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The Environmental Impact of Shrimp Aquaculture: Causes, Effects, and Mitigating Alternatives

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ABSTRACT / Attracted by the demand for shrimp in the developed countries, shrimp aquaculture has expanded rapidly, mainly in the subtropical and tropical lowlands of America and Asia. This work provides a global review and viewpoint on the environmental impacts of shrimp aquaculture, considering the causes and effects of the siting and operation of shrimp ponds and abandonment of farm facilities. Additionally, mitigating alternatives are discussed. To date, approximately 1–1.5 million ha of coastal lowlands have been converted into shrimp ponds, comprising mainly salt flats, mangrove areas, marshes, and agricultural lands. The impact of shrimp farming of most concern is the destruction of mangroves and salt marshes for pond construction. Compatibility with other users, the presence of buffer zones, maintaining an acceptable balance between mangroves and shrimp pond area, improved pond design, reduction of water exchange, and an improved residence time of water, size and capacity to assimilate effluents of the water body, are examples of ways to mitigate the adverse effects. The use of mangroves and halophytes as biofilters of shrimp pond effluents offers an attractive tool for reducing the impact in those regions where mangrove wetlands and appropriate conditions for halophyte plantations exist. Healthy seed supply, good feed with the use of prophylactic agents (including probiotics), good water quality, and lower stocking densities are examples of actions suggested to control disease in shrimp farming. Finally, in the context of integrated management, research priorities are suggested.

Attracted by the demand from North America, Europe, and Japan in the last two decades, large-scale shrimp farming has arisen. High profitability and the generation of foreign exchange have provided the major driving forces in the global expansion of shrimp culture (Primavera 1997). The expansion of this activity has occurred in the tropical and subtropical coastal lowlands and, as with other aquaculture practices, can compete for wet spaces in common with waste disposal from different important economic activities (industrial, agriculture, tourism, traditional fisheries) and rural development. Additionally, shrimp farming can degrade the environment, jeopardize the integrity of ecosystems, and compete for food and habitat with natural populations.

It is estimated that 1–1.5 million ha of coastal lowlands have been converted into shrimp farms, mainly in China, Thailand, India, Indonesia, Philippines, Malaysia, Ecuador, Mexico, Honduras, Panama, and Nicaragua (Figure 1) (Rosenberry 1998, FAO 1999). In some of these countries, the growth of the shrimp aquaculture industry has created various environmental impacts. These impacts have led to reductions in production, disease outbreaks, and implementation of regulations on aquaculture operations and the use of the coastal zone. This work examines the causes, effects, and possible mitigations related to environmental impacts during the siting, operation, and abandonment of shrimp farms. In addition, recommendations on research priorities are presented.

KEY WORDS: Shrimp aquaculture; environmental impact; mangroves; salt marshes; water quality; integrated management

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Global Production and Shrimp Cultured Species

Wild catches of shrimp from the world's oceans are estimated to have a maximum sustainable yield of 1.6–2.2 million metric tons, and future demands for shrimp apparently can only be satisfied through aquaculture production. In 1998, the world's shrimp farmers produced an estimated 840,200 metric tons of whole shrimp in an operating area of 999,350 ha (Figure 1). The Asian region produced the largest amount of cultured shrimp followed by Latin America (Rosenberry 1998, FAO 1999). From 1975 to 1985, the production of farmed shrimp increased 300%; from 1985 to 1995, 250%. If production were to increase by 200% in 1995–2005, the yield would be about 2.1 million tons in 2005

