way, however, that should boost individual and private initiatives. Introduction of import feeds and foreign expertise are also stimulating factors.

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CHAPTER 36

Greg B. Maguire and Geoff L. Allan

SHRIMP CULTURE INDUSTRY IN AUSTRALIA

36.1 INTRODUCTION

Overviews of shrimp farming in Australian states and nationwide have been prepared for domestic audiences (Heasman 1984; Allan and Maguire 1986; Maguire and Allan 1987a, 1988; Kelemec 1987; Kenway 1987a; Wu 1987; Robertson 1988; Allan 1989a). The present overview is aimed at a wider audience, and was prepared at a time of rapid expansion in the Australian shrimp farming industry. Shrimp farming in Australia has much in common with the U.S. situation (Lawrence and Huner 1987). There is an increasingly sophisticated research base, relatively low land costs but high labour costs, a wide range of climatic conditions, high production from existing fisheries, and low total production from shrimp farms.

36.2 HISTORICAL DEVELOPMENT

After some unsuccessful initial commercial trials in the various Australian states (Heasman 1984), shrimp farming during the late 1970's was virtually restricted to government research activities, mostly in New South Wales (NSW). Much of this work was based on "feed lot" culture of Metapenaeus macleayi, as there was not a reliable hatchery supply of postlarvae (PL) for any penaeid species in Australia. Subsequently, this research was successfully expanded to a pilot-scale operation (Maguire and Allan 1985) which stimulated construction of commercial ponds in the Yamba area in northern New South Wales (Fig. 1).

Construction of shrimp hatcheries in the mid- 1980's near Darwin (Northern Territory), Innisfail (Queensland, QLD) and Yamba (NSW) (Fig. 1), allowed for more reliable stocking of ponds and diversification of penaeid species. As a result, additional ponds were constructed in these areas chiefly for Penaeus monodon culture. Other factors which encouraged rapid expansion of shrimp culture were the successes of Asian shrimp farming industries, particularly in Taiwan, an investment boom in novel agricultural ventures in Australia, and depressed world prices for sugar which encouraged a number of growers to construct ponds on sugar cane lands.

Provided that the industry can achieve sustained profitability, it is likely that Queensland will be the major state for shrimp farming in Australia

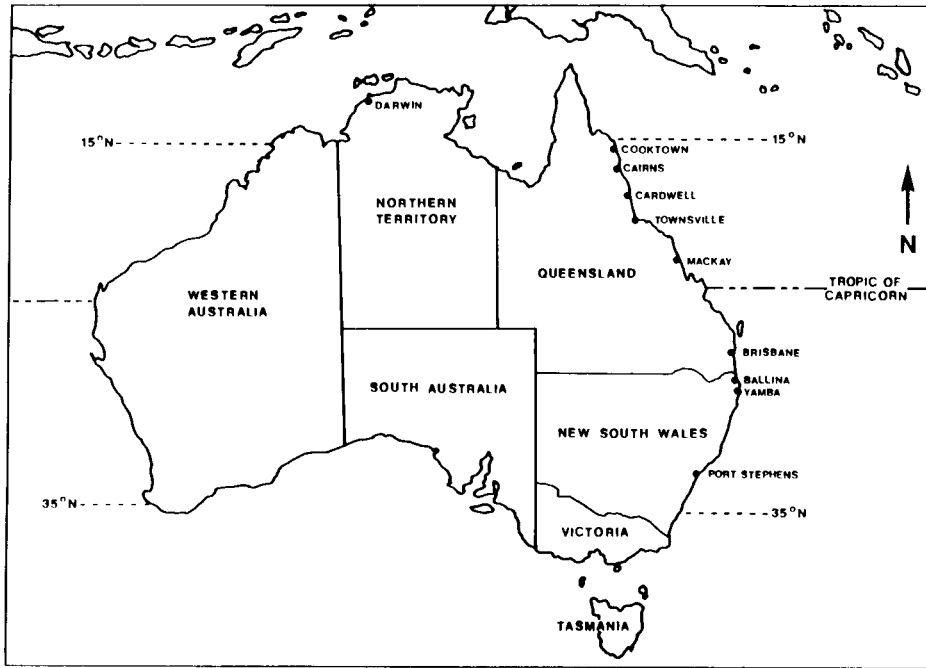


Figure 1. Australian shrimp farming and research centers.

(Table 1). Currently, the largest areas of ponds are in the tropical Cooktown to Mackay region with Cardwell emerging as a major centre for growout operations (Fig. 1). Several hatcheries have been established in northern Queensland, but there are also very productive hatcheries around Brisbane and in northern New South Wales.

A significant prawn culture exists in New South Wales and production is still expanding (Table 1). Although the Yamba-Ballina area has only a warm-temperate climate, the available research base and commercial expertise acquired over several years have encouraged farmers to intensify their efforts. A major advantage for this region is its proximity to the large population centres of Sydney, Brisbane and the southern Queensland - northern New South Wales coastal tourist area.

Despite major investment in South Australia and the Northern Territory, and pilot scale work in Western Australia and Victoria, production from States other than Queensland and New South Wales is negligible; although the Darwin area has in the past been a major supplier of *P. monodon* PL.

Overall production of farmed shrimp has increased rapidly during recent years with estimated production for 1988/89 of 353 MT. Production estimates for 1989/90 indicate that this rapid expansion will continue (Table 1). Some

TABLE 1. Production of shrimp from Australian fisheries and farms 1986-1990.

Year	Production from fisheries (x10 ³ MT) ^a	Production from farms(t)			Total Pond area stocked
		NSW	QLD	Total ^b	
1986/87	20.8	15	na	<30	na
1987/88	22.6	40	<40	<80	na
1988/89	19.4	118	235	353	250
1989/90	21.7	460 ^c	880 ^c	1340 ^c	400

na Not available

^a Data provided by the Australian Bureau of Agricultural and Resource Economics (ABARE); 1989/90 data are based on projected estimates (ABARE, 1989, pp 410-412).

^b Production for other Australian states and territories is negligible.

^c Predicted production based on estimates provided by farmers; unexpected problems often reduce production below levels anticipated.

individual farmers have concluded that their growout facilities are being operated on at least a break-even basis; however, the long term viability of the shrimp culture industry in Australia will depend greatly on future ex-farm prices for cultured shrimp.

36.3 CULTURED SPECIES

Cultured shrimp production in Australia is predominantly P. monodon (Table 2), a proven species which accounted for about 33% of world production of cultured shrimp in 1989 (Rosenberry, 1990). Unfortunately, this species forms a very minor component of the Australian penaeid catch fisheries, and hence the availability of broodstock for this species remains a major problem. Despite not being a commonly encountered species, P. monodon from Australian farms has proved to be a highly acceptable product for the Australian domestic market.

Aquaculture potential for several Australian penaeid species has also been assessed because of their market price and broodstock availability. Large numbers of Penaeus plebejus PL were produced in northern New South Wales in the mid-1980's, but growout results with this warm-temperate species were usually poor. Aquacop (1985) concluded that P. plebejus was not promising for aquaculture, although they noted the possibility of better results at cooler temperatures. Subsequently, however, Maguire and Allan (1987b) demonstrated that P. plebejus grew faster at tropical temperatures (27 to 30 C) than at lower temperatures (18 to 24 C).

In Queensland, many farmers have stocked Penaeus esculentus but production results have often been disappointing, confirming earlier

Table 2. Estimated relative contribution of various species of shrimp to total production of cultured shrimp during 1988/89 (NSW) and 1988 (QLD).

Species	Common name	% of Production	
		NSW	QLD
<u>Penaeus monodon</u>	Leader prawn	83.2	89.2
<u>Metapenaeus macleayi</u>	School prawn	16.6	0
<u>Penaeus esculentus</u>	Australian tiger prawn	0.2	8.4
Other penaeids ^a		<0.1	2.4

^a Other species harvested include banana prawns (Penaeus merguensis) and eastern king prawns (Penaeus plebejus).

experimental results (Maguire and Allan 1987a; Aquacop 1985). However, P. esculentus is likely to receive continued attention from aquaculture research workers, especially in terms of feed formulation, for several reasons: 1) it has excellent hatchery attributes (Kenway 1987b), 2) it attracts premium prices in Japan, the major market for Australian penaeids (Baulch 1987), and 3) cultured P. esculentus have been successfully marketed live in Australia. This species is an important component of several Australian penaeid fisheries and has been the subject of a great deal of fisheries research, some of which is relevant to aquaculture (Crococ 1987; Wassenberg and Hill 1987).

Although Penaeus merguensis accounted for 8% of world production of cultured shrimp in 1989 (Rosenberry 1990), less emphasis has been placed on banana prawns. Again Australian pond results have not been encouraging with this species (Kenway 1987a). A number of farmers have stocked Penaeus japonicus for the first time in 1989/90, while other species which may warrant further investigation include Penaeus longistylus and Penaeus semisulcatus (Dall 1987).

The only other Australian penaeid of major interest is M. macleayi, juveniles of which can be collected in large numbers from estuarine fisheries near Yamba (NSW) (Fig. 1). This species is popular on the domestic market, but unfortunately, it has a restricted spawning season, low fecundity, and is too small for export (Kenway 1987a). Maguire and Allan (1987b) found that this species can be grown at relatively low temperatures (21 to 27 C) and high densities (60/m²). It is grown in New South Wales as an autumn-winter crop, particularly at farms very close to an estuarine fishery. In 1988/89 some 29MT of this species were produced (Allan 1989a).

36.4 PRODUCTION TECHNOLOGY

36.4.1 Hatchery Methods

Except for those stocked with M. macleayi, all growout operations in Australia are based on hatchery reared PL. There are currently eight major

penaeid hatcheries operating in Australia, with additional hatcheries being developed. Other multi-species hatcheries could be adapted for production of penaeids, and some non-operational penaeid hatcheries could be recommissioned. Australia is moving from a position where an inadequate PL supply was limiting production to one where excess hatchery capacity is now causing the previously established penaeid PL prices (about A\$30/1,000) to decline considerably during 1989/90. Spawner supply is still a problem, but maturation facilities are being constructed. Australian hatchery procedures are not well documented, with the exception of Kenway (1987b). Such information is often proprietary, but generally the hatcheries use Taiwanese systems (Chiang and Liao 1985; Chwang et al. 1986) or western intensive systems with parabolic tanks, high larval densities (often >100 larvae l^{-1}) and artificial larval feeds as supplements to microalgae and *Artemia* nauplii (Scura and Yunker 1987).

36.4.2 Nursery and Growout Methods

Nursery systems are not widely used in Australia. Most farmers stock advanced *P. monodon* PL₁₅. In more temperate areas, however, several farmers have constructed nursery ponds or raceways within greenhouses. Growout ponds stocked with these juveniles produced high yields (3.75 MT/ha, average from 9 ponds) in 1988/89 (Allan 1989a). Unfortunately, cost effectiveness of intensive nurseries in Australia and elsewhere remains unproven (Juan et al. 1988).

A variety of growout approaches for penaeids have been adopted in Australia, although they are all essentially semi-intensive culture as defined by Wickins (1976). There is a trend towards intensification, although it is unlikely that the very high densities used in Taiwan will be adopted in Australia. In 1988/89, the average stocking density for all farms was 16.8 prawns/ m^2 in Queensland, and 12.8 PL/ m^2 in New South Wales, with the latter limited by PL availability (Table 3). Average pond size for individual farms was < 1 ha in Queensland, but 1.84 ha in New South Wales. Precise production estimates are difficult to obtain, but apparently averaged 2.5 to 2.7 MT/ha/year for the two states (Table 3). Farmers expect production levels to rise significantly as expertise improves and increased PL availability allows more farmers to grow two crops per year. This is evident in estimates of total production and pond area for 1989/90, which indicate a national average yield of 3.4 MT/ha/yr. These yields are modest compared to those possible from intensive culture (Wickins 1976), but they do exceed national averages for other major shrimp culture industries in 1989, with the exception of Taiwan (Rosenberry 1990). They also exceed average results from semi-intensive farms in Texas (Chamberlain 1989).

Table 3. Pond size and shrimp production data for Australian shrimp farms for 1988/89^a.

State	Pond size (ha)			Stocking density (number m ⁻²)			Production (t ha ⁻¹ year ⁻¹)			FCR		
	x	(range)	n	x	(range)	n	x	(range)	n	x	(range)	n
NSW	1.89	(0.2-3.5)	6	12.8	(5-25)	6	2.7	(0.4-6.8)	6	2.4	(1.6-4.6)	6
QLD	1.05	0.4-2.8)	18	16.8	(7-30)	15	2.5	(0.4-5)	17	2.3	(1.5-4.1)	15

^aData are average for all farms - no weighting has been applied for farm size. All data based on preliminary results of a telephone survey by Queensland Department of Primary Industries. Production results for New South Wales are higher than those estimated by Allan (1989) for the same period.

Generally, farmers manage their ponds by maintaining phytoplankton blooms as advocated by the authors, rather than by maintaining benthic algae (Cordover 1987). Comparisons of the two approaches in test ponds stocked with *P. monodon* indicated that filamentous algae were a major risk with the latter management approach (Allan and Maguire 1988). This finding confirmed trial results in commercial ponds.

Environmental protection constraints on development of intertidal land have necessitated construction of non-tidal ponds, equipped with efficient pumping systems. Water exchange rate is a major pond management variable, but Allan and Maguire (1988) concluded that in test ponds stocked with *M. macleayi* at 20 to 50 prawns/m², daily water exchange was not needed. Similarly, many Australian farmers adjust water exchange according to phytoplankton blooms and shrimp stress symptoms. Robertson (1988) summarized average water exchange for a commercial facility in Queensland where rates increased from 1.6% day⁻¹ to 25.0% day⁻¹ as *P. monodon* grew from 2 g to >35 g. Allan and Maguire (1988) found that water exchange rates had to increase (5.9% day⁻¹ to 11.5% day⁻¹) as stocking density increased (5 prawns/m² to 40 prawns/m²) for juvenile *P. monodon* in test ponds. Greater emphasis is placed on installation of aerators, although some farmers prefer to rely only on rapid water exchange to avert crises.

Harvest is usually achieved in Australia by netting prawns from effluent water while draining ponds. Pond bottom slopes and channel configurations vary, but Robertson (1988) noted slopes of 0.5% to 2.0% for Queensland ponds. Many older ponds in New South Wales have far more gentle pond bottom slopes.

36.5 ARTIFICIAL FEEDS

Artificial feeds used in early growout trials were pelleted diets developed for poultry or trout (Maguire and Hume 1982; Maguire and Allan 1985). Subsequently, specialized shrimp diets were developed by research workers and commercial feed companies. Unfortunately, Australian diets proved inferior to imported Taiwanese diets even though their chemical composition seemed appropriate (Maguire et al. 1988). Greater emphasis has now been placed on the inclusion of protein sources of marine origin, such as from mollusks (Maguire and Allan 1989). Australia produces a wide variety of protein rich meals from terrestrial plants, including soybean and lupin meals, and has a sophisticated feed industry for livestock. Local fish meal production, however, has only recently begun and virtually no other protein rich meals from aquatic sources are produced (i.e. no squid or crustacean meals). Hopefully, co-operative research programs on shrimp nutrition and feed formulation by feed companies and public sector research workers will result in more cost effective local feeds.

Considerable emphasis has been placed on optimizing feeding rates (Maguire and Leedow 1983; Allan 1989b), as overfeeding has probably been the major cause of unsatisfactory food conversions and associated pond management problems (Maguire 1987). Most farmers use Taiwanese-style feed trays to adjust feeding rates based on feed consumption by shrimp, although feed rates as a percentage of shrimp biomass are still the overall guide. Many farmers use feeding rates substantially below those recommended for more intensive *P. monodon* culture in Taiwan (Allan 1989b). Emphasis has also been placed on feed storage problems on tropical farms, where fungal aflatoxins can develop quickly (H. T. Ostrowski-Meissner, personal communication 1989).

36.6 ADVANTAGES AND CONSTRAINTS

36.6.1 Climatic Attributes

While considerable climatic diversity occurs in Australia, and in theory provide a basis for a diverse aquaculture industry, there are some constraints for shrimp culture in Australia. Apart from destructive cyclones in tropical areas, water temperatures are the major concern. Even the important tropical shrimp farming region from Cooktown to Mackay (Fig. 1) does not have ideal temperatures for culture of tropical species on a year round basis, and the situation is much worse in the warm-temperate area near Yamba. Attempts to overcome these limitations include; (1) reduced feeding rates during cooler weather, as optimum feed conversion efficiency occurs at water temperatures 3 C below the lower limits for optimum growth of *P. monodon*

and M. macleayi (Maguire and Allan 1987b), (2) use temperate species for farming during cooler months, such as M. macleayi in New South Wales, (3) passively heat nursery systems (with or without supplementary heating) to extend optimum growing seasons, (4) leave ponds fallow during the coolest months, and (5) construct ponds in the warmest (most northern) coastal areas of Australia. Unfortunately, these are the areas with the lowest population and poorest infrastructure (Maguire 1990). A feature of many Australian tropical areas is a prolonged dry season during cooler months (Maguire and Allan 1987a). This problem is less prevalent in warm-temperate areas. Fortunately, freshwater supplies are available at some sites, although this remains a major limiting factor at many farms. Some farmers grow P. esculentus during this period, but none of the local species have proved ideal for cooler, hypersaline conditions which are inappropriate for P. monodon (Maguire and Allan 1987a)

36.6.2 Site Availability and Costs

Site availability problems may still inhibit future growth of the Australian shrimp culture industry. This is particularly true in tropical areas with high silt levels in coastal waters protected by the Great Barrier Reef (10°N to 25°N, Fig. 1), which adversely affect hatchery operations. Perhaps for this reason, hatcheries have developed in warm-temperate areas south of the Great Barrier Reef, even though most of broodstock are from tropical areas.

Australia currently places high emphasis on conservation issues, and new projects, particularly those which involve effluent discharges, are rigorously assessed by governmental authorities before they can be approved (Allan and Maguire 1987). The net result for shrimp culture is that projects can experience substantial delays, but few shrimp farms have experienced pollution of their water supply. Furthermore, a large number of approved pond sites have yet been developed, and many existing ponds not yet operated at full production (Maguire and Allan 1988).

Although Australian coastal land prices vary depending on region and alternative land uses (e.g. tourism), land suitable for shrimp ponds can usually be purchased for A\$2,000 to 3,000 per ha. Such low land prices would normally favor construction of larger ponds, and low stocking densities (Scura 1987), but instead the tendency has been to subdivide larger ponds and intensify pond management (Maguire and Allan 1988). In many cases, potential farmers already owned land but were seeking alternative uses for it. With greatly improved prospects of the sugar industry (ABARE 1989, pp 385-387), less cane land is likely to be converted to shrimp farms in the future.

36.6.3 Marketing

As Australia is a relatively affluent country with its population centers near the coast, there is strong local demand for shrimp. Unfortunately, this advantage is negated somewhat by the country's small population (17 million). Information provided by ABARE indicates that the Australian domestic shrimp market is similar to the catch produced by fisheries (approximately 20,000 t heads-on); yet most of the catch is exported. Prices for cultured shrimp in recent years have usually been in the range A\$10-15/kg. The outlook is for weakening international prices, however, which is likely to depress domestic prices (ABARE 1989, pp 410-412). For this and other reasons, Australian cultured shrimp prices were depressed in 1988/89. Furthermore, with increased world production, competition will likely increase from imports. ABARE data indicate that Australian imports of chilled/frozen shrimp (heads-on equivalents) increased from 5910 MT in 1987/88 to 7140 MT in 1988/89. While export-size Australian cultured shrimp have been produced, Scura (1987) argued that Australian producers would find it difficult to compete with Southeast Asian farmers. Thus the Australian industry could be limited by both market size and depressed prices.

36.6.4 Diseases and Predators

In the longer term, a major industry concern could be shrimp diseases, especially since disease problems have been strongly implicated in the collapse of the Taiwanese shrimp culture industry (Kwei Lin 1989). While a variety of bacterial, fungal and protozoan diseases occur in Australian shrimp hatcheries and ponds, most of these are not major problems because of moderate stocking densities and high water exchange rates (Paynter and Lester 1987). Of more serious concern are viral diseases. Thus far, the Australian industry has only been troubled by Baculovirus in hatcheries (Doubrovsky et al. 1988) and this is usually only associated with inappropriate hatchery procedures (Paynter and Lester 1987; Paynter 1989). Specifically, infectious hypodermal and hematopoietic necrosis virus (IHHNV), which has caused major problems in other countries, has not yet been found in Australia (Lightner 1985). To protect native species and to reduce the risk of disease introduction, no live penaeids may be brought into Australia. In contrast, importations have been commonplace in other countries, which contributed to their disease problems.

Coarse filtration of incoming seawater has reduced predatory fish problems, but at some farms in southern areas, such as Yamba, predatory cormorants (Phalacrocorax spp.) are still a problem.

36.6.5 Other Factors

Fortunately, Australia has a sophisticated research, technical, and educational infrastructure which should allow for development of more cost effective technology. Aquaculture has only become a priority area for national research funding in recent years, but research projects relevant to shrimp culture are developing rapidly (Maguire 1990). One initiative of particular significance is the establishment of a long term selective breeding program for penaeids in Queensland (Benzie 1988). Australian companies are now producing specialized aquaculture equipment and are becoming increasingly involved with exporting technology, such as pumps and aerators, to shrimp culture industries overseas. Educational support includes establishment of a national centre for aquaculture teaching and research, which along with other tertiary institutions is producing trained technicians and research workers who are finding employment in jobs of value to the shrimp culture industry (Maguire 1989). This is helping alleviate a major problem with aquaculture expertise shortages in Australia. Fortunately, technical staff recruited from other countries have contributed greatly to the Australian industry, particularly in the hatchery sector. Labor and interest costs are of serious concern in many western economies, although the major decline in the Australian dollar has reduced local labor costs in a relative sense.

36.7 CONCLUSION

Australia has the physical, intellectual, and technical resources needed for the establishment of a large shrimp culture industry. Limitations include available species and sites, and production costs. Marketing considerations are crucial to the short term future of this rapidly expanding industry. High product quality has been maintained for cultured shrimp. As in the U.S., however, it will be difficult to ensure differentiation of local product from imported shrimp (Rhodes 1989). In the longer term, the shrimp culture industry in Australia must depend on export markets. An intensive phase of research and development is required to improve production efficiency if Australian shrimp farmers are to effectively compete with their Southeast Asian neighbors. Fortunately, there are clear indications that research and development efforts are yielding positive results in Australia.

