19
Marine Shrimp

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19.1 Introduction

Shrimp farmers represent the transition from sea hunters to farmers of the sea, a transition that has been and will be followed with many more commercially-important aquatic species.

19.1.1 History of shrimp farming

In the last three decades, farming of various marine shrimp species has developed tremendously. Shrimp farms now contribute a substantial proportion of the world's shrimp demand, rapidly replacing traditional fisheries as market demand suppliers. In addition to generating billions of dollars in trade, shrimp farming also provides employment for millions of people in developing nations, brings into production vast areas of previously unutilised coastal land unsuitable for other types of development, and produces a valuable export commodity that generates needed hard currency. The industry has also generated some environmental issues that are for the most part being acknowledged and addressed.

Marine shrimp have been grown in South-East Asia for centuries by farmers who raised them as incidental crops in tidal fish ponds. Modern shrimp farming began in the 1930s, when Motosaku Fujinaga, a graduate of Tokyo University, succeeded in spawning the Kuruma shrimp (*Marsupenaeus japonicus*). He cultured larvae through to market size in the laboratory and successfully mass produced them commercially. Dr Fujinaga generously shared his findings and published papers on his work during the next 40 years, and was honoured by Emperor Hirohito with the title 'Father of Inland Japonicus Farming'. In the early 1970s, researchers and entrepreneurs in various countries in Asia and Latin America became involved in promoting development of the industry, which grew steadily. Marine shrimp farming has come a long way in the last 25 years, and enormous progress has been made in developing technologies and methods to culture shrimp. The industry began a tremendous expansion in the early 1980s. Major references on global shrimp farming include Wyban (1992), Browdy & Jory (2001) and Rosenberry (2001).

19.1.2 Current status and production

Marine shrimp farming is currently practised worldwide in over 60 countries, but production is concentrated in about 15 nations in Asia and Latin America. Since 1992, 12 countries have contributed about 95% of farmed shrimp production. The top world producer of farmed shrimp has changed several times in the past, from Ecuador to Taiwan, Indonesia, China and Thailand. Thailand has been the world's leading producer of farmed shrimp in recent years, despite having to deal with serious shrimp disease problems.

Jory (1998) provided a detailed account of the industry in different nations (Table 19.1). Asia has much more land area and more farms than the Americas. The average farm size in Asia is 4.4 ha, compared with ~100 ha in the Americas. Mean annual production per hectare is slightly greater in the western hemisphere than in Asia, 1797 kg/ha vs. 1455 kg/ha. Farmed production could be increased by responsibly intensifying culture methods, without having to develop large areas. Most of the best locations for farms have already been developed, but the industry can still expand in several countries, including Brazil, Venezuela and several African nations. Shrimp culture is a minor activity in a few European countries (Spain, Italy), and Japan and the USA are relatively small producers owing to cool weather, high production costs and limited areas with suitable conditions. These and other developed countries are, however, significantly involved in the shrimp culture industry:

- as large consumers of shrimp
- as producers of supplies and materials used by the industry
- in providing substantial technical expertise on production and processing techniques.

Rosenberry (2001) reported, based on FAO data, that global production of farmed shrimp reached 1 130 000 mt in 1999, considerably higher than his estimated 660 200 mt of 2 years before (Table 19.1). The substantially greater FAO value for 1997 production, 1 000 000 mt (FAO, 2001), was published much later than Rosenberry (1997). The discrepancy between these 1997 data show how difficult it is to produce accurate and timely production data for cultured shrimp. The shrimp farming industry continued expanding in 2000 and 2001, especially in Vietnam, Taiwan and China, but also in Belize, Venezuela and Brazil. This is despite the white spot syndrome virus (WSSV) epidemic (section 19.8.4), which probably cost 300 000 mt of production in 2001, worth over one billion US dollars. Annual catch from the commercial shrimp fishery is ~2 000 000 mt, bringing total global production of shrimp to ~3 300 000 mt, with farmed shrimp contributing about 40% of this total. Shrimp farmers in the eastern hemisphere produce ~90% of the world's crop. Since the economic troubles and currency devaluations in Asia began in 1997, small-scale shrimp farmers throughout the region have adopted various management strategies to circumvent WSSV (Rosenberry, 2001).

Between 1975 and 1985, global production of farmed shrimp increased by 300%, and between 1985 and 1995 by 250%. Since 1995, however, industry growth has been slower due to viral and bacterial diseases. Costs have increased (also, market prices have dropped in the last 2 years), as the industry moves to comply with new international standards on product quality and the environment. If it were to increase by 200% in the 1995–2005 decade, production would be 2 100 000 mt in 2005. Production from the commercial shrimp fishery has averaged ~2 000 000 mt for the last 5 years, but has recently shown a declining trend. Global shrimp production by 2005 could be over 3 500 000 mt, with farmed shrimp contributing over half of this total (Rosenberry, 2001).

19.2 Cultured species

19.2.1 Current taxonomy

There is a new taxonomy for marine shrimp, prepared by Pérez Farfante & Kensley (1997). It recognises seven families and 56 genera of Penaeoidea and Sergestoidea shrimps. The main change for shrimp farmers in the western hemisphere is that *Penaeus vannamei* and *P. stylirostris* (Fig. 19.1) are now grouped in the new genus *Litopenaeus*. For shrimp farmers in the eastern hemisphere, *P. monodon* remains the same, whereas *P. japonicus* is now *Marsupenaeus japonicus*, and *P. indicus*, *P. penicillatus* and *P. chinensis* have been reclassified into a new genus, *Fenneropenaeus*. This new classification has its critics and is not totally accepted by the global shrimp farming community, but is used here.

There are about 2500 species of shrimp worldwide, but only 12 or so species are farmed to some degree. All belong to the family Penaeidae, characterised by a rostrum with ventral and dorsal teeth, and last thoracic segment with gills. Out of the

Table 19.1 Summary of global data for the shrimp farming industry in 1997

Country	Production (heads-on) (mt)	World total (%)	World rank	Grow-out area (ha)	Average production (kg/ha)	Estimated number of hatcheries	Estimated number of farms
Eastern hemisphere							
Thailand	150 000	22.7	1	70 000	2143	1000	25 000
China	80 000	12.1	3	160 000	500	1500	8000
Indonesia	80 000	12.1	3	350 000	229	400	60 000
India	40 000	6.1	4	100 000	400	200	100 000
Bangladesh	34 000	5.1	5	140 000	243	45	32 000
Vietnam	30 000	4.5	6	200 000	150	900	8000
Taiwan	14 000	2.1	8	4500	3111	200	2500
Philippines	10 000	1.5	10	20 000	500	90	2000
Malaysia	6000	0.9	12	2500	2400	60	800
Australia	1600	0.2	16	480	3333	12	35
Sri Lanka	1200	0.2	17	1000	1200	40	800
Japan	1200	0.2	17	300	4000	100	135
Other EH countries	14 000	2.1		20 000	700	30	2000
EH total	462 000			1 068 780		4577	241 270
Average					1455		
Global percentage		70		82		91	99
Western hemisphere							
Ecuador	130 000	19.7	2	180 000	722	350	1800
Mexico	16 000	2.4	7	20 000	800	23	220
Honduras	12 000	1.8	9	14 000	857	13	90
Colombia	10 000	1.5	10	2 800	3571	15	20
Panama	7500	1.1	11	5 500	1364	10	40
Peru	6000	0.9	12	3 200	1875	3	45
Brazil	4000	0.6	13	4 000	1000	18	100
Nicaragua	4000	0.6	13	5 000	800	4	25
Venezuela	3000	0.5	14	1 000	3000	5	8
Belize	2500	0.4	15	700	3571	1	7
United States	1200	0.2	17	400	3000	8	20
Other WH countries	2000	0.3		2 000	1000	5	15
WH total	198 200			238 600		455	2 390
Average					1797		
Global percentage		30		18		9	1
World totals	660 200			1 307 380	1626	5032	243 660

Jory (1998) adapted from Rosenberry (1997) with permission from *Shrimp News International*.

Fig. 19.1 The western or Pacific blue shrimp (*Litopenaeus stylirostris*).

commercially farmed species, two account for probably 90–95% of global production:

- the black tiger shrimp (*Penaeus monodon*) in Asia and Australia
- the Pacific white shrimp (*Litopenaeus vannamei*) in the Americas.

Penaeus monodon alone probably constituted 60–70% of the world's production of farmed shrimp in the last decade. Both species are popular in local and export markets, and are relatively easy to produce. Their seedstock can be produced in hatcheries using relatively simple technologies. Both can tolerate a wide range of salinity, from slightly greater than freshwater (1–2‰) to full-strength ocean water (35–40‰). Both species readily eat formulated commercially manufactured feeds, and require high-quality water for adequate health and growth.

Information on the major cultured species of shrimp, summarised from Rosenberry (2001) and others, is detailed below.

19.2.2 Black tiger shrimp (Penaeus monodon)

Penaeus monodon is the largest (363 mm maximum length) and fastest growing (up to 5.5 g/week) of the farmed shrimp. The species is native to the Indian Ocean and the south-western Pacific Ocean, from Japan to Australia, and dominates production everywhere in Asia except for Japan and China. This species can tolerate a wide range of salinities and is grown in inland low-salinity ponds in some countries. It is, however, very susceptible to two of the most lethal shrimp viruses, YHV (yellowhead virus) and WSSV (section 19.8.4). Breeding in captivity is difficult to induce and hatchery survival is low (20–30%). Seedstock production is mainly from wild broodstock, which are often in short supply in many areas. The protein requirement of *P. monodon* in formulated feeds is ~35%. They are widely exported from South-East Asia and marketed in Japan, the USA and Europe.

19.2.3 Western white shrimp (Litopenaeus vannamei)

This species, which is also known as the Pacific white or whiteleg shrimp, is the primary species farmed in the USA, Latin America and the Caribbean region. It ranges from the Gulf of California southward to northern Peru. Males reach a total length of 187 mm, and females 230 mm. It is well suited for farming, because it:

- breeds well in captivity
- can be stocked at small sizes
- grows fast and at uniform rates
- has comparatively low protein requirements (20–25%)
- adapts well to variable environmental conditions.

Litopenaeus vannamei is the leading farm-raised species in Ecuador and everywhere else in Latin America. It breeds in captivity better than *P. monodon*, but not as readily as *Fenneropenaeus chinensis* and *M. japonicus* (see following). In hatcheries, overall survival is relatively high at 50–60%. Some hatcheries in Latin America have captive stocks of *L. vannamei* broodstock, some pathogen free, some pathogen resistant, with some in captivity for 30 years. Production is mostly exported to the USA.

19.2.4 Western blue shrimp (Litopenaeus stylirostris)

Another important species in the western hemisphere is the western or Pacific blue shrimp, *Litopenaeus stylirostris*. It occurs from the Gulf of California south to Peru. Males reach 215 mm in total length, females 263 mm. They have a faster growth rate than *L. vannamei*, but their growth is not uniform, and this results in harvests with very broad size distributions. *L. stylirostris* tolerates lower water temperatures than *L. vannamei* but requires higher oxygen levels, turbidity, salinities, deeper ponds and formulated feeds with higher protein levels. It was often grown in combination with *L. vannamei* (at around 20% and 80% stocking respectively) and produced excellent results in many farms in several Latin American countries. It was a commonly farmed species until the late 1980s, when the IHHN virus appeared, to which *L. stylirostris* is highly susceptible. Captive stocks kept at several locations around the world, through selective breeding, developed resistance to the IHHN virus. During 1992–97, when *L. vannamei* stocks were being devastated by the Taura syndrome virus (TSV) everywhere in the western hemisphere, some shrimp producers determined that some of the captive stocks were resistant to both IHHN and TSV. Between 1997 and 2000, *L. stylirostris* made a comeback on farms throughout the western hemisphere, especially in Mexico. In the USA market, *L. stylirostris* and *L. vannamei* are often mixed together and sold as western white shrimp.

19.2.5 Chinese white shrimp (*Fenneropenaeus chinensis*)

Fenneropenaeus chinensis occurs off the coast of China and the western coast of the Korean peninsula. It tolerates muddy bottoms and very low salinities, and can withstand much lower water temperatures (down to 16°C) than *L. vannamei* and *P. monodon*. It readily matures in ponds, unlike most other commercially farmed species. However, it requires high protein levels (40–60%) in formulated feeds, reaches a relatively small size (183 mm maximum length) and has a lower meat yield (56%) than *P. monodon* (61%) and *L. vannamei* (63%). Between 1988 and 1993, during the boom years of Chinese shrimp farming, this species was marketed extensively around the world.

19.2.6 Japanese kuruma shrimp (*Marsupenaeus japonicus*)

Marsupenaeus japonicus is native to the Indian Ocean and the south-western Pacific Ocean from Japan to Australia, and is commercially cultured in Japan and Australia. Attempts to farm Kuruma shrimp elsewhere have met with limited success. They are relatively easy to ship live without water and packed in chilled sawdust and other materials (section 11.7), and they will mature and spawn in ponds. They need clean, sandy bottoms and high protein levels (55–60%) in formulated feeds. They can tolerate low water temperatures (down to 10°C) better than any other farmed species. Marketed live, they command extremely high prices in Japan, bringing up to US$200/kg.

19.2.7 Indian white shrimp (*Fenneropenaeus indicus*)

This species is native to the Indian Ocean from southern Africa to northern Australia and to all of South-East Asia. It is one of the major species in the commercial fisheries of these regions. *F. indicus* is primarily grown on extensive farms throughout South-East Asia, and it is widely cultured in India, the Middle East and eastern Africa. It tolerates low water quality better than *P. monodon*, grows well at high densities and salinities, reaches sexual maturity and spawns in ponds, and is widely available in the wild.

19.3 Grow-out systems

Shrimp grow-out operations span a wide continuum in terms of intensity, complexity and technology. Globally, four grow-out production systems are generally recognised, which share some characteristics, but differ in other aspects (Table 19.2).