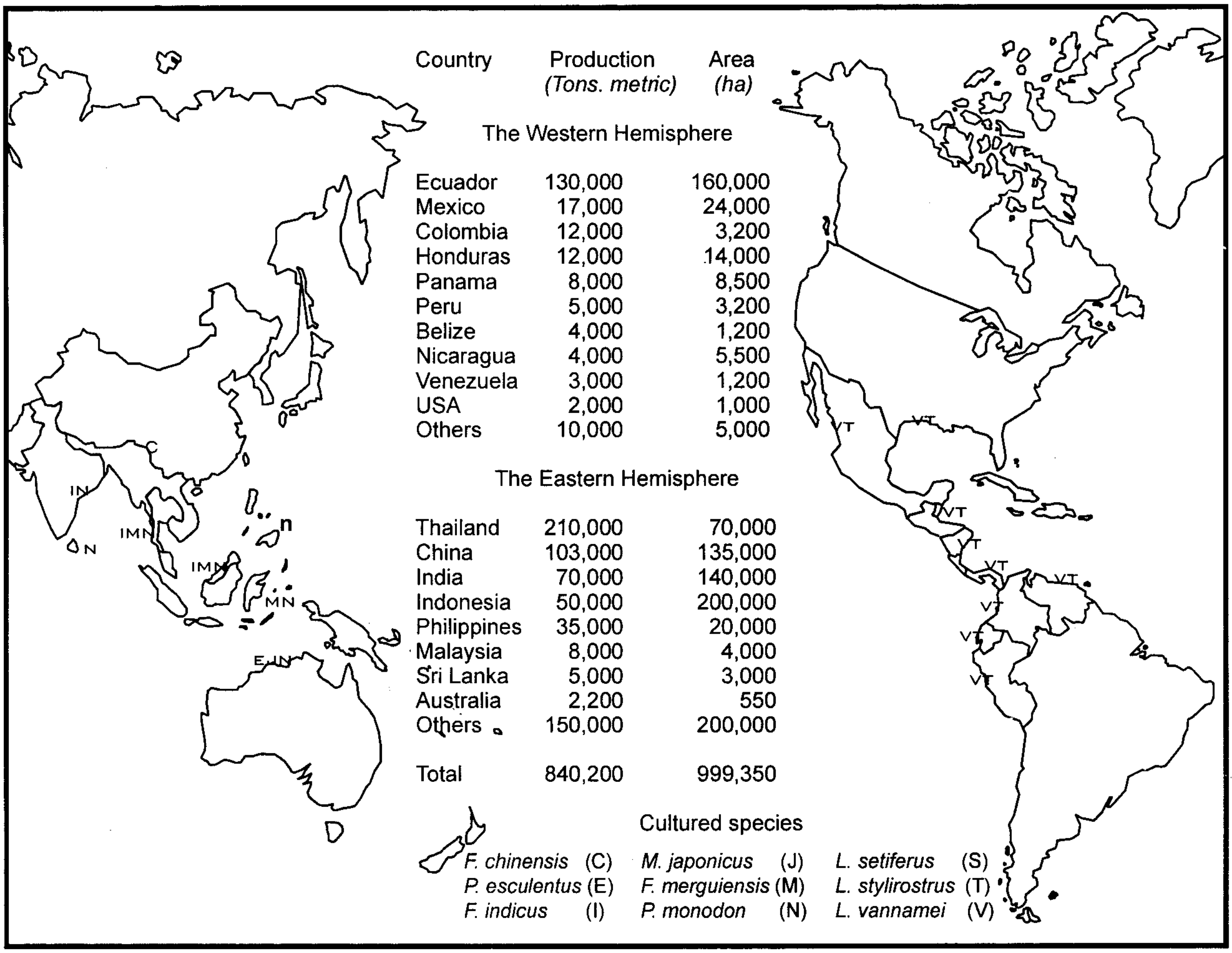

Figure 1. Shrimp species cultured and worldwide 1998 production by country (modified from Rosenberry 1998). Others countries in the Western Hemisphere include Argentina, Brazil, Canada, Costa Rica, and El Salvador. Others countries in the Eastern Hemisphere include Albania, Bangladesh, Guinea, Italy, Madagascar, Myanmar, New Caledonia, Saudi Arabia, Singapore, Vietnam and Yemen. In the case of China, production values are for 1997 (FAO 1999).

(Rosenberry 1998), an amount comparable to the production from the commercial shrimp fisheries.

Over 30 species of shrimp have been cultured in ponds. However, only a few species are of most importance in terms of large-scale commercial production (Figure 1). In Asia, five species comprise almost all of the cultured shrimp production. The giant tiger shrimp (*Penaeus monodon*) is the most attractive due to its large size and rapid growth. *Fenneropenaeus merguiensis* and *Fenneropenaeus indicus* together are the second most commonly cultured species in Asia. Other important species in the region are *Fenneropenaeus chinensis*, cultured in China, and *Marsupenaeus japonicus*, cultured in Japan, Taiwan, and China (Rosenberry 1998). In America, there are two commonly cultured species, *Litopenaeus vannamei* and *Litopenaeus stylirostris*, while the *Marsupenaeus japonicus* is grown in Brazil.