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CHAPTER 37

L. James Lester

OVERVIEW OF SHRIMP FARMING IN THE WESTERN HEMISPHERE

37.1 HISTORY

There is no tradition of shrimp culture in the Western Hemisphere equivalent to the Asian tradition of capture and hold in intertidal ponds (see Chapter 15). Modern shrimp farming in the Western Hemisphere began in 1968 with the construction of the first shrimp farm in Ecuador in El Oro Province (Rosenberry 1990). In the same year, shrimp culture trials were conducted in Honduras (Weidner and Neimeier 1988). Since that time the activity has expanded into 20 more countries in the hemisphere (Table 1). Only two Western Hemisphere countries are treated in detail in this book, Ecuador (Chapter 38) and the United States (Chapter 39). Ecuador is by far the largest producer, but other countries have enough potentially suitable land to rival Ecuador's production. The U.S. has been the source of

Table 1. Time sequence of shrimp culture development in the Western Hemisphere. Dates are given for the initial production from the first pond-based shrimp culture facility in each country.

YEAR	COUNTRY
1969	Ecuador
1973	Honduras
1974	Panama
1975	Peru
1978	Costa Rica
	Nicaragua
1979	Guatemala
1980	Mexico
1981*	Brazil
	United States
1982	Cuba
1983	Columbia
	Dominican Republic
1985	El Salvador
1986	Venezuela

* In 1981 production from the Western Hemisphere surpassed 10,000 MT.

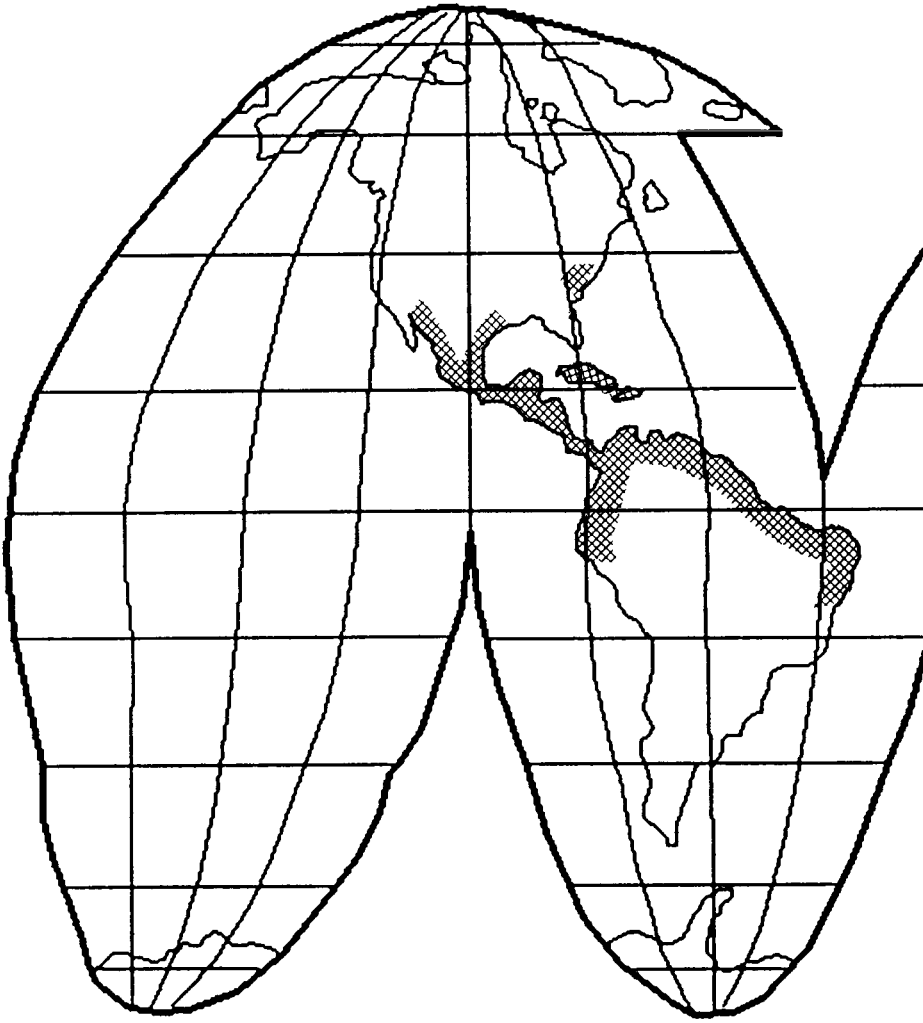


Figure 1. Map of the Western Hemisphere on which current and potential shrimp farming areas are designated by shading.

considerable research on marine shrimp culture and many consultants active in the shrimp culture industry in the Western Hemisphere are U.S. citizens.

In 1990, global production of cultured shrimp was estimated at 632,900 MT. Only 15% of this production came from the Western Hemisphere and 76% of that came from Ecuador. The countries surveyed in this chapter accounted for 97,400 MT of shrimp which came from 129,450 ha of ponds

(Rosenberry 1991). In the early 1980's, Ecuador produced more cultured shrimp than any other country in the world. By contrast, at the present time, China, Indonesia and Vietnam are all reported to have more hectares of shrimp ponds than the total for the entire Western Hemisphere. Also, China, Indonesia and Thailand are each reported to have produced greater quantities of shrimp than all of the countries in the Western Hemisphere combined (Rosenberry 1991).

Shrimp culture activity in Asia has developed out of a tradition of aquaculture. The industry in the Western Hemisphere has developed independent of an artisanal tradition and with much new technology. Some of the technology has been borrowed from Asia and some developed independently. There is a large difference between the development patterns of the shrimp culture industries in the Eastern and Western Hemispheres. In Asia there were fish and shrimp ponds that could be improved; in the West, all of the ponds had to be constructed. In Asia there were people with knowledge of fishpond management; in the West, the knowledge was obtained from biologists and engineers or by trial and error.

There is considerable potential for expansion of the industry in Western Hemisphere countries, with the exception of Ecuador which has exploited much of the land suitable for shrimp ponds. There are small shrimp farming industries in Mexico, Guatemala, Columbia and Brazil; all of which have sizeable coastal areas offering potential sites. The areas of the Western Hemisphere in which shrimp farming is developing are shown in Figure 1.

37.2 SPECIES

In Table 2 each country in the region is listed with the species that are reported to have been used in that country's shrimp culture operations. The list contains two species from the Eastern Hemisphere, P. japonicus and P. monodon. There is some effort to transfer the Taiwanese intensive culture methods to the Western Hemisphere using P. monodon, but these operations are rare. The use of P. japonicus is limited to an experimental operation in the Bahamas which is now closed and to Brazil where a more cold tolerant species was sought for growth in temperate regions. Most of the growers in Latin America are located on the Pacific coast in regions where P. vannamei and P. stylirostris can be obtained as PL or as gravid females. These are the species preferred for culture in North and South America. P. vannamei is used in all U.S. farms and in nearly all of the farms which purchase PL from hatcheries and collectors in Latin America. Farms on the Caribbean or Atlantic coasts often utilize indigenous species, such as P. schmitti, P. subtilis, and P. brasiliensis, especially in Brazil. The use of indigenous species is

encouraged in several countries and the importation of exotic shrimp is regulated in many countries.

37.3 SEEDSTOCK SOURCE

The source of seedstock for Western shrimp aquaculture has always been collection or rearing of PL. The practice of constructing ponds which can be stocked through tidal influx of PL has not been part of the tradition as it has in Asia. Instead there are many individuals involved in seed collection through out Latin America. As capital investment has increased, the unreliability of natural production of PL has led to increased dependence on hatchery production. Nevertheless, many thousands of individuals currently gain their livelihood as "larveros" or "semilleros", collecting PL along the beaches of Latin America with push nets. Earnings from sale of PL to farmers are often greater than other jobs available to the rural poor. PL collectors operate on most of the beaches in Ecuador and in many beach and

Table 2. A listing of species used in shrimp culture in Western Hemisphere countries.

Country	Species									
	PV	PY	PS	PB	PA	PD	PC	PM	PJ	
Brazil	x	x	x		x			x	x	
Columbia	x	x	x							
Ecuador	x	x								
Peru	x	x								
Venezuela	x	x	x	x						
Belize	x	x	x							
Costa Rica	x	x								
El Salvador	x	x								
Guatemala	x	x								
Honduras	x	x								
Mexico	x	x	x		x	x	x			
Panama	x	x								
United States	x	x						x		
Bahamas	x	x							x	
Cuba			x							
Dominican Republic	x	x	x					x		
Puerto Rico	x							x		

Species abbreviations: PV= P. vannamei; PY= P. stylirostris; PS= P. setiferus and P. schmitti; PB= P. brasiliensis; PA= P. aztecus and P. subtilis; PD= P. duorarum; PC= P. californiensis; PM= P. monodon; PJ= P. japonicus.

estuarine environments of other Latin American countries. The collectors have an impact on other marine species collected as by-catch and on the shoreline where they often construct temporary dwellings (Epler 1990).

The estimated number of hatcheries in each country producing farmed shrimp is listed in Table 3. The fluctuation of PL supply in Ecuador in 1985 and 1986 led to the realization that a major industry needed a reliable source of seedstock. Thus dependence on hatcheries has been growing. Hatchery seed had been considered less desirable than wild prior to the great shortage.

Hatchery technology had developed in the U.S. by the early 1970's as a result of experimental work at the National Marine Fisheries Service laboratory in Galveston, Texas. The French AQUACOP laboratory in Tahiti developed similar expertise about that time. Taiwanese hatchery technology was also imported into Latin America for hatchery development. The Galveston method of larval rearing is described in Chapter 6 and the Taiwanese method in Chapter 7. These technologies are the basis for all of the hatcheries operating in the Western Hemisphere today.

Some hatcheries have departed from the traditional production of PL from wild-caught mature females. Granada Corporation operated a hatchery during 1990 in College Station, Texas which used a closed seawater system because it was over 200 km from the coast and marketed PL that were treated with a vaccine said to increase resistance to diseases. Amorient and Laguna Madre Shrimp Farm (now Harlingen Shrimp Farm, Ltd.) have marketed PL from domesticated stocks that reportedly offer improved performance. Unfortunately, it has proven very difficult to maintain a captive broodstock free of IHNV virus.

37.4 GROWOUT METHODS

South American countries, Mexico, Guatemala and Honduras have large areas of low cost land available for the development of shrimp culture and have focused on extensive production systems with limited inputs. Panama, Costa Rica, United States, and Caribbean countries have higher land costs and, in most cases, less land available for production ponds. These countries have primarily developed semi-intensive production systems. In Hawaii and some Caribbean countries, intensive systems are considered feasible due to the very high land costs and the presence of a local market for high value seafood. None of the U.S. production facilities constructed for ultra-intensive production have proven profitable (see Chapter 18). Western Hemisphere countries tend to have lower population densities and less infrastructure in shrimp farming areas, e.g., electrical service and roads, than Asian countries. This may result in less pressure toward intensification of production.

Table 3. Shrimp farms, farming area, production and numbers of hatcheries found in Western Hemisphere countries.

Country	Number of		Hatcheries	Production
	Farms	Area		
Brazil	50	9,500	14	4,000
Columbia	40	4,000	10	3,000
Ecuador	1,500	121,000	120	40,000
Peru	60	4,300	5	3,000
Venezuela	2	160	1	100
Belize	5	200	2	200
Costa Rica	5	30	1	150
El Salvador	6	120	1	100
Guatemala	10	1800	0	1,200
Honduras	65	4500	0	4,000
Mexico	100	7000	7	6,000
Panama	35	3300	5	1,000
United States	31	420	8	1,200
Cuba	na	700	3	650
Dominican Republic	3	150	2	1,000
Puerto Rico	1	0.1	0	-
St. Kitts	1	3	1	4

This information is compiled from Rosenberry (1990, 1991), Shleser et al. (1989), Weidner and Niemeier (1988) and Chapter 39. These figures are the maximum estimate from one of the sources or an interpolation between two sources.

37.5 PRODUCTION AND MARKETING

Shrimp ponds are harvested by a variety of methods. Ponds that do not drain are harvested by repeated use of cast nets or seine. This was the approach used in the early, extensive phase of shrimp culture in the West. More production now occurs in drainable ponds which are harvested by net or baskets attached to a drain pipe. In some cases, harvest technology has progressed to use of a fish pump pulling from a catch basin. The harvest is usually iced at the pond side and rapidly transported to a processing plant. Larger farms sometimes build processing plants on site.

Farms that are near a large market or airport often sell a heads-on fresh product. Most production is frozen, shell-on tails. Some cultured production is being given value-added processing such as, butterfly or peeled-deveined for sale in the U.S. restaurant market.

Cultured shrimp are an export commodity in all Western Hemisphere countries except United States and some Caribbean countries where the restaurant industry provides a specialty market. Even as an export commodity

some growers are able to market their cultured product in the U.S. and Europe as a specialty item and obtain high prices.

37.6 FINANCIAL AND GOVERNMENTAL SUPPORT

Several types of financial approaches have been involved in the expansion of shrimp farming in the Western Hemisphere (Weidner 1985a and b; Weidner and Neimeier 1988). Primarily private sector venture capital has been used to fund projects in these countries. This is particularly true in Ecuador and the U.S. At the other end of the spectrum are projects that have been funded with international development money from World Bank, International Development Bank, the United Nations, U.S. Agency for International Development and other international aid agencies. National development banks have been involved in financing shrimp farms, often with low interest loans, in Brazil, Mexico, Cuba, Nicaragua and Costa Rica among others.

In several countries, the governments lease the coastal land to the shrimp farms. This is true in Ecuador and Panama and is usually associated with the placement of shrimp farms in mangrove or other intertidal areas. Many governments make concessions to the shrimp farming industry to encourage its development as an earner of foreign currency. These concessions usually take the form of tariff and tax reductions. Sometimes export earnings are converted to national currency at a more favorable rate than the official exchange rate.

Technical support from government agencies is often difficult to obtain. This is one reason for the extensive use of consultant services in Ecuador. Several countries have made significant investments in research and extension support for shrimp farming; these include Brazil, El Salvador, Mexico, Peru and United States (Rosenberry 1990, 1991). Often technical support is provided as foreign aid or as part of a private investment arrangement. The primary sources of this type of technical consultancy are Taiwan, U.S., France and Japan. It is interesting that these consulting activities sometimes take place in countries with existing expertise. For example, Japanese and Taiwanese expertise has been used in the development of several projects in the U.S. and U.S. consultants have been called on to solve problems in Taiwan. This is an indication that not only the product, but also the technology for shrimp production, is freely traded in the international economy.

37.7 ECONOMIC IMPACT

Shrimp farming operations are typically financed by wealthy individuals or corporations. Profits usually flow into the urban or international economies and less into the areas surrounding the farms. Shrimp culture, in most Western Hemisphere countries, should not be viewed as a development activity for the benefit of rural poor, although there have been some projects which have been perceived in that context. Shrimp farming projects for ejidos and cooperativos in Mexico were developed for the benefit of the rural population, but the technical complexity and labor requirements led to a poor fit with the life style of the participants (Cruz 1990). Participants from some communities in which the farms were constructed reported negative impacts on health and insufficient compensation (Cruz 1990).

In many cases, it can be documented that construction and operation of shrimp farms creates new jobs in a region; however, these jobs are commonly low paying. The labor which goes into these jobs is often taken from agricultural or fishing activities that were uncompensated, but provided food for the laborers' families. Technical jobs are usually filled by personnel brought from outside the area.

The construction and operation of shrimp farms can have a negative economic impact on a region in some cases. When farm construction destroys nursery habitat for local fisheries, the economic return from fishing will decrease, but this is seldom considered a cost of the shrimp farm. When labor is obtained from an agricultural or fishing labor pool and poorly compensated, the workers may have a lower standard of living after being employed by the farm. When shrimp larvae or broodstock are obtained from the wild and reduce the production of the local fishing industry, the local economy may decline, but the cost would not be attributable to the shrimp farm (Meltzoff and LiPuma 1986).

It is possible to construct shrimp farms that do not reduce estuarine nursery areas, that use captive stocks for seed, and that do not negatively impact local fisheries. Properly managed shrimp farms are more productive than most agricultural production systems; therefore, it should be possible to provide enough compensation to laborers to replace the value of lost agricultural production. When shrimp farming is used for rural development as is proposed in El Salvador, Nicaragua and Mexico, these problems should be considered by the planners before construction.

Large integrated shrimp farming industries, like the one which has developed in Ecuador, have a major impact on the economy of the country (see Chapter 38). Manufacturing of supplies and feed and processing of the harvested shrimp create uses for raw materials and new jobs. Transportation infrastructure tends to improve in coastal areas and transportation activity

increases. The impact of such an industry on the economy of any Western Hemisphere country will be beneficial if the development is supported by local capital and the market value of the product remains high. If foreign capital is used, the terms of the loan or expatriation agreements must be carefully considered. If market value of shrimp falls as a result of greatly expanded aquacultural production, then the profitability of shrimp farming must be carefully compared to other aquacultural or agricultural crops.

37.8 ENVIRONMENTAL IMPACT

One difference between the impact of Eastern and Western Hemisphere shrimp culture approaches results from the dependence of much Western culture on collection of wild PL. The larvae of many other species are collected with the penaeid PL and killed as a result. Similar impact might also occur from the fishing pressure on gravid *P. vannamei* females. However, this should not be qualitatively different from the impact of the capture fishery.

Shrimp farms are sometimes built in ecologically sensitive areas such as mangroves or marshes (see Chapter 34), but often the characteristics of intertidal soils are detrimental to pond culture and encourage the use of agricultural lands.

37.9 REGULATIONS

There are many ways in which government regulations impact the operation of shrimp farms. The general categories of regulation do not differ greatly between capitalistic and socialistic governments. Regulations can be categorized according to resource utilization, environmental conservation, and financial regulation. U.S. regulations, which may be the most extensive, are discussed in Chapter 39. Western Hemisphere countries, particularly Mexico, have a history of regulation quite distinct from the countries in the Eastern Hemisphere.

There is considerable variation among Western Hemisphere countries in the degree to which they regulate their common resources and their economy. Those countries which have governmental ownership of the affected lands usually require some evaluation of the impact of a shrimp farming operation. In many cases, this evaluation is primarily concerned with the economic impact of the activity on the capture fishery, etc. If the land is privately held, there is often no evaluation of the proposed use. Water to supply the ponds is always a public resource, but there is seldom monitoring of the amounts pumped and the quality of the effluent returned to the water source.

Conservation of natural stocks of shrimp has received some attention from regulatory agencies. There have been attempts in Ecuador to preserve the natural stock from PL overfishing by declaring closed seasons on all shrimp fishing. However, Ecuador recently passed legislation permitting export of seedstock (Rosenberry 1991) which indicates a relaxation of concern for the shrimp stock. In Venezuela, indigenous species must be used in addition to exotic species and exotics are quarantined for at least 30 days. Also, it is illegal to capture wild PL's for stocking ponds. Some farms have dealt with the quarantine on P. vannamei by using pond-reared broodstock for maturation. Mexico and Panama have had regulations on the capture and export of wild seed and broodstock, but this may change as a result of the new government in Panama and shifts in policy of the Mexican government. Once the industry has a domesticated shrimp breed which is superior to the wild stock this problem will diminish.

Another aspect of concern for the natural stocks is the potential impact of releases of exotic shrimp and/or their disease organisms. Much attention in the U.S. has recently been directed to this issue. It is hoped that regulations on certification of larval and PL health and screening of pond outfalls will prevent any transfer of shrimp or shrimp diseases to the wild. New regulations in Texas declare all non-indigenous Penaeus species to be potentially dangerous. Farms are required to obtain an exotic species permit and to destroy the farm's stock in case of flooding or overflow of ponds into natural waters.

Conservation of natural habitats is also of concern in Ecuador and other countries because many of the farms are constructed in mangrove areas which serve as nursery grounds for fishery species. About 40% of the shrimp farms in Ecuador are in intertidal areas, most of which was mangrove before conversion. Other countries in the region are showing concern about permitting the development of farms in these areas. In the Caribbean, there may be an additional concern about the health of coral reefs located near outfalls from shrimp ponds. The organic-rich effluent will encourage the growth of algae which can cover and kill the coral. In typical estuarine areas this nutrient-rich effluent may only contribute to productivity and not significantly change the community ecology.

37.10 ACTIVITY BY AREA

The hemisphere can be divided into three areas, South America, North America and the Caribbean. In the latter, one can only discuss potential because there is as yet very little industry.

In South America, there are two countries that have great potential for shrimp farming, Brazil and Columbia (Weidner and Neimeier 1988;

Rosenberry 1990, 1991). In the case of Brazil, the economy is a major impediment to the flow of investment capital into shrimp culture projects. Poor performance of early projects, some of which used P. japonicus, has not encouraged local enthusiasm. The Superintendencia de Desenvolvimiento Pesquero has provided low interest loans and assistance to shrimp farms, but it is not clear how many of these projects qualify as financial successes. The political situation in Columbia is a deterrent to development of rural projects, such as shrimp farms. This situation has exacerbated problems associated with weak infrastructure. Commerce in seedstock is difficult and unreliable. Management has been unable to solve some of these problems and a number of farms are reported to have temporarily ceased operation.

North America has another country of great potential, Mexico. A 1989 change in the Fishery Development Law will permit private sector shrimp farming and minority foreign investment after April, 1990 (Rosenberry 1991). Prior to this only cooperativos and ejidos were permitted to participate in shrimp fishing or culture. Encouragement by the government of President Salinas de Gortari may lead to development of shrimp culture in the southern Pacific Coast states of Chiapas and Oaxaca and in the Yucatan Peninsula. The Mexican government is already sponsoring shrimp culture research in several government institutions and has an ambitious plan for development, the Programa Nacional de Cultivo de Camaron, which calls for construction of 70,000 ha of ponds by 1994.

There are very few shrimp culture operations in the Caribbean (Shleser, Alston and Arthur 1989). The shortage of suitable sites and absence of processing and distribution infrastructure are certainly impediments to the development of an industry. However, when one looks at the alternative industries for this region, aquaculture does not seem unreasonable. Capital construction costs are not as high as for manufacturing. The technical infrastructure for construction and operation are in place. On the larger islands, Cuba, Puerto Rico and Hispaniola, there are sizeable areas of suitable land. Labor costs are reasonable and nearby tourist markets offer premium prices. The government of Cuba appears to be providing support for development of its shrimp culture industry and achieving some success. It appears that what is lacking in most other Caribbean countries is the active support of the government through its financial and permitting agencies.