Moving from the lowest towards the highest stocking systems, there is:

- progressive reduction in the area of ponds used
- progressive increase in capital, production costs and stocking densities
- a trend for increased use of intermediate nursery or multiple phases
- an overall intensification in production practices and technology.

The last involves a more thorough preparation of

Table 19.2 Various shrimp farming systems, based on stocking density, production inputs and operational parameters

Parameter	Intensity			
	Extensive (low density)	Semi-intensive (medium density)	Intensive (high density)	Intensive (very high density)
Stocking density (PL/m²)	1–5	5–25	25–120	120–300
Construction cost (US$/ha)	> $5000	$5000–25 000	$25 000–200 000	> $200 000
Production cost (US$/kg)	$0.9–2.0	$2.5–5.0	$5.0–8.5	?
Pond/tank area (ha)	Ponds(5–100)	Ponds (1–25)	Ponds/tanks (0.1–5.0)	Tanks (0.1–1.0)
Seedstock source	Wild	Wild and laboratory	Laboratory	Laboratory
Water exchange (% daily)	Tidal (<5%)	Pumping (5–12%)	Pumping (up to 25%)	Pumping (25%+)
Management requirements	Minimal	Moderate	High	Very high
Feed	Natural productivity	Natural productivity and formulated feeds	Natural productivity and formulated feeds	Natural productivity and formulated feeds
Fertilisation	No	Generally yes	Sometimes	No
Mechanical aeration	No, minimal water exchange	Water exchange and some mechanical aeration	Mechanical aeration	Mechanical aeration
Energy use (hp/ha)	0–2	2–5	6–20	20–60
Production cycle (days)	100–140	100–140		
Annual production (kg/ha)	50–500	500–5000	5000–20 000	20 000–100 000 (estimated)

PL, postlarvae.
Modified from Jory (1993) and Fast & Menasveta (2000) with permission from CRC Press.

ponds, increased use of laboratory-produced seedstock, use of better formulated feeds, improved pond management practices and others. Up to the mid- to late 1990s, it also involved higher rates of water exchange, but for the last 3–5 years there has been a global trend towards reducing exchange rates and the volume of water required to produce shrimp (i.e. m^3 water/kg shrimp). This has even developed to the point of reaching zero exchange and recirculation to improve biosecurity and operational cost-efficiency. There are also trends towards increased use of technology, aeration, technical and professional labour, and a tendency to move away from the coastline to higher ground. Most farms produce at least two crops per year, although some farms can reach or surpass three or more annual crops, particularly those using nurseries or multi-phase production systems.

Early on, when the industry was young, farms were mostly extensive, and there are still many such farms in Thailand, Indonesia, India, Vietnam, Bangladesh, Central America and Ecuador, among other countries. Since around 1980, however, there has been a trend towards refitting farms to increase intensity of production. The more intensive farms are more typical in countries such as Taiwan, Japan and the USA (Jory *et al*., 2001; Rosenberry, 2001).

19.3.1 Extensive systems (low stocking densities)

Shrimp farms with low stocking densities are typically located in tropical water impoundments ranging from ~2 ha to > 100 ha and located adjacent to estuaries, bays, and coastal lagoons and rivers. They

Fig. 19.2 A paddy in which shrimp are cultured extensively after rice harvest (Mekong, Vietnam) (photograph by Dr Michele Burford).

Fig. 19.3 Sieving wild-caught juvenile shrimp to sell for stocking extensive shrimp farms (Chalna, Bangladesh) (photograph by Professor Clem Tisdell).

frequently involve polyculture with herbivorous fishes such as mullet, milkfish and others. At some low stocking farms, liming materials are applied to ponds if soils are acidic, and they sometimes use animal manures or other organic materials to stimulate production of natural food for their shrimp (section 9.9). Ponds are filled by tides and any water exchange (typically < 5% per day) is also by tidal action. Ponds are stocked with wild shrimp postlarvae (PL), when naturally available, by opening pond gates to incoming tides. Fig. 19.2 shows a pond in the Mekong region, Vietnam, where shrimp are cultured extensively in ditches and paddies after the rice harvest. After the harvest, saline water from the Mekong River penetrates up into ditches and paddies containing rice stubble. The water brings shrimp PL for culture.

Alternatively, or additionally in various regions, juvenile shrimp may be netted from shallow coastal waters and stocked into ponds (Fig. 19.3).

In all cases, these shrimp feed on natural phyto- and zooplankton, small plants and animals living in or on the pond substrate, and particulate organic matter suspended in the water or lying on the bottom. This natural production may be promoted with applications of organic or chemical fertiliser. It is extensive aquaculture, as defined in Chapter 2 (section 2.3.3), e.g. the cultured shrimp are essentially part of a natural ecosystem that provides their nutritive and other requirements. Construction and operating costs are typically low, with the latter ~US$1–3/kg live shrimp, and production rarely surpasses 400–500 kg/ha in production cycles that last 100–140 days. Almost no new extensive shrimp farms are being built any more, because it is now illegal in several countries to build new shrimp farms in tidal and mangrove areas (Boyd, 1998; Rosenberry, 2001).

19.3.2 Semi-intensive systems (medium stocking densities)

Shrimp farms that operate at medium stocking densities (Table 19.2) are built above the high-tide line and include a pumping station and water distribution canals and reservoirs, and use of formulated feeds. In general, farm layout is relatively symmetrical and ponds are harvested by draining through a net or by using a harvest pump. Pond preparation may be elaborate, with dry-out once or twice a year, tilling and liming with various liming materials, and fertilisation with N, P and Si compounds to promote natural production. Producers may also apply various extracellular enzyme preparations and bacterial inocula to improve water quality, but the benefits of these treatments remain to be conclusively established. Organic fertilisers (mostly manure and agricultural by-products) are sometimes used. Although the water exchange rates typically used are 5–15% of pond volume per day, in recent years many farmers have adopted exchange practices of 2–5%. These lower exchange rates reduce pumping costs, and minimise fertiliser needs and the possibility of pathogen introduction. Formulated and pelleted feeds with 20–40% crude protein are usually applied

1–3 times per day, typically by manual broadcasting over pond surfaces from boats and levees. Feed quantity applied is calculated and adjusted based on the shrimp biomass estimated from results of cast net sampling and feeding charts typically provided by feed manufacturers. Natural productivity in the ponds is important for juvenile shrimp growth during the early weeks at all intensities of shrimp culture. Subsequently, there is variation in the degree of dependence on formulated feeds. Dependence on formulated feeds is not as great at this moderate density as it is at higher culture densities; hence, in the continuum of culture practices, this is semi-intensive culture (section 2.3.4).

19.3.3 Intensive systems (high stocking densities)

Shrimp farms using intensive culture (section 2.3.2) and high stocking densities (Table 19.2) typically have ponds of 0.1–2 ha, although various designs of raceways and above-ground tanks are also used, sometimes in greenhouses or other enclosures. Preparation before stocking is more meticulous, and management is often more elaborate, with feed applied 6–8 times a day. Mechanical aeration is needed to support the large shrimp biomass and heavy feeding rates needed. Aerators are placed in ponds and operated throughout the cycle, usually with increasing number of units and longer hours of operation as the cycle progresses. Generally, 4–12 hp/ha is used, with the amount increasing as the biomass of shrimp increases (Table 19.2). In Asia, several chemicals, including calcium peroxide, burnt lime, zeolite, chlorine, iodine, formalin and bactericides, are applied to ponds to improve water quality and prevent water quality deterioration and disease. Various probiotics, such as bacterial inocula and enzyme preparations, are added as in semi-intensive systems.

19.3.4 Intensive systems (very high stocking densities)

At the upper end of the continuum, systems with very high stocking densities (Table 19.2) include the highest level of environmental control, to the point of some being located indoors in greenhouses

Fig. 19.4 The Labelle facility owned by OceanBoy Farms, Florida, shows recirculation and reduced water exchange technologies on a commercial scale. The treatment raceway (long and narrow on the right) is where suspended solids are removed and water is treated before re-use in lined and highly aerated ponds (photograph by OceanBoy Farms).

and other structures. Annual production can reach 20–100 mt/ha and higher, but there are currently only a few of these farms, in Thailand, the USA, and possibly several other countries (Rosenberry, 2001). Examples of these advanced farms and technology include the pioneer Belize Aquaculture Ltd (BAL) in Belize and OceanBoy Farms in Florida, USA (Fig. 19.4). Pond management at these farms is based on zero water exchange, heavy aeration (up to 50 or more hp/ha) and the promotion of a bacteria-dominated and stable ecological system. This compares with the highly unstable and traditional phytoplankton-dominated system. The feeding regime used promotes the growth of heterotrophic bacteria, and essentially makes the pond into a large outdoor bioreactor, akin to a sewage oxidation pond. In these high-density, zero-water-exchange systems, the pond ecology shifts (at weeks 9 to 10 after stocking) during the production cycle from an autotrophic phytoplankton-based community to a heterotrophic bacteria-based community. This shift improves water quality through fast digestion (oxidation) of organic waste and without production of toxic metabolites. At BAL, feeding rates have exceeded 350 kg/ha/day without resulting in deterioration of water quality once this heterotrophic bacterial community has been developed and established in ponds. The shift also recycles wastes into nutritious bacterial flocs, the basis for 'natural production' in this system (McIntosh, 2000).

19.4 Preparation of ponds

General details of ponds, site requirements, layout, design and water turnover are given in sections 2.2.1–2.2.4.

Adequate pond preparation provides young shrimp with an environment that is relatively free of predators and competitors, with an ample supply of adequate natural food organisms, and environmental conditions that minimise stress and promote growth and survival. Pond preparation involves several sequential procedures including:

- pond draining and drying
- pH mapping
- soil tilling
- disinfection and liming
- fertilisation
- weir gate preparation and maintenance.

Some excellent reviews of these procedures are available, including Clifford (1992), Chanratchakool *et al*. (1998) and Cook & Clifford (1998).

19.4.1 Pond draining and sludge disposal

Effective removal of sludge that has built up on the pond bottom over a prior crop cycle is a very important step. If not removed, it will become an anaerobic, reduced sediment (Fig. 3.4). This will generate toxic metabolites such as methane, hydrogen sulphide, ammonia, nitrite, ferrous iron, etc., affecting pond water quality and production during the following crop cycle. This can be particularly relevant with some species of shrimp, which burrow periodically over the day/night cycle and after moulting. After a production pond is harvested, all water inlet/outlet gates are opened to generate a strong water flow through the pond, to resuspend and flush out as much accumulated sludge as possible. It is important to do this before the sludge dries out and solidifies. One technique that works in ponds with heavy sludge accumulation is to use heavy chains and rakes dragged along the bottom. Several people may walk along the internal canals to assist in resuspending sludge material as the pond is flushed. Most farms are located in areas with clearly defined dry and wet seasons, and it is not possible to dry pond bottoms effectively during the wet season. In addition, many ponds will not drain adequately because of defective design, construction or both. Low areas with standing water can be pumped dry or drainage ditches can be dug to facilitate drainage. These methods are only appropriate for production areas with sedimentation ponds and discharge canals that meander through coastal land, allowing sediment and organic matter to settle out before entering the coastal waters.

19.4.2 Pond drying and pH mapping

Earthen ponds must be allowed to dry out for 2–4 weeks to:

- promote decomposition of organic matter by bacteria
- eliminate pathogens and eggs, larvae and adults of predator and competitors
- dry out undesirable filamentous algae.

The rate of organic matter decomposition is greatest at a soil pH of 7.5–8.5 and, for ponds built on acidic soils, farmers add various lime products to improve

Fig. 19.5 Drying of pond bottoms until they crack and subsequent application of liming materials are important steps in pond preparation.

soil pH and promote decomposition of organic matter (Fig. 19.5).

Optimal microbial action for decomposition of organic matter occurs at about 20% soil humidity. Ponds infested with burrowing callianassid shrimp (snapping shrimp) must not be allowed to dry out, as this will cause these animals to burrow even deeper. Pond dry-out and disinfection may be the most effective methods for controlling epidemics of various shrimp pathogens, as well as various predators and competitors. UV radiation (via sunlight) and temperatures above 55°C will destroy several pathogens. If diseases have been detected within the last production cycle, a longer dry-out (2–3 months) may be helpful. The pond surface must be cracked to a minimum of 5 cm, to oxidise the soil and eliminate anaerobic conditions (Clifford, 1992). In acidic soils with pH < 7, pond bottom pH must be mapped promptly by sampling soil pH at various stations within the pond while soil humidity is about 30%, to calculate lime requirements. Once the pond surface is hard enough to walk on, soil pH is measured using standardised procedures. This technique involves collecting representative pond bottom soil from different sites throughout the pond. Appropriate addition of lime is then calculated (section 19.4.4).

Ploughing or turning the bottom soil of ponds (top 10–20 cm) is another optional step, which will depend on soil condition. Tilling the bottom soil of ponds can significantly promote oxidation of the lower layers of anaerobic sediments. Alternating cycles of tilling and flushing is a common action to reduce levels of iron compounds in acid-sulphate soils. It is also common to incorporate a N source such as urea into the soil before tilling, to increase the rate of organic matter decomposition. Some farmers will add 50% of the calculated lime requirements before tilling.

19.4.3 Disinfection

Disinfection is important to eliminate eggs, larvae, juveniles and adults of species of fish, crustaceans, insects, and other predatory and competitor species. Inadequate disinfection of ponds can considerably affect the yield of a pond. For example, the gobiid mudfish known as 'chame' (*Dormitator* species) can be a serious problem in Latin America. These fish can complete their life cycle in ponds, and will bury in the bottom mud and survive extreme conditions, including near desiccation, until the pond is filled again. They compete for feed and space, and can significantly affect the carrying capacity of a shrimp pond. Mudfish harvests of several mt have occurred where ponds were not adequately disinfected during preparation.

Several commercial products have been used to disinfect ponds before stocking shrimp. The use of pesticides (particularly chlorinated hydrocarbons and organophosphates) is not recommended because of their slow biodegradation, potential to accumulate in sediments and bioaccumulate in the food web. Chlorination has been the disinfection method of choice for many farmers, and its use has become prominent in the fight against WSSV, although lately it has been significantly discontinued in Latin America.