Causes, Effects, and Environmental Mitigation Related to Shrimp Aquaculture

Shrimp farming can generate environmental impacts as a function of: (1) The siting locations for shrimp pond construction; (2) the management and technology applied during the operation of shrimp ponds; (3) the size or scale of the production and the surface dedicated to it, and; (4) the capacity of the receiving waters. Independent of these factors, different environmental effects have been discussed in the literature (Primavera 1991, 1997, 1998, Chua 1992, Hopkins and others 1995,

Table 1. Causes, effects, and mitigating actions related to environmental impact of shrimp aquaculture

Cause	Effect	Mitigating action(s)
During siting of shrimp ponds		
Wetland destruction (mangroves and salt marshes)	Loss of habitats and nursery areas; coastal erosion; reduced biodiversity; reduced catch yields of commercially important species; acidification; and alteration of water drainage patterns	Siting in areas adequate considering the topography, tidal regimen, residence time of water, size of the water body and capacity to assimilate effluents; including buffer zones separating shrimp farms from each other; acceptable balance of mangroves and shrimp pond area and/or buffer ponds and shrimp pond area
Conversion of agricultural land (rice fields and orchards)	Saline soil production and alteration of water drainage pattern	Require socio-economic justification and consider the water drainage pattern
Conversion of salt-flats	Alteration of water drainage pattern	Consider the ecological role of these ecosystems and the water drainage pattern (?)[a]
During operation of shrimp ponds		
Wild fry bycatch	Decline in wild shrimp stocks and biodiversity; reduced catch yields of commercially important species	Hatchery postlarvae: definite specific areas and regulate wild fry bycatch
Discharge of shrimp pond effluents	Water quality deterioration in the receiving waters (oxygen depletion, light reduction, and changes in benthic macrofauna) eutrophication	Polycuture including fish, mollusks, mangroves, halophytes, Artemia; reduction of water or zero exchange rates; use of oxidation-sedimentation ponds; improving the delivering and composition of the feed
Escape of aquaculture stocks	"Biological pollution" of wild populations	Optimize management and include new technology
Release and spread of diseases	Disease outbreaks, infection in the wild populations	Good water quality and lower stocking densities; environmental control; high health seed and disease control (good feed with the use of prophylactic agents, including probiotics)
Discharge of chemical substances	Drug resistance among pathogens and unknown effects on nontarget organisms	Chemicals used should be safe; apply effective anti-bacterials and prevent discharge of effluents with toxic levels into adjacent water bodies
Salt water intrusion	Contamination of ground water aquifers	Avoid pumping of groundwater to shrimp ponds; reduce or avoid the use of fresh water; use pond liners.
Sediment disposal	Release of nutrients, organic matter and chemical substances	Use pond liners and probiotics; utilize sediment discarding areas; to spread the dry sediment back over the areas of the bottom pond; to collect shrimp pond sludge and use to mangrove planting
Excessive water use	Competition with other users for water (?)[a]	Reduced or zero exchange rate
Abandoned shrimp farms		
Shrimp pond abandoned	Competition with other users for space (?)[a]	Use to halophyte and/or restore to mangrove plantings; rehabilitate for shrimp ponds or to buffer ponds

[a](?) Is unknown or there is significant uncertainty.

Flaherty and Karnjanakesorn 1995, Stonich 1995, De Walt and others 1996, Dierberg and Kiattisimkul 1996, Beveridge and others 1997, Páez-Osuna and others 1998, 1999, Boyd and Clay 1998, Phillips 1998). Environment impacts of interest are related to cause and effect that occur relative to the siting and operation of shrimp ponds, and when the farms are abandoned (Table 1).

Wetland Destruction and Saltwater Intrusion

The coastal lowlands that have been converted into shrimp ponds (Figure 1) include mainly salt flats, marshes, mangrove areas, and agricultural lands. The most evident impact of and major concern for shrimp aquaculture is the destruction of mangroves and wetlands (inner lagoons and marshes) in the construction of shrimp ponds. Mangrove depletion is associated with shrimp aquaculture in Asia and Central America. Large areas of mangrove wetlands have been converted into milkfish and shrimp farms in the Philippines (205,523 ha) (Chua 1992) and Indonesia (211,000 ha) (Chua 1992). Similarly, 69,400 ha of lowlands have been converted into shrimp farms in Thailand (Dierberg and Kiattisimkul 1996), 102,000 ha in Vietnam (Primavera 1998), 6500 ha in Bangladesh (Primavera 1998), 21,600 ha in Ecuador (Alvarez and others 1989), and 11,515 ha in Honduras (Stonich 1995, De Walt and others 1996). Mangrove communities also have likely been converted to shrimp ponds in other nations, but there is no information available. However, of a total of 1–1.5 million ha dedicated around the world, it is now possible to estimate that 14%–43% of this surface was obtained from mangrove areas.