37.11 CONCLUSION

Although the current climate for development of shrimp culture in the Western Hemisphere does not match the "gold rush fever" of the early 80's, there is still interest and commitment on the part of many knowledgeable people. It is interesting to note that many Taiwanese are investing in

Western Hemisphere projects subsequent to the crash of P. monodon culture in Taiwan. The variable which will determine rate of development of shrimp culture in the Western Hemisphere is the commodity price of shrimp. As Asian production continues to climb, the potential profit for investors is likely to decline. This would significantly slow the expansion of the industry. Independent of this factor, the region possesses the natural and human resources to support a much larger industry.

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CHAPTER 38

Yosuke Hirono and Mark Leslie

SHRIMP CULTURE INDUSTRY IN ECUADOR

38.1 INTRODUCTION

For the past several years, Ecuador's seafood exports values were second only to oil. Shrimp production from the culture industry has increased 1,400% over the past 10 years, with a compounded annual growth rate of 36.5%. Until recently, Ecuador was the leading producer of cultured shrimp in the world. Ecuador's shrimp exports reached approximately US\$ 350 million in 1988. Shrimp export products have increased 123 times over 1978 values. Cultivation areas are 30 times greater than during 1978, and farm expansion has exhausted almost all the cultivable land. Thus, future shrimp production increases can only come from higher pond production through technical innovations and intensification. Ecuadorian shrimp culture still depends heavily on the availability of wild seed stocks, since hatcheries cannot produce adequate quantities of quality postlarvae (PL). Consequently, shrimp yield (kg/ha/yr) has not improved but by only 2-5% annually. Ecuadorian shrimp farmers have come to realize that their technology and production methods are not as adequate as some foreign counterparts. Previous high profit margins for cultures shrimp have inhibited creativity or improvements in production methods. The expected downward trend in the international shrimp market, and current internal economic troubles in Ecuador may now change that. Furthermore, the shrimp culture industry in Ecuador is periodically impacted by the effects of El Niño. Ecuadorian shrimp farms then feel the deprivations of basic raw materials such as natural seed stock, feed ingredients, etc. Thus, the expanding shrimp culture industry is presently transforming its semi-intensive production methods to more cost-effective production systems.

38.2 HISTORY OF SHRIMP CULTURE INDUSTRY

The idea of establishing shrimp farming was born by accident in 1962 when two local farmers discovered many birds feasting on large shrimp which had grown inside small puddles of water in a coconut plantation at the southern edge of the Gulf of Guayaquil. The first company to cultivate

shrimp in a pond was legally formed in 1968. The company began by constructing a 20 ha pond with heavy equipment in 1969, and expanded in increments of 30-40 ha each year thereafter. Although the first harvests were not promising, it did not discourage Ecuadorian investors. By 1977, enthusiasm for shrimp farming had reached a "Gold-Rush fever" and the number of ha under cultivation increased more than 37 fold in less than 12 years.

The shrimp farming industry in Ecuador has developed through three phases. The first phase was the initial 10 years of extensive culture. This era started in 1968 with the formation of a shrimp farm in El Oro province, bordering with Peru, and ended in 1977. The second phase encompassed the era of the "Gold-Rush fever", and rapid expansion. In this period, almost everyone who had economical and financial support became involved in shrimp farming, often with indiscriminate land use. This sudden interest in the shrimp culture was triggered by the introduction of more modern and productive culture systems and methods by experienced foreign culturists. Semi-intensive culture was first introduced by running experimental trials with imported feed on several shrimp farms in El Oro province in 1977 and 1978. Results of feeding experiments encouraged many farmers to convert and/or construct semi-intensive production systems with larger pumping capacity and better water distribution (reservoir) canal systems. This second historical phase began with about 3,000 ha in 1977, and ended in 1988 with 120,000 ha. The latter is close to maximum utilization of land suitable for this activity. Today we have entered the third phase, with shrimp farmers having difficulties operating their farms mostly due to a lack of essential materials and management skill; including seed stocks, inexpensive feeds, repair parts, working capital, etc.

38.3 NAUPLIUS PRODUCTION

Ecuador has abundant populations of wild broodstock shrimp (*Penaeus vannamei*) which spawn naturally, and abundant mangrove areas which provide a vast nursery ground. Ecuador is thus blessed with abundant wild PL for over half the year (Dec.-May). Ecuador has, however, a year-round shrimp culture growing season that requires a continuous supply of PL. Farmers are able to supplement their PL requirements with hatchery-reared PL, especially during those months when wild PL are scarce.

38.3.1 Wild Nauplii

Availability of sufficient quantities of quality nauplii is the foundation for successful production of shrimp PL. In Ecuador, nauplii are produced from wild gravid females, as well as from induced maturation of captive broodstock.

There are numerous companies dedicated to the procurement of wild gravids, which in turn sell nauplii to the various hatcheries. There are more than 25 spawning stations located in the northern province of Esmeraldas where gravid females are sporadically available throughout the year. At any given time, 10-15 of these facilities are in production. During the warmer months of the year (Dec-April), many wild spawners can also be captured farther south, especially in the "Hatchery Row" area of San Pablo. During these months, numerous hatcheries in that region use their own facilities to spawn the gravid females. Even though production from Ecuador's shrimp breeding grounds is inconsistent, it still provide more than 50% of the hatcheries' nauplii needs.

A typical spawning station consists simply of a series of spawning tanks enclosed under one roof. Spawning tanks vary in size and shape. They commonly are dark in color and circular. The bottoms can be flat or conical, and range in size from 100 liter plastic garbage cans to 5,000 liter cement tanks.

Wild gravid females are collected each night by shrimp trawlers and local artisan fishermen using gillnets. The mated females are sold on the beach. The current selling price for an impregnated gravid *P. vannamei* female averages US \$ 60 to 100/each. Price can vary greatly depending on hatchery demand and competition among buyers. Gravid females are then delivered by truck to nearby spawning stations. The number of females placed in each spawning tank depends on the size of the tank, and whether a decision is made to screen individual females for *Baculovirus penaei* virus.

Each gravid female spawns between 100,000 and 250,000 eggs of which 40-60% hatch out to become healthy nauplii. Therefore, each female can produce 40,000 to 150,000 nauplii/spawn with the average near 100,000. Many hatcheries treat the eggs prior to hatching to reduce the levels of viral, fungal and bacterial contamination. Argentyne Iodine solution and Malachite green are commonly used for this dip treatments. Hatching water is usually filtered through 5u mesh, and sometimes sterilized with ultra-violet light. Nauplii are collected from the spawning tanks by light separation, drawing off the most active larvae from the surface.

Before transport, nauplii are packed in oxygen-filled, double plastic bags, which hold 15 l of filtrated seawater. Stocking densities average 20,000 to 30,000 nauplii/l. Shipping temperatures average 24-26 C. From the spawning stations, nauplii are delivered to the hatcheries by plane, truck or taxi. Transport mortalities are normally less than 1%. Selling price of the wild nauplii ranges between US \$ 0.80 and \$1.20/1000, depending on demand and availability. In 1988 over three billion wild nauplii were purchased by local hatcheries.

38.3.2 Maturation and Spawning

Due to the irregular and sometimes limited availability of gravid females, most larger hatcheries construct maturation facilities to assure a year-round of nauplii supply. Ecuador's first maturation facility at Semacua began producing in 1980. Within six years, Ecuador developed enough maturation capacity to produce enough of nauplii to supply all its hatcheries on a year-round basis. Unfortunately, maturation produced nauplii have not been readily accepted throughout the industry. Even though Ecuador has developed technology for producing large quantities of nauplii, the quality of these nauplii have not yet equalled those produced by wild gravid females.

There are currently more than 25 hatcheries operating in Ecuador which have the necessary infrastructure to produce nauplii in captivity. In total, these maturation facilities have more than 600 maturation tanks. Production per tank varies depending on stocking densities and methods. On average, each tank can produce at least 100,000 nauplii/night. By extrapolation, Ecuador's hatcheries are capable of providing more than 15 billion nauplii/year, assuming 70% tank utilization. That is more than 250% of the Ecuadorian hatcheries' present requirements. As previously mentioned, however, the demand for maturation nauplii is much less. In 1988 approximately three billion maturation produced nauplii were used in larviculture. Currently, maturation produced nauplii sell for US \$ 0.50 to \$ 0.75/1000.

Broodstock used for maturation are collected offshore by both shrimp trawlers, as well as local fishermen in canoes. Hatcheries pay US \$ 1.50 to \$ 2.00 for non-inseminated females and males. The hatcheries prefer females greater than 45 g, and males of at least 40 g.

The broodstock are usually held on-site for 1 to 2 weeks before transfer into productive maturation tanks. This time for the animals to acclimate, and to recover from the stress caused by their capture and subsequent transport. It is not uncommon for mortality of 20% between delivery and ablation. Some hatcheries screen the broodstock for viral infections before use in an attempt to obtain virus-free nauplii.

Most Ecuadorean maturation facilities rely on female eye ablation to accelerate ovarian development. Slicing open the eye and crushing the eye stalk is most widely used. Recent studies have also indicated that the molt stage at ablation has an effect on spawn productivity. Ovarian maturation without ablation has been achieved in Ecuador, but has not yet developed on a commercial scale.

A typical maturation tank is usually round and approximately 4 m in diameter. Numerous hatcheries have constructed oval tanks to better use available space. Water depths range from 50 to 70 cm. Water exchange range from 100 to 200 %/day. Incoming water is usually untreated except for

filtration, if any, that occurs at the main seawater intake. Water temperatures are maintained at 27 to 28 C by industrial-scale boilers and titanium heat-plate exchangers. Several maturation facilities recirculate seawater and maintain acceptable water quality by ultra-violet light and bio-filters. By recirculating the same water, some biologists believe that the shrimp's pheromone will accumulate in the tank water and enhance mating activity.

The one important parameter which no two maturation departments seem to have in common is the light regime and intensity used to accelerate ovarian development and promote mating activity. Those which use artificial light, normally use fluorescent cool-white bulbs. The main objective of over-head lights is to increase the hours of light each tank receives daily. Some of the most productive maturation facilities in Ecuador, however, operate without artificial light and rely solely on natural illumination.

A proper diet is extremely important to achieve successful maturation and mating of P. vannamei. As with light cycles, diets vary from hatchery to hatchery. Maturation feeds include fresh oyster meat, adult Artemia, squid, frozen bloodworms, and a high protein dry pellet. The addition of bloodworms have proven to be extremely successful in inducing maturation copulations in P. vannamei. Food quantity fed daily depends on a tank's shrimp biomass, and averages 10 to 15% (wet weight) of the shrimp's weight. Broodstock are fed at least twice daily, and as much as 5 times/day. As soon as female broodstock acclimate, they can be ablated and transferred. Ovarian development normally begins within 7 to 14 days. Some females may spawn within the first week, depending on their initial stage of ovarian development. Natural copulations do not normally occur until 4 to 8 weeks after ablation. In a productive maturation facility 2 to 7% of the ablated females spawn each night. These females are identified and manually removed from the maturation tanks prior to spawning. They are transferred to separate spawning tanks. The actual time of spawning depends on the light regime used in maturation. Spawned females are generally removed from the spawning tanks the subsequent morning, and returned to their maturation tanks. Most maturation facilities in Ecuador use only naturally inseminated females to spawn. Still, several hatcheries remove gravid females prior to copulation and inseminate the females artificially. Artificial insemination requires the manual extraction of the spermatophore from the male. This causes a substantial male mortality, and leaves many males unable to regenerate fertile spermatophores. Natural insemination allows the facility to reuse the males, which frequently become scarce during certain times of year. The ability to successfully inseminate P. vannamei artificially, however, will enable scientists in the future to genetically manipulate shrimp stocks.

Nauplii production varies greatly depending on broodstock diet, broodstock age, and the form of insemination. Typically, a naturally

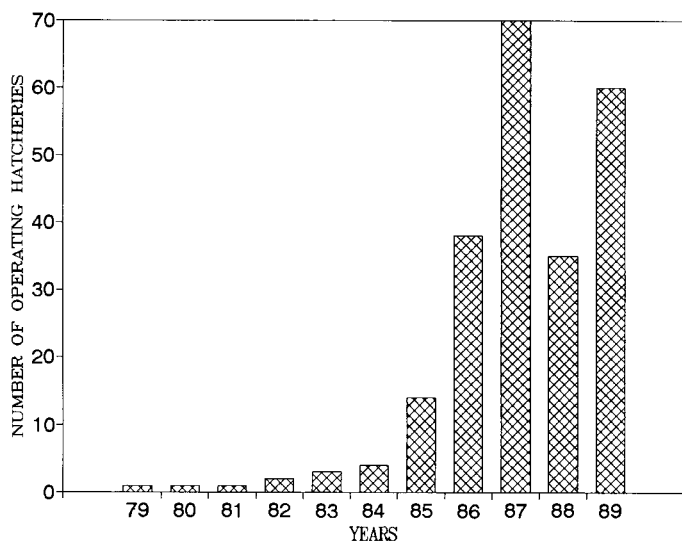


Figure 1. The number of hatcheries in operation in Ecuador in each year since 1979.

inseminated female in captivity can produce more than 80,000 to 100,000 nauplii per spawn. Artificially inseminated females on the other hand, average 30,000 to 60,000 nauplii/spawn. On-going studies are evaluating the differences between nauplii quality from artificial and natural inseminations, and its effects on larval survival and pond performance.

Females are returned to the maturation tanks after spawning where they again undergo ovarian redevelopment. Studies suggest that the number of repeat spawns may adversely effect nauplii quality. Tagging studies also reveal that a small percentage of the females in the maturation tank produce of the nauplii.

Seawater for spawning tanks is typically filtered through 5u mesh with minimal additional water treatment. Spawning tank water temperature is similar to that of the maturation tanks. Eggs are hatched either inside the same spawning tank, or in separate hatching trays. In both cases, nauplii are separated from the unhatched eggs by light separation. Active swimming nauplii are positively phototactic, and therefore can be drawn to the surface and collected. Many biologists believe that light separation provides only the most vigorous, healthiest nauplii for larval rearing. Biologists frequently sample the hatching eggs and view them under a microscope to estimate the percentage of fertilized eggs and quality nauplii available for stocking. Some hatcheries in Ecuador spawn the gravid female inside the larval tank. They believe that larger spawning areas yield more nauplii, even though unhatched eggs and ovarian debris remain inside the rearing tank.

Table 1. Production capacities of Ecuador's hatcheries.

Monthly Production (x10 ⁶)	Percent of Total Hatcheries	Percent of Total Production
0-5	33	7
5-10	24	13
10-15	19	27
15+	24	53

Source: personal communication

38.4 PL PRODUCTION

38.4.1 Hatchery Methods

Most *P. vannamei* PL stocked in Ecuador's shrimp farms are collected from the wild. Ecuador requires about 16 billion seed each year. As with wild nauplii, wild seed availability is seasonal and depends greatly on ocean water temperatures. Originally, Ecuador's hatcheries were built to reduce dependence on wild PL. Unfortunately, inconsistency in hatchery PL quality has done little to achieve this goal. Consequently, hatchery PL are currently used only to supplement wild PL, particularly during May-November when wild PL are scarce.

Due to seasonal and frequent PL shortages, a major effort was made in 1984-1986 to increase Ecuador's hatchery production capacity. During the peak of Ecuador's hatchery "boom" in 1987, over 70 hatcheries were in

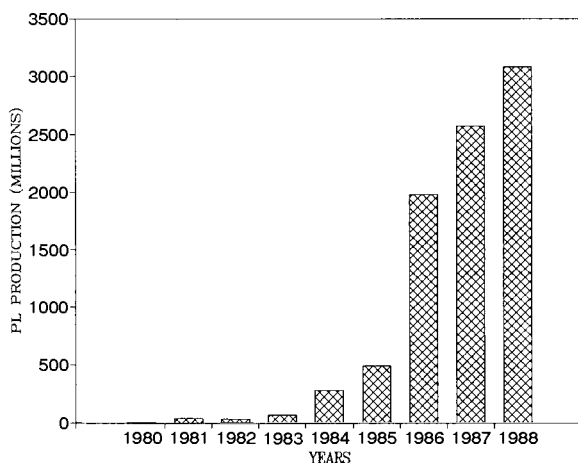


Figure 2. Increases in production of hatchery reared PL in Ecuador since 1980.

operation (Fig. 1). More than 50% of these hatcheries were "backyard" larval rearing facilities in Manabi province. By 1988, hatchery production peaked at more than 3 billion (Fig. 2). In years with abundant wild PL (late 1987-1988), the number of operating hatcheries dropped to 35. When cooler waters (1989) limit wild PL production, the number of producing hatcheries doubled.

Production capacity, or hatchery size is related to farm requirements (if they own a farm), and available capital. As can be seen in Table 1, a large percentage of Ecuador's hatcheries produced less than five million PL/month. The bulk of total PL production comes from the five largest hatcheries, which produce more than 50% of the country's hatchery PL.

Most of Ecuador's hatcheries are situated near the large P. vannamei breeding grounds, especially San Pablo. The availability of broodstock, wild nauplii and consistently good water quality were major factors in site selection for Ecuador's hatcheries.

During the past ten years, more than US \$ 50 million has been invested in Ecuador's hatcheries. Hatchery construction costs varied greatly, as did size and technology level. Many of Ecuador's "mom and pop" hatcheries include only one or two larval rearing tanks and cost less than US \$2,000. On the other hand, some of Ecuador's largest hatcheries, complete with maturation and capable of producing more than 20 million PL/month are valued at more than US \$2 million.

38.4.1.1 Source water for hatcheries

Most of Ecuador's hatcheries take their seawater from Pacific Ocean beaches. Various types of seawater intakes include direct pumping, infiltration galleries, wellpoints, and wells. Facilities that pump directly usually pass the water through a separate sand filter. Numerous hatcheries use large cisterns to store water before use, especially when they are unable to pump continuously. Larviculture water is frequently further filtered through 1 micron. Ultra-violet irradiation is almost always applied to algal culture water, and is frequently used for larviculture water. EDTA is always added to the algal and larviculture water to chelate potentially harmful heavy metals (1-5 g/m³). In areas of poor water quality, some hatcheries chlorinate-dechlorinate their seawater before use.

38.4.1.2 Larval feeding

A typical feed regime use in larval rearing includes both live feeds, primarily Chaetoceros sp. and Artemia sp., and "artificial" feeds, including microcapsules, microparticulates and flakes. Please note that the artificial diets do not completely replace live diets, but instead supplement live diets.

Table 2. Larval feeding regime.

Stage	Standard		Optional Artificial Feed Supplements			
	Algae	Artemia	Frippak	Nippai	Higashimaru	Art.system
	(#/ml)			(grams m-3 day-1 / size #)		
N 5	50,000		1#1	2#AP ²	4#0	Topal ³
Z 1	100,000		2#1	4#AP	6#0	Topal
Z 2	120,000		2#1	4#AP	6#0	Topal
Z 3	130,000	0.3 ^f	3#1/#2	4#AP	6#0	Topal
M 1	100,000	0.5 ^f	4#1	6#0	8#1	Topal
M 2	60,000	1	4#2	6#0	8#1	
M 3	50,000	1	2#2/2#3	6#1	10#1	
PL1		1.5	3#3/3F1 ^a	8#1	10#1	
PL2		1.5 ^e	2#3/3F1 ^a	8#1	12#2	Selco
PL3		2 ^e	4F1 ^a	8#1	12#2	Selco
PL4		2.5 ^e	4F1 ^a	10#2	15#2	Selco
PL5		3 ^e	5F1 ^b	10#2	18#2	Selco
PL6		4 ^e	6F1 ^b	14#2	24#3	Selco
PL7		5 ^e	6F1 ^b	18#3	24#3	Selco
PL8		6 ^e	6F1 ^b	18#3	24#3	Selco

1 Doses for individual feeds, not used in conjunction

2 Artificial Plankton

3 g equivalent to algal level desired

a 200 um mesh Flake

b 500 um mesh Flake

e Enriched (optional)

f Frozen (optional)

Source: Griffith (1989) "Artificial Diet Use in Penaeid Larval Rearing", Instituto de Comercio Exterior Boletín De Camarones #15 Lima, Peru.

By late PL stages, however, artificial diets may represent 80 to 90% of the total diet. A typical feed regime used in Ecuador is shown in Table 2.

Algal culture of Chaetocerus is achieved through sequential batch culture, beginning with 10% inoculum at each step, and two to three day cycles per step. Algal culture cycle times depend upon the hatchery's specific algal growth rates. Final production elements are generally 1 m³ tanks, although production units of up to 12 m³ are used. Total cycle time from 10-20 ml test tubes to 1 m³ tanks is about 20 days. Algal production is continuous, once begun, and is only stopped for hatchery dry-outs. Total algal rearing capacity is directly related to the size of the larval rearing department. Typically, 15 to 25% of the hatchery's total tank capacity is dedicated to algal production.

Consistent light levels, temperature and water quality are maintained throughout the algal production process, with aseptic techniques through the 3 l Fernbach flasks, to preserve algal culture quality. All utensils and culture media are sterilized, and periodic isolations (by serial dilution) are frequently done with tube cultures to maintain strain integrity. Air enrichment with CO₂ is frequently used, especially at the larger hatcheries. Incoming air is cartridge filtered (nominally to 1 μ m) before use in algal culture. On occasion, air filter discs (0.2 to 0.45 μ m) are used for the small volume, stoppered vessels. Since the primary, potential contamination source is considered to be the incoming water, rigorous water treatment is carried out before use. Thus, cartridge filtration down to 1 μ m, ultra-violet sterilization, chlorination and autoclaving are all common practices with seawater for algal culture.

Finally, seawater enriched for algal culture with Guillard's f/2 for tube and small volume culture (up to 3 liter fernbachs), and with f/4 or f/8 for larger culture volumes is used. Occasionally, enrichment of the larval rearing water with only the major nutrients is practiced to maintain an algae bloom within a larval tank.

Artemia hatching is conducted in brightly lit, 250 to 350 l conical, bottom draining tanks at densities of 1 to 2 g of cysts/l using previously decapsulated cysts under strong aeration. Normally the cysts are incubated for 24 hrs, after which time the Artemia Nauplii are light separated and rinsed with freshwater. Artemia enrichment has been accomplished in Ecuador using emulsified fats, rich in the vital w-3 series lipids. Microencapsulated diets have also been used, allowing for even longer periods of enrichment.