About 7 days into the dry-out period, all cement structures (inlets and outlets) must be cleaned, and mud, barnacles, oysters and algae removed. It is important to remove bivalves because they can reproduce in ponds, their filter feeding activity can quickly deplete plankton and they can be intermediate hosts of some shrimp parasites.

Applying calcium oxide or calcium hydroxide at 5000 kg/ha will raise the pH to greater than 10 and will destroy pathogens. Only muddy areas must be treated like this, not the entire pond bottom, as this process will destroy desirable bacteria needed to promote the development of productive benthos (section 19.4.6). Piscicides such as rotenone and teaseed cake are routinely used to eliminate fish, including mudfish.

19.4.4 Liming

Liming pond bottoms is a critical step in preparing earthen ponds. When calculating liming requirements the type of lime product to use must be considered, as this will influence the amounts required (Table 19.3). One lime application is generally added 2 days after tilling with lime spreaders, applying lime more heavily to wet low areas than to higher dry areas. One week is allowed for the lime to react with the soil before applying fertiliser. The calculated

Table 19.3 Neutralising values of various compounds used in pond liming

Compound	Chemical name	Neutralising value (%)
Agricultural limestone	Calcium carbonate	100
Agricultural limestone	Dolomite	109
Burnt lime	Calcium oxide	179
Burnt lime	Calcium magnesium oxide	208
Hydrated lime	Calcium hydroxide	135
Hydrated lime	Calcium magnesium hydroxide	151
Soda ash	Sodium carbonate	94
Baking soda	Sodium bicarbonate	59
Other compounds	Calcium silicate	86
Other compounds	Calcium phosphate	65

Reproduced from Boyd (1995) with permission of the World Aquaculture Society.

neutralising values of various compounds used in pond liming range from 59% (sodium bicarbonate) to 208% (calcium magnesium oxide) (Table 19.3).

When liming requirements cannot be calculated, the following liming rates, using calcium carbonate, $CaCO_3$, can be used (Boyd, 1995):

- for pH 6.5–7.5 (500 kg/ha)
- for pH 6.0–6.5 (1000 kg/ha)
- for pH 5.5–6.0 (2000 kg/ha)
- for pH 5.5–5.0 (3000 kg/ha)
- for pH < 5.0 (4000 kg/ha).

19.4.5 Weir gate preparation and entrance screening

One of the most important aspects of pond preparation is the maintenance and preparation of weir gates (monks). Configuration and placement of weir gate restriction boards and screens to prevent escapes and entry of predators, while at the same time allowing water to enter and exit continuously, is vital for cost-effective production. Entrance and effluent structures are scraped clean of barnacles, bivalves and filamentous algae. Screens with mesh of varying sizes are used to keep unwanted organisms out. Water filtration has become an important tool in recent years to exclude WSSV carriers from ponds. Clifford (1999) indicated that most WSSV carriers in the water can be selectively removed by properly screening intake water. Although it may not be feasible to totally eliminate all WSSV carriers from the ponds by screening, the more their numbers are reduced, the lesser the probability of WSSV transmission. Various sizes of mesh screens are used depending on their positions. Screens are placed after the discharge of the pumps (2-cm mesh), in the lateral branches of the main supply canal (1- to 2-mm mesh), in the inlet structure(s) of each pond (500-μm mesh as a secondary screen, followed by 300 μm or smaller as a primary screen), and in drainage canals (2- to 3-cm mesh). To initially fill ponds, very fine (200–250 μm) screens are installed in the inlet structure. When pond filling is complete, these filters are replaced with 300- to 500-μm screens. Bag net filters are used in the inlet structures to augment effective filtering surface area, and reduce screen clogging. Bag net filters of 2–5 m in length are the best, but there is no limit to the length or size of the bag net filter and, in general, the longer the better (Fig. 19.6). Multiple bag configurations (where a filter bag is placed inside another) are a cost-effective means of decreasing the mesh aperture size without installing a finer screen. Seines or gill nets (2- to 3-cm mesh) are installed in the drainage canals to prevent infected shrimp from escaping (Clifford, 1999). Ponds are inspected for proper completion of necessary preparation steps before filling with water.

19.4.6 Natural productivity

Proper management of natural productivity in shrimp ponds is critical to promote and sustain plankton blooms and microbial and benthic community productivity. A vigorous phytoplankton bloom will support a healthy benthic community and will contribute

Fig. 19.6 A battery of bag nets used to filter the inflowing water at a shrimp farm in north-west Mexico.

significantly to stabilising and maintaining adequate water quality in shrimp ponds. This happens through several mechanisms (Cook & Clifford, 1998):

- by increasing oxygen production through photosynthesis during daylight hours
- by decreasing levels of various metabolites and toxic substances such as ammonia, nitrate, nitrite, hydrogen sulphide, various heavy metals and other undesirable compounds
- by regulating pond water and bottom pH (extremely important in ponds with acid-sulphate soils)
- by providing shade to prevent the establishment of filamentous bottom algae
- by increasing turbidity with a consequent reduction in predation by diving birds, among other mechanisms.

Natural productivity is also important because it supports the generation of detritus, the particulate organic material produced from the dead bodies, non-living fragments and excretions of living organisms. In nature, organic detritus is an important food source for many estuarine organisms, and in shrimp ponds it can have an important role. Shrimp feed on detritus, and derive nourishment by stripping the micro-organisms from the detrital material as it passes through their gut. In addition, their faecal pellets may be recolonised and the process repeated until all the organic material has been utilised. Maximising the recycling capability of organic detritus within the culture environment, nutritionists and pond managers have an opportunity to reduce feed and production costs, improve FCR, and reduce environmental impacts.

As a source of carbon for growth, natural productivity is much more important in shrimp ponds with moderate stocking densities than in high densities. In the latter, formulated feeds provide most of the feed consumed by shrimp from the start of the production cycle. In comparison, natural productivity in moderately stocked ponds can sustain shrimp for about 30 days (ca. 20–30% of the duration of a typical grow-out cycle), depending on the stocking density (10–20 shrimp/m^2). This is until a critical shrimp biomass (100–300 kg/ha) is reached and additional subsidies, in the form of added formulated feeds, are needed to sustain shrimp growth and production. There is extensive evidence that juvenile shrimp feed on plant material and, although generally via intermediate prey species, algae are probably a major source of carbon for these shrimp.

19.4.7 Initial fertilisation

Fertilisation of shrimp ponds is an effective means of stimulating natural food production that can help reduce feed costs (e.g. Chanratchakool *et al*., 1998; section 9.9). Through fertilisation, managers can promote those pond ecosystem components that are beneficial to shrimp production and discourage those that are detrimental. Several organic and inorganic nutrient sources can be used to fertilise shrimp ponds. They vary in their effectiveness because of differing nutrient density, solubility in water, potential toxicity, C/N ratios and other factors. Appropriate fertilisation rates vary depending on fertiliser type and the ambient nutrient concentration in the water. Various dynamic processes in ponds can also affect fertilisers, producing dissolved nutrient concentrations after fertilisation that may substantially differ from calculated concentrations.

Fertilisation involves the application of fertilisers over the entire pond bottom before filling with water. The objective of inorganic fertilisation during preparation and during the grow-out cycle is to promote and maintain populations densities of diatoms and green algae of at least 80–100 000 cells/mL. These algae groups are reportedly the most nutritionally desirable for shrimp (Clifford, 1994). Desirable

Table 19.4 Desirable phyto- and zooplankton densities in shrimp ponds with medium culture densities

	Minimum number of organisms per mL	Maximum number of organisms per mL
Phytoplankton		
Diatoms: bacillariophytes and chrysophytes	20 000	–
Chlorophytes (green algae)	50 000	–
Cyanophytes (blue-green algae)	10 000	40 000
Dinophytes (dinoflagellates)	–	500
Total phytoplankton cells	80 000	300 000
Zooplankton (copepods, rotifers)	2	50
Protozoans	10	159

Adapted from Clifford (1994) with permission.

phyto- and zooplankton densities in semi-intensive shrimp ponds are shown in Table 19.4.

There is no universally optimal N/P ratio, and each farm must determine by trial and error the most suitable inorganic fertilisation regime for its prevailing conditions and needs. In areas that have markedly different dry and wet seasons, there are different optimal fertilisation ratios for each season, as well as different optimal stocking densities and other significant management differences. It is only through experience and monitoring that the best fertilisation regime is determined for the prevailing conditions.

When selecting inorganic fertilisers, the type (nutrient class, composition and solubility), the N/P ratio, the daily dosage rates and the frequency of application must be considered. The main nutrients needed in shrimp ponds to promote phytoplankton blooms are N, P and Si. Si compounds stimulate production of the very desirable diatoms. Commonly used inorganic fertilisers are urea and sodium nitrate as N sources, and monoammonium phosphate (MAP), diammonium phosphate (DAP) and triple superphosphate (TSP) as P sources. Urea is the most commonly used source of N because it is widely available, inexpensive and effective. Nitrate-based fertilisers are very effective, but more expensive and less available. The most common silicate fertiliser used is sodium metasilicate, which is expensive and not widely available. A N/P ratio of 15–20:1 promotes the development of diatom blooms; however, the N/P ratios used in many shrimp farming areas worldwide can vary from 1:1 up to 45:1.

Organic fertilisers promote production through direct consumption by the shrimp. Shrimp graze on the bacterial detritus that forms on the fertiliser particles and on other natural food organisms whose populations are promoted by fertilisation. Chicken manure was the main organic fertiliser used in shrimp ponds for many years, with various other manures (duck, cattle and swine) also used to some extent. In recent years, however, farmers have switched to finely ground vegetable meals (wheat, soybean, rice, sorghum and others). These agricultural by-products serve as substrate for bacteria, zooplankton and meiofauna, and they can be consumed directly by shrimp (Cook & Clifford, 1998).

Initial fertilisation enhances the natural productivity of a newly filled pond, reducing the need for costly high-protein start-up feed, and also supplying richer more digestible protein, lipids, phospholipids, fatty acids, cholesterol and trace nutrient sources through planktonic and benthic organisms. The juvenile shrimp in a well-fertilised pond that was stocked at 15 PL/m^2 can usually reach an average weight of 2 g in 30–35 days with minimal supplemental feeding.

19.5 Reproduction and maturation

19.5.1 Hatchery production and the life cycle

The typical life cycle (Fig. 19.7) of a marine shrimp in nature begins with adult animals migrating up to several kilometres offshore, maturing and spawning. The eggs initially sink, but after a few hours they

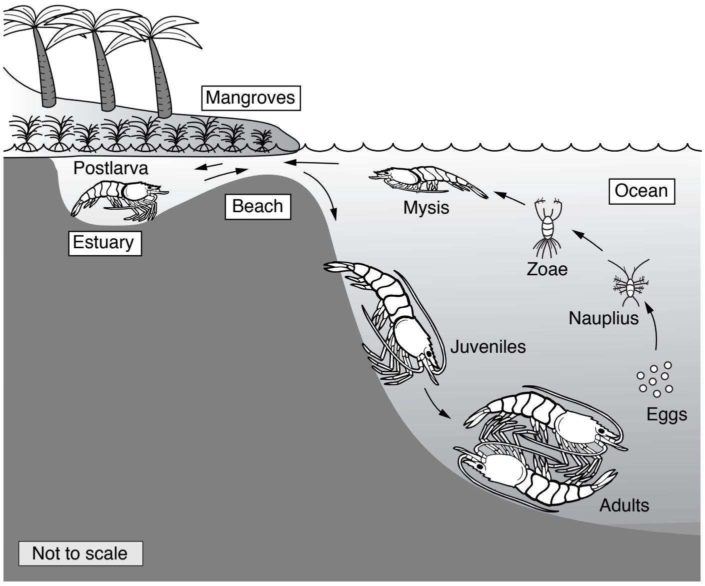

Fig. 19.7 A typical life cycle of a marine shrimp (from Rosenberry, 2001).

hatch and the nauplii (the first larval stage) float to the surface. Marine shrimp usually spawn in areas where favourable currents will eventually bring the developing larval stages inshore into nursery areas such as estuaries, large bays and coastal lagoons. These areas provide abundant natural food and adequate conditions for survival and growth. Developing shrimp remain in nursery areas for several months, and then begin maturing and moving offshore to spawn and complete their life cycle.

Hatcheries in the western hemisphere are generally large (Fig. 19.8), often belong to a vertically integrated operation that includes a grow-out farm and a processing plant, and they frequently produce excess nauplii, which are sold to smaller hatcheries. Eastern hemisphere backyard and medium-scale hatcheries produce most of the seedstock used by farmers (Rosenberry, 2001). Hatcheries produce seedstock ready for stocking into nursery or grow-out ponds and tanks. Shrimp are very fecund animals, producing 100 000–1 000 000 eggs per spawning in the wild, and 50 000–400 000 eggs per spawning in captivity (depending on species, size, water temperature, wild or captive origin, and the number of previous spawns). In the hatchery, gravid female shrimp (wild or matured in captivity) spawn at night, and eggs hatch the following morning.

Larval development from egg to PL is complex and involves three stages: nauplius, zoea and mysis. The first has five or six substages, and the next two generally have three substages each, with each substage lasting some to many hours. The larval development process takes ~15 days. As larvae develop and consume the yolk sac, their diet switches to phytoplankton and then to zooplankton. After the mysis stage, they consume a variety of organisms, including the brine shrimp (*Artemia* species). All these live organisms are produced in the hatchery, but major advances have been made recently to develop alternative inert diets (section 9.6). After they become PL, the animals look like small adult shrimp and are able to feed on zooplankton, detritus and commercial feeds. After several days as PL, they are ready to be

Fig. 19.8 Outdoor tanks for larval culture in a hatchery in Brazil.

stocked into nursery or grow-out systems. With the increasing importance of genetic improvement programmes to address biosecurity concerns for various shrimp diseases, hatcheries will play an increasingly important role in the support and expansion of the industry (Jory, 1996, 1997). For detailed information on hatchery procedures refer to Bray & Lawrence (1991) and Treece & Fox (1993).