Although it is commonly argued that many commercial and noncommercial species use mangrove ecosystems as nursery grounds and shelter during early stages of their development, it is necessary to develop a full understanding on the role in this respect. The concerns, functions, and services of mangrove ecosystems have been established with reasonable certainty. In contrast, there has been discussion relative to low ecological value of tropical and subtropical marshes and salt flats, which have been conceived as coastal wastelands with low ecological and economic value (King and Lester 1995). This situation has led to considerable loss of marshes through land development or modification for use in agriculture, industrial developments, marinas, and shrimp farming. Few attempts have been made to value salt marshes in economic and ecological terms (King and Lester 1995). In areas susceptible to expansion of shrimp farms, it is urgent to identify and evaluate the ecological services of salt marshes, to consider their value adequately in the context of integrated coastal zone management (ICZM).

A common type of environmental impact associated with intensive shrimp culture is the seepage of brackish water from the culture ponds into groundwater supplies and adjacent rice paddy fields. In some locations in Thailand, it is indicated (Flaherty and Karnjanakesom 1995, Dierberg and Kiattisimkul 1996) that new shrimp pond construction occurs behind mangrove zones where freshwater wetlands and rice-growing areas are affected by surface and subsurface saltwater intrusion generated by pumping groundwater to the ponds. This can eventually lead to social costs, such as a reduction in domestic and agricultural water supplies, decreases in fish production, further marginalization of coastal fishermen, and displacement of labor (e.g., Bailey 1988, Primavera 1991). Another impact reported in certain localities in Asia related with the use of groundwater, has resulted in land subsidence. The alternative in these cases is simply to avoid pumping groundwater into shrimp ponds, and in critical cases of groundwater salinization to use a pond liner.

Shrimp Pond Effluents

There are some potential deleterious effects from shrimp pond effluents on the water quality of the estuarine/lagoon environments. They depend on various factors: (1) The magnitude of the discharge, (2) the chemical composition of the shrimp pond effluents (suspended solids, nutrients, organic matter), and (3) the characteristics of the receiving waters (e.g., dilution rate, residence time, and, receiving water quality).

Effluents from shrimp ponds are typically enriched in suspended solids, nutrients, and biochemical oxygen demand (BOD) (Table 2) with concentrations largely depending on whether the management is intensive or semiintensive (Páez-Osuna and others 1994, Sandifer and Hopkins 1996). Chemical characteristics of shrimp pond effluents have been evaluated in different shrimp culture systems (e.g., Phillips 1994, Briggs and Funge-Smith 1994, Páez-Osuna and others 1994, 1997, Rivera-Monroy and others 1999). When the range of concentrations of most water quality variables are compared, it is difficult to find differences between intensive and semiintensive shrimp effluents. In part, this is due to the fact that a significant portion of nutrients is accumulated in the sediments. In the case of nitrogen, a fraction is volatilized and another fraction is accumulated in the sediments (Páez-Osuna and others 1997). However, detailed studies have clearly shown that BOD, ammonia, chlorophyll *a*, and total suspended solids increase with stocking density (Tunvilai and others 1993, Robertson and Phillips 1995). While extensive shrimp ponds produce few wastes, semiintensive ponds produce intermediate waste loads. It is clear that the degree of intensification, i.e., higher stocking density, use of water, feeds and fertilizers, produces an increased waste load. With the exception of Thailand, where ca. 55% of the shrimp farms are managed intensively, the dominant system used worldwide is semiintensive (Rosenberry 1998). When effluents derived from agriculture, industry, and municipal areas are

Table 2. Range of water quality characteristics (mg/liter) of shrimp pond effluents with semiintensive and intensive management[a]

Water quality variable	Case 1 (semiintensive)	Case 2 (Intensive)	Case 3 (intensive)	Case 4 (intensive)	Case 5 (intensive)	Case 6 (intensive)
NO_2–N	<0.1	0.01–0.08	—	<0.1–0.10	0.5–1.3	<0.1
NO_3–N	<0.1	0.07–0.15	0.003–0.1	<0.04–0.3	3.9–9.8	<0.1–0.44
NH_3–N	0.1–0.53	0.98–7.87	0.03–1.02	<0.2–2.0	0.5–3.0	0.14–1.0
Total N	—	3.55–20.9	—	0.57–5.14	6.5–15.4	—
PO_4–P	<0.1–0.15	—	0.02–0.13	<0.1–0.09	0.6–2.2	<0.1–0.12
Total P	0.06–0.31	0.18–0.53	—	0.10–0.69	—	0.2–0.36
BOD	0.15–7.4	10.0–33.9	—	2.1–13.2	8.5–18.8	0.4–9.9
TSS	16–98	92–797	119–225	43–258	157–196	11–79
Chl*a*	3.8–58	70–460	20–250	<10–313	—	5–248