Different Artemia strains are used depending on the larval shrimp stage being fed. San Francisco Bay strains are used for the Z3/M3 stages, which require small, highly nutritive nauplii, while less expensive strains of Utah strains are used for mysis. Hatch rates for the San Francisco Bay strains average 250,000 to 300,000 nauplii/g of cysts, while the Utah cysts produce 150,000 to 220,000 nauplii/g. On average, the hatchery requires 5-7 Kg of Artemia cysts to produce 1 million PL8.

Chaetocerus and Artemia are the predominate but not the only live feeds used in larval culture. Some hatcheries use other algal species, such as Tetraselmis chuii, Skeletonema sp., Isochrysis sp. and Chloromonas sp.; as well as nematodes (Pangrellus redivivus) and rotifers (Brachionus sp.). Finally, a small section of the larviculture community use more "exotic" feeds, including oatmeal, egg yolks, lightly cooked blended meat, and fish flesh.

Of the numerous artificial diets available, the following four are commonly used in shrimp larviculture:

- 1) Frippak Feeds (microcapsules/flakes)
- 2) Nippai (microparticulates)

3) Higashimaru (microparticulates)

4) Artemia Systems (enriched yeasts/emulsified lipids).

In practice, not much mixing occurs at a given hatchery with different diets, although certain dietary forms are better at certain larval stages. Furthermore, feeding regimes are unique to each hatchery depending upon tank design, stocking density, the aeration system, production cost expectations and, probably most importantly, individual preference. Artificial feeds are used in larval culture to supplement live diets, while at the same time, provide the hatchery with a consistent quality feed. Table 2 therefore represents an average feed regime, and includes several artificial dietary alternatives.

38.4.1.3 Shrimp larviculture practices

In contrast to the various types of larval feeding regimes, larval culture practices are more consistent throughout Ecuador. Stocking densities are fairly high, with between 70 and 150 nauplii/l stocked (based on eventual total tank volume), in tanks of 6 to 20 m³ capacity. Nauplii are usually stocked in 1/2 to 1/3 of the total tank volume (140 to 300/l). Water levels are gradually raised during these early larval stages in accordance with shrimp densities and algal cell counts. Thereafter, daily water exchanges of increasing percent tank volume are carried out using filtered seawater at 28 to 30 C. As previously mentioned, EDTA is routinely added at 1 to 5 ppm. Production cycles are generally 16 to 18 days, producing PL8 to PL10. Survivals range from between 50 to 90%, averaging about 60% at harvest.

Recently, some hatcheries have successfully used larger outside tanks (20 to 60 m³) for PL nursery rearing. This process involves the transfer of young PL's to outside tanks at much lower stocking levels than in the larviculture tanks (15 to 25/l). Larvae feed on natural phyto- and zooplankton blooms, as well as reduced amounts of Artemia and artificial feeds.

Throughout the larval production cycle, samples of larvae are taken twice daily to assess to following:

- 1) Phototaxis and general swimming activity,
- 2) Development,
- 3) Cleanliness,
- 4) Gut fullness,
- 5) Hepatopancreal lipid presence,
- 6) Chromatophore development,
- 7) Disease presence,

Based on these observations, decisions are made regarding water exchanges, feeding rates, and chemical or/and antibiotic treatments. Such samples are never returned to the culture tanks. This is typical of larval husbandry practices throughout the industry. Each tank has its own

thermometer, samplers, filters and screens. Chlorine footbaths are commonly found in doorways, and access between process areas is restricted. Despite such measures, disease outbreaks occur requiring occasional antibiotics use for preventive as well as curative purposes.

Prior to PL harvest, shrimp condition is assessed; including size, lipid presence, and resistance to a given stress test. The latter usually involves a sudden drop in both temperature and salinity for up to two hours. Percent survival is then correlated with farm survival results. Larval tank counts are made before harvesting. There is much variation in count methodology and accuracy. Counting is generally done volumetrically, with all the harvested PL in a small volume container (5,000 PL/l) from which subsamples are taken for either direct counting, or for further subsampling. While subsampling is much quicker than direct counts, it allows introduces a source of additional error. Some people count PL by weighing the total harvest, and then counting weighed subsamples. This tends to be more accurate, especially when PL are larger and more active.

Finally, consideration must be given to the problems of disease and bacterial resistance in larviculture. Since most hatcheries run continuous larviculture cycles, they eventually develop problems with bacterial build-up and resistance. Unfortunately, large hatcheries with high fixed operating costs are obliged to continue production as long as possible. Over-use of prophylactic antibiotics to maintain production creates bacterial resistance. Such problems are monitored by bacteriological analysis of incoming water and culture tanks. By changing antibiotics regimes or changes in tank management, i.e., lowering stocking densities, the production cycle can be prolonged. Regardless, most hatcheries must periodically shut down and undergo a complete disinfection. Hatchery disinfection (dry-outs) involves high concentrations of chlorine, as well as various other chemical treatments (e.g. formalin, sodium hydroxide, and hydrochloric acid). Following such treatments, the hatchery is thoroughly dried for a period of 3 to 7 days before resuming culture.

38.4.2 Postlarval Transport

Once PL reach the desired size in the hatchery, they are harvested and transported to the farm. PL size when shipped depends mostly on its age, but average standard size is 5.7 to 6.2 mm, and 2.5 to 2.8 mg. Depending on buyer preference, differences between hatchery salinity (32-35 ppt) and farm salinity (0-50 ppt) can be adjusted either at the hatchery prior to shipment, at the farm site, or a combination of the two. Depending on the distance and location of the farm, PL can be transported by air, land, or sea. When transported by air, the PL are packed in 15 l double plastic bags at 2,000 to 4,000 PL/l. Of course, larger PL, are shipped at lower densities. Bags are

filled with oxygen prior to shipment. Larvae are frequently cooled to 22 to 25 C prior to packing. When larvae are acclimated to salinities below 5 ppt, transport temperatures between 19-21 C are necessary. No additional food is given to PL once they are packed in bags. When PL are transported by land or sea, they are shipped in various types of open recipients ranging in volume from 150 to 3000 l. Bottled oxygen is administered during shipment to maintain sufficient oxygen concentrations throughout the journey (>6ppm). Additional water mixing is frequently created by small battery-powered compressors. During lengthy transport when refrigeration equipment is lacking, it is difficult to regulate temperatures. Frequently, such PL shipments are made at night to avoid temperature stress. Transport densities range from 500 to 1000 PL/l, again depending on PL size and shipping distance. Some shipments take up to 24 hrs, in which case feeds are provided as live or frozen Artemia, or as various dry feeds.

38.4.3 Wild Seed

Initially, shrimp culture in Ecuador began with wild PL entrapment and growth in coastal enclosures. The continued success of this industry still relies heavily on wild seed collection. Peak seasonal abundance for P. vannamei seed is normally from October/November until March/April. There is little continuity in wild seed availability, as can be seen from their price fluctuations (Table 3).

Ocean water temperatures have a direct effect on wild seed availability. The longer warm waters remain inshore, the more extended the shrimp breeding season, which in turn increases seed production.

Table 3. Wild Post-Larvae Prices in Ecuador

Year	US\$/1000 PL
1982	3.05
1983	4.40
1984	10.00
1985	20.00
1986	5.30
1987	5.00
1988	4.45
1989	8.00

source: personal communication

Shrimp species composition is also quite variable from wild caught seed. Only *P. vannamei* PL are suitable for growout, and normally range between 70-90% of total. Seed with less than 50% *P. vannamei* are normally considered not worth purchasing, due to excessive amounts of undesirable species. Wild seed caught during May-September tend to fall in the undesirable category. Ecuador has developed a large artesanal fishery for penaeid seed. Perhaps more than 32,000 people are actually involved in wild seed capture. During periods of seed abundance, large work groups can be seen pushing large triangular nets through wave washed beaches, as well as mangrove entrances.

Due to PL value and the large demand created by Ecuador's 120,000 ha of ponds, the seed fishery and its associated intermediaries has become an important source of revenue for coastal communities. Whole families work during the rising and full spring tides to capture and clean (remove fish, crabs, and rubbish) wild PL. They then sell their penaeid PL to intermediaries. Intermediaries may work directly for large farms, or work on contract to smaller farms. Using pick-up trucks with receptacles of various shapes and sizes equipped with oxygen, intermediaries travel up and down the beaches buying seed in small lots from the collectors. The seed is stored on the truck until a sufficient quantity has been collected to warrant the often long trip to the farm. Prior to shipment, tank water may be exchanged. Supplemental feeding is rarely done during wild seed transport.

As previously mentioned, most farmers prefer wild seed because they believe that seed is more hardy and provides better survivals and growth rates compared to hatchery seed. Indeed, so strongly held is this belief that many farms would rather leave their ponds empty than to buy hatchery seed.

Due to unreliable PL stocking counts, data on seed performance in ponds is not readily available. Results tend to suggest, however, that the differences between wild seed and hatchery seed reared from naturally spawned gravid females are minimal, as long as the hatchery seed is not unduly stressed during the growout cycle. On the other hand, hatchery seed reared from maturation nauplii appear somewhat inferior.

38.5 POND PRODUCTION

Total shrimp exports from Ecuador reached 52,600 MT in 1988, of which 87% (45,590 MT) was from shrimp culture. Productivity (kg/ha/yr) has doubled since initiation of the second phase. Production increases have come from both increased production area and increased productivity (Table 4).

The 1983 El Niño substantially affected Ecuador's pond production, as a result of sustained higher ocean temperatures and lower pond salinities created by heavy rainfall. Besides higher primary and secondary productivities

Table 4. Ecuadorean shrimp pond area and production values from 1977 through 1988.

Year	Total (ha) in production	Production (metric tons)	Tail Production (Kg/ha)
1977	3,000	818	258
1978	5,500	1,682	306
1979	8,200	2,545	310
1980	18,570	5,955	321
1981	27,000	9,091	336
1982	40,000	13,955	349
1983	55,000	23,227	422
1984	60,000	21,818	364
1985	70,000	19,636	281
1986	80,000	28,364	355
1987	91,500	42,525	465
1988	100,000	45,591	456
1989*	75,000	32,600	435
1990*	90,000	45,450	505
1991*	100,000	52,000	520
1992*	120,000	66,000	550
1993*	130,000	78,000	600

Sources: Estadísticas and Dirección General de Pesca and Personal Communication

* Estimated

in the ponds, growth of shrimp was phenomenal and Ecuador had abundant wild seed for an extended period. The El Niño negatively impacted estuarine ecology. Consequently, wild seed were not found in estuaries where many artisanal fishermen collected them in previous years. Since the 1983 El Niño, the Government has instituted closed fishing seasons for both wild seed and adult shrimp to protect both the shrimp boat fishery and the shrimp farm industry.

38.5.1 Cultivation areas

All four coastal provinces have pond culture areas with similar characteristics. Ecuador is blessed with a good climate, ample land with fertile soil, a cheap labor pool and above all the shrimp *P. vannamei* which easily adapts to culture conditions.

Ecuador has three major pond production areas; El Oro, Guayas, and Manabi, as well as a minor production area in Esmeraldas (Table 5). Total current area in operation is 121,369 ha, with 1,422 shrimp farms. Many of these shrimp farms, however, have had difficulties operating their farms recently because of seed shortages and lack of operating capital. Thus, total area under cultivation was about at 100,000 ha in 1988. Guayas Province is the most recently developed area, provides the most production, is more intensely farmed, and gives higher yields than any of the other areas. The

Table 5. Distribution of shrimp culture activities in principal areas of Ecuador

PROVINCE	# OF SHRIMP FARM	TOTAL	
		HECTARES	%
El Oro	358	20,449	18.1
Esmeraldas	104	3,428	3.0
Guayas	675	80,290	71.2
Manabi	229	8,623	7.7
Total	1,366	112,790	100.0

Source: Chamber of Shrimp Producers (Dec.31, 1987)

pioneers of shrimp farming in Ecuador started in El Oro. This region has the second largest area in production, but most farmers there still operate with extensive to semi-extensive production methods. The third area, Manabí, has attained maximum land use with growout systems representing a mixture of those found in El Oro and Guayas. Esmeraldas Province has greater potential than Manabí, but the infrastructure in that area has not developed sufficiently.

38.5.2 Culture Methods and Pond Construction

38.5.2.1 Extensive pond culture

Until 1978, Ecuador's shrimp farms used primitive extensive production systems with minimum infrastructure. Some of the shrimp ponds were built by hand and there were no water exchange during growout. Pond filling was done by direct pumping without attempts to eliminate predators and/or competitors. Many ponds were inter-connected for water interchange between ponds. Pumping had two objectives; pond filling, and introduction of wild seed to stock the ponds. Pumping was also used to maintain desired water depths in the ponds. Thus, water exchange was almost nil. There was no control over shrimp stocking densities. Additional seed or juvenile shrimp were sometimes collected from small ditches of 2 to 5 m(wide) x 5 to 200 m (long) x 0.3 m (deep) and stocked in the ponds. These semilleros were located at the edge of the shrimp farm near the mangrove estuary. Shrimp seed were stocked at maximum sustainable yield of the pond without supplemental feeding. In the beginning, no outlet gates were used to drain water and harvest the shrimp. This was done by simply opening a part of the berm and gradually collecting the shrimp with seines and cast nets. Today, many extensive shrimp farms operate with more sophisticated pumping and water exchange systems. Stocking densities of up to 30,000 shrimp/ha without feeding is practiced in extensive culture systems which, yields about 270 kg

tail/ha/year. Pond size varies in extensive culture, from less than 5 ha to 120 ha. About 60% of the shrimp farms in Ecuador use extensive culture. Nevertheless, total production from these farms contributed only 36.3% of the country's production in 1987 (Table 6).

38.5.2.2 Semi-extensive pond culture

Semi-extensive culture in Ecuador has a slightly better infra-structure than extensive culture, with more control over production, more regular water exchange, and a supplemental feeding program. Semi-extensive culture is a mixture of two systems, extensive and semi-intensive. Semi-extensive culture uses few or no nursery units, with large growout ponds of up to 40 ha. The water distribution, canal is narrow with a maximum capacity of about 5% of the farm's pond volume. Some farms depend heavily on organic and/or inorganic fertilizers to encourage natural productivity, while others use feed once shrimp reach 8 to 13 g, or when growth rates start to decrease. Semi-extensive culture yields an average of 540 kg tail/ha/year with stocking densities ranging from 20,000 to 50,000 shrimp/ha. There were 25,000 ha under semi-extensive culture, which produced 30.2% of total shrimp output in 1987 (Table 6).

38.5.2.3 Semi-intensive pond culture

Expatriate shrimp culturists have had a major impact on Ecuadorean shrimp culture since 1978; particularly on farm design and culture practices.

These influences include, pumping and water supply systems, use of nursery units, transfer and stocking of juvenile shrimp, feeding and harvesting programs. This has led to replacement of some traditional extensive culture by semi-intensive culture methods. Most shrimp farms built within the last few years are of this type particularly in Guayas Province. Semi-intensive culture uses a central reservoir canal. This canal is large enough so that the reservoir can distribute water to any pond at almost any time with an average water exchange capacity of up to 15% per day. Some farms use nursery ponds. The ratio by area between growout and nursery is about 10:1, while the ratio by unit number is 1:1. Average stocking density in growout ponds is between 40,000 to 120,000 juvenile shrimp/ha. About 15% of the shrimp farms use semi-intensive culture, produce 33.5% of the total output, with average yields of approximately 1,000 kg of tails/ha/year (Table 6).

38.5.2.4 Intensive pond culture

Intensive culture has been used experimentally in Ecuador since 1984, without significant results until recently. A variety of methods were tested. It has been difficult for Ecuadorian shrimp farmers to practice this new and risky method without sufficient knowledge of proper pond management,

Table 6. Comparison of shrimp production (tail weight) with different operational systems in Ecuador during 1987.

System	Hectares	%	Production (x1000 MT)	%	Yield (Kg/ha/yr)
Extensive	60,000	60.0	16.3	35.0	273
Semi-Extensive	24,900	24.9	13.6	29.2	544
Semi-Intensive	14,990	14.9	15.1	32.4	1,004
Intensive*	200	0.2	1.6	3.4	8,000
Total	100,000	100.0%	46.6	100.0%	
Mean					465

Source: Dirección General de Pesca (1988)

*Personal communication

nutritional requirement, proper equipment, etc. Intensive ponds vary in size from less than 1 ha to 5 ha. Aeration is by air diffusers made locally, or by imported aerators. Stocking densities vary, but maximum stocking density is less than 600,000 shrimp/ha, averaging about 350,000 shrimp/ha. Yields are a promising 6,150 kg/ha/crop (heads-on). Intensive culture produces only 1.6% of total production from 0.2% of total pond area (Table 6).

Most shrimp farms in Ecuador are smaller than 100 ha. Size trends are toward farms as production systems intensify. At the same time, large plot availability has been greatly reduced (Table 7).

Extensive farms have tended to intensify to semi-intensive culture to not only obtain production consistency but to also gain higher yields. This has

Table 7. Shrimp farm size in Ecuador

Size range (ha)	Total Hectare	%
1-50	61,000	61.0
51-100	15,000	15.0
101-150	8,000	8.0
151-200	7,000	7.0
201-250	6,000	6.0
251+	3,000	3.0
	10,000	100.0%

Source: Dirección General de Pesca (1988)

note: There are many large shrimp farms in Ecuador some of which are divided into many smaller companies that use the same basic infrastructure.

increased their profitability from existing farm areas. Meanwhile, pond size has become smaller for the same reason.

38.5.3 Pond Preparation

Procedures for filling both nursery and growout ponds are basically the same. Prior to filling, ponds are sun-drying for a minimum of three days whenever possible, and inspected for competitors and/or predators in and around the remaining water puddles. Small canals are dug to drain the puddles. Rotenone (10 ppm) or chlorine (100 ppm) is sprayed in any remaining puddles of water. Lastly, the pond bottom condition is inspected by technical personnel for accumulations of organics and the state of decomposition. Depending upon conditions, 100-500 g/m² of lime as CaCO₃, Ca(OH)₂ or CaO may be applied.

After pond bottom treatment is completed, the pond is filled to maximum water depth as soon as possible. Influent water is filtered through 1.56 and 8.5 mm mesh screens to restrict entry of predators and competitors. During filling, inorganic fertilizers are placed at the entrance gate to allow a gradual nutrient dissolution and distribution. Urea and super triple phosphate are used at maximum dosages of 16 and 8 kg/ha, respectively. Dosages depend upon ambient nutrient availability in the pond and incoming waters. Ponds should be stocked with shrimp within 7 to 10 days of filling.

38.5.4 Nursery Pond Operations

Nursery units range from 0.5 to 5 ha. Normally, they are clustered in one area of the farm. Some are located between growout ponds for operational reasons. Because wild seed are seasonally available, most shrimp farms reserve approximately 10% of total farm growout area for nurseries. Seasonal fluctuations in wild seed obligate shrimp farmers to stockpile this essential commodity in nurseries. Nursery ponds thus serve several purposes, to stockpile seed, to provide larger seed for growout ponds, and to provide better inventory control. The nursery phase takes 30 to 240 days, depending upon schedule and needs. Normally, juveniles are harvested at 0.5 to 1.5 g within 45 days.

38.5.4.1 Pond acclimation of PL

Seed stock acclimation is one of the most important factors in obtaining good results from nursery and growout operation. In Ecuador, only 20% of the PL come from hatcheries. The remainder comes from wild PL collected from estuaries and beaches. During the rainy season (Dec.-April), all nursery units are replenished with abundant wild seed, with enough to stock as many as two growout pond crops.

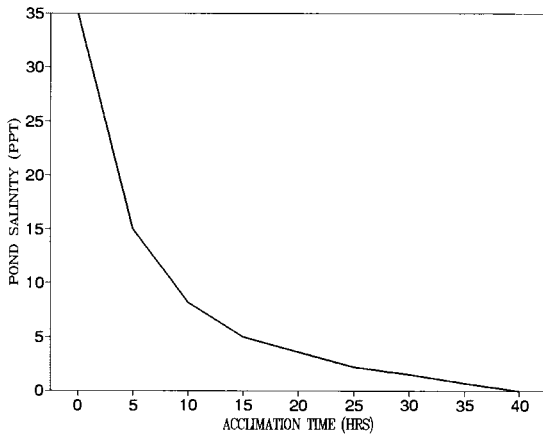


Figure 3. Acclimation times for PL from seawater to a range of pond salinities (Llano 1989).

Once the seed arrives at the farm, they are acclimated to their new environment. The acclimation system used is unique to every farm. Those farms which have lower salinity waters, and therefore must take more care acclimating the seed tend to have larger, more sophisticated facilities. Regardless of the size and degree of sophistication, all systems involve the gradual and continual mixing of the farm's pond water until the PL have adequately adjusted to the farm's water conditions.

The acclimation rate depends greatly on the PL size, PL quality, and salinity differential. For example, if it takes 10 hrs to acclimate a PL6 to 25 ppt salinity water from 35 ppt, a PL10 can be acclimated to the same salinity in only 6 hrs. Larval branchia size and osmoregulatory ability are directly correlated. In other words, larger PL have more developed branchia, and can more readily acclimate to reduced salinities. Healthy, wild *P. vannamei* PL can be acclimate to 5 ppt salinity in only 16 hrs. A questionable batch of hatchery PL may require twice that time. The health (i.e., activity and feeding behavior) of the seed is frequently monitored throughout acclimation for possible adjustments in acclimation rate. Acclimation from 35 to 30 ppt may be done in as little as 30 minutes. Acclimating seed from 35 ppt to zero ppt may take more than 48 hrs. Typical acclimation rate can be seen in Figure 3. Seed density during acclimation is related to acclimation duration, with typical densities of 500 to 1000 PL/l. Supplemental feeding is recommended if acclimation lasts more than a few hrs. Survival during acclimation also vary. An 80% survival of *P. vannamei* acclimated to less than 5 ppt is considered successful. Survival of other species during acclimation is generally much less. One must balance the acclimation rate and

osmoregulatory ability of the seed with risks of density stress, oxygen depletion and cannibalism.