It is commonly believed that PL from females matured in the wild are superior and are generally preferred over PL from eyestalk-ablated females (section 19.5.4), which are considered of inferior quality. This 'lower' quality of PL from ablated shrimp could be due to less than optimal treatment of broodstock at a time (after ablation) when there are increased energy requirements (proper nutrition) and disease susceptibility. Nauplii production from captive broodstock maturation varies considerably, but has several advantages, including known origin, species and age, increased biosecurity, and relatively predictable availability. These are all very important for production planning and forecasting, and even more relevant in genetic improvement programmes. The use of wild seedstock can also introduce pathogens, competitors and predators into grow-out systems (Jory, 1996, 1997). The dependence on wild broodstock is more serious in Asia than in the western hemisphere, because there has been less interest in captive reproduction of cultured broodstock in the former. Hatcheries in Asia have had little interest in using domesticated broodstock, as they have had few problems sourcing wild broodstock for their operations. The domestication of shrimp stocks in Asia generally trails that of the Americas, and the majority of *P. monodon* broodstock used by Asian hatcheries are from wild stocks. *P. monodon* has been reared in captivity many times since the 1970s, but a combination of cost, technical constraints and a lack of demand for domesticated stocks are the reasons for a lack of application on a commercially significant level. There also remains a widespread belief that domesticated shrimp are somehow not as hardy or as well suited for culture as their wild counterparts.

19.5.2 Broodstock maturation

The ability to produce seedstock on demand, consistently and in sufficient numbers to support the industry is extremely important. Maturation of shrimp broodstock is undertaken routinely in many countries, and at least 26 penaeid shrimp species have been matured and spawned in captivity to produce viable eggs. The life cycle has only been closed consistently and dependably for a few shrimp species, however, and most shrimp hatcheries around the world still depend significantly on wild broodstock. Some shrimp species appear more suited to captive maturation than others: *P. monodon* is comparatively difficult to mature in captivity, whereas *L. vannamei* and *L. stylirostris* are relatively easier. There are three approaches to maturation:

- Procure wild, sperm-bearing females that can spawn right away. This usually produces high quality eggs and larvae.
- Obtain wild adults, and mature and spawn them in captivity.
- Mature and spawn adult shrimp that have been grown in captivity.

The first two approaches are widely practised in most shrimp farming countries. The third strategy, producing succeeding generations in captivity, is the only one that will lead to successful stock domestication and selection for commercially important traits such as fast growth and disease resistance (Jory, 1996).

Large hatcheries typically have separate infrastructure to carry out broodstock maturation. The maturation section of a hatchery is normally isolated from other sections, to reduce noise levels and stress caused by human activity (section 2.7). Maturation tanks are typically round, about 3–5 m in diameter and 60–100 cm in height, and gently sloped towards a central drain to facilitate removal and siphoning of uneaten food and other undesirable debris. They are generally arranged in batteries or rows in a dedicated room. Tanks are generally black on the inside, and vinyl or PVC liners are commonly used to reduce construction costs, reduce injuries to animals caused by jumping into tank walls, and to facilitate cleaning and disinfection. A sand or pebble substrate is sometimes provided for burrowing species.

Environmental conditions in maturation facilities duplicate or even intensify conditions known to stimulate reproduction (section 6.3). Parameters such as water temperature, salinity, photoperiod, light intensity, lunar phase, maturation room and tank characteristics, and diet may be manipulated and adjusted. Each species has optimum ranges at which maturation will be facilitated. The value of these parameters and their rate of variation over time are critical to stimulate the reproductive process. The water supply system, closed or open, must continually provide maturation tanks with clear unpolluted water with oceanic characteristics and a daily exchange capacity of 200–300%. Optimum water temperature for maturation is typically around 28–29°C. An oceanic salinity of 30‰ is considered optimum, although maturation may occur between 28‰ and 36‰, and pH must be maintained between 8.0 and 8.2.

19.5.3 Open vs. closed thelycum species

Penaeid shrimp belong to two groups based on the structure of the female thelycum. This is a receptacle structure on the ventral thorax of females where the spermatophore is deposited by the male at mating. The open-thelycum species are indigenous to the western hemisphere and include *L. vannamei*, *L. stylirostris* and *L. occidentalis*. The closed-thelycum or 'brown' shrimp species include *P. monodon*, *M. japonicus*, *F. merguiensis*, *F. indicus* and several others.

- Open-thelycum species: moult → mature → mate → spawn.
- Closed-thelycum species: moult → mate → mature → spawn.

Consequently, the management of maturation procedures is different for open- and closed-thelycum species. For example, natural photoperiod is normally used in maturation facilities for most closed-thelycum species, whereas for open-thelycum species a reversed photoperiod regime is typically used (with artificial lights) so that animals will spawn during daylight or normal working hours.

19.5.4 Maturation procedures

The maturation process is relatively simple and includes selecting or sourcing good prospective broodstock (screened for absence of viruses) and holding them under stable, optimal environmental conditions, minimal stress and adequate nutrition using both natural and artificial diets. Exclusion and control of opportunistic shrimp pathogens, such as various bacteria, fungi and protozoea, is critical. It is accomplished by maintaining the best water quality possible and by periodic prophylactic treatments. Depending on animal size, maturation tanks are stocked at 3–8 animals/m^2 and at ratios from 1:1 to 1:4 males to females for closed-thelycum species, or 1:1 to 3:1 males to females for open-thelycum species. Eyestalk ablation is a relatively simple procedure and is normally done only on female shrimp that are hard shelled (section 6.2.2), not on animals that are about to moult or that have recently moulted. Prospective broodstock are normally acclimated for several weeks in maturation tanks before undergoing ablation. It is possible to mature, mate and spawn several shrimp species without resorting to eyestalk ablation, by subjecting animals to a controlled, manipulated photoperiod and water temperature regime (Bray & Lawrence, 1991; Treece & Fox, 1993; Jory, 1996).

Adequate nutrition is another factor critical for shrimp maturation, promoting sexual maturation and mating, and improving fertility and offspring quality. Maturation diets typically include combinations of commercial dry pelleted feed supplements and natural organisms such as various molluscs (clams and other bivalves, squid), crustaceans, fish and bloodworms. Bloodworms are marine polychaetes rich in the polyunsaturated long-chain fatty acids (PUFAs) that are essential for shrimp to mature.

There are five ovarian maturation stages in female shrimp: from stage I (immature) to stage IV (ripe or mature) and stage V (spent after spawning). Assessment of the progression in ovary development can be performed by holding animals against a light source, or by shining a flashlight from above over animals in the tanks to determine ovary size and colouration. In a stage I animal, the ovaries are very thin and look like almost invisible strands. As the ovaries develop through stages II to IV, they become progressively thicker and darker as seen through the animal's exoskeleton.

19.5.5 Mating and spawning

Mating in shrimp is characterised by particular courtship behaviour, and various pheromones are involved in sex attraction. Elaborate behaviour with extended and elaborate chasing, contortions and other activities has been described for different species. Mating in closed-thelycum shrimp normally happens at night. In closed-thelycum species, a hard-shell male mates with a soft-shell female that has just moulted, inserting its spermatophore into the female's thelycum near the female's gonopores. The female carries the sperm packet internally until it spawns or moults, and mating typically occurs again shortly. Mating in open-thelycum shrimp normally occurs late in the day between hard-shell males and hard-shell females. Males attach the spermatophore to the ventral surface of the female's body and close to the gonopores. As females of both types spawn and discharge their eggs through their gonopores, sperm exude from the spermatophore and fertilise the eggs. The species and size of the spawner determines spawn size, with larger species and larger animals producing more eggs per spawn. Ablated females will normally spawn multiple times over a period of several weeks. Nauplii can be collected directly from maturation tanks, but mated females are usually removed and placed in individual spawning tanks (100–500 L).

19.6 Hatchery design and larval culture

19.6.1 Hatchery design

Shrimp hatcheries can be set up in a warehouse structure or building shell, and have indoor and outdoor infrastructure and facilities. Hatchery design follows the typical pattern (section 2.7), with various areas for microalgae culture, laboratory, brine shrimp production, seawater treatment and holding, spawning, larval and PL rearing. Support infrastructure includes storage space, offices, and aeration and electrical power generating capability. There are small, medium and large shrimp hatcheries, and all have the same basic infrastructure.

(1) Small hatcheries are usually a family operation, with very low set-up and operating costs, using simple techniques and untreated water, low culture densities, and with larval culture tank capacity under 50 000 L. These generally produce either nauplii or PL, and often suffer disease outbreaks and water quality problems, but can readily shutdown and restart in a relatively short time. These hatcheries have been very successful in South-East Asia, but are not so common in Latin America.
(2) Small- and medium-scale hatcheries are usually based on the Taiwanese design (section 19.6.2), with large culture tanks between 5000 and 50 000 L.
(3) Large hatcheries use elaborate techniques to operate controlled culture environments. They target annual production of 100 million PL or more and are typically based on the 'Galveston' system (section 19.6.2). When large hatcheries have water quality and disease problems, they usually require several months to get back on line (Rosenberry, 2001).

19.6.2 Larval culture methods

Worldwide, various methods are used to produce shrimp larvae in hatcheries. These are all modifications of the two basic methods, the Taiwanese and the Galveston methods. The latter is a modification of the former and differs from it in that microalgae are cultured outside the larval tank and are added as required. Over the years, many researchers have helped modify and refine these techniques.

(1) The Galveston or 'clear water' method is based on the procedures developed at the Galveston Laboratory (National Marine Fisheries Service) in Texas in the 1970s, and has been successfully adapted to local conditions and implemented throughout the western hemisphere. It uses high densities of 100 or more larvae per litre, relatively high water exchange rates and elaborate water filtration and conditioning, and produces 6- to 12-day-old PL. Microalgae and brine shrimp nauplii are cultured separately and added to larval culture tanks as required.
(2) In the Taiwanese method, lower stocking densities and larger larval culture tanks are used. This method requires large broodstock numbers, and the microalgae blooms are promoted '*in situ*' by

directly fertilising larval culture tank water. The Taiwanese method performs well in temperate areas, where there is a short production time, but it can be comparatively harder to manage because of the large water volumes involved. This method is generally not used in tropical areas because of the management difficulties inherent to tropical conditions (Treece & Fox, 1993; Jory, 1997).

19.6.3 Larval nutrition

The larval feeding regime of shrimp hatcheries is typically based on microalgae and brine shrimp (section 9.5) or on live feeds combined with formulated/prepared diets (Table 19.5). The latter can be produced at the hatchery, although in recent years several commercial brands have become available. Most are 'dry diets' packaged under vacuum or in nitrogen-filled cans or pouches, and are produced in a range of particle sizes suited to the feeding habits of the larval stages for which they are intended. Although the sizes of particles may vary from one manufacturer to another, in general zoea diets are < 50 μm, mysis 50–100 μm, PL1–PL4 100–150 μm and PL4–PL8 150–250 μm. Crude protein levels typically range from 42% to 48%, whereas lipids are 12–16% and fibre is less than 5%. Artificial diets are not a complete replacement for natural food, but when used supplementary to natural food they can increase both survival rate and growth, when compared with the feeding of natural diets (algae and brine shrimp) alone. Determining which diet to use on a cost–benefit basis should be a high priority with the hatchery manager, and diets have been used successfully by several hatcheries feeding several dry formulations (Laramore, 2000). It is likely that in the near future these diets will totally replace live feeds in hatcheries (Jory, 1997).

Several species of microalgae are commonly produced in shrimp hatcheries, including species of the genera *Tetraselmis*, *Isochrysis*, *Chaetoceros*, *Skeletonema* and others. Table 19.6 shows some of the microalgae species typically cultured and used in shrimp hatcheries. *Isochrysis galbana* and *Chaetoceros gracilis* are among the best, because of their relatively small size and significant content of highly unsaturated fatty acids (HUFAs). It is common to enrich brine shrimp nauplii with HUFA before feeding these to larval shrimp (section 9.4.7).

19.6.4 Probiotics, vaccines and immunostimulants

The ability to control pathogenic organisms, particularly bacteria, has been very important to the success of commercial-scale hatcheries. Until recently, the general method to control pathogenic and undesirable bacteria was through various water filtration and disinfection techniques (e.g. UV, chlorination). Other common procedures include implementation of hygienic procedures (personnel and equipment disinfection) and use of non-infected cultures of microalgae and brine shrimp. Various biocides and chemotherapeutics are also used to indiscriminately eliminate or reduce the numbers of pathogenic bacteria, frequently as a routine procedure and not necessarily when needed. This practice can bring serious consequences, including development of resistance, chemical traces in shrimp tissues, and environment impacts. Probiotics are single or mixed cultures of some harmless or beneficial bacteria bacterial strains that are widely used to promote survival and growth of larval shrimp. Probiotics can be an effective hatchery tool by:

- competitively excluding pathogenic bacteria
- producing substances that inhibit growth in opportunistic pathogen species
- providing essential nutrients
- promoting digestion by supplying essential enzymes
- direct uptake of dissolved organic material mediated by bacteria.

There is much potential for improvement of probiotics, but more research is needed to identify suitable species and how to promote their population growth in larval culture tanks (Jory, 1997).