[a]Study cases 1 and 6, Páez-Osuna and others (1994); case 2, Tunvilai and others (1993); case 3, Robertson and Phillips (1995); case 4, Briggs and Funge-Smith (1994); and case 5, Hopkins and others (1993).

[b]Chl*a*: chlorophyll *a* in μg/liter.

combined, sources of good quality water are sometimes scarce. Similarly, when weather and tidal conditions (i.e., cloudy days, low winds, and neap tides) are combined temporally, the result is a serious and critical degradation of water quality in the shrimp ponds and the adjacent estuarine/lagoon waters. In some areas of northwestern Mexico, significant losses in shrimp yield have been described in connection with this combination of events, resulting in a massive mortality of shrimp caused by the anoxia that occurs during night and pre-dawn.

Several alternatives have been considered for resolving or mitigating the impact of shrimp pond effluents on water quality of adjacent coastal waters. The polyculture of bivalve mollusks, fish, and shrimp, using pond water to feed oysters, mussels, and seaweed in the effluent streams have been positively evaluated in various studies (e.g., Lin and others 1993, Sandifer and Hopkins 1996). Similarly, the potential use of shrimp farm effluents to irrigate salt tolerant crops has attracted attention. Glenn and others (1991) and Brown and others (1999) found that various plants in low salinities (*Salicornia bigelovii*, *Atrilplex*, *Distichlis*) and high salinities (*Suaeda esteroa*) remove nitrogen from shrimp effluents effectively. Brown and Glenn (1999) have estimated for shrimp farms that discharge water only at harvest, the water from 1-ha, could be used to irrigate 18 ha of halophytes for one week or 1 ha of halophytes for 18 weeks. The authors suggest that this interesting option would be more effective in areas where land is not a limiting resource or in areas where mangroves do not grow, such as salt flats. Similarly, they explain that a possible consequence of use of this halophyte technology is to produce hypersaline drainage water that could be used to grow *Artemia* or the salt-tolerant alga *Dunaliella*. Finally, excess water from these operations could be used to produce salt. Alternatively, Brown and Glenn (1999) explain that terrestrial halophytes could also be grown in conjunction with natural filters such as mangroves.

Improved pond designs (Dierberg and Kiattisimkul 1996, Sandifer and Hopkins 1996), construction of wastewater oxidation–sedimentation ponds, and a reduction of water exchange rates are also examples of actions to mitigate water quality deterioration. There is an increasing trend towards "zero discharge" or reduced water exchange systems (e.g., Hopkins and others 1993, Martínez-Cordova and others 1998). The use of such a system could reduce significantly the effluent load to adjacent waters. The treatment of the harvest discharge from intensive shrimp ponds by settling has been investigated recently by Teichert-Coddington and others (1999). They examined the shunting of the last 10%–20% of discharge through a settling pond with no more than 6 hours of residence time. This treatment removed 61% of settlable solids, 40% of total suspended solids, 12% of BOD, 7% of total N, and 14% of total P from the total pond.

Improving the method for feed supply (Páez-Osuna and others 1998) and nutrient composition of the feed (Avnimelech 1999) could be an effective strategy for lowering the load of nitrogen and phosphorus released into the environment. Development of a low protein, low pollution diet with higher nitrogen and phosphorus digestibility could reduce nutrient loads. Shishehchian and others (1999) examined ammonia and nitrite excretions by shrimp (*Penaeus monodon*) when fed different diets (artificial and natural). The experiment indicated that nitrogenous excretion was predominant in shrimps fed with artificial diets. Live food, such as algae and chironomids, despite a high protein content, contributes to low nitrogenous excretion and hence has less adverse effects on water quality compared to artificial diets.