38.5.4.2 Quantification and quality control of PL

Prolonged PL transportation, and especially the diverse species composition of wild seed makes it essential to identify and quantify species in the larval shipment prior to stocking nursery or growout ponds. Counts are generally done by volumetric approximations. Some farms take 1 l aliquot samples and multiply the number of seed in the sample by the total volume of water in the shipping container. Larvae counting is done on a screen, where the sample is filtered. Others take five to nine aliquot samples of either 30 or 250 ml after acclimation, depending on consistency of counts and shipping density. The population is then calculated based on sample average multiplied by water volume. PL are then taken to a field lab for species identification, and estimation of dead PL. Seed are frequently purchased by weight, however, with approximations for the number of shrimp per pound (i.e. 120,000 to 180,000/lb). In both cases, since the farmer only pays for P. vannamei, it is common practice to underestimate the real percentage as well as the total count. This process, known as "machete", often results in nursery and pond estimates of more than 100%.

It is particularly difficult to evaluate PL quality with size ranges from 5 to 10 mm. Stunted growth and poor survivals in growout ponds with hatchery PL has drawn attention to this problem. A procedure to systematically establish PL quality, called "stress test", is presently under evaluation at many hatcheries and farms. The stress test is intended to evaluate PL hardiness by subjecting them to sudden changes in salinity and water temperature. Salinity is decreased to 10 ppt, and the temperature is decreased from shipping temperature to 20 C instantaneously. The PL are then checked after 24 hrs for survival and condition.

38.5.4.3 Transfer and stocking procedures

After PL acclimation and quantification, the PL are placed in special fiberglass transfer tanks with supplemental oxygen. These tanks normally have a capacity of 1,500 l, with a special baffle system to minimize water movements during transport. The PL are then hauled to the nursery pond and siphoned into a circular pen, or directly into the pond. A circular pen is sometimes used to facilitate feeding and observation for 7 to 10 days.

A minimum of 200 PL are counted and placed into one or two special containers with fine mesh to check for stocking mortality. The containers should have a small amount of formulated feed. Survival is checked after 24 hrs.

38.5.4.4 Water quality control

Many pond operators often ignore the importance of water quality management, especially at low stock densities. Dissolved oxygen and water temperatures are measured in the mornings, and turbidity (Secchi) readings at mid-day. Periodical, pH and salinity readings are also taken. Little attention is given to the nursery unit, where water exchange rate is normally higher than in growout ponds. Water exchange ranges from zero for the first 7 to 14 days, with gradual increases to 20 to 25%/ day in nursery units.

38.5.4.5 Feeds and feeding

Nursery feed is 10 to 30% higher in protein than growout feed. Nursery feed size is smaller, being either granulated or almost a powder. A set amount of feed is fed per day, rather than as a percentage of biomass. Initially, one million PL are contained in 13 m diameter circular pens for 7 to 10 days. Feeding is done once a day in the morning.

38.5.4.6 Harvest methods and procedures

Pond water depth is lowered in advance. The harvest begins in late evening and concludes before sunrise to avoid higher daytime temperatures. The nursed shrimp are attracted by light to the sluice gate where they are collected in a 10 m long harvest bag with 6.4 mm mesh. Shrimp are removed repeatedly from the bag to avoid unnecessary stress. They are gently placed in plastic baskets and inspected for undesireables, such as fishes, crab, detritus, mud, etc., and weighed. At each weighing, most shrimp farms remove a sample of shrimp to determine individual weight and species composition. Some farms take three 500 g samples during the night. Baskets are weighed with a hanging balance after dewatering for about 30 seconds. Net weight of shrimp in each basket should not exceed 10 kg to avoid crushing. The shrimp are then placed into cages inside a transport tank with oxygen, and quickly transferred to the growout ponds.

38.5.5 Growout Operations

Culture intensity varies significantly from one farm to another, as do production ponds sizes. Growout ponds varying from 5 to 120 ha each. Growout pond size have become smaller than 15 ha as Ecuadorian shrimp farms intensified to semi-intensive levels. Average growout pond size in Ecuador is between 10 and 15 hectares each, with average water depth of slightly less than 1 m.

38.5.5.1 Stocking procedures

In the early days, many Ecuadorean shrimp farmers practiced direct stocking of PL into growout ponds. Seed were was either purchased and

stocked, or pumped into the ponds. Experience now shows that this approach gives inconsistent results. Today, the two phase system, with nursery ponds and juvenile shrimp is the most popular method of stocking growout ponds.

38.5.5.2 Juvenile shrimp transportation

Juvenile shrimp are transported between the nursery ponds and growout ponds using the same tanks used to transport PL between the acclimation facilities and the nursery pond. The tank is trailer mounted and pulled by an agricultural tractor. Three inner cages, covered with a fine mesh net are placed in the transport tank and oxygenated with pure oxygen. The maximum load of shrimp per trip is 30 kg, depending upon distance and duration of the haul. Tank water is replaced periodically as it becomes fouled.

38.5.5.3 Quantification

Farmers should use at least two inventory counts to establish the number of juveniles stocked in a growout pond. The first count is the number harvested from the nursery and transferred to the growout pond. The other estimate is the number surviving in the growout pond after stocking. These estimates are probably the most important information required for pond management.

A method for making the first estimate was given above, while survival estimates are commonly made by the following methods:

(a) All the shrimp stocked in the growout pond are placed on a horizontal net approximately 30 cm below the water surface. Healthy juvenile shrimp can crawl or swim away from the "hammock" without difficulty. The net dimensions are 5 m (wide) x 75 m (long) and a mesh size of 3.2 mm. The net is kept in place for a maximum of 8 hrs. The net can be located anywhere most convenient for stocking but placing the net close to the pond water inlet facilitates water exchange. When the net is lifted, the dead or weak shrimp are counted, and this count subtracted from the harvest estimate from the nursery pond. Normal transfer mortality ranges from 0.5 to 3%.

(b) A second method for estimating stocking mortalities involves a minimum of three boxes (1m x 1m x 1m), covered with 3.2 mm mesh. These are placed in the pond, and about 100 to 150 juvenile shrimp are counted and placed in the boxes with feed. The number surviving after 24 hrs is estimated and used to calculate the number surviving stocking.

38.5.5.4 Water quality management

At dawn, dissolved oxygen and water temperatures from all nursery and growout ponds are measured. Readings are taken from the bottom water as it surfaces at the drain box. The data are checked and evaluated by the chief technician before daily activities start. Lab technicians will make another

round of checks in all the ponds with a secchi disc and plastic meter stick to measure turbidity and water outflow from the drain box of each pond. The technicians will also note the condition and appearance of the water, its color, presence of benthic algae, foam, condition and mesh size of the filters, etc. In the afternoon, dissolved oxygen and water temperature are measured again.

Some progressive shrimp farms periodically measure various chemical/physical parameters, such as; ammonia, nitrite, nitrate, phosphate, hydrogen sulfide, B.O.D., C.O.D., etc. Furthermore, some farms also assess phytoplankton, benthic fauna and microbial populations in an effort to better understand pond ecology.

38.5.5.5 Water exchange

Most semi-intensive shrimp farms possess a minimum water exchange capacity of between 10 and 15%/day for all ponds. Almost all of extensive farms have maximum water exchange capacity of about 5%/day. Not all shrimp farms can pump 24 hrs/day, and/or have a reservoir canal large enough to hold and exchange water continuously. A large tidal range of 3 to 5 m twice daily requires use of larger and/or more pumps at the pumping station(s) to satisfy the daily needs. Most farms are further complicated by limited pumping hours (ie. 12 and 20 hrs/day). Thus the heart and main artery of shrimp farm, the pumping station and central canal respectively, require vital attention at all times.

Water exchange rate in the growout ponds varies depending upon stocking density, total biomass, level of natural productivity, turbidity, and water source. Water requirement may vary depending upon seasons, days in production, or by analysis of physical-chemical parameters to evaluate the accumulation of toxic metabolites. It is essential, however, for each farm to establish their maximum sustainable yield relative to their pumping capacity. Once the desired water exchange rate is determined, water exchange is controlled by wedging a piece of wood between the downboards of inlet gate, thereby regulating the flow of incoming water. Water exchange rates vary from 0 to 25%/day during the course of a production, with an over-all average daily exchange of about 8%.

38.5.5.6 Pond fertilization

Good pond management practice consists of three principal programs; proper feeding, water exchange, and fertilization.

Fertilization should be assessed using periodic analysis of ammonia, nitrite, nitrate and assimilable phosphate in the growout pond. Fertilization is used not only to propagate phytoplankton, but also to support aerobic bacteria. Aerobic bacteria remove waste products from the pond by breaking

them down into carbon dioxide and water. Bacteria can decompose organic materials relatively fast, but their activity often become limited by factors such as insufficient oxygen and fluctuations in nutrient supply.

The fertilization rates vary for every pond, the same a production procedures differ between farms. Nobody quite knows exactly how much nitrogen and phosphate to add, and when to supplement. Some pond managers have tried to add silicate to propagate diatom blooms without success. The ratio between N and P added range from 6:1 to 15:1. Currently, total ammonia ranges between 0.6 and 2 ppm.

38.5.5.7 Growth monitoring

The best method to evaluate crop performance in growout ponds is to sample the shrimp periodically. Normally, samples are taken weekly from each growout pond. Shrimp are caught by cast nets along the bank, and from the pond center. Selective capture should be avoided. The shrimp are taken to the laboratory for weighing and a careful visual observation. At least 50 shrimp should be collected from each pond; but the number of shrimp sampled depends principally upon size ranges of shrimp in the sample. In other words, a larger sample should be taken if large size variation exists.

Another benefit of the weekly samples is that the condition and behavior of the shrimp, pond condition, presence of competitors and predators in the pond and other factor can be assessed through visual observations.

38.5.5.8 Population estimates

It is extremely difficult to estimate shrimp population size in a pond. There have been many attempts by scientists and farmers to estimate shrimp populations in ponds, with little success so far. Nevertheless, shrimp farmers still try to make these estimates, even if they are subjective. *P. vannamei* is notoriously active during certain moon phases, especially during new and full moons. Many shrimp farmers take 4 to 5 castnet samples per ha at predetermined spots at these times to estimate shrimp density and species composition. It is customary to make population estimates beginning 30 days after stocking until harvest.

Physical check: Visual observations of shrimp are made routinely at almost all shrimp farms, regardless of their production methods. Shrimp are brought to the field lab either for weekly growth samples, population estimates, or when especially large samples are taken a few days before harvest to establish the value of the crop and physical conditions of the shrimp (i.e. molting, soft shell, bacterial and protozoan infections, off-flavor, etc.)

38.5.5.9 Feeding

Feeding practices with formulated feeds vary greatly depending upon water and soil richness and stocking densities. Normally, no feed is applied for extensive culture where stocking density is below 30,000 shrimp/ha, but some feed may be given during the last few weeks if growth rates decrease before harvest. The same is true for many semi-extensive shrimp farms where supplemental feed is applied when shrimp reach a certain size, and/or after a certain number of days in production. When the stocking densities reach about 8/m², feed is given from the beginning of production until harvest with feeding rates of 29 to 30% of their biomass when the shrimp are 1 g in size, decreasing to 2 to 2.5% at 20 g. Shrimp biomass calculations for feeding rates is based upon either a predetermined survival curve, or on sampling as discussed above. The survival estimate is multiplied by the average shrimp size, which is established by weekly sampling. Once total biomass is calculated, the farmer checks his feeding table which determines the appropriate feeding rate.

In case of low dissolved oxygen levels (generally below 3.0 ppm), feeding is suspended. Most shrimp farms apply formulated feed by using men with small shovels who distribute the feed as evenly as possible throughout the pond from a small boat or raft. Some farms feed twice a day, but most feed only once in the morning. Some farms only feed once when the shrimp weigh less than 8 g, then increase feeding frequency to twice daily. Feed distribution pattern changes daily to avoid an accumulation of excess feed in certain pond areas. Some shrimp farms feed using blowers mounted on a boat. Others feed by airplanes, which can feed up to 300 ha per hour.

38.5.5.10 Predator and competitor control

Care should be taken to control predators, especially before stocking shrimp in growout ponds. Liquid or powder Rotenone (5-10 ppm), chlorine (100 ppm) or 300 g/m² of urea are used, as mentioned earlier in the Pond Preparation section. It is extremely difficult to eliminate predators or competitors from large growout ponds once production has started, unless the shrimp are harvested prematurely. It is also recommended that a pond be filled no more than a week before stocking, to avoid giving predators or competitors a head-start in growth. To assure that incoming water is relatively free of competitors, many shrimp farms employ special laborers dedicated to keeping intake screens clean at all times. There are many predatory fish, birds and two legged animals that thrive on shrimp. Fireworks, shotguns, rifles and even machine guns are often used to scare away predatory birds.

38.5.6 Harvesting methods

Many farms in Ecuador still use primitive harvest methods. Some ponds were built on low flat land where drainage is inadequate. Cast nets and long seines must be used to harvest, taking many days and nights. The majority of shrimp farmers, however, harvest through outlet gates with a large bag fasten to the gate frame. Lights are used to attract shrimp to the outlet. The bag is made of 6.4 to 8.5 mm mesh net, 1 to 2 m diameter (stretched), and 20 m long. These nets can hold as much as 1 to 1.4 MT. The net is emptied every 2 to 4 hr.

A few years ago, a progressive shrimp farmer started using vortex "fish" pumps to harvest shrimp, with great success. These pumps minimize shrimp damage, reduce labor, and improve product quality. In spite of these benefits, only one shrimp farm is currently harvesting with a pump, even though the pump can handle approximately 4,000 kg/hr of shrimp.

Shrimp samples are taken randomly at least three times during harvest, including the beginning, middle, and end of harvest. Each sample contains about 35 to 40 kg of shrimp. The samples are classified by size groups and species, and each group is weighed and counted.

38.5.7 Post-harvesting Handling

Shrimp processed for Europe requires special handling since their market requires a head-on product. Ecuadorian shrimp growers have taken steps to insure this high quality. The harvested live shrimp are submersed immediately in chilled or icy water. The shrimp are then transferred to the processing plant via boat or truck in square plastic boxes with 2 to 3 layers of ice between the shrimp. Typically, 2 kg of ice is used to transport 1 kg of shrimp. Shrimp are normally processed within 24 hr of harvest.

38.6 FEED

A shrimp feed industry was not in existence until the second phase of shrimp industry development in 1978. There are now at least 25 feedmills in the country dedicated to the production of shrimp feed, with total output in 1988 of about 120,000 MT.

Presently, 40 to 60% of the shrimp farms in Ecuador are said to use feed at least sometime during a crop cycle, and the demand for the feed has increased exponentially. When seed scarcity exists, most shrimp farms without hope of obtaining a constant supplies of PL will resort to less costly extensive culture methods to avoid excessive increases in operating costs. Therefore, the feed industry will experience periodic excess production capacity and a sluggish market situation, at least until hatchery problems are resolved.

There are still many unknowns regarding feed formulation for P. vannamei. Nevertheless, all the feedmills have developed their own formulas with different protein levels, but without any quality control by reputable institutions, public or private. Furthermore, unstable agriculture programs have caused uncertainty in the supplies of essential raw materials. The costs of these materials required by the feedmills has skyrocketed. Consequently, the quality of raw materials used in the feed has been downgraded, or materials replaced with others to lower feed cost to the shrimp growers.

Many farmers are considering more intensive culture to more efficiently use their land, and to fend-off inflation. New and expensive feeds for intensive culture, with all supplements added have appeared in the market. Some of the ingredients used in the feeds are imported.

38.7 DISEASE

Disease is often the major cause of mortality in shrimp culture, particularly at the hatchery level. Even so, it remains difficult to separate effects due to biotic (i.e., bacterial, viral, fungal), and abiotic (management, nutrition, physical parameters) conditions. Disease outbreaks at the hatchery or the farm can almost always be directly attributed to a given stress. Unfortunately, it remains difficult to remove all stresses considering that the whole culture process is artificial. This section examines only the biotic factors in both hatchery and growout phases.

38.7.1 Disease in Hatchery

Disease outbreaks are not generally a problem during the early rearing stages (i.e., eggs, nauplii and zoea). Occasionally problems exist with the fungal infestations (Lagenidium spp.), as well as the presence of virus, (i.e., Baculovirus penaei in P. vannamei, and IHHN in P. stylirostris). Fungal infestations are readily treated using a suitable iodophor bath (i.e., Argentyne at 0.5 ppm) for eggs, and daily Treflan treatments (10 to 20 ppb in nauplii and zoea, 20 to 80 ppb in PL) throughout the larval rearing period. Viral infections are currently untreatable. As previously mentioned, attempts are made to assess the presence of virus in the spawners before transferring nauplii to larviculture facilities. Improved hatchery management techniques have been important in reducing viral-related mortalities by removing stressful conditions in the larval culture area.

Bacterial necrosis is not generally lethal except in advanced stages, and is infrequent in larval stages up to late mysis, unless cultured at above normal densities. Generally, the antibiotic furazolidone (0.2 to 0.3 ppm) or chloramphenicol (1 to 2 ppm) are used prophylactically. Treatments are seldom applied in the zoeal and mysis stages, though if necessary, PL may

need stronger (0.3 to 0.6 ppm furazolidone or 2 to 4 ppm chloramphenicol), and more frequent treatments due to their greater biomass, higher bacterial counts, and occasional cannibalism.

Protozoan infestation is easily treated in PL stages with formalin (25 to 50 ppm), although little can be done at the zoeal stages except for better algal maintenance. Formalin is also effective at these concentrations controlling filamentous bacteria and to reduce the general fouling of PL caused by poor water quality and/or overfeeding.

38.7.2 Disease in nursery and growout

The four main causes of nursery and growout mortality include:

- 1) Poor pond management
- 2) Predation and competition
- 3) Nutrition
- 4) Disease

Unlike larviculture, the nursery and growout phases are less susceptible to direct disease-related mortalities, primarily because of the relatively low rearing densities used in Ecuador's growout ponds. For this same reason, however, little practical treatment of disease is undertaken except for the occasional use of medicated feeds in the nursery ponds.

Some evidence suggests that IHHN viral infections are a major cause of P. stylirostris mortality in ponds. Baculovirus penaei is occasionally found in nursery ponds, particularly with underfeeding and/or overstocking. Mortality is, however, low grade for P. vannamei, and P. stylirostris appears unaffected by this virus.

Bacterial necrosis is commonly seen in pond culture, especially under conditions of high stocking densities. This is primarily an induced or secondary infection, and probably of little importance apart from reducing the shrimp quality at harvest.

Idiopathic muscle necrosis, or cramped shrimp is common, again under stress conditions, particularly during times of low dissolved oxygen or sudden temperature drops. Mortality may be high or low grade, depending upon time taken to restore water quality to acceptable levels.

A small percentage of hatchery-reared shrimp have shown a tendency to stunt and display twisted rostrums. The cause of this is unknown, but usually results in reduced pond production. Generally, symptoms can be first observed when the shrimp reach 10-12 g, and may affect up to 30% of the shrimp in a pond. This abnormality seems more prevalent among hatchery-seed reared from maturation nauplii. Nevertheless, twisted rostrums have also been seen in wild PL.

Although not disease-related, the presence of high levels of blue-green algae can adversely effect shrimp quality. Under conditions of reduced

salinities created by heavy rainfall, these cyanophyte algae can dominate pond flora. A metabolite, geosmin, produced by this bloom can adversely effect the shrimp flavor. High water exchanges must be used prior to harvest to flush out the algae. Once the musty-odor is no longer present in the shrimp, the shrimp can be harvested.

38.8 PROCESSING

The shrimp export industry in Ecuador began about 1950, long before the development of shrimp culture in Latin America. All shrimp production in Ecuador until 1976 came from the fishing fleet. The first commercial pond harvests did not begin until 1979. Since Ecuador had a substantial shrimp processing infrastructure already in place, they were able to readily process cultured shrimp production. Processing capacity kept pace with increased production from an increase in shrimp ponds. From 1979 to 1984, processing capacity in Ecuador increased twenty-fold. Shrimp are transferred from ponds to packing plants by land or sea, depending on the farms' location. This fresh product is transported inside insulated trucks or boxes, kept cold with ice. Usually, transport times run from 1 to 4 hours. Once the whole shrimp arrive at the plant, they are immediately washed in ice water, or stored in separate tanks with fresh ice. After the shrimp are cleaned, they are weighed and transferred to the deheading tables. Once deheaded, the tails are graded by machine or hand. The product is then boxed by size and immediately frozen in plate-freezers or freezer tunnels at -30 to 35 C. The frozen tails are then stored in maintenance freezers at -15 to 20 C until shipment.

During all phases of Ecuador's shrimp processing operations, the product is frequently sampled to maintain quality standards. For example, samples are taken from incoming pond shipments to pre-screen for off-flavors, as soon as they enter the plant. Samples are continually taken from the processing line, as well as the storage freezers to monitor counts, uniformity, and weights.

Until recently, almost all of Ecuador's shrimp were packed as frozen, shell-on tails in five pound boxes and sold in the United States. Since 1987, Ecuador has begun to pack head-on shrimp for Europe, using low levels of metabisulfite as a preservative. Current exports to Europe account for more than 10% of the country's production. More recently, Ecuador had begun to conduct value-added processing prior to export. Various plants have begun to individually quick freeze (IQF) their shell-on product using brine or liquid nitrogen. Shrimp are now being peeled by hand or machine in various forms, including; butterfly, tail-on, and peeled-deveined. Peeled products are being sold to U.S. shrimp processors. Market diversification will help Ecuador compete against ever expanding world production of cultivated shrimp.

Table 8. Employment in shrimp culture and related industries.

Category	# of Employees
Artesanal Fishermen	32,400
Shrimp Farms	41,024
Hatcheries	1,600
Processing Plants	5,800
Transport	800
Total	81,624

Source: Chamber of Shrimp Producers

38.9 ESTABLISHMENT OF A SUPPORT INDUSTRY

The shrimp culture industry in Ecuador has created not only jobs for thousands of people, but it has also created numerous industries which are directly or indirectly related to the shrimp business.

Seed collection and production from hatcheries is the one of the principal support industries that currently employs more than 1,600 people. More than 32,000 artesanal fishermen are involved in the capture of wild seed and adult shrimp for spawners in the estuaries and beaches. About 75 processing plants have also made a social impact, with 5,800 employees (Table 8).

In addition, there are manufacturing industries created to support shrimp culture; such as feed, fertilizers, papers, plastics, heavy equipments, etc. Nevertheless, the raw materials and processing of the materials to produce feeds are still in need of further development.

The service industry for the shrimp activities developed as the industry grew. This includes construction, transport, insurance, security, computer programing, consulting, agency for import/export, etc.