The immune system of crustaceans does not produce antibodies and is relatively primitive, with non-specific immune responses, which means that they cannot be 'vaccinated' in the traditional sense. In recent years, several commercial products have claimed the ability to stimulate disease resistance

Table 19.5 Feeding schedules of microalgae and brine shrimp nauplii used successfully by several hatcheries for rearing shrimp larvae and PL. In addition, the diet included a dry commercial diet. Z, zoea; M, mysis, PL, postlarvae

			Cells/mL*		
Day	Stage and substage	Estimated survival (%)	*Chaetoceros gracilis*	*Tetraselmis chuii*	Brine shrimp/mL†
1	Z1	90	40 000	–	–
2	Z1/Z2	85	50 000	–	–
3	Z2	82	60 000	–	–
4	Z2/Z3	80	70 000	–	–
5	Z3	78	80 000	–	–
6	Z3/M1	75	70 000	10 000	0.1
7	M1	70	60 000	15 000	0.2
8	M2	65	50 000	20 000	0.4
9	M3	62	40 000	25 000	0.7
10	M3/PL1	60	20 000	25 000	1
11	PL1–2	58		20 000	2
12	PL2–3	56		10 000	3
13	PL3–4	54			3
14	PL4/5	52			4
15	PL5/6	51			3
16	PL6/7	50			2
17	PL7/8	49			0
18	PL8/9	48			0
19	PL9/10	47			0

*Algae count expressed as desired number of cells.
†Use frozen or killed *Artemia* species to feed Z3/M1.
Temperature, survival and water quality may affect consumption and, therefore, feeding rates may be modified to prevent overfeeding and tank fouling.
Reproduced from Laramore (2000) with permission.

and promote shrimp health by preventing and minimising the impact of outbreaks of pathogenic bacteria both in hatcheries and during grow-out. In hatcheries, these products can be administered to late mysis and PL by immersion or by microencapsulation using brine shrimp. Results reported from field-testing indicate that some of these products can stimulate non-specific immune responses and improve survival and growth of treated animals, thus enhancing production (Jory, 1997).

19.7 Seedstock quality and stocking

19.7.1 Seedstock packing, transportation and reception

It is important that the delivery of seedstock (PL) is well coordinated with the farm, and good planning and communication are required to ensure a smooth transition from the protected conditions of a hatchery to the conditions of an outdoor pond, tank or raceway. Timing is critical to ensure that the PL are going into a grow-out environment that has been adequately prepared and has the proper conditions to promote acceptable survival and production. Of particular importance, in the case of outdoor ponds, is that there is sufficient natural productivity to provide adequate nutrition to the animals being stocked. There is a window of about 10 days, starting about 10 days after pond filling begins, when pond conditions should be adequate for stocking. In general, ponds should not be stocked beyond 20 days after filling has begun.

Seedstock of great quality may be severely stressed by inadequate water quality or high packing densities. Inadequate packing and transportation of

Table 19.6 Microalgae species typically used in penaeid shrimp hatcheries

Class	Species
Bacillariophyceae	*Skeletonema costatum* *Thalassiosira pseudomonas, T. fluviatilis* *Phaeodactylum tricornutum* *Chaetoceros calcitrans, C. curvisetus, C. neogracile, C. simplex* *Ditylum brightwelli* *Scenedesmus* sp.
Haptophyceae	*Isochrysis galbana*, *Isochrysis* species (Tahitian) *Dicrateria inornata* *Cricosphaera carterae* *Coccolithus huxley*
Chrysophyceae	*Monochrysis* species
Prasinophyceae	*Pyramimonas grossii* *Tetraselmis suecica, T. chuii* *Micromonas pusilla*
Chlorophyceae	*Dunaliella tertiolecta* *Chlorella autotrophica* *Chlorococcum* species *Nannochloris atomus* *Chlamydomonas coccoides* *Brachiomonas submarina*
Chryptophyceae	*Chroomonas* species
Cyanophyceae	*Spirulina* species

Reproduced from Treece & Fox (1993).

shrimp seedstock will significantly affect survival and health. Care must be taken to minimise stress and to provide the best handling and conditions possible. When possible, a farm representative should be present during harvesting of larval tanks and packing of PL for transport to the farm. They should also be involved during counting of PL, to calculate numbers as accurately as possible, and to observe any undesirable conditions and practices. The farm representative may also accompany the shipment, to ensure fast movement without unnecessary delays and to maintain adequate transportation parameters (mainly temperature and dissolved oxygen, DO) during transit.

Methods of packing and transportation of shrimp PL can vary significantly, depending on origin, species, distance to farm, resources available and other factors. PL are typically transported to farms from hatcheries or from collection and consolidation stations (wild PL):

- in plastic bags with water and added oxygen, within polystyrene foam or cardboard boxes and cooled to 18–22°C (down from the typical 28–29°C in hatchery larval culture tanks)
- in tankers ranging in water capacity from 2 to 20 mt and set up to provide water aeration/ oxygenation.

Feed (e.g. frozen brine shrimp) is added to prevent cannibalism. Packing densities vary between 500 PL/L and 2000 PL/L, depending on species, age and estimated time in transit. When possible, PL are transported early in the morning or in the evening, to avoid high temperatures. Transport time should be as short as possible, ideally not exceeding 6–8 h. Reduced water temperature (18–22°C) and the addition of various compounds to shipping water (including ammonia suppressants, buffers and activated carbon) increase PL survival over extended shipping schedules.

Upon arrival, parameters such as water temperature, salinity, dissolved oxygen, pH and alkalinity must be determined to serve as the baseline for acclimation adjustments to match pond water characteristics. Upon arrival, PL may be transferred to counting or acclimation tanks, which can be located next to the pond(s) to be stocked. Care must be taken to maintain water parameters and avoid any sudden drastic changes.

19.7.2 Counting and quality control

There are various methods used to count shrimp PL, and controversy regarding the accuracy of each. According to Cook & Clifford (1998), volumetric subsampling is the most common technique. It involves concentrating all or most of the PL in a known volume of water, and drawing a fixed number of subsamples (around five) using a beaker or similar container of known volume. The subsamples are counted and their average is extrapolated to the larger volume.

Stocking only the best-quality shrimp PL is critical to the success of a shrimp farm. Several well-established criteria are used to assess PL quality, including:

- their origin and hatchery reputation
- visual evaluation
- stress tests
- various tests to detect the presence of pathogens.

Strict use of PL quality assessment criteria in the evaluation and selection of PL for stocking, and a careful acclimation procedure using the best-quality seedstock available, will have a significant effect on the production and profitability of a shrimp farm. Detailed information on PL quality assessment procedures are given in Clifford (1992).

The strength or 'hardiness' of PL from different hatcheries or batches can vary significantly and the acclimation schedule must be tailored to the PL 'fitness'. Stronger animals can be acclimated at a faster rate than weaker PL. Various stress tests are used to challenge PL and determine a suitable acclimation schedule. These tests typically involve subjecting a PL sample of 100–200 individuals to a thermal, osmotic or chemical shock for 1–4 h and counting the survivors. For example, Clifford (1992) proposed a standardised 'stress test' method whereby a sample of PL is placed in a container and the salinity and temperature are simultaneously brought down to 20‰ and 10°C, respectively, for 4 h (a test lasting under 4 h does not adequately account for lingering PL mortalities). Survival of 80–100% of the test animals indicates high-quality PL, but 60–79% survival is considered acceptable.

19.7.3 Acclimation and stocking

Most shrimp farmers spend substantial resources and effort during pond preparation to enable them to stock their PL into a grow-out environment with the best possible environmental conditions, as free of predators, competitors and stress as possible, and with ample supply of adequate food organisms. Still, the transition from relatively benign conditions in hatcheries to those prevailing in open grow-out systems, such as tanks and ponds, where water conditions continually or unpredictably change (day/night, dry/rainy seasons over the production cycle) can be a traumatic experience for PL unless the transition is gradual and stress is minimised.

Proper preparation of the acclimation station and equipment is a critical step in PL acclimation. The acclimation station, including all tanks and other water reservoirs and equipment (nets, siphons, buckets, tubing, others), is thoroughly cleaned and disinfected by scrubbing with chlorine or other disinfecting agent. Well-functioning and calibrated equipment to monitor water parameters (temperature, salinity, pH and dissolved oxygen) before the PL arrive at the acclimation station is critical.

The typical acclimation process involves holding the PL for a period in tanks and slowly adding water from the pond to be stocked to equalise various parameters (mainly salinity and temperature). General acclimation recommendations that have been used for many years include:

- Increase/decrease salinity by no more than 3‰/h.
- Avoid sudden temperature changes (> 3–4°C).
- Maintain DO levels at 6–7 ppm.

Acclimation densities should not exceed 300–500 PL/L depending on animal size and duration of acclimation.

Salinity is probably the most critical parameter to manipulate during PL acclimation. Table 19.7 suggests salinity acclimation rates for various scenarios, including when handling PL of different ages and condition (strong, weak). These recommended schedules may be used as the basis for developing in-house acclimation procedures. (Note that 'acclimation' is used here in the sense of rapidly developed tolerance of changed conditions, rather than long-term mechanisms of developed tolerance such as are described for temperature acclimation in section 3.3.1.)

Acclimated PL may be released into the pond using buckets or other containers at points at least 50 cm in depth, at 50-m intervals and on the upwind side of the pond to maximise PL distribution throughout the pond. Excessive turbulence at release must be avoided to prevent damage to animals.

Survival cages, buckets or net enclosures are commonly used to estimate PL survival 24–48 h after stocking. This information is very important because it is the basis for additional compensatory stocking if initial survival is not satisfactory. Chanratchakool *et al*. (1998) described the use of net enclosures (no less than 2 m^2 and 1 m deep) to monitor survival of stocked PL in Thailand. About 1000–2000 PL are placed in the enclosure and fed normally, and counted after 3–5 days. Clifford (1992) provides detailed descriptions of the use of survival cages in Latin America.

19.8 Production management and harvest

19.8.1 Water and sediment quality

Some water quality parameters must be routinely monitored to effectively manage shrimp production systems during grow-out. Controlling various parameters can be difficult, but, if not managed properly, pond carrying capacity can be rapidly exceeded and ponds can crash within a few hours or days. Shrimp mariculture requires high water quality to function efficiently and maintain farm productivity and profitability. Therefore, monitoring the quality and properties of intake water, pond water/soil conditions and organics in effluent are essential for good animal husbandry. It is also important for farms to be environmentally aware and maintain water management programmes to minimise any potential 'downstream' impacts (section 4.2). Table 19.8 shows the general range and monitoring frequency recommended by Clifford (1997) for various water quality parameters that are important in shrimp production systems. These standard parameters are described in section 3.2. They are measured in the field with probes and meters or by taking water samples that are analysed in a laboratory on site. Measurements and samples are taken at several places within a pond, including the water intake, the central region, drain, and surface and bottom layers. This will provide a more representative assessment of the parameter. Boyd (1990) provides detailed information on pond water parameters and their monitoring.

DO is one of the most critical physical parameters of a pond culture. Low DO is one of the most common causes of mortality and poor growth in high-density shrimp ponds. Lethal levels seem to vary from about 0.5 to 1.2 ppm, depending on the species and hardiness of a particular population. DO levels can be relatively unstable as a result of wide fluctuations in photosynthetic oxygen production and the bacterial population affecting BOD. DO levels in the water column fluctuates over a day/night cycle, from a low at dawn to a high in mid-afternoon, particularly due to phytoplankton photosynthesis during the day and then respiration at night. Hence it is appropriate to sample DO at dawn and mid-afternoon. DO readings in the water column immediately adjacent to the bottom are essential, because shrimp spend most of their time feeding and resting in or on the sediment.

Salinity and temperature are extremely important parameters that affect several biotic and abiotic processes in the production system environment, but there is usually relatively little that can be done to modify them. Water temperature, however, may be controlled in indoor systems of high stocking density. Farms with free access to both good-quality seawater and freshwater can mix these to desired salinities.

pH does not usually reach levels that affect the shrimp. Values seldom exceed the range of 6–9 in sediments or the water column (except in acid-sulphate soils). High pH (> 9) is a lesser risk than low pH (< 6). Low pH may affect the mineral deposition of the shrimp's exoskeleton after moulting,

Table 19.7 Suggested salinity acclimation rates for 'strong' and 'weak' PL. 'Strong' refers to animals older than 10 days (> PL10) or strong larvae. 'Weak' describes animals younger than 8 days (< PL8) or weak animals

Salinity change	Suggested acclimation rate (‰/h)	
(‰)	Strong PL	Weak PL
From 35 to 20	5	3
20–15	4	2
15–10	3	2
10–5	2	1
5–2	1	0.5
2–0	0.5	0.2
30–40	4	2
40–50	2	1

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Table 19.8 General range and recommended monitoring frequency for various water quality parameters in shrimp ponds

Parameter	Minimum value	Maximum value	Monitoring frequency
Water temperature (°C)	24	30	2×/day
Salinity (‰) (very species specific)	15	45	1×/day
DO (ppm)	3	12	2×/day
pH	8.1	9.0	2×/day
Secchi disc (cm)	30	50	1×/day
Alkalinity (mequiv.)	100	200	1×/week
Total ammonia-N (ppm)	0.1	1.0	2×/week
Non-ionised ammonia-N (ppm)	–	0.2	2×/week
NO_3 (ppm)	0.6	1.2	2×/week
NO_2 (ppm)	–	0.5	1×/week
Total N (ppm)	0.6	2.5	2×/week
Phosphate (ppm)	0.2	0.5	2×/week
Silicate (ppm)	1.0	4.0	1×/week
H_2S (ppm)	–	0.1	1×/week

Adapted from Clifford (1997) with permission.

resulting in 'soft' shrimp, and can destabilise some phytoplankton species that prefer alkaline conditions. pH in the water column fluctuates with phytoplankton photosynthesis and respiration in proportion to dissolved CO_2, which is the reciprocal of DO. pH is lowest at dawn when dissolved CO_2 is highest and highest in mid-afternoon when dissolved CO_2 is lowest. Sediment pH varies less on a diel basis than water column pH, but sediment pH tends to decrease progressively towards the end of the production cycle, due to accumulation of organic acids and nitrification of ammonia.

Nitrogenous wastes resulting from protein digestion can accumulate and even reach dangerous concentrations, particularly at high stocking densities. Nitrite and unionised ammonia can accumulate to toxic levels periodically, particularly during massive die-offs of phytoplankton. Nitrate is usually not toxic at levels typically found in ponds. Total ammonia and nitrate are managed through water exchange.

Water transparency is an index of plankton biomass present and is measured with a Secchi disc, typically once per day at mid-morning (Fig. 3.1). Acceptable values are between 30 cm and 50 cm. Readings of < 30 cm indicate high phytoplankton biomass or suspended sediment or both in the water column. Pond water colour usually reflects the predominant phytoplankton species, i.e. golden brown = diatoms; green = green flagellates; blue-green = blue-green algae; and red = dinoflagellates.