Another alternative is to use mangrove wetlands as filters of pond effluents prior to their release into adjacent waters. Alongi and others (1992) and Boto (1992) have shown that mangroves are highly efficient in removing solids and nutrients from sewage or aquaculture effluents. Robertson and Phillips (1995) estimated that 2–3 ha of mangrove forest would be required for each hectare of pond, while for intensive ponds, up to 22 ha of *Rhizophora* forest might be required to process the N and P contained in pond wastes, depending on the pond management regime. The ratios of mangrove forest area to shrimp pond area on a regional scale have been proposed to produce the correct balance between areas dedicated to shrimp farming and mangrove ecosystems. Denitrification in mangrove sediments can potentially improve the environmental quality of shrimp pond effluents. Rivera-Monroy and others (1999) estimated that 0.04–0.12 ha of mangrove forest is required to completely remove the dissolved inorganic nitrogen load from effluents produced by a 1-ha semiintensive shrimp pond.

Evidently, the use of mangrove as filters for shrimp pond effluents constitutes an attractive tool for ameliorating the impact of shrimp pond effluents over those regions where mangrove wetlands occur. However, in those localities where mangroves have been eliminated and in the case of the subtropical dry coasts, where shrimp ponds are located in regions that do not coincide with the distribution of the mangrove areas, other alternatives should be considered. In this context, the case of the Red Sea farm constitutes a good example; it is presented (New-OBE 1999) as a third-generation shrimp farm. The Red Sea farm consists of circular ponds with central drainage, and is considered unique because from the total surface, only 108 of 220 total ha are actual rearing ponds. More than 50% of its water surface (represented by 50 ha of upstream buffer ponds and more than 60 ha of treatment ponds is for treating drainage water before discharging it into the sea) is dedicated to water quality control.

Release and Spread of Diseases

Diseases present the biggest obstacle to the future of shrimp farming. Farms and hatcheries are susceptible to the invasion of protozoa, fungi, and bacteria, but viral diseases provoke the greatest losses (Rosenberry 1998). Taiwan (1987–1988), China (1993–1994), Indonesia (1994–1995), and India (1994–1996), Ecuador (1993–1996), Honduras (1994–1997), and Mexico (1994–1997) have faced significant reductions in production because of different diseases, although they include varying degrees of intensification, different climates, and distinct cultured species. The common disease-promoting factors were rapid expansion and lack of environmental control for increased incidence of disease (Browdy and Hopkins 1995).

The discharge of pond effluent is one activity associated with environmental degradation of receiving waters. These same receiving waters often serve as intake water for neighboring farms and could provide the means to spread water-borne disease agents from farm to farm. Healthy seed supply, good feed supplemented with the use of prophylactic agents, including probiotics (Primavera 1998), good water quality, and lower stocking densities are examples of actions suggested to attain disease control in shrimp farming.

Chemical and Biological Products Used in Shrimp Aquaculture

The use of chemical substances in shrimp aquaculture is small in comparison with agriculture and other economic activities. However, various chemical and biological preparations are applied to pond sediment and water or incorporated in shrimp feeds. Based on their action, the products reported to be used in the shrimp farms can be classified into the following groups (Primavera and others 1993):

(1) Therapeutic and disinfectants (e.g., iodine, formalin, malachite green, oxytetracycline, chloramphenicol),
(2) water and sediment conditioners (e.g., lime zeolite),
(3) organic matter decomposers (bacteria and enzyme preparations),
(4) algicides and piscicides [e.g., copper compounds, teaseed (saponin)],
(5) phytoplankton growth promoters (inorganic and organic fertilizers), and
(6) feed additives (vitamins, minerals, and hormones).

The most common substances used in shrimp ponds are fertilizers and liming materials; other substances are used less frequently (Boyd and Massaut 1999). The results of a survey on intensive shrimp farms in the Philippines conducted by Primavera and others (1993) found that around 40 chemical and biological preparations were in use.

The increased use of antibiotics in intensive shrimp farming has raised concern about the possible effects of their release into adjacent habitats. From historical records, antibiotics are closely associated with intensive shrimp culture, both in the hatchery and the grow-out ponds (Phillips and others 1993). The main concern is related to the repeated and prolonged use of antibiotics that leads to the development of resistance among pathogens. Unfortunately, no information exists that details the effects on bacterial populations from the aquaculture facilities and the associated receiving waters.