38.10 FUTURE SHRIMP INDUSTRY IN ECUADOR

In ten short years, Ecuador has become one of the world's largest producers of cultured shrimp. The presence of an indigenous species suitable for culture and a year-round growing season pushed Ecuador to the forefront of penaeid culture. Even though Ecuador has the potential and ability to expand, there are many factors which will eventually decide the future of Ecuador's shrimp industry. For example, the availability of quality nauplii and wild seed abundance are predominately determined by ocean currents. The demand for quality nauplii by Ecuador's hatcheries will keep the wild gravid collection facilities in operation for years to come. The availability of wild nauplii is cyclic but relatively untapped. Ecuador's present gravid collection

centers are collecting a small percentage of the available impregnated females. This would indicate that several large shrimp breeding grounds remain untouched. Ecuador has enough maturation tanks to produce four times its current nauplii production. Major advances in current maturation techniques and diet will be needed to improve the quality of Ecuador's maturation nauplii. Once this problem is solved, Ecuador's hatcheries will be able to produce enough nauplii to potentially supply growout farms with almost 50% of its yearly requirements, regardless of gravid female availability.

Even though shrimp farmers still prefer wild seed over hatchery seed, major advances have been made to improve the quality of hatchery seed. Marketing larger PL improved larval diets, and a better understanding of the proper handling of hatchery seed at the farm have enabled hatchery seed survivals and performance to improve. Future studies involving shrimp genetics, pathology and nutrition should provide a higher quality PL and increased farmer acceptance.

Ecuador possesses the necessary technology and technicians to maintain its present production, and remain as one of the world's leading shrimp cultivators. Nevertheless, large volume exports do not necessarily equate with high profitability. Scarcity of seed can create severe cash flow problems, especially with the smaller farms. Run-away inflation, restrictive export exchange rates, and lack of available credit has severely effected the industry.

Numerous farms have begun experimenting with various forms of intensification. Even though Ecuador's mean production per unit area has not increased drastically over the past few years, many farms have begun to increase their stocking densities, water exchanges and feeding levels. Others have begun to experiment with various forms of aeration. Regardless, any type of intensification requires larger quantities of PL. If seed shortages persist, the farmers would be better off stocking all their ponds at lower density rather than stocking a few high-density ponds and leaving others idle. Ecuador must first increase its production of quality hatchery seed as well as developing a quality shrimp feed before this country can consider large scale intensification.

No matter what advances Ecuador achieves in pond production, they can be easily overshadowed by international shrimp market prices. With more and more hectares of shrimp ponds being constructed around the world, Ecuador could continue to lose its world market share. This is exemplified China, who in only a few short years replaced Ecuador as the leading shrimp exporter to the United States. Current increases in world shrimp production will soon overtake present consumer demand, and therefore adversely effect world shrimp prices. The "gold-rush" days of Ecuador's shrimp industry are long gone, and it must now struggle to trim production costs and increase efficiencies in order to maintain even their presently market position.

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CHAPTER 39

J. Stephen Hopkins

SHRIMP CULTURE IN THE UNITED STATES

39.1 INTRODUCTION

Environmental and socioeconomic conditions in the United States (U. S.) make shrimp farming technologically feasible but economically questionable. The growing season is restricted by climate in most parts of the country. Soil and water resources are adequate, but highly regulated by various government agencies. High labor costs favor automated production processes. Land costs, especially coastal lands, are becoming expensive.

The U.S. domestic shrimp capture fisheries are no longer able to meet ever increasing U.S. market demands for shrimp. Imported shrimp set market prices making shrimp fishing in the U.S. less profitable than it once was. Much of the U.S. shrimp demand is satisfied by imported, farm reared product.

The large market demand for shrimp in the U.S. has led to considerable interest in shrimp culture. This interest resulted in technological breakthroughs and improvements in shrimp reproduction, larviculture, nutrition and growout. Many of these developments have been transferred to other countries where shrimp culture is likely to be more profitable, while in the U.S. shrimp culture is still largely in the developmental stage.

In this chapter, we will review conditions affecting shrimp culture in the U.S., the nature of the U.S. market, and the status of shrimp culture in the U.S. Discussion of culture sites will be limited to those areas where shrimp are currently being cultured: South Carolina, Florida, Texas, Hawaii and Puerto Rico (Figure 1). Lastly, we will speculate on the potentials for development of an economically viable industry in the U.S.

39.2 ENVIRONMENTAL CONDITIONS

39.2.1 Climate

The continental U.S., between 25° and 45°N latitude (excluding Alaska) has a temperate climate with seasonal growing conditions for marine shrimp. Hawaii (21° N) and Puerto Rico (18° N) have warmer climates with year-round growing conditions.

Ambient temperatures are suitable for survival and growth of commercially important penaeids in the continental U.S. for perhaps only six

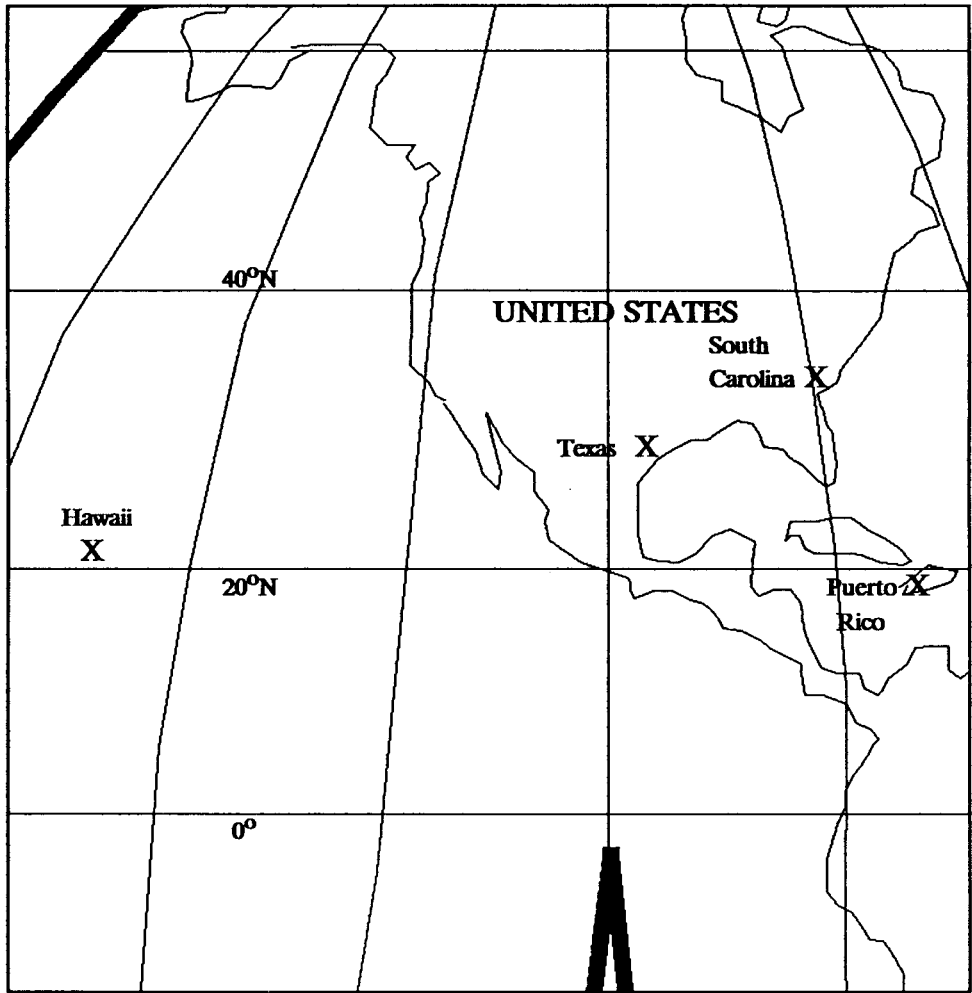


Figure 1. Map showing the primary shrimp farming areas of the United States.

to eight months per year (Sandifer et al. 1988). Precipitation is highly variable between different areas of the U.S. Precipitation exceeds evaporation in South Carolina, Florida, the north Texas coast, Hawaii, and the north coast of Puerto Rico. The south Texas coast and the south coast of Puerto Rico are semi-arid.

39.2.2 Water Resources

Water temperatures along the Pacific coast are generally low due to the southerly California Current. Atlantic coast water, from the Carolinas south, is warmer due the Gulf Stream. Ocean currents are less pronounced in the

Gulf of Mexico. Puerto Rico and Hawaii are in the Atlantic and Pacific North Equatorial Currents respectively, with temperatures of 24 C or greater all year.

Expansive estuarine and barrier island systems exist along South Carolina, Texas, and to a lesser extent, the Florida coast. In South Carolina, the northern coast of Texas, and Florida, estuaries typically have salinity gradients resulting from freshwater stream inflows. Farms built at these sites are occasionally subject to excessively low salinities. Barrier islands, and arid conditions in south Texas often result in hypersaline conditions of up to 60 ppt. Several Texas shrimp farms seasonally have 45 to 50 ppt in their source water. Near-shore ocean salinities are usually 35 ppt in Florida, Texas, Hawaii and Puerto Rico, and about 30 ppt in South Carolina. U.S. shrimp farms normally do not use freshwater to lower source water salinities.

U.S. shrimp farms are located in less industrialized areas, and pollution has not been a major problem to date. At least one farm, however, has had occasional problems with toxic agricultural wastes in their source water.

In addition to marine and brackish surface waters, some U.S. farms use saline groundwater, including farms in Texas and Hawaii. Hawaii uses saline groundwater from wells drilled into porous calcareous strata near the ocean. In Texas, some shrimp farms use saline groundwater from wells located inland, over a salt dome. Saline groundwater quality varies widely from site to site, with some being excellent for shrimp farming, and others producing marginal quality water.

39.2.3 Soil Resources

Soil quality varies greatly between and within regions of the U.S. In South Carolina, many areas adjacent to adequate seawater sources have soils which are too sandy for pond construction. Upland soils are generally within acceptable pH ranges. Soils in tidal impoundments are highly organic, undergo an acid-sulfate reaction when dried and are thus susceptible to low pH problems.

Florida too has a variety of soil types ranging in texture from sand to clay, with various amounts of humic material. Much of south Florida is porous limestone rock which is very amenable to construction of water table ponds, but makes construction of above ground ponds difficult.

In Texas, most property within one to two km of marine waters has an elevation of less than 1.5 m (Miget 1985). There are more clay soils adjacent to seawater sources in Texas than in South Carolina or Florida. Acidic soils are generally not a problem in areas that can be permitted for construction, although some arid sites may have alkaline soils.

Hawaiian soils vary from lava rock to fine red clay. Land availability is limited, and steep terrain or lava fields prohibit pond construction in many

parts of the state. In Puerto Rico, adequate soils are found scattered along the northern coast, but rocky terrain hinders pond construction along portions of this coast. The southern coast has abundant clay soils. The southern coast also has more mangrove areas, although these are not available for pond construction.

39.3 REGULATORY CONSTRAINTS

39.3.1 Federal and State Interaction

Regulations generally address issues of: a) wetland modifications, b) water intake and obstruction of navigatable waters, c) water discharge and effluent quality, and d) importation of exotic species. In many cases, some or all of these responsibilities are assigned to individual state agencies through a federally approved regulatory system.

Three Federal agencies regulate shrimp farming impacts. The U.S. Army Corps of Engineers (COE) regulates maintenance of navigatable waters. Pump stations which draw seawater for a shrimp farm must not obstruct free access to navigatable water. The U.S. Environmental Protection Agency (EPA) regulates discharge of industrial waste water. A permit is required if an aquaculture operation produces more than 45 metric tons (MT) of product per year, or discharges more than 30 days per year. A National Pollution Discharge Elimination System (NPDES) permit may be required for large shrimp farming operations. The U.S. Fish and Wildlife Service (USFWS) regulates maintenance of important wildlife habitat and importation of exotic species. Wetlands, an important resource, are protected and shrimp farms which potentially impact wetland areas are scrutinized by the USFWS. Exotic shrimp postlarval (PL) importations must be cleared through the USFWS.

39.3.2 Wetlands use

Regulation of wetlands alteration have become particularly stringent during the past two decades. Typically, each coastal state has a coastal zone management program which administers a portion of federal regulations. In general, alterations to maritime wetlands are not allowed. Coastal wetlands are critical nursery grounds for important sport and commercial species, including penaeid shrimp. In some cases, mitigation may be used to compensate for minor wetland modifications.

In South Carolina, alterations to maritime wetlands is regulated by the S.C. Coastal Council through a joint permit application with the COE. Wetlands are classified primarily by vegetative types, with upper growth limits for vascular halophytes considered the critical line. Some coastal South Carolina wetlands were, however, impounded prior to inception of coastal

zone management programs. Roughly 28,000 ha of such impounded wetland exists within the state. Where perimeter dikes were maintained, these impoundments may be used for some private activities, including aquaculture.

Florida has a variety of maritime wetland habitats, including salt marsh cordgrass, mangrove stands, and eel grass flats. Wetland resource modification requires separate permits from the Department of Environmental Regulation (DER), Department of Natural Resources (DNR) and the U.S. Army Corps of Engineers (COE) via a joint application. There have been few dredge and fill applications for aquaculture activities so there is a general lack of information on the impacts (pers.comm. Michael Ednoff, Florida Dept. Agriculture, 1989). In Florida, a permit to construct or alter a pond is required from the local Water Management District (WMD).

The Texas General Land Office's, Land Management Program regulates construction on Texas state lands, including coastal wetlands (Younger 1985). Much low-lying coastal area in Texas with an elevation of less than 1.5 m is designated as wetland (Miget 1985). Precise differentiation of wetland from high ground is based primarily on elevation, soil salinity, and vegetation.

Steep topography in Hawaii limits coastal wetland area. Ancient tidal fish ponds are impounded shallow coastal water, and represent a private use of wetlands. Some protected sections of coast are vegetated by mangrove, alteration of which is strictly regulated by the State Department of Land and Natural Resources.

In Puerto Rico, destruction of mangrove areas is regulated. A project Environmental Assessment is circulated by the Planning Board to appropriate agencies including the Department of Natural Resources and the Corporation for Development of Maritime Resources (CODREMAR). The Environmental Quality Board must also sign-off on projects.

39.3.3 Seawater use

Most U.S. shrimp farms use surface seawater. From a regulatory standpoint, this usually involves permitting for both pumping water and construction of structures associated with pump stations. Construction physically impacts wetlands and submerged lands, while water use impacts marine life through impingement of planktonic species.

In South Carolina, permitting is regulated by the S.C. Coastal Council. Pump stations and intake structures are handled similar to dock permitting (DeVoe & Whetstone 1987). Applicants must not build structures upon wetland, and must avoid shading wetland vegetation. Pumped water volumes versus stream volume is considered for sites located along tidal creeks and rivers. Some recent permits for shrimp farms have stipulated that material collected on pond inlet screens must be returned to the estuary.

In Florida, pumping station structural components are scrutinized for compliance with wetland protection guidelines. The local Water Management District may have to issue a permit as well.

The Texas Water Commission regulates water pumping in that state. Recently, the state has required that shrimp farm pump intakes be screened to 500 microns. While such screening is common practice for shrimp pond predator control, it is physically easier to screen pump discharge where water flow can be used to make screens partially self-cleaning.

In Hawaii, it is difficult to obtain a permit to pump seawater into ponds. Permit applications are reviewed by the Department of Land and Natural Resources, and others. Most existing shrimp farms in this state draw water from seawater wells drilled into porous coral rock near shore. Thus, entrainment of marine life is eliminated and filtration for predator control is not necessary.

In Puerto Rico, seawater pumping systems are part of Environmental Assessment plans as distributed by the Planning Board and reviewed by the Department of Natural Resources, Department of Agriculture, CODREMAR and the Environmental Quality Board. In addition, blueprints and engineering aspects of pump station construction must be approved by the Administration for Regulations and Permits (ARPE).

39.3.4 Effluent Discharge

Shrimp pond effluents have not been associated with environmental damage but may be perceived as an environmental hazard due to nutrient content, solids, and biological oxygen demand (Hopkins et al. 1988). Permitting systems do not differentiate point-source discharges from shrimp ponds from those of sewage treatment plants or heavy industry. On a federal level, discharges are regulated by the U.S. Environmental Protection Agency (EPA) through the National Pollution Discharge Elimination System (NPDES). Broad guidelines of NPDES require a permit for aquaculture operations when annual production exceeds 45 MT. In most states, programs are administered by a state agency acting on behalf of the EPA. EPA Guidelines are interpreted slightly differently in each state.

In South Carolina, the state agency administering federal law is the S.C. Department of Health and Environmental Control. Potential impacts of shrimp farm discharges are predicted during permit review using a computer-based model. The model considers effluent water quality and volume, as well as receiving body physical and biochemical characteristics, in determining mixing and dilution rates and final impacts on estuarine water quality. Thus, there are finite limits to the amount of pond-reared shrimp which can be produced along a given estuarine tributary without effluent pretreatment.

In Florida, marine discharges are regulated by the Department of Environmental Resources (DER). A permit may not be required if DER determines that the discharge is confined to private property or will not create a source of pollution. Discharges which threaten to result in pollution require a permitted industrial wastewater treatment system. In addition, discharges to public waters require a NPDES permit from the EPA. The standard federal criteria for defining who needs a permit are used.

The Texas Water Commission acts as a contract agent for EPA in regulating coastal discharges. A permit may not be required, but it is recommended that an application be filed (Younger 1985).

In Hawaii, marine discharges are regulated by the State Department of Land and Natural Resources and the State Department of Public Health. Permits are required for any discharge. Ocean discharge permits have been issued recently, but earlier operations had to construct dispersion wells and/or settling ponds. The Board of Water Supply also regulates impacts on ground water resources.

The Territory of Puerto Rico strictly regulates discharges through the EPA system and local regulation. An Environmental Assessment distributed by the Planning Board includes effluent specifications, and is reviewed by the Department of Natural Resources, Department of Health, CODREMAR and the Environmental Quality Board. To date, only three permits for shrimp farm discharges have been issued.

39.3.5 Importation of Exotic Species

Nearly all cultured shrimp in the United States are Mexican white shrimp (*Penaeus vannamei*). It is not native to the principal culture areas of the U.S. with many PL imported from Latin America. These importations require permits at both the State and Federal level. The U.S. Customs Service inspects shipments, while the U.S. Fish and Wildlife Service issues import permits. To date, these regulations have not created major problems, and are handled as a matter of routine.

The South Carolina Wildlife and Marine Resources Department, the Florida Department of Natural Resources, the Texas Parks and Wildlife Department and the Hawaii State Plant and Animal Quarantine Department issue importation permits for exotic species into their respective states. In Puerto Rico, exotic species importations are handled as part of a project's master plan and Environmental Assessment as distributed by the Planning Board for agency review.

39.3.6 Other Regulations and Permits

Many states have other regulations, permits and licenses required to commercially farm shrimp. All states have food processing regulations,

whether it is from farms or capture fisheries, administered by a state health department. South Carolina and Texas have a general aquaculture permit, in addition to above-mentioned regulations. A license to possess and distribute cultivated saltwater products may be required in Florida.

39.4 SOCIOECONOMIC CONDITIONS

39.4.1 Labor Cost and Availability

High labor costs are a potential disadvantage for shrimp culture in the United States. This high labor cost has also fostered development of equipment and techniques which partially automate shrimp cultivation and processing. The Federal Government sets a minimum wage for agricultural workers. At present, this minimum wage is \$4.25/hr. In some places, it is often not possible to attract quality labor at minimum wage.

In addition to unskilled labor, shrimp culture requires special expertise, especially at the larger farms. Many U.S. farms are small, owner operated which do not hire a staff. Fortunately, many states offer technical support for these farmers through aquaculture extension services.

There are many skilled shrimp culturists in the United States, compared with the number of shrimp farms. Many work as expatriate technical managers for foreign operations (Chamberlain, in press; Hopkins, in press; Pruder, in press).

39.4.2 Land Cost and Availability

Land costs in the United States are moderately high, particularly in coastal areas. At present, U.S. population densities in coastal areas are increasing dramatically. Potential revenues from coastal housing and tourism may be much higher than from shrimp culture. Shrimp farmers must therefore compete with other development interest for limited coastal property.

In South Carolina, Texas, Puerto Rico and some parts of Florida, it is still possible to buy agricultural land adjacent to a good source of seawater for \$7,000 to \$10,000/ha. In Hawaii, and certain developed areas of other states, suitable sites are difficult to find, and costs are much higher.

Some shrimp farms in the U.S. are on leased land. This can be an attractive arrangement for farmers, as capital investment costs are lower and land use costs appear as operating expenses. It is also an attractive arrangement for some land owners, since income from land lease may enable owners to pay property taxes, meet other financial obligations, and maintain land ownership until development pressure increases its value.

39.4.3 Support Services

Development of a viable shrimp farming industry in the U.S. requires the establishment of necessary support services. These support services include processing and marketing channels, PL sources, quality feed, specialized equipment, and technical management consultation.

Shrimp processing facilities and marketing channels exist along the Gulf of Mexico, and the South Atlantic states in conjunction with established fisheries. Farms in Hawaii and Puerto Rico generally develop their own processing and marketing capabilities.

Growout intensification is possible due to PL availability and to readily available, high quality feeds. There are two major U.S. shrimp feed suppliers, one generally serves the eastern, and the other company the western half of the U.S. Recently, additional feed companies have developed shrimp rations and placed them on the market. Shipping can substantial increase real costs of shrimp feeds, and lead to spoilage problems.

Shrimp farming equipment is readily available in the U.S. including: pumps, aerators, feeders, test equipment, harvesters, and processing equipment. This equipment is available from domestic and foreign manufacturers. Domestically produced shrimp farming equipment is also exported to other countries, particularly Central and South America.

Many technical consultants are available in the U.S. Private consultants provide services to large domestic shrimp farms, and to a greater extent to foreign ventures.

Government sponsored extension support is available in most parts of the U. S. where a shrimp farming industry is developing. In South Carolina, extension support is provided through the Clemson University Marine Extension Service, Sea Grant Consortium Marine Extension Service and, especially, the Waddell Mariculture Center. Extension support in Texas is available through the Texas A&M Sea Grant College Program and the Texas Agricultural Extension Service. Extension support is available in Hawaii through the University of Hawaii and cooperative research and technology transfer is provided through the Oceanic Institute.