Pond sediments tend to deteriorate with successive cycles and within production cycles due to accumulation of organic matter and sludge deposition. Sediment quality can be determined from hydrogen sulphide level and redox potential (E_h) (section 3.2.8), and by visual examination of sediment cores. Smelling a scoop of surface mud from various areas of the pond bottom is a quick check for hydrogen sulphide sediment. Redox potential of sediment is another quantitative indicator of sediment conditions. It is a measure of the proportion of oxidised to reduced substances, and is an indicator of the relative activity of aerobic and anaerobic bacteria in the sediment profile (Fig. 3.4).

19.8.2 Water management

Water exchange is an effective tool for pond management, i.e. to flush out wastes and, in some cases, to improve DO levels. At many large farms, water exchange often follows a fixed schedule rather than being a flexible alternative used when pond conditions require it. High exchange rates can be wasteful and have a negative effect on fertilisation and natural productivity by flushing out nutrients. As much as 35–40% of pond volume may be exchanged daily in some ponds stocked at high and very high densities. More typical exchange rates for medium and high stocking densities are, however, about 5–25%. With increasing incidence of various shrimp viruses and declining shrimp prices, there is a global trend to reduce water exchange rates to maximise biosecurity through exclusion of pathogens, to increase mechanical aeration and to promote improved assimilation of nutrients into shrimp biomass (section 19.10).

Fertilisation of ponds with inorganic and organic nutrients is an effective means of stimulating the production of natural foods and reducing feed use. In the first few weeks, it may be necessary to fertilise a pond every day, then every other day, and eventually biweekly. Routine fertilisation should be enough to maintain adequate water transparency (30–50 cm). Proper maintenance fertilisation can provide a continual natural food supplement and improve water quality. Once feed applications reach about 25–30 kg/ha/day, no additional N or P fertilisation is usually needed, because uneaten feed and shrimp faeces supply enough. Liming compounds are added to ponds in some farms (~20–100 kg/ha/week) during the cycle to increase alkalinity, particularly during the rainy season or in areas where low-salinity waters are prevalent. Liming compounds are also added under the presumption that water quality will be improved and pathogens in the water reduced.

19.8.3 Water aeration and circulation

Pond aeration is the primary life support system of many aquaculture ponds, including shrimp ponds. Management of DO aims at maintaining DO levels over 3.0 ppm throughout the pond, using the least equipment and with minimum cost. Efficient use of aeration and circulation equipment should take advantage of the oxygen supplied by photosynthesis during the day and by diffusion across the pond surface at night. Aerators are mechanical devices that act as the heart and lungs of an aquaculture pond, providing distinctive circulation and aeration effects, increasing the rate at which oxygen enters water. There are two basic techniques for aerating pond water: one is to splash water into the air and the other is for air bubbles to be released into the water, so there are 'splasher' and 'bubbler' aerators (Boyd, 1990). The splash created by paddlewheels and the bubble-jet from aspirators improve the exchange of dissolved gases between air and water, allowing oxygen to enter the pond and carbon dioxide and ammonia to escape. Splasher aerators include vertical pump, pump-sprayer and paddlewheel aerators. Pump-sprayer aerators use a centrifugal pump to spray water at high velocity through holes in a manifold and into the air. Vertical pump aerators comprise a motor and an impeller (propeller) attached to the shaft. The motor is suspended below a float with a centre opening and the impeller jets water into the air. Paddlewheel aerators splash water into the air as the paddlewheel rotates (Fig. 3.10). Bubbler aerators include diffused-air systems and propeller-aspirator pumps. In a diffused-air aeration system, an air blower or air compressor is used to deliver air through an airline, and the air is released through air diffusers located on the pond bottom or suspended in the water. Propeller–aspirator pump aerators have a high-velocity impeller at the end of a hollow shaft and housing. During operation, air moves down the shaft by the Venturi principle and flows into the water as fine bubbles. Most aerators are powered by electric motors.

Shrimp ponds require mechanical aeration when production biomass exceeds 2 mt/ha and additional aeration at a rate of 2 kW for each additional mt. The moderate circulation effect provided by one or two aerators is desired from the time of stocking. Surface circulation must be ~4 cm/s during feed applications. This speed will not disturb fresh pellets, but will keep finer particles and organics in suspension. Excessive water circulation may be managed by arranging aerators in uniform configurations or by other means. In a typical configuration, aerators generally create a central area of sediment deposition, and sometimes the sludge deposited may be removed by using suction hoses. There are central drains in some ponds with high stocking densities. Proper positioning of aerators and circulators is very important, because the operating efficiency of aerators is highly dependent on achieving adequate water circulation (Fig. 19.4). They must be positioned to generate a whole-basin flow pattern and produce an efficient water movement. This is achieved by aligning the current from each unit so that it supplements rather than conflicts with the overall flow pattern in the pond. Aeration equipment must be placed at the points of lowest DO within a flow pattern that encompasses the entire pond.

One of the needs for circulation and aeration is thermal stratification. Thermal stratification can occur in ponds when surface waters warm faster than deeper waters during the day. This may lead to DO depletion in the bottom water, because most of the DO in pond water originates from photosynthesis in the upper stratum of water or by diffusion from the air through the water surface. One kind of mechanical device often accomplishes aeration and circulation. Paddlewheel and propeller–aspirator pump aerators are especially efficient in circulating pond water. There are also circulators that supply little aeration but can prevent stratification. These are generally large, slowly revolving (50–150 rpm) propellers installed in ponds to quietly move large volumes of water.

19.8.4 Population sampling and health assessment

Periodic sampling of shrimp populations is an important management tool during the production cycle. Cast netting is about the only effective sampling tool currently available and it is widely used. The process of sampling has the objective of generating information about a large group of individuals, a shrimp population in a pond, by looking at a small number of individuals. Most shrimp farms routinely carry out sampling programmes to:

- monitor population size
- monitor individual and average size/weight of animals
- evaluate the animals' physical condition, appearance and product quality
- assess the animals' overall health, and to test for the possible presence of known pathogens or diseases.

In the last few years, and as their use becomes widespread, it has been realised that properly managed feed trays (section 19.9.8) or lift nets can provide adequate population estimates by combining daily feed consumption rates with percentage body weight curves.

One of the most important considerations is to eliminate or minimise sampling bias. In general, the biases are relatively consistent and, with experience, correction factors can be developed to compensate and produce good workable approximations of shrimp size and populations. Estimates of shrimp population size and survival rates can be remarkably accurate if properly carried out or very inaccurate owing to variable shrimp activity, e.g. moulting, lunar and tidal cycles of behaviour, size differences in habitat preference and catchability. In general, to improve the validity of a shrimp population sampling programme, sample collection must be carried out after lowering the pond water level by experienced personnel using a large and heavy cast net, and the number of sampling stations and frequency of sampling must be as large as possible. It is important for a farm to establish adequate in-house sampling methods that adequately reflect its needs and capabilities (Clifford, 1997).

Health assessment and management on shrimp farms has become an important issue in the last 12 years or so, because of the increased importance of various diseases, particularly of viral origin. There are ~20 distinct viruses (or groups of viruses) known to infect marine shrimp. Viral diseases have had a severe impact on the shrimp farming industry worldwide, causing very important production and economic losses. Viruses belonging to the WSSV, MBV (monodon baculovirus), BMN (baculoviral mid-gut gland necrosis), HPV (hepatopancreatic parvovirus), IHHNV (infectious hypodermal and haematopoietic necrosis virus) and yellowhead virus (YHV) groups have been important pathogens of cultured shrimp in Asia and the Indo-Pacific regions, whereas TSV (Taura syndrome virus), IHHNV and BP (baculovirus penaei) have been the most important in the Americas. Once thought to be limited to Asia, WSSV and YHV have been found in cultured and wild shrimp in the USA, and both viruses have been shown to be present in commodity shrimp imported from Asia and sold directly on the USA market. WSSV was first reported in Central America in 1999, and from there it expanded to most of the shrimp-farming countries in the region, causing severe economic losses.

Several strategies have been tried to control viral diseases in shrimp farming, ranging from improved husbandry practices to stocking ‘specific pathogen-free’ (SPF) or ‘specific pathogen-resistant’ (SPR) species or stocks. Further information on shrimp diseases is provided by Lightner (1996) and Alday de Graindorge & Flegel (1999) and in section 11.5.2.

A cost-effective health management and biosecurity programme requires reliable diagnostic tools that shrimp farmers can use to make adequate and timely decisions on management procedures to control or exclude pathogens. Virulent pathogens can produce catastrophic mortalities very rapidly, and shrimp farmers need this fast diagnostic capacity in order to respond effectively. Practical diagnostic methods that are accurate, sensitive, rapid and economical to conduct are already available, including polymerase chain reaction (PCR), dot-blot gene probes and various methods for rapid fixation and staining (Fegan & Clifford, 2001).

Early signs of many health problems can be promptly observed by examining shrimp during regular feed tray monitoring or from weekly sampling. Some of these signs include:

- loss of appetite (empty guts)
- changes in colour (blueish or reddish)
- persistent soft shells or shell fouling
- red discolouration (particularly in appendages and uropods)
- lethargic or disoriented, behaviour
- fouled or discoloured or black gills
- blackened lesions on shell
- opaque or white tail muscle
- various morphological deformities, such as cramped tail.

19.8.5 Harvest and transport to processing plant

Shrimp are highly perishable and delicate, and no amount of manipulation can restore product quality once it is lost. Therefore, proper preparation, harvesting and preservation are critical for the product to be the best quality and command the best price. This preparation can be quite elaborate, because a pond ready to be harvested may have 10–20 mt or more of shrimp, which must be properly collected, handled and packed (Fig. 19.9). The most important objectives at harvest are to:

- minimise the quantity of shrimp left on the pond bottom
- immediately chill shrimp to near freezing
- pack the shrimp in a manner that avoids physical damage.

The most important considerations of when to harvest a pond are shrimp size, price and maximising the economic return of the production cycle. Many shrimp farmers use the moon phase to programme their harvests, targeting periods of full and new moon. About 3–5 days before the harvest date, the

Fig. 19.9 Harvesting procedures are critical for the best-quality product that commands the best price.

texture (representative of the stage in the moulting cycle) of shrimp to be harvested is monitored by daily collection of a sample (100–300 animals/pond) to determine the percentage that are moulting. The particular requirements of the processing plant and the intended market determine what percentages of hard, soft and semi-hard (post-moulting) shrimp, as determined during pre-harvest sampling, are acceptable to proceed with a planned harvest. For example, for shrimp to be marketed whole, typically less than 5–8% of the animals sampled should be soft, and less than 15–20% should be semi-hard. Some farmers also stop feeding a few days before the harvest, but this is a decision that really depends on each pond, its biomass and its overall condition (Clifford, 1997).

Most shrimp are harvested by draining the production ponds, tanks and raceways. In preparing ponds for harvest, water levels are typically lowered to ~70% of their operational levels, beginning 24–48 h before the harvest. In larger ponds it is often necessary to reduce water levels to 50% or so before beginning the harvest, so that the harvest does not last excessively long, which would stress the shrimp and reduce their quality. Most pond harvests are undertaken during the night to avoid high water temperatures. A net is placed covering the out-flowing water and any shrimp remaining are picked up by hand or dip nets. The quality of these residual animals is generally reduced because of mud embedded in their gills and joints between tail segments, and delayed chilling. Harvested shrimp are immediately separated into size classes and layered with ice or immersed in an ice slurry for transport to the processing plant. Within minutes after death, shrimp begin to deteriorate at normal pond temperatures (25–30°C) that promote bacterial decomposition. Initial spoilage, however, is due to digestive enzymes from the hepatopancreas. These break down proteins and reduce product weight, and quickly break down tissue at the junction of the head and tail, making the head appear loose and sagging, which is unacceptable to the European market for head-on shrimp. Bacterial and enzymic activity can be stopped by immediately reducing temperature to near freezing. It is very important that shrimp are killed by thermal shock when immersed in chilled water (4°C is maintained from the time the animals are harvested to the time they reach the plant). Often additional processing takes place at the pond bank. This includes dipping the shrimp in chlorinated water (50–60 ppm) or a solution of sodium bisulphate to reduce blackening of the head for head-on shrimp product, removing crabs, fish and plant material, and selecting the largest animals to be used as potential broodstock (if needed). Shrimp are handled carefully during packaging to minimise damaging the product and reducing its acceptability in markets. Mechanical harvesting systems are being developed to harvest shrimp ponds and assure product quality.

Further details of post-harvest technology for shrimp, including safety and health, live transport, post-mortem processing and chilled storage life, are provided in sections 11.3, 11.7, 11.9 and 11.12 respectively.

Shrimp are marketed in a variety of forms: heads-on shrimp (including live), shell-on tails, peeled tails (included canned), breaded tails and other value-added products. These are transported to various markets in a variety of forms and packaging.

19.9 Nutrition, formulated diets and feed management

19.9.1 Nutritional requirements and formulated diets

The nutritional requirements of marine shrimp, their feed formulation and manufacture have been extensively discussed and documented, but much remains to be learned. With industry expansion there has been an intensification of production and an increased dependence on the use of manufactured dry feed, which often represents the highest production cost. Protein is typically the most expensive macronutrient in shrimp feeds, and dietary protein levels from 18% to 60% have been recommended for various species and sizes of marine shrimp species, possibly because of their wide range of natural feeding habits. PL shrimp require a higher dietary protein level than older shrimp. Formulated shrimp feeds are complex products and the main components typically are wheat flour (20–35%), soybean meal (15–25%) and fish meal (15–30%). These few ingredients contribute most or all the protein, amino acids and energy. The remaining ingredients include various lipids and micro-ingredients that provide essential fatty acids, vitamins, minerals, attractants, binders, preservatives, pigments and health additives (Table 19.9).

Chamberlain & Hunter (2001) recently reviewed additives used in formulated shrimp feeds. In total, ~110 additives are commonly used as ingredients in shrimp feeds today.