Pond Sediment Disposal

Extensive shrimp farming produce little waste. With intensification, however, comes higher stocking densities and greater use of water, feeds, and fertilizers, which leads to increased waste production. This is reflected in the bottom sediments. Briggs and Funge-Smith (1994) have estimated that 31% (245 kg/ha/cycle) of nitrogen and 84% (243 kg/ha/cycle) of phosphorus wastes from intensively managed shrimp ponds are trapped in the sediments, while in semiintensive shrimp ponds <27.4% (<38.8 kg/ha/cycle) of nitrogen and 63.5% (17.6 kg/ha/cycle) of phosphorus have been measured (Páez-Osuna and others 1997).

The sediment that is accumulated in the shrimp ponds during each production cycle is eventually removed or allowed to oxidize after each harvest as a maintenance practice to obtain an acceptable water quality for the next production cycle. Dierberg and Kiattisimkul (1996) explain that this practice occurs in some places of Thailand and has led to water pollution, salinization of soils and water, and a solid waste disposal problem. To solve this, sediment discarding areas have been designated or, alternatively, the dry sediment is spread over the areas of the pond bottoms from which it was removed. This promotes the oxidation of the low organic matter content typically found in pond bottom sediments (Boyd and others 1994). Another interesting mitigating option is the collection and use of sediment for mangrove reforestation (Primavera 1998).

Capture of Wild Postlarvae and Wild Shrimp Stocks

The capture of wild penaeid postlarvae to stock shrimp ponds is another critical point of shrimp farming. Although hatchery postlarvae are now available in many regions, wild fry still provide the major source of seed in many localities (Primavera 1998). The problem is that during collection of the wild fry of interest, other organisms such as shrimp fry, fish fry, and zooplankton are also caught and discarded. In Honduras, for example, the collection of 3.3 billion larvae of *L. vannamei* and *L. stylirostris* destroys 15–20 billion fry of other species (DeWalt and others 1996). Mortality of shrimp fry bycatch, loss of mangrove ecosystems, and genetic degradation of native populations may all contribute to a decline in biodiversity (Primavera 1998). The alternative in these regions is to regulate wild fry bycatch by establishing suitable sites, periods, and catch effort and stimulating the use of hatchery postlarvae.

Some indicators suggest that the practice of wild postlarvae capture has significantly reduced the abundance of penaeid species in the shrimp fisheries of the affected regions, provoking the inverse production effect. This effect may be defined as the conversion of wild shrimp to farm shrimp and occurs when the wild shrimp catch decreases while the catch of shrimp farm production increases. Examples of this have been reported in the Philippines (Primavera 1997) and Thailand (Dierberg and Kiattisimkul 1996). Regional data in NW Mexico already show a similar pattern (Anonymous 1995) evidencing the inverse production effect. Another factor connected with such effect is a mangrove destruction or conversion of mangrove wetlands into shrimp ponds or for other uses. As previously explained, numerous authors (e.g., Dierberg and Kiattisimkul 1996, Primavera 1998) have shown that mangrove ecosystems have several valuable functions and services, including the provision of nursery grounds for crustaceans in early stages.

Abandoned Shrimp Ponds

Continual expansion of the shrimp industry usually results in catastrophic collapses, primarily caused by viral and bacterial diseases, throughout extensive regions (Phillips and others 1993). The average lifetime of a shrimp pond is variable depending on various factors (management, water quality, and sediment characteristics) but a viability of 7–15 years has been estimated, considering improved management (Flaherty and Karnjakesom 1995). However, abandonment of ponds is common in some localities. In Thailand, the extent of abandoned ponds was 4500–16,000 ha (MIDA Agronomics 1995 in Dierberg and Kiattisimkul 1996).

The restoration of abandoned shrimp ponds is complicated because many of the environmental conditions that originally fostered the growth of mangroves have been altered. Drainage patterns have been interrupted and the ability of the substratum to support vegetation has been destroyed (Flaherty and Karnjakesom 1995). Rehabilitation of abandoned ponds is also complicated. The alternatives for use are to convert to salt ponds, culture of other species (shellfish and crabs), and to restore the ponds for halophyte and/or mangrove plantings.

Sustainable Shrimp Aquaculture

There is a consensus among the researchers who have examined shrimp aquaculture in different nations that sustainable shrimp aquaculture development may be attainable with coastal aquaculture practices that are environmentally nondegrading, technically appropriate, economically viable, and socially acceptable. Two relevant problems have been recognized by the shrimp industry (Rosenberry 1998): the diseases that have caused significant declines in the total production of farm-raised shrimp, and militant attacks from environmentalists. To meet the concerns of the latter, the Global Aquaculture Alliance (GAA) has emerged. This organization promotes aquaculture products and encourages sustainable, environmentally friendly production systems. The GAA has developed a series of management recommendations based on the guidelines for responsible aquaculture formulated by the Food and Agriculture Organization (FAO).