At present, the U.S. Department of Agriculture supports much of the research and development effort in marine shrimp farming through a consortium of institutions which include the Oceanic Institute, University of Arizona, Texas A&M university, Gulf Coast Research Lab, Tufts University and the Waddell Mariculture Center. This program includes a technology transfer component and works closely with the commercial shrimp farms in the country (Pruder, in press).

Table 1. Five-year (1983-1987) average of domestic shrimp landings in the United States by geographic region in metric tons, head-off (NMFS 1989).

REGION	LANDINGS
New England	3,749
South Atlantic	10,890
Gulf of Mexico	116,075
Pacific	19,103
Other	42
TOTAL	149,859

39.5 U.S. SHRIMP CAPTURE FISHERIES

39.5.1 Predominant Species

Most of the penaeid shrimp fishery in the United States is based on gulf brown shrimp (Penaeus aztecus). Brown shrimp from the Gulf of Mexico fishery accounts for about 75% of total domestic landings (Table 1). Other important species include Atlantic and Gulf white shrimp, (Penaeus setiferus), Gulf and Atlantic pink shrimp, (Penaeus duorarum), grey shrimp (Crangon franciscorum) in California, and the North Atlantic and Pacific pink shrimps (Pandalus borealis and Pandalus jordani) (Dore and Frimodt 1987). There is limited fishing effort for royal-red shrimp, (Pleoticus robustus) and rock shrimp (Sicyonia brevirostris). Some Penaeus schmitti and Penaeus notialis are captured around Puerto Rico. Hawaii has attempted to develop a fishery for deep water shrimp, (Heterocarpus spp.).

Attempts at cultivation have been made with most indigenous species (Parker and Holcomb 1973; Stokes et al. 1985). Penaeus setiferus and P. schmitti gave better culture performance than P. duorarum, but are generally considered inferior to the Americas Pacific coast species, P. vannamei and P. stylirostris.

39.5.2 Major Fishing Grounds

The Gulf of Mexico is the major U.S. shrimp fishing grounds (Table 1). Establishment of exclusive economic zones in territorial waters has excluded U.S. fleets from Mexican waters, but also prohibits foreign fleets in U.S. waters. Brown shrimp are the principal species in open Gulf of Mexico fishery. The Gulf states (Texas, Louisiana, Mississippi, Alabama, Florida west coast) also harvest white shrimp from inshore or near-shore waters.

A shrimp fishery also exists along the south Atlantic states (North Carolina, South Carolina, Georgia, Florida east coast). The predominant

Table 2. U.S. supplies of shrimp from domestic fisheries, imports and aquaculture in metric tons of tails or equivalent (NMFS, 1989).

YEAR	DOMESTIC FISHERIES		FOREIGN IMPORTS		DOMESTIC AQUACULTURE		TOTAL
	MT	%	MT	%	MT	%	
1979	93,449	43.3	122,392	56.7	0	0.0	215,841
1980	94,486	44.6	117,304	55.4	0	0.0	211,790
1981	99,500	45.8	117,778	54.2	33	0.0	217,311
1982	79,824	35.5	145,271	64.5	68	0.0	225,163
1983	70,723	27.0	191,445	73.0	68	0.0	262,236
1984	85,514	30.8	191,973	69.2	112	0.0	277,599
1985	94,200	31.4	205,560	68.5	142	0.1	299,902
1986	111,095	33.2	223,639	66.7	378	0.1	335,112
1987	101,597	27.7	265,014	72.1	777	0.2	367,388
1988	92,432	25.3	271,914	74.5	646	0.2	364,992

species here are white shrimp (*P. setiferus*), with Gulf brown shrimp (*P. aztecus*) of secondary importance. Coldwater shrimp fisheries harvest pandalid shrimp off the New England and Pacific coasts.

39.5.3 Economic Viability of U.S. Fishery

Annual production from U.S. shrimp fisheries has remained relatively stable for a decade, while imports have increased substantially (Table 2). Shrimp imports have tended to stabilize supply, and to set prices received for the domestic shrimp catch, while boat operating costs continue to rise (NMFS 1989).

39.5.4 U.S. Shrimp Market

Consumer demand for shrimp in the U.S. has increased dramatically in recent years. Shrimp accounts for 32% of the total edible imports of fishery products into the U.S. This is reflected in total supplies of shrimp products, and per capita consumption (Table 2). Shrimp consumption is related to individual disposable income. Shrimp are generally considered a luxury product, with about 70% consumed in restaurants. Restaurant trade relies heavily on disposable income.

39.6 TECHNOLOGY DEVELOPMENT

All of the U.S. shrimp farms known to the author are listed in Appendix A with their location and the characteristics of their production methods. This list is a summary of the discussion below of the use of various technologies by U.S. farms.

39.6.1 The Recruitment Method (capture and hold)

Shrimp culture in the U.S. began much as it did in Ecuador (Hirono 1983), Taiwan (Liao and Murai 1985), and other places. Wild shrimp PL were inadvertently introduced into tidal coastal ponds where they grew and were later harvested. Stocking impounded wetlands with wild PL through water inflows is termed the recruitment method (Hopkins, et al. 1987).

Recruitment involves both physical and behavioral processes. Penaeid shrimp PL migrate into nursery grounds in the upper reaches of estuaries. Impounded wetlands adjacent to tidal estuaries are equipped with flap gates which regulate tidal water flow into and out of ponds. Gates are opened to allow water and entrained shrimp into ponds while PL are migrating into the upper estuary. Tidal exchange is also used to partially flush ponds during the growing season. Finally, the gates are opened, the pond drained, and the crop harvested. Typically, the impoundment cannot be fully drained, and the remaining shrimp must be captured with nets. Thus, shrimp culture in these impoundments is generally inefficient and harvesting is labor intensive.

Predator control is difficult and only partially effective with the recruitment method (Lunz and Bearden 1963). After harvest, ponds are drained to the extent possible and attempts are made to eradicate remaining predators with nets and fish toxicant. During water inflows, gates are screened with a course mesh (5-10mm) to allow shrimp PL to pass, while excluding large fish. Unfortunately, many eggs, larvae, and juveniles of potential predators are recruited along with shrimp PL.

The combined effects of the above problems make extensive shrimp culture by recruitment stocking an unpredictable endeavor. It is unlikely that this form of shrimp culture will ever expand greatly in the U.S. These impoundments, in areas such as South Carolina may, however, be intensified using more sophisticated technologies.

39.6.2 Postlarval Production

Cost effective PL production from hatcheries has provided shrimp farmers much greater control over growout. The capability to stock hatchery-reared PL of known species has made shrimp farming a more predictable endeavor in terms of predator and competitor control, and inventory manipulation.

The U.S. has made major contributions to hatchery technology development. At the NMFS Galveston, Texas laboratory, a method of raising live phytoplankton and zooplankton in separate tanks and delivering these live feeds to shrimp larval rearing tanks was developed (Cook and Murphy 1966; Mock and Murphy 1970). Modifications of the "Galveston Method" are now used to raise nearly all hatchery-produced PL in the Americas.

Following these advances in larviculture, breakthroughs were also made in captive maturation and spawning during the mid-1970's. Commercial and research projects in Florida (Hopkins, in press), Texas (Chamberlain, in press) and Hawaii (McGovern 1988) further refined shrimp maturation and spawning methods.

Captive reproduction is particularly important for shrimp culture in the U.S. because of climatic and species considerations. A restricted growing seasons makes it imperative that ponds are stocked as soon as water temperatures permit. If wild P. setiferus broodstock are collected during their normal spawning season, PL are not available for pond stocking until at least four to six weeks after optimum stocking times. More importantly, the preferred species in the U.S. is the Mexican white shrimp (Penaeus vannamei). Since this species is not indigenous to the U.S., closed-life cycle culture is needed. Finally, closed life-cycle culture makes it possible to begin domestication processes (Lester 1983).

All U.S. shrimp hatcheries have controlled maturation, and most use pond-raised broodstock from their own farm. Both Amorient Aquafarms in Hawaii, and Laguna Madre Shrimp Farm in Texas use broodstock which have been in captivity for five to eight generations. Continental Fisheries Ltd. in Florida used imported wild broodstock, as this company did not operate growout ponds in the U.S. The Granjas Marinas de San Bernardo hatchery in Florida has initially imported broodstock from Hawaii and their Honduras operations. Several U.S. research projects, including the Oceanic Institute in Hawaii and the Waddell Mariculture Center in South Carolina, have maintained shrimp for several successive generations.

The number of U.S. growout farms without hatcheries has increased dramatically in recent years, resulting in a shortage of domestically produced PL at times. Insufficient hatchery capacity, and price competition has led to increased PL importation. In recent years, growout farmers in the U.S. have stocked PL from hatcheries in Florida, Texas, Hawaii, Panama and Costa Rica. Shortages of PL are, at times, a major concern of shrimp culturists in the U.S. and such shortages resulted in a decline in the total U.S. production of farm-raised shrimp in 1989 (Table 3).

PL of P. vannamei from many hatcheries harbor viruses (Lightner 1985) which may or may not be present in the local environment. Investigations of shrimp viruses have been hastened by aquaculture development which, in turn, has raised concerns about possible detrimental impacts of imported PL on native shrimp stocks. This issue may eventually result in state or federal government restrictions on importation of hatchery PL into certain areas.

Table 3. Estimated annual production of farm-raised shrimp in the United States by state or territory (metric ton, head-off).

YEAR	HAWAII	TEXAS	SOUTH CAROLINA	PUERTO RICO	OTHER	TOTAL
1979	0	0	0	0	0	0
1980	0	0	0	0	0	0
1981	0	33	0	0	0	33
1982	0	66	2	0	0	68
1983	0	66	2	0	0	68
1984	8	83	8	0	13	112
1985	51	62	15	0	14	142
1986	161	175	42	0	0	378
1987	308	366	103	0	0	777
1988	159	335	152	0	0	646
1989	141	174	85	0	0	400

Sources: Aquaculture Development Board, Chamberlain in press; Chamberlain, 1986; Chamberlain, 1985; Hopkins, 1988; Pruder, in press; Rosenberry, 1988; Bannon,

39.6.3 Stocking of Extensive Growout Ponds

The first U.S. projects to stock hatchery-reared PL were built in Florida during the late 1960's and early 1970's (Hopkins, in press). The Turkey Point project, the Crystal River project, the Sea Farms group, and the Marifarms group all had shrimp hatcheries. Marifarms' assets were eventually sold to Continental Fisheries Ltd. which, until recently, operated a hatchery in Florida. Sea Farms was reorganized as Shrimp Culture Inc. This company recently reopened its hatchery in Summerland Key, Florida to serve their farm in Honduras, Granjas Marinas de San Bernardo.

Farms operating by the recruitment method began to stock hatchery PL when they became commercially available. Facilities did not require modifications to use hatchery produced PL, and many problems encountered using the recruitment method were avoided (Hopkins et al. 1987). In South Carolina, Palmetto Aquaculture was the first group to stock hatchery PL in existing tidal impoundments. Palmetto Aquaculture has since increased production to semi-intensive levels. A brackish impoundment in Texas was stocked in 1984 and 1985 for extensive production (Chamberlain 1990). Also in Texas, the U.S. Army Corps of Engineers and MariQuest, Inc. demonstrated extensive culture using hatchery PL in dredge disposal areas.

39.6.4 Semi-Intensive Pond Growout

Development of captive reproduction and larviculture of exotic shrimp species in the U.S. and improvements in growout technology prompted development of large-scale, semi-intensive shrimp farms during the late 1970's.

Semi-intensive growout technology includes use of formulated feeds, higher water exchange rates, some aeration for emergencies and, of course, higher PL stocking densities (Clifford 1985).

Based upon successful production trials at Texas A & M University (Parker et al. 1974), Laguna Madre Shrimp Farm was built in South Texas. Laguna Madre is the largest shrimp farm in the U.S. A few years later a second large farm, Amoriant Aquafarm in Hawaii, began to switch hatchery and growout production from freshwater prawns (Macrobrachium rosenbergii) to P. vannamei. About this same time, Plantation Seafarms was constructed in South Carolina. Plantation Seafarm was the first major marine shrimp project in the U.S. which did not include a hatchery. Soon thereafter, Plantation Seafarms moved to a larger site at higher elevation, and was reorganized as Edisto Shrimp Co.

Construction of farms which only have growout facilities continues today in South Carolina, Texas, Hawaii and Puerto Rico. Prices of commercially available PL have tended to decline slightly over time. PL availability tended to increase for a while, but rapid farm growout expansion created a PL shortfall in 1989. This shortfall is also the result of growout intensification, where more PL are stocked per unit land area.

39.6.5 Intensive Pond Growout

High land costs and limited investment capital availability has made intensive culture an attractive alternative (Rhodes, in press). Farms designed for intensive culture are being built, and production levels are being increased at existing farms (Hopkins, in press; Chamberlain, in press; Pruder, in press). Farms originally designed for semi-intensive culture are often able to intensify, if ponds are relatively small, if ponds are completely drainable, and if electrical aeration equipment is installed (Sandifer, in press).

The first U.S. corporate farm constructed specifically for intensive shrimp culture was Orca Seafarm in Hawaii (now Molokai Sea Farm). At present, there are five other farms in Hawaii equipped for intensive production. In Hawaii, there is commercial interest in farms designed to utilize the intensive round-pond technology developed at the Oceanic Institute (Wyban and Sweeney 1989).

In South Carolina, there are now twelve shrimp farms in intensive culture (Appendix A). Edisto Shrimp Co. has intensified production through installation of aeration equipment. Two additional farms represent corporate investments, Sea Fare and Atlantec. Most farms are, however, owner-operated businesses. Richardson Plantation, a pilot facility, has demonstrated the viability of small, owner-operated farms.

In Texas, Ocean Ventures was the first farm built for intensive culture. Since that time, three additional intensive farms have been constructed.

Laguna Madre has intensified production, although limited by large pond size. As in Hawaii and South Carolina, all new Texas farms are small compared to Laguna Madre, Amorient and Edisto Shrimp.

The first marine shrimp farms in Puerto Rico have recently been completed. These farms will use intensive culture methods. One of the intensive farms in Puerto Rico and another in Texas culture Penaeus monodon instead of P. vannamei.

39.6.6 Intensive Tank Growout

There have been several attempts at intensive tank culture of shrimp in the U.S. (Colvin 1985). The first commercial in-door, intensive tank culture of shrimp was the King James Shrimp Co. in Chicago, Illinois during the 1970's. A second project was conducted in northern Mexico in cooperation with the University of Arizona and Coca-Cola Inc. This project later moved to Hawaii to become Marine Culture Enterprises (MCE) and was eventually sold to Pacific Seafarms. These intensive tank projects made numerous technological advancements, and MCE was able to produce more than 100 MT/ha/yr. The MCE system used P. stylirostris, which often grows faster than P. vannamei, but is much more susceptible to IHHN virus infections (See Chapter 26, this volume).

39.6.7 Nursery Systems

There are two basic shrimp nursery approaches commonly used in the U.S., those intended for improving inventory control, and those intended to head-start a crop before the beginning of a restricted growing season. Many farms do not use nursery systems, and stock PL directly into growout ponds.

Inventory control is improved by nursing PL where predators, water quality, and nutrition can be monitored more closely. An accurate estimate of the stocking density of juveniles into growout ponds improves growout pond management. In areas where consecutive crops are grown without an off-season, nursery ponds allow a subsequent crop to be started before the current crop is harvested.

In the continental U.S., shrimp size and number of crops/yr are determined largely by growing season (i.e. water temperature). Shrimp size and number of crops may be increased by head-starting PL in an elevated temperature environment prior to pond stocking. Heat is usually from passive systems, such as greenhouses, but may be from induced heating. PL are normally stocked at very high densities in a nursery two to six weeks prior to pond stocking for growout (Lawrence 1988). Nursery costs may be justified by increased income from larger shrimp size and higher value when marketed (Juan et al. 1988).

39.7 ECONOMIC VIABILITY AND DEVELOPMENT POTENTIAL

The U.S. is still a minor producer of cultured shrimp with only 646 mt (head-off) cultured in 1988 after a record year of 777 mt in 1987. Production figures for 1989 are still preliminary but indicate that production dropped again to 400 mt (Table 4). There are roughly 400 ha of shrimp production units constructed in the U.S. although recent declines are attributed to reductions in the number of production units being stocked by three of the larger farms.

There have been economic studies of shrimp farming in Texas (Hollin and Griffin 1985; Huang et al. 1984), South Carolina (Rhodes 1989; Rhodes et al. 1987a,b) and Hawaii (Wyban et al. 1988). These studies indicate that either semi-intensive or intensive systems have a higher probability of economic success, given past price and cost structures.

Economic studies are not available for the Puerto Rico territory and the new farms have not yet been harvested (Table 3). Shrimp farming in Puerto Rico is more similar to that of Latin America than the continental United States, it is likely that Puerto Rican shrimp farms can be more profitable once the industry becomes established there.

Only some existing U.S. shrimp farms are economically successful. In general, small owner-operated farms are more likely to be profitable. Successful operations are characterized by good technological and business management, sound financial structuring and good marketing (Hopkins 1990). The most successful farms usually capitalize on product quality, and sell to high-value niche markets.

If shrimp prices rise faster than U.S. operational costs, the U.S. industry could prosper and expand dramatically. The estimated total annual economic benefits could be in excess of \$1 billion in South Carolina alone (French et al. 1988). Unfortunately, the opposite situation, that is, stable or declining shrimp prices and higher U.S. operating costs is a real possibility.

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Appendix A. Partial list of shrimp farming operations in the United States including location and production characteristics.

PROJECT	LOCATION	PRODUCTION CHARACTERISTICS
Amorient Aquafarm	Hawaii	A,2,3,5,7,8,9,10,11
Aquatic Farms	Hawaii	B,2,3,7,11
Atlantec Seafarms	South Carolina	A,3,
Aurea Marine	Hawaii	A,3,9,
Bowers Shrimp Farm	Texas	A,2,3,
CLP Trading Co.	South Carolina	A,3,
Coastal Science & Eng.	South Carolina	A,11,
Commercial Shrimp Culture	Texas	B,2,6,9,
Continental Fisheries	Florida	B,5,
Crystal River Project	Florida	B,2,3,7,
Del Encanto Enterprises	Puerto Rico	A,3,5,
Dow Chemical	Texas	B,2,
Edisto Shrimp Co.	South Carolina	A,2,3,6,8,9,
Edisto Mariculture	South Carolina	A,2,3,5,9,
Eureka Marine Products	Puerto Rico	A,3,5,7,
Genesis Aquaculture	Texas	A,2,
Guffy Seafood	Texas	A,3,
Granada Corp.	Texas	A,7,10,
IKKO	Hawaii	B,3,7,
Inland Sea, Inc.	Texas	B,2,
Kahuku Shrimp Co.	Hawaii	A,3,9,
King James Shrimp	Illinois	B,4,6,7,
King Ranch	Texas	B,1,2,
Laguna Madre Shrimp	Texas	A,2,3,5,7,8,10,
Lone Star Shrimp	Texas	A,3,7,
Marifarms	Florida	B,1,7,
Marine Culture Enterprises	Hawaii	B,4,6,7,
MariQuest, Inc.	Texas	B,4,6,7,
Martin Shrimp Farm	South Carolina	A,2,3,
McKaskle Shrimp Farm	Texas	A,2,
Molokai Sea Farm	Hawaii	A,3,5,7,
Ocean Ventures	Texas	A,3,6,8,
Ohia Shrimp Farm	Hawaii	A,3,8,
Orca Sea Farms	Hawaii	B,3,5,7,
Pacific Sea Farms	Hawaii	A,4,6,7,
Palmetto Aquaculture	South Carolina	A,2,8,
Port Lavaca Plantation	Texas	A,3,

Appendix A. continued

PROJECT	LOCATION	PRODUCTION CHARACTERISTICS
Rabbit Point Plantation	South Carolina	A,2
Richardson Plantation	South Carolina	A,3
RPI International	South Carolina	A,11
Sal Del Ray	Texas	B,2
Sand Creek Shrimp	South Carolina	A,2,3,8,9
Sea Farms, Inc.	Louisiana	B,1
Sea Fare, Inc.	South Carolina	A,2,3
Sea Island Mariculture	South Carolina	A,2
Shrimp Culture Inc.	Florida	A,1,2,7,10
Spring Island Plantation	South Carolina	A,1
Stansell Shrimp Farm	South Carolina	A,3,6
Taylor Creek Shrimp	South Carolina	A,2,3,6,9
Tullifinny River Co.	South Carolina	B,2
Turkey Point Project	Florida	B,2,7,8,10
A - presently operating	5 -outdoor nursery	
B - no longer operating	6 -enclosed nursery	
1 - extensive growout	7 -hatchery	
2 - semi-intensive growout	8 -shellfish biculture	
3 - intensive pond growout	9 -fish or prawn culture	
4 - intensive tank growout	10 -foreign operations	
11 - consulting services		

CHAPTER 40

Arlo W. Fast and L. James Lester

FUTURE OF WORLD SHRIMP CULTURE

40.1 INTRODUCTION

Shrimp culture's near future is perhaps much easier to predict than its distant future. A look at the recent past, and present status of the industry tells us much about where technology and economics are leading shrimp culture. In this chapter, we will attempt to forecast developments during the next 10 years or so.

Future shrimp culture, like the present and past, will be driven by economic considerations. Shrimp culture will flourish in those countries that culture shrimp profitably at world market prices. Elsewhere, shrimp culture will supply small, specialty markets, if it exists at all. Shrimp culture systems that produce shrimp at costs competitive on the world market will become the dominant culture systems.

Profitability is largely determined by the relationship between supply and demand, and by the cost of production. During recent times, demand for shrimp exceeded supply, and the costs to catch shrimp from the world's oceans have been high. Shrimp have been profitably cultured in ponds using a wide range of culture techniques and culture intensities. This situation is rapidly changing due to large production increases from shrimp pond culture. These production increases are narrowing the gap between supply and demand, and at times, resulting in excess supply. The latter situation happened during 1989, and resulted in sharp price drops for shrimp. While prices have rebounded since the summer 1989, the long-term prospects are for a downward price trend.