(1) Attractants include animal by-products (crustacean tissue meals, squid by-products, low molecular weight fish and meat extracts), and purified compounds (free amino acids, artificial flavours, betaine and nucleotides).
(2) Enzymes supplements improve digestibility of phytate, fibre, indigestible sugars and other components.
(3) Various additives, including coccidiostats, antibiotics and hormones, have been used as growth promoters in shrimp.
(4) Other additives, including immunostimulants, probiotics and vaccines used to stimulate the immune system of shrimp and improve resistance to disease. This has become especially important to reduce outbreaks of shrimp viral diseases. The immunostimulants used include beta-glucans, bacterial extracts, blood plasma, seaweed by-products and yeast.
(5) Wheat flour is the principal binder used in shrimp feeds but, by itself, may not provide proper water stability, especially if the manufacturing process does not include fine grinding, extended conditioning, and post-pellet conditioning. Therefore, additional binders are often needed to assure water stability.
(6) Additives are used to improve shrimp pigmentation, which is significantly determined by dietary

Table 19.9 Recommended nutritional composition of shrimp feeds. Only critical nutrients for feed formulations are listed on as-fed basis

Nutrient	Shrimp 0–3 g	Shrimp 3–15 g	Shrimp 15–40 g
Protein (minimum)	40.0	38.0	36.0
Lipid (minimum)	6.2	5.8	5.5
Lipid (maximum)	7.2	6.8	6.5
Fibre (maximum)	3.0	4.0	4.0
Ash (maximum)	15.0	15.0	15.0
Calcium (maximum)	2.3	2.3	2.3
Phosphorus available (minimum)	0.8	0.8	0.8
Potassium (minimum)	0.9	0.9	0.9
Lysine (minimum)	2.12	2.01	1.91
Arginine (minimum)	2.32	2.20	2.09
Threonine (minimum)	1.44	1.37	1.30
Methionine (minimum)	0.96	0.91	0.86
Methionine/cysteine (minimum)	1.44	1.37	1.30
Phospholipid (minimum)	1.0	1.0	1.0
Cholesterol (minimum)	0.35	0.3	0.25
20:5*n*-3 (minimum)	0.4	0.4	0.4
22:6*n*-3 (minimum)	0.4	0.4	0.4

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carotenoids. Some markets have a premium demand for shrimp with strong natural pigmentation, and ovarian pigmentation is important for maximum reproductive performance.

(7) Finally, because shrimp feeds are typically stored for several weeks in humid tropical environments, antioxidants (BHT, BHA and ethoxyquin) and preservatives are generally added to prevent oxidation of fats and mould infestation (Chamberlain & Hunter, 2001; section 9.10.4).

19.9.2 Feed management

Shrimp feed management is a critical aspect for cost-efficient, environmentally responsible shrimp production. Appropriate practices will produce maximum shrimp growth and survival concurrent with the lowest feed conversion, while reducing feed inputs and minimising impact of effluents. Efficient feed management is the summation of several sequential steps, including feed selection, storage and handling, application methods, and feeding regimes. Determining when to feed requires knowledge of diel activity patterns, feeding frequency and time (subject to change with geographical location, season, species, size, age, stocking density, unusual environmental conditions and other stimuli). Calculating feed rations involves estimating survival, population size and biomass, and size distribution. Monitoring and continuously adjusting the amount of feed applied, according to changes in consumption caused by various biotic (e.g. amount, quality and availability of natural food items) and abiotic (water quality and other environmental parameters) factors, is important for effective feed management. Evaluating and adjusting feed input involves regular population sampling and proper monitoring of various water quality parameters. Shrimp are bottom feeders, and it is difficult to estimate their feed consumption, unless feed trays (section 19.9.8) or lift nets are used. Inadequate feed management may promote the onset of various diseases and water quality-related problems, and may adversely affect production. Ineffective practices often include:

- applying feed during times convenient for employees (during daylight hours), but not necessarily at the best times for shrimp
- inadequate handling and storage practices during bulk feed storage and after feed distribution to pond side
- overfeeding.

The best shrimp feed in the world will yield poor results if it is not handled, stored and used properly.

19.9.3 Factors that affect feed consumption

Several factors can affect shrimp feeding behaviour, and it is important to understand these factors to make proper and timely management adjustments (Clifford, 1992, 1997; Jory *et al*., 2001). The major factors affecting feeding behaviour are:

(1) Species, age and size. There are marked differences between species. Some species are much more active and aggressive while foraging for food, and this has to be incorporated into a feeding strategy. Feeding rate is a physiological function dependent on the growth stage of the animal; it decreases as the animal grows and approaches maturity. Growth immediately after pond stocking can be 12–15%/day, decreasing to 1–2%/day towards the end of the production cycle.

(2) Availability of natural food. When natural food is very available, the demand for formulated feeds is reduced. This is typical when the biomass of stocked shrimp is low during the first few weeks after stocking and until the natural carrying capacity of the pond is reached.

(3) Water quality. The most important parameters are temperature, DO, pH and salinity, but other parameters also influence the shrimp (Table 19.8). For each parameter, animals have a range of tolerance and a narrower optimum range that promotes optimum feeding, growth and overall well-being (section 3.3).

(4) Moulting. Shrimp moult periodically (days–weeks) throughout their lives, and this is a stressing period during which their appetite diminishes markedly. It can take 2–5 days for normal feeding to resume after moulting. Thus, it is important to recognise when there is a significant reduction in feed consumption (use of feed trays is a good method) indicating high incidence of moulting in a pond.

(5) Quality of commercial feeds. Shrimp eat to fulfil their nutritional needs, and if the feed they consume does not have enough energy or appropriate nutritional profile, their feeding activity will increase. Feed attractability and palatability are also important factors.

19.9.4 Feed handling and storage

Feed management at a shrimp farm begins upon arrival of a feed shipment. Poor storage and handling of feeds will result in product deterioration, reduced feed attractability and palatability, possible nutritional deficiencies and disease outbreaks, and reduced growth rates and overall production (sections 9.10.3 and 9.10.4). Upon reception of a feed batch, a few randomly selected bags are examined for physical integrity. In addition, twice a year feed samples are collected from newly received shipments (or when using a new feed) and analysed for proximate composition, mycotoxins and selected pesticides if pertinent (Jory, 1995; Jory *et al*., 2001).

Feed is ideally used within the first 2–4 weeks after manufacture and must not be stored for more than 2–3 months. At farms that feed several times over 24 h, the total feed ration is often distributed from the farm warehouse to the ponds once, usually early in the morning. The feed bags must then be protected from sunlight and rain by storing them off the ground in simple pond-side sheds.

19.9.5 Application and distribution

Formulated feeds can be applied in a variety of ways to shrimp production systems (section 9.11.2). Feeds may be distributed manually in large ponds from boats or mechanically using blowers mounted on vehicles and boats (Fig. 19.10). Even crop-dusting aeroplanes have been used to distribute feed to very large ponds. In small ponds, tanks and raceways, automatic feeders with timing mechanisms can be used (section 9.11.2). At many farms in several countries, all feed is applied exclusively using feeding trays. Broadcasting feed from paddle- or motorboats is typical at many farms in Latin America. The use of feed blowers is not widespread yet, but could gain popularity in coming years because of their efficiency.

Fig. 19.10 A feed blower used to feed shrimp in ponds on a farm in Mexico.

It is important to distribute the feed evenly early in the grow-out cycle, but, as the cycle progresses, shrimp react to changing pond microhabitats. They avoid areas where anaerobic sediments accumulate and noxious compounds, such as H_2S, are produced, including internal drainage canals and areas close to the drainage structures. In addition, many shrimp will move to the deeper areas of ponds during the day to avoid light. Therefore, it may not be appropriate to provide feed to very shallow areas during daylight hours, because it is unlikely shrimp will consume it. It is also important to recognise that shrimp distribution in ponds is generally not uniform along the linear dimensions of the pond.

19.9.6 Frequency and timetables

All formulated feeds have an ideal feeding rate range that optimises growth and feed efficiency. This range varies with species, age and weight, stocking density, water quality, availability of natural foods, stress and other factors. At many farms, feeding is based on tables that do not properly consider natural feeding habits of shrimp or their physiological state. Increasing the frequency of feeding generally produces immediate benefits, including reduced nutrient and feed loss, and increased growth and feed utilisation efficiency. In Asia, it is common practice to feed up to six to seven times over a 24-h period. Because *L. vannamei* appears to be less nocturnal than *P. monodon*, most shrimp farms in Latin America feed one to three times/day, usually between the morning and late afternoon. Because of the higher degree of activity shown by *P. monodon* at night, many farms in Asia provide most of the daily ration during night hours.

How many times and when to feed is an important decision that each shrimp farm must determine, based on experience, production system used, season, environmental conditions, species, stocking densities and available resources. Feeding during the night typically becomes more important as the production cycle progresses and the availability of natural feed diminishes. In general, a minimum of two feed applications per day are needed at the beginning of the production cycle, increasing as the cycle progresses to at least three or four applications per day.

19.9.7 Feed rations

Feed rations can be calculated using a set schedule that accounts for animal weight and estimated biomass/survival in the pond. Feeding based on tables is still widely practised (section 9.11.1).

There are several problems with relying on feeding tables.

(1) There are problems in accurately estimating survival, particularly when dealing with small animals in large (< 5 ha) ponds.
(2) Various factors (section 19.9.3) affect feeding rates.

Feed consumption changes can usually be detected by proper monitoring of feed trays (section 19.9.8). Feeding rates are adjusted periodically (usually weekly), based on sampling estimates for individual average body weight, population size distribution and pond shrimp biomass. As shrimp grow the feed amounts used decrease as a percentage of the total shrimp biomass, but the absolute amount of feed increases together with increasing shrimp biomass (Jory *et al.*, 2001).

19.9.8 Use of feed trays

Feed trays are also called feed monitoring trays, observation or lift nets, feed inspection trays or umbrella nets. They are simple devices usually consisting of a frame and fine mesh that is lowered to the floor of the pond. There are several ways feed trays can be used, including:

(1) as indicators of feed consumption, population and health assessments and other observations
(2) to apply all feed (Peruvian system)
(3) a combination of these two.

In using the feed trays as indicators of feed consumption, about four to eight trays per hectare are used in ponds < 5 ha, whereas two to five trays per hectare are used in larger ponds (10–20 ha). A small percentage of the ration is placed in the trays and the ration is distributed throughout the pond. Trays are checked after 2–3 h and the data are used to adjust rations. In the Peruvian system, the entire ration is applied in trays, which requires many more trays per pond. Disadvantages of using feed trays to feed the entire pond include high costs and increased training and supervision in feeding practices, because two people are required daily for 12-h shifts for every 10 ha of pond. But additional construction, labour and equipment costs are reportedly covered by the resulting reduction of feed costs, precise feed consumption estimates and good FCRs. Finally, the Peruvian system may be used initially and then trays are just used as consumption indicators (Clifford, 1997).

The reliability of feed trays for estimating food consumption has been questioned by some, because shrimp may use trays as a refuge from reduced pond sediments. Crabs are attracted to feed trays, where they feed on shrimp pellets or prey on shrimp. Their presence in or near feed trays can keep shrimp away from trays, resulting in an underestimate of feed consumption and underfeeding. The main argument against using feeding tables is that it is very difficult to continuously estimate with accuracy the survival of animals in a pond. Therefore, it has become common for most farms, when feeding a pond for the first time, to initially follow their own or the feed manufacturer's guidelines and tables, and then begin adjusting daily rations using feed trays (Jory *et al.*, 2001).

In general, observation of feed consumption from a small number of trays is not an adequate measure of actual feed consumption, especially in large ponds. This is because there are considerable day-to-day variations in feed consumption as outlined in section 19.9.3.

19.10 Emerging production technologies and issues

19.10.1 Diseases and biosecurity

Viral diseases have had a considerable impact on commercial shrimp farming during the last decade (section 19.1.2), significantly affecting the operation, management and design of shrimp farms. Another resulting consequence is increased awareness of the need for better husbandry methods to reduce the risks of exposure to pathogens, and also of the need for improved management practices to enhance shrimp health. Shrimp farming is a relatively new industry and has lagged behind in the development of practices for standard health management. This in part results from the relatively poor level of understanding of shrimp physiology and their production systems. Also, there has been limited involvement by veterinarians and animal health specialists to develop health management practices like those in use in terrestrial animal husbandry.

The modern poultry industry, with its considerable advances in production and disease control, best exemplifies the advantages of biosecure animal production, and shrimp farming must adopt similar practices to become more competitive. Biosecurity in shrimp aquaculture involves those practices that will reduce the probability of introduction and dissemination of a pathogen. Shrimp producers often give only limited attention to routine biosecurity on their farms. This is because of the misconception that the potential costs of implementing biosecurity measures will outweigh the benefits or because they do not have appropriate knowledge. Effective implementation of biosecurity protocols requires awareness, discipline and a commitment by farm owners to implement them. We have improved our knowledge of shrimp viral diseases significantly during the past 15 years, mainly due to their negative impact on the industry, but biosecurity is still very new to shrimp farming (Fegan & Clifford, 2001).

A cost-effective, biosecure shrimp-farming protocol involves:

- aggressive methods for pathogen exclusion from production systems
- effective screening of seedstock
- appropriate environmental management
- effective health management, integrating genetic selection
- specific pathogen-free and pathogen-resistant stocks
- limited or zero water exchange
- stocking strategies
- feed management and use of immune stimulants to increase host defences
- strict and proactive health monitoring and farm management strategies.

Also important are farm location (site selection) and design. Currently, only a few shrimp farms have been specifically designed to prevent diseases, although it is more cost-effective to incorporate disease prevention and treatment aspects during the planning stage than to redesign or refit existing farms. Eliminating or reducing water exchange is an important aspect to prevent viral diseases, to exclude viral carriers or free virions from production systems, and to minimise stressful variations in water quality, which may trigger disease outbreaks. There are several examples of successful commercial farms in Asia and Latin America which use low or zero water exchange (section 19.10.5).