As we have seen in the experience chapters of this volume, cultured shrimp production is increasing very rapidly in most countries that have interests in shrimp culture, and have devoted resources to its development. In 1980, only about 2% of the world's shrimp production came from pond culture with 98% from the world's oceans. The ocean catch has now reached a maximum sustainable yield and no further increase is expected. During 1989, 26% of the world's shrimp production was from the pond culture and 74% from the ocean (Rosenberry 1990). By the year 2000, perhaps 45% will be from farms, if present trends continue (Fig. 1). These changes will have profound impacts both within the shrimp culture industry, as well as on ocean fisheries. In this chapter, we will attempt to predict some of these changes,

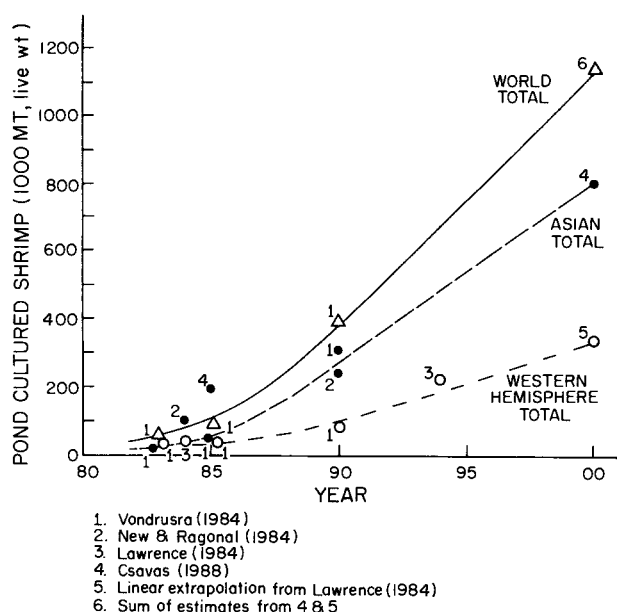


Figure 1. Estimated and projected production of pond cultured shrimp for the world, Asia, and the western hemisphere between the year 1983 and 2000.

and to discuss some research needs which must be addressed for continued the transformation of shrimp culture from an artisanal husbandry into a scientific technology. This prognosis has a large element of subjectivity, of course, and for that reason we will not attempt to belabor all possibilities.

40.2 SHRIMP CULTURE SYSTEMS

As a consequence of the large profit margin between the costs to culture a unit weight of shrimp and the price to the farmer, a wide variety of culture systems have evolved. Most of these were profitable at some time and place. With falling shrimp prices, changes will occur in system profitability, and therefore in the type of culture systems used to culture most shrimp.

Basic research on pond culture, and those things that impact profitability of pond culture (except for seed production), has not received much attention. Most research to date has focused on seed production, nutrition and disease. While there are still problems with seed production, this is not the main impediment to shrimp culture profitability. Most profits or losses are made during pond growout because this culture phase has the highest variable costs. We can expect more research attention devoted to pond

growout, and ultimately some major breakthroughs in culture technology. Perhaps these will occur within 5 to 10 years.

40.2.1 Extensive and semi-intensive shrimp culture

A consistent observation throughout this volume was that extensive (except for very low intensity extensive), and semi-intensive culture systems have the greatest profit per unit production, and have remained profitable during declining shrimp prices when more intensive systems were clearly unprofitable. The reason for this observation and conclusion is that there is a greater profit margin per unit production than with more intensive culture, although the potential profit per unit land area is less (Hirasawa 1985). We do not expect this situation to change soon. Significant cost reductions would need to occur in several shrimp culture inputs before profit from higher intensity culture would equal or exceed profit per unit from extensive or semi-intensive culture.

Extensive shrimp culture would benefit most from a better understanding of pond dynamics processes, since this presumably would result in greater natural productivity, higher stocking densities, and greater shrimp yields (Table 1). Extensive culture would also benefit from biological characterization of shrimp species and from improvements in reproduction and seed production. It would benefit least from advances in nutrition and feeds.

Semi-intensive culture would benefit most from advances in pond management, biological characterization of shrimp species, seed production and genetics (Table 1). Semi-intensive culture would probably benefit less from advance in micro-computer applications, nutrition, and feeds.

40.2.2 Intensive shrimp culture

Development of intensive shrimp culture technology in Taiwan, and its transfer elsewhere was one of the most interesting aspects of the 1980's. The prospect for its continuance is now bleak. A combination of disease and economic problems with this system in Taiwan makes its survival there questionable, particularly for production of an export crop (See Chapter 31). Even without the added problems of disease, intensive culture elsewhere is not likely to be profitable. The exception to this conclusion is Penaeus japonicus culture for the live shrimp market in Japan.

Intensive culture potentially would be profitable again if substantial improvements occur in virtually all aspects of shrimp culture, but especially in feed and seed since these two costs typically account for more than 50% of total production costs (Table 1). While understanding pond dynamics is important for intensive culture, it is perhaps relatively less important than with less intensive culture systems.

Table 1. Relative importance of future significant breakthroughs and developments in shrimp culture for different culture systems. (5 = highest importance; 1 = lowest importance; 0 = not applicable)

Innovation	Extensive	Semi-Intensive	Intensive	Ultra-Intensive
1. Pond dynamics control	5	5	3	2
2. Microcomputer applications	1	2	5	5
3. Physiological manipulation	3	4	5	5
4. Reproduction and seed production	2	4	5	5
5. Feeds and nutrition	0	2.5	5	5
6. Selection and genetic changes	1	4	5	5
7. Disease control	1	3	5	5
8. Market development	4	5	5	5

40.2.3 Ultra-intensive shrimp culture

With the exception of round-pond culture of *P. japonicus* in Japan for a brief time, ultra-intensive culture systems have never been profitable. They are troubled by high production costs and high risk of crop loss from disease, mechanical failure, or some other factor. We do not expect this to change in the foreseeable future.

40.3 POND DYNAMICS

Most pond research has been applied, and much of that has been done by the private sector. This has resulted in development of many pond culture approaches, even though our understanding of the underlying principles is not very thorough. Basic research on physical, chemical and biological pond dynamic problems should improve our understanding and lead to improved technology for pond culture of both shrimp and fish. Research is particularly needed on phytoplankton density and composition, water and effluent management, sediment chemistry and deposition and nutrient flow from fertilization. Extensive and semi-intensive shrimp culture are likely to benefit most from breakthrough in pond dynamics if these result in improved natural food production, greater shrimp yields, and reduced risks of crop loss as production intensity increases.

40.4 MICROCOMPUTER APPLICATIONS

Microcomputer monitoring and control systems are now used in pond and tank management for trout (Moller and Dahl-Madsen 1987), catfish and other aquaculture applications (Arnason and Scuse 1987, Rogers et al. 1988, Fridley 1986), but it has been used principally at the experimental level with marine shrimp (Fast, in press, b.). Even those systems now used for trout and catfish are not well developed. Furthermore, the full benefits of microcomputers cannot be realized until we better understand pond dynamics, and how to manipulate these processes. Microcomputers and software applicable to aquaculture are well developed, but monitoring probes are still too costly and unreliable.

40.5 OCEAN SHRIMP FISHERIES

On a world wide basis, shrimp culture undoubtedly has a greater profit margin per unit weight produced than shrimp captured from the ocean, although this is not well documented. There are some exceptions, but on average this appears to be the case. Furthermore, many of the ocean shrimp fisheries, such as the Gulf of Mexico and Gulf of Thailand appear overfished. As cultured shrimp production increases and world shrimp prices decline, we can expect many of the ocean shrimp capture fleets to reduce their size. This may not initially result in reduced catches, or reduced value of the catch, since those remaining boats are expected to increase their catch rate and size of shrimp in the catch (Vodruska 1987, National Marine Fisheries Service 1984). Eventually, if shrimp prices decline sufficiently, total catch from the ocean would be reduced.

There are few studies that compare economics of shrimp culture with shrimp culture fisheries. We know, however, that shrimp trawling is very energy, capital and labor intensive. U.S. shrimp trawlers in the Gulf of Mexico consumed 11.1 liters of diesel fuel per kg of shrimp captured during 1973 (Wardlaw and Griffin 1974). Thai trawlers (<14 m length) in the Gulf of Thailand consume about 1.9 liters of diesel fuel of every kg of shrimp captured (Boonchumong and Lawapong 1988). Shrimp trawling has one of the highest energy consumption rates of any fishery (Rawitscher and Mayer 1977). Shrimp culture, on the other hand, is not energy intensive in most forms. Further improvements in shrimp culture technology are likely to further reduce shrimp culture production costs and widen the gap between shrimp culture and capture profit margins. Costs to capture shrimp from the oceans are not likely to decrease.

40.6 PHYSIOLOGICAL CHARACTERIZATION

We know very little about some basic biological characteristics of even the mostly commonly cultured shrimp species. Aspects as basic as their growth responses to temperature and salinity conditions are not documented for the entire life cycle of even a single species. We know little about control of molting and molting cycles. Burrowing and other aspects of shrimp behavior are virtually unstudied. We need to know much more about these and other basic biological characteristics of shrimp before we can improve shrimp culture technology and greatly reduce production costs. As we learn more about these characteristics for many shrimp species, we may, as suggested by Boddeke (1983) culture many other species profitably, as well as culture the most commonly reared species even better.

40.7 REPRODUCTION AND SEED PRODUCTION

After feed, seed costs are the most important production costs of most culture systems. Seed costs are high largely because of costs and uncertainties of broodstock procurement and labor costs of larviculture.

40.7.1 Broodstock

At present, virtually all hatchery broodstock comes from the wild, and most of that is gravid when delivered to the hatchery. Non-gravid, wild caught broodstock are matured and spawned by some hatcheries, but the results are variable and considerable capital and labor is required. Pond reared broodstock typically have low spawn quality compared with gravid wild stock. While wild caught, gravid broodstock is preferred by most culturists, it is only reasonably available in most places, and sometimes unpredictable. Furthermore, many countries are considering restrictions on wild stock collection in order to protect their indigenous shrimp populations.

A proposed solution is endocrinological manipulation of captive broodstock. This would not only produce spawns on demand, but it would assist in selective breeding programs, establishment of pathogen-free stocks, and improved culture of exotic shrimp species. Before such manipulations become reality, however, we need to better understand shrimp endocrinology (See Chapter 4) and factors affecting egg quality. There has been little basic research on these topics, and we do not expect major advances soon.

40.7.2 Controlled Fertilization

Techniques for artificial insemination of open thelycum species have been in use since the late 1970's (Persyn 1977; Laubier-Bonichon and Ponticelli 1981; Bray et al. 1982; Aquacop 1983) and were developed for P. monodon

in the mid 1980's (Lin and Ting 1986). Some progress has been made recently with induced spawning and in vitro fertilization (see Chapter 5). Although the first report of in vitro fertilization was made by Clark et al. in 1973 for *P. aztecus*, there has not been another report of successful in vitro fertilization using a Western Hemisphere *Penaeus*. Pillai et al. (1988) have experimentally induced spawning of the penaeid shrimp *Sicyonia ingentis* by oviduct probing, while Lin and Ting (1986) have successfully fertilized spawns of *P. monodon* in the spawning tank using sperm suspension from extruded spermatophores. Some experimental work has also been done on storage of gametes, but the results are not yet published (Addison Lawrence, Texas A&M University, personal communication). Taken together, these techniques would lead to improved spawning efficiencies and a mechanism for controlled crosses. These techniques are now experimental, but could become commonplace within a few years.

40.8 NUTRITION AND FEEDS

Some basic research has been done on marine shrimp nutrition, particular at Texas A&M University (See Chapter 25), but it is trivial compared with the amount of research conducted on cattle, swine, chickens, and other domesticated species. Feed conversion ratios and feed costs for shrimp are still excessively high, particularly for intensive growout systems, even when compared to other aquacultured species. High quality trout feed is available at U.S. \$0.55/kg or less, with FCR of 1.2 or less. Channel catfish feed costs even less. By comparison, shrimp feed for intensive culture costs from U.S. \$0.75 to U.S. \$1.50/kg, and gives FCR of 1.7 to 2.0 or more. Feed costs per kg of production can thus run as high as U.S. \$3.00/kg, compared with U.S. \$0.66/kg for trout.

Not only do we need to reduce growout feed costs and FCR, we also need to develop better quality larval feeds. Good progress has been made with prepared larval feed products, but these are still not substitutes for live feeds. High quality larval feeds could well be available within the next few years, which would reduce labor costs, improve larviculture success, and reduce seed costs.

40.9 SELECTION AND GENETICS

If shrimp aquaculture is to progress like agriculture, domestication of the animal is essential. Most of the seedstock for shrimp farming is obtained either by collecting wild seedstock or by spawning locally collected gravid females. Over the next ten years, cultured strains will begin to appear as shrimp farms close the cycle for production of broodstock. There are already

isolated stocks of shrimp undergoing domestication at the Aquacop research facility in Fiji, in several Italian lagoons, at one research facility and two shrimp farms in the U.S. and at one shrimp farm in Panama. There may be other stocks under domestication of which we are unaware.

As the industry matures, some companies and government labs will specialize in production of improved seedstock. The marketing of improved P. vannamei will occur within five years and of P. monodon within ten to 15 years. This difference is predicted due to the lower level of control over maturation and reproduction of P. monodon.

Initially broodstock management programs will focus on increasing survival and growth which will be relatively easy to improve. Selective breeding will then expand to include more commercial traits, such as resistance to diseases that are difficult to treat or prevent. This phase will be followed by more difficult objectives requiring greater understanding of the genetic system of the shrimp.

As shrimp farming becomes more economically significant, geneticists will be called on to produce a linkage map of the genome, to clone important genes and to insert these or foreign genes into the shrimp genome.

40.10 DISEASE CONTROL

Shrimp pathology is at an intermediate stage in which many common lethal diseases have been characterized and the disease agent described. However, there is much work to be done before a thorough understanding of shrimp health is obtained. Bacterial and fungal diseases were the first to be identified and characterized, but viral diseases are currently causing the greatest concern in the industry (see Chapter 26). Viral diseases will require considerable research effort before satisfactory control measures are developed. Bacterial diseases of larvae and broodstock should receive considerable attention in the next ten years as the dependence on hatcheries grows and progress will be made in diagnosis and treatment.

Diagnosis of a disease of viral etiology is usually accomplished with histological methods. These methods are laborious and can result in false negatives. However, histology and bioassay are currently the only applicable techniques and their use should increase over the near term. Rapid, reliable diagnosis will require the development and marketing of sophisticated molecular techniques which should not be expected in the next ten years.

The lack of highly reliable techniques for screening and treatment of disease will result in increased use of quarantine facilities. Also, large growers may choose to close their stock and not import any shrimp.

There is preliminary evidence that immunization may be applicable to prevention of shrimp diseases. This technique will be limited for viral diseases

until there are reliable techniques for producing large quantities of virus or at least viral antigen. Immunization against bacterial diseases may become commonplace in the next ten years for large seedstock producers.

Concern about bacterial diseases may increase in the future with the development of antibiotic resistant strains. It is common practice in hatcheries to use antibiotic prophylaxis. This selects for antibiotic resistant strains of bacteria and fungi. Antibiotic resistance can be spread in the aquatic environment and become a general problem. It can lead to a need for larger quantities or more expensive antibiotics and an increase in the cost of producing seedstock. Despite concerns about the development of resistance, we expect to see more sophisticated delivery systems for antibiotics to larval and grow-out stages.

Mortality patterns in the future will change from a high chronic mortality in all culture units to occasional epidemic mortality. This decline in normal mortality will be associated with the provision of a better culture environment, better understanding of nutritional requirements and improved genetic stocks. However, epidemic diseases will always threaten shrimp farmers, just as they do human and domestic animal populations.

40.11 GOVERNMENT REGULATIONS AND POLICIES

As the industry develops, there will be increasing regulation due to concern for the economic costs of mismanagement and for the environmental impact of unlimited expansion. There is already significant government regulation in most countries (see Chapter 39 especially).

Water resources will cause more conflict in the future and aquaculture will be a major user in some countries. Both Asia and South America will experience more problems arising from organic enrichment of coastal waters due to effluent from a variety of inputs. Most countries will feel compelled to implement more stringent regulations on quality of water that is discharged to public water bodies. This will cause more intensive shrimp farms to recycle or treat their effluent.

Many countries have laws or regulations protecting wetlands of various types, including mangrove forests. As more countries adopt these regulations and more stringent enforcement occurs in the countries that have such rules, fewer shrimp farms will be sited in wetland areas. This will primarily affect extensive operations that attempt to use minimal pumping and low cost pond construction.

Concern for indigenous wild stocks may lead to more regulation of shrimp culture in two ways. More countries may limit fishing for wild, gravid females as complaints grow about the impact on recruitment to wild stocks. Also, more regulations may govern the transport and culture of exotic species

in the future as more reports occur of capture of exotics from areas adjoining shrimp farming operations.

Inspection of the harvested or processed shrimp will become more general and more rigorous as the export market becomes more competitive. Domestic markets will be less affected, but in some countries may also require high quality standards. This will cause more processing plants to be built in the vicinity of farms or for farmers to treat the product differently at harvest.

Many governments currently view shrimp culture as a viable route for agricultural diversification and should provide more support services to shrimp farmers in the future. These services may take the form of extension services, financial subsidies, or regulatory changes which improve the business climate for aquaculture. One vital area of government involvement will be in providing education and training in aquaculture for the potential labor force.

40.12 COUNTRY AND REGIONAL PRODUCTION TRENDS

Despite considerable potential for shrimp culture in Central and South America, development of these industries have been slow. Only Ecuador has a major industry, whose growth rate has apparently tapered off due to land availability, seed supplies, world market prices of shrimp, and government monetary and tax policies. Mexico has a very large potential which may not be realized for many years due to restrictive laws and policies which have only recently begun to change. Other countries in these regions likewise have developed their shrimp culture industries slowly for a variety of reasons.

The U.S. has perhaps invested more money in basic shrimp research and development than all other countries combined, with the possible exception of Japan and France. Nevertheless, the U.S. still does not have a shrimp culture industry that can compete on the world market. Japanese, French and U.S. shrimp culturists primarily target small specialty markets for high quality, fresh, whole shrimp. These markets pay high prices for these shrimp which can justify costly intensive production methods. It is unlikely that foreign produced shrimp can satisfy this market since the shrimp must be delivered within days of harvest to the buyer on ice or alive. This market is relatively small, and not likely to become a major component of the world market.

Major innovations in almost all aspects of shrimp culture (Table 1), might lead to development of a significant shrimp culture industry in the U.S., which has many potential farm sites (Fast, in press, b.), but we do not foresee this happening within the next 10 years. Shrimp farming could also expand considerably in Europe and Japan if major changes occur in the technology and the market; however, the current trend is not favorable to this development. More likely, the U.S., Europe and Japan will continue to

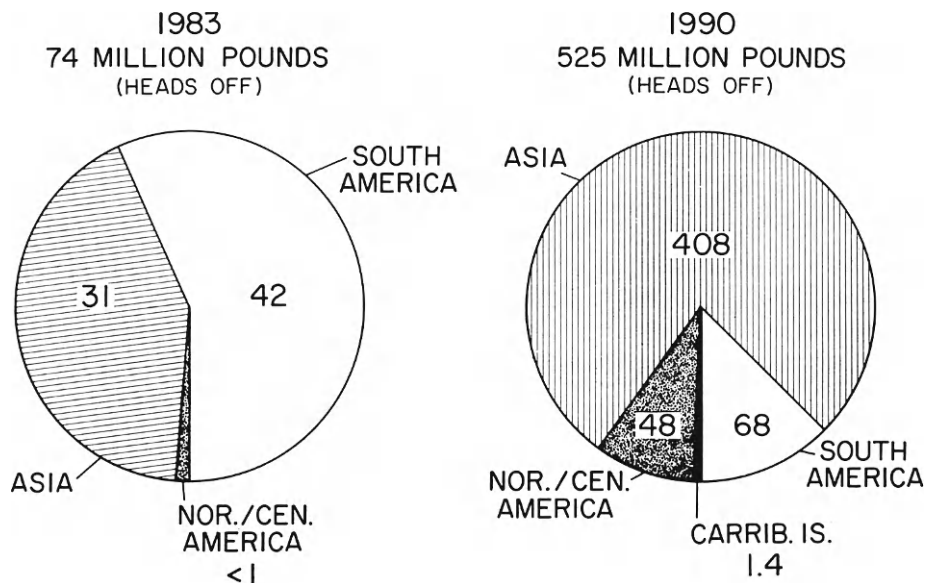


Figure 2. World shrimp farm production estimated for 1983 and 1990 by region (Vondruska 1987).

import more and more shrimp. Reduction of the U.S. shrimp fishing fleet could further increase U.S. imports.

The most likely prospect for increased shrimp production from the Western Hemisphere in the near term is Ecuador. Ecuador still relies heavily on semi-intensive and extensive culture methods, presently the most profitable types. It is likely that yields can be increased cost effectively through appropriate application of pond aeration technology combined with water exchange.

The center of shrimp culture has clearly shifted to Asia, and this trend should continue. During 1983, 42% of the world's cultured shrimp production was from Asia and 58% was from the Western Hemisphere (Fig. 2, National Marine Fisheries Service 1984). By 1990, 78% percent of production is projected from Asia and only 22% from the Western Hemisphere. As indicated above, the main reasons for this shift are government policies, coupled with respective environmental potentials.

The People's Republic of China has taken the lead in shrimp culture. During 1989, China produced about 30% of the world's cultured shrimp (Rosenberry 1990). This trend is likely to continue for several reasons. First, the principal growout system is semi-intensive culture which produces shrimp

at a low cost. Secondly, the government wholeheartedly endorses and sponsors shrimp culture. Government policy supports shrimp culture expansion, technology development, and increased exports to the world markets.

The Philippines, Thailand, Indonesia and Vietnam will continue to produce large quantities of cultured shrimp. The Philippines and Indonesia possess particularly good potentials because of their large areas of existing brackishwater ponds. These ponds are predominantly extensive, for polyculture of milkfish and shrimp. Intensive culture systems in these countries and Taiwan are not likely to survive, unless production costs can be substantially reduced.

40.13 MARKET DEVELOPMENT

The three major markets for shrimp imports are likely to remain the U.S., Japan and Europe. The European market has the greatest growth potential, but will require strong marketing activities. The U.S. and Japanese markets will certainly increase, perhaps faster than before if shrimp prices continue to decline and marketing efforts increase.

Another perhaps overlooked market is the domestic market of some of the major shrimp producers. If economic growth continues in these countries, and is shared with a large portion of their population, sizable markets for more shrimp and larger shrimp could develop. Most of these countries now consume a large per capita amount of shrimp and fish, but mostly of small sizes and low cost. This could change if world prosperity continues to increase.

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