19.10.2 Probiotics and microbial management

As described, the use of probiotics is relatively common to limit pathogenic bacteria in the disease-prone intensive systems used to produce shrimp PL in commercial hatcheries (section 19.5.3). For some time now, the use of bacterial amendments has been recommended for use in aquaculture ponds to obtain a number of benefits (Boyd, 1995), including:

- reducing blue-green algae populations
- preventing off-flavour
- reducing N and P levels
- increasing DO
- promoting decomposition of organic matter.

There is ongoing research on the use of probiotics, which could be important in promoting shrimp yield in intensive systems, in the implementation and optimisation of low- and zero-water exchange production systems, and in managing the quality of pond effluents.

The pond microbial community plays a major role in the natural food availability, mineral recycling rates and DO dynamics in shrimp ponds. Effectively managing the microbial community can help prevent or reduce the risk of a disease outbreak, but, if mismanaged, the microbial community can also promote disease by creating conditions that facilitate growth of pathogenic bacteria.

19.10.3 Nursery systems

Jory & Dugger (2000) recently reviewed the use and advantages of nursery systems for PL shrimp. These systems generally produce higher overall survival rates per production unit area and more efficient capital utilisation than direct stocking into grow-out systems. They also provide better management of environmental conditions, feeding, and exclusion of pathogens, predators and competitors. It is critical to know the survival, quantity, condition and quality of seedstock before stocking into ponds before investing several months of effort and resources into a production cycle. Nursery strategies involve holding seedstock at very high densities (5000–10 000 PL/m^2) in specially designed facilities for 20–40 days, with precise technical management, feeding and water quality monitoring (Fig. 19.11).

A two-stage grow-out system using a nursery phase as a quarantine area increases biosecurity. Indoor nursery systems increase turnover (number of grow-out production cycles) by reducing culture time to market size in grow-out ponds. Therefore, the grow-out pond is being used more efficiently as a biological system, and with greater capital and operating efficiency. A nursery system also provides improved accuracy to estimate the juvenile population before actual stocking in grow-out ponds. Thus, stocking juveniles allows for a more accurate estimate of the initial population and biomass, and improving feeding rate estimates when formulated feed becomes up to 60% of the production cost. Indoor, intensive nursery systems can further broaden the effective temperature, stocking windows for seasonal hatchery outputs, allowing greater efficiency for the hatchery and farm. Shrimp farms in areas of lower salinities can use the nursery as an acclimation system. Nursery head-start strategies may allow farms without hatcheries to purchase seedstock in advance of the peak demand periods, possibly at lower cost and with improved certainty of seedstock delivery.

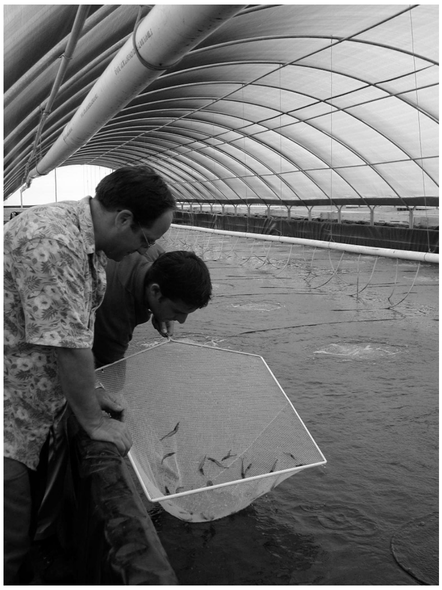

Fig. 19.11 An intensive nursery system culturing shrimp seedstock before transfer to ponds (photograph by OceanBoy Farms).

Managing nursery systems in tanks and raceways is relatively more difficult than standard grow-out ponds stocked directly, but the many benefits derived from a two-phase grow-out strategy, using first a nursery system (indoor) followed by final grow-out to market size (outdoor pond) can significantly improve production and profitability.

19.10.4 Inland shrimp production

Marine shrimp farms have traditionally been built in tropical coastal areas, very close to the ocean or to an estuary or river. Recently, shrimp farms have been built in other environments such as inland areas that, in principle, do not appear suitable for this activity. Some of these farms are located in inland deserts with available undergroundwater having specific chemical characteristics. They could provide a new direction for the expansion of the industry, because deserts and other dry lands constitute over 40% of the global land area.

Establishing shrimp farms far from the ocean using low-salinity waters has been successfully implemented with *P. monodon* in South-East Asia. The effluent can be used to irrigate various crops, thus minimising effluent disposal efforts. These emerging technologies offer opportunities to establish shrimp culture operations on marginal arid land or agricultural sites, reducing demand for shrimp farming on limited, high-cost coastal land. Limited seawater use during a relatively short acclimation phase and complete re-use of effluent water for irrigation of agricultural crops can provide for environmentally friendly integrated systems. *L. vannamei* is being successfully raised in low-salinity groundwater with varying ionic compositions and salt concentrations in several regions of the world, including the USA and Ecuador (McMahon *et al*., 2001).

Chapter 5 gives further examples of inland aquaculture in saline water and its integration with agriculture.

19.10.5 Recirculation and reduced water exchange systems

The shrimp farming industry can benefit significantly from improved water management regimes. In particular, these can help address viral disease problems and also issues raised by environmental groups that have targeted marine shrimp farming, pressuring the industry to adopt more sustainable production practices.

Large-scale application of zero-exchange and recirculation technologies on existing farms has already increased producer confidence in the potential for reducing or eliminating routine water exchange through most or all of the growing season. The Arroyo Aquaculture Association facility in southern Texas has been successful in recirculation and reduced water use so that the water required per kilogram of shrimp production has been reduced by 96%, from 37.6 m^3 to 1.5 m^3 (Hamper, 2000). It is interesting to consider that the ratio of water consumption to shrimp production was initially 37 600:1 in what was regarded as intensive culture at high stocking density. At a further stage, there are several successful examples of the implementation of zero-exchange production systems, including those in Belize, Panama and Florida (Fig. 19.4). In particular, McIntosh and co-workers at Belize Aquaculture Ltd have shown the tremendous potential these production systems have (section 19.3.4).

Browdy *et al*. (2001) recently reviewed various aspects of intensive closed technologies for shrimp production. Nutrient-rich effluents from intensive production systems can contribute to the eutrophication of receiving waters, potentially affecting both natural biota and local culture operations. Water exchange can be reduced or eliminated, and supplementary aeration can have an essential role in the successful operation of intensive closed systems. Paddlewheel aeration must be increased by 10% or more over levels traditionally applied in intensive culture to maintain appropriate DO levels. Better placement of mechanical aerators and use of back-up aeration and alarm systems are also necessary. Formulated feeds are the main nutrient input into shrimp production systems and, as water exchange is reduced or eliminated, feed formulations and feed management fast become critical factors as stocking densities increase. The design and management of production facilities to re-use water, minimise exchange and eliminate discharge will improve the outlook for more profitable and sustainable production technologies.

19.10.6 Effluents

General impacts of effluents from coastal aquaculture farms on marine environments are considered in section 4.2.1. This is an issue that shrimp producers and processors need to address while they are discharging effluents.

Settling basins are especially efficient for treating shrimp farm effluents because the high concentrations of cations in seawater and brackishwater tend to neutralise the negative charges on suspended clay particles, which will flocculate and settle. Plankton cannot be removed efficiently by sedimentation, and products such as aluminium sulphate, lime and selected organic colloids, often used in wastewater treatment to promote sedimentation, are not needed in shrimp farm settling basins.

According to Burford *et al*. (2001), the shrimp farming industry will face increasing pressure to develop new practices and technologies that more efficiently convert the N in shrimp feeds to shrimp biomass, and to minimise or eliminate residual N waste before effluent discharge into receiving waters. Meeting these goals will require an understanding of the fate and transformations of dietary N in shrimp production ponds and effluent treatment systems. These authors discussed the development of new technologies to reduce N waste from shrimp ponds, including improvements in feed formulations and feed management, genetic selection for improved FCR, improved in-pond processing of N, and improved design and management of effluent treatment systems (section 23.3.5).

19.11 Responsible shrimp farming and the challenge of sustainability

19.11.1 Domestication and genetic improvement

During its first three decades, commercial shrimp farming has depended significantly on wild seedstock and broodstock. Wild seed supply has often been unreliable and limited, and PL shortages have severely afflicted the industry. Many factors may affect broodstock and wild larvae supply, from global weather phenomena, such as El Niño and annual monsoons, to localised pollution and environmental degradation, and overfishing or over-regulation of fisheries.

Marine shrimp are promising candidates for domestication and genetic improvement, because of their high fecundity, short generation interval and the presence of additive effect of genetic variance for growth rate (Jory, 1996) (Fig. 19.12). When compared with most livestock industries, however, shrimp farming is still at an incipient stage of domestication and selective breeding. International discussion and collaboration in both conventional selective breeding techniques and the application of the tools of modern molecular biology are needed to promote global progress and efficiency of genetic improvements in the industry (Preston & Clifford, 2002).

The global survey of shrimp farming practices recently conducted by the Global Aquaculture Alliance showed the significant differences in progress in the genetic improvement of farmed shrimp between geographic regions and among the dominant farmed species. In the western hemisphere, the domestication and selective breeding of the dominant species (*L. vannamei* and *L. stylirostris*) have become a widespread practice with clearly demonstrated benefits. The benefits include improved production efficiency and a more reliable supply of seedstock, the results of selection of genotypes with improved tolerance to disease and faster growth rates. Domesticated lines of *L. vannamei* have been reared in captivity for > 15–30 generations in various countries. In the eastern hemisphere, progress in the domestication and selective breeding of the dominant farmed species, *P. monodon*, has been very slow. Significant advances have been made, however, in the domestication and selective breeding of species that are less commonly farmed there, including native species such as *M. japonicus*, and *F. chinensis*, and introduced western species such as *L. stylirostris* and *L. vannamei*.

Achieving domestication of selected shrimp species, together with selection, genetic improvement and, possibly, hybridisation and ploidy manipulation, should be major research objectives. An industry with the global importance that shrimp farming has achieved cannot depend on nature to supply its seedstock reliably.

19.11.2 Nutritional requirements and formulated feeds

The development and use of compound feeds have been major factors in the expansion of the industry and will continue gaining importance. Growing demand for formulated feeds will increase competition for component resources, particularly fish meal. There is an enormous but still unrealised potential to reduce the production cost and improve the nutritional performance of compound feeds for shrimp. Extensive research must continue to improve our knowledge of the nutritional requirements of shrimp and to develop new diets that are species, area and even season specific. These diets could include innovative processing methods, lower-cost ingredients, health additives and growth promoters that improve survival, growth, yield, FCR and disease resistance

Fig. 19.12 Genetically based variation in size among sibling *Penaeus monodon* postlarvae (photograph by Dr Nigel Preston).

while reducing environmental concerns. Reducing the cost of feeds is an aspect critical to further expanding the industry and improving its competitiveness relative to other protein sources, such as beef, pork and poultry. Low-pollution or 'environmentally friendly' feeds must be developed to reduce the environmental impacts of shrimp feeds. Currently, emphasis is on 'least cost' feed formulations for minimising feed cost while optimising aquaculture production. In the future, emphasis will also be on 'least polluting' feed formulations for minimising environmental impacts with the greatest compatible aquaculture production.

19.11.3 Disease prevention, diagnosis and control

As described earlier, there have been spectacular collapses of shrimp farming industries in a number of countries, including the top producing countries, China, Thailand, Indonesia, Taiwan and Ecuador. Standard denominators among the shrimp farming industries of these countries were very fast, unregulated development and an increased incidence of diseases, particularly viral diseases. There are no known treatments for viral infections, and the best procedure for disease management is exclusion (section 19.8.4). There will undoubtedly be new pathogens that the industry will have to confront and manage. Accurate and prompt diagnosis of infectious agents has to be a research priority (Jory, 1996, 1997).

The application of effective pathogen detection and disease diagnostic methods, particularly those based on molecular biology and recently developed by the industry (section 19.8.4), are essential to better understand and prevent losses due to disease. Much progress is evident in the last few years: there were only a few shrimp disease diagnostic laboratories a decade ago in the Americas, but there are many more serving the industry today.

19.11.4 Best management practices

The resolution of environmental and social conflicts can be accomplished through regulations, technical assistance, education and voluntary measures. Some local and regional governments are already exercising increased pressure in regulating the shrimp farming industry. For example, there are regulations governing water quality parameters in effluent waters from shrimp aquaculture operations in a number of areas, and these will become increasingly strict. On the other hand, because shrimp farming is such a young industry, there are inadequate regulations and guidelines in most countries. Most countries will take years before they can formulate and enforce reasonable shrimp farming regulations, so the industry needs to be proactive and voluntarily adopt measures of self-regulation.

Best management practices (BMPs) are a practical way to approach environment management for shrimp farming. They are practices considered the most effective methods of reducing environmental impacts, while being compatible with resource management goals. Producers may adopt them voluntarily to show environmental stewardship and reduce the urgency for governmental regulations. BMPs may also be the backbone of environmental management in activities whose effects are diffuse and located over large areas. The shrimp farming industry, by voluntarily preparing and adopting BMPs, is demonstrating environmental responsibility to reduce the need for future regulations, and to provide a basis for the form of future regulations. A system of BMPs, however, is typically needed to prevent a particular type of farming from causing negative impacts. Shrimp farming is conducted over a wide range of coastal environments, with significant differences in resource patterns, and physical, chemical and biological conditions, so a single system of BMPs for use in all situations is not possible. Systems of BMPs must be developed by country or by region, and the national or regional system must be customised for site-specific conditions on each farm. Where voluntary adoption of BMPs is used to improve environmental management, it is convenient to establish it as a Code of Practice. This document usually asserts the commitment of adherents to the code to use environmentally and socially responsible management, states the purpose of the code and provides a list of BMPs to be used by the industry. Codes of Practice for shrimp farming already exist in Australia, Belize, Thailand and some other countries, and shrimp farming organisations in several more countries are intent on producing their own Codes of Practice (Boyd, 1998).

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