It is recognized that shrimp farming is not always harmful to the environment (Boyd and Clay 1978). Undoubtedly, shrimp farming is having significant benefits in environmental and socioeconomic terms. The shrimp industry has been recognized as an alternative that will supplement fishery production, generating various types of job opportunities for the rural people. However, due to poor planning and management by shrimp farmers, as well as inadequate application or nonexistent regulations, numerous examples of decline in production and of environmental impacts have occurred around the world. The perception is that shrimp farming is clearly less destructive to the environment than other economic activities such as intensive agriculture, industry, or tourism, but it is important and urgent to consider the implementation of ICZM to prevent adverse effects in vulnerable coastal waters and the spread of diseases to wild fauna and man. For the creation and effective implementation of ICZM, it is necessary to deal with five impediments commonly present in undeveloped or developing nations: lack of recognition of the issues, poor coordination among sectors, administrative discontinuity and inefficiency, diversion of resources, and inadequate information.

Growing concern about environmental deterioration derived from all uses of the coastal zone has led to recognition of the need for an ICZM (Black and others 1997, Beveridge and others 1997). In this context, it is necessary to implement an accessible methodology for users and related personnel where ICZM is focused and to achieve a balance between protection of valuable ecosystems and the development of coast-dependent economies (agriculture, industry, shrimp aquaculture, tourism). Scientific criteria play a key role in defining those coastal habitats that should be protected and in establishing an optimum balance for the use of natural resources. Unfortunately, the incorporation of qualified experts in most areas where shrimp industry expansion is now present is difficult because of their scarce availability and/or simply because of the lack of knowledge of the farmers, people, and the authorities.

Conclusions and Research Needs

1. The general conclusion that may be drawn from this study is that although significant advances have been made recently, these advances are still not sufficient regarding the siting, operation, and abandonment of shrimp farms.

2. Sound scientific information on different potential adverse impacts of shrimp aquaculture on the environment remains scarce. However, the concerns expressed by different sectors, even of a speculative character, indicate the need for more investigation. It is necessary to implement appropriate studies to discover and evaluate the magnitude of any impacts.

3. It is crucial to recognize the potential conflicts between shrimp aquaculture (i.e., competition for wet spaces, conflict over waste spaces with traditional fisheries, recreation, and rural development) and implementation of an effective resource management regime.

4. There is still a lack of understanding on the functioning of ecosystems involved in the shrimp industry in aspects related to perturbation. It is necessary to evaluate the assimilative capacity of nutrient and organic matter additions into the estuaries and lagoons of tropical and subtropical environments that receive shrimp pond effluents.

5. The relationship between mangroves and coastal fisheries is complex and not sufficiently known. There is a need for research and validation of the mangrove–offshore fisheries connection and a need to refine and complement the valuation of mangroves.

6. Regarding mangrove ecosystems, some of the functions and services have been established with reasonable certainty. In contrast, marshes and salt flats have typically and speculatively been seen as having low ecological value. It is necessary to identify and evaluate their ecological services in the context of ICZM.

7. Although important and interesting advances have been made in the management of saline aquaculture effluent through the production of halophyte crops, it is recognized (Brown and Glenn 1999) that more research in integrating the production of halophytes with marine aquaculture production is needed. Similarly, the future use of halophytes as biofilters of the effluents of marine aquaculture operations depends on whether the resulting crops have an economic value.

8. To alleviate the problem of water quality deterioration in the adjacent coastal waters, the siting of shrimp farms in adequate areas (e.g., waterbodies with good tidal flows and dilution rates, compatible with other economic activities, and with an acceptable balance of mangroves and shrimp pond area) should be considered. The factors involved in defining adequate areas need to be refined.

9. Although the use of chemical substances in shrimp aquaculture is small in comparison with other economic activities, the increased application of antibiotics in intensive shrimp farming has brought concern about the possible effects of their release into adjacent habitats. It is necessary to investigate the effects of these on nontarget organisms (cultured species, human consumers, and wild biota) with field and laboratory studies.

10. A serious decline in production has occurred in countries where shrimp farming expansion has been moderate/rapid. The cause may be related to the introduction of infected postlarvae from other regions; however, it is necessary to investigate the spreading mechanisms of diseases. Additionally, poor water quality has been repeatedly connected with the presence of diseases. However, the magnitude of chemical components and their variation are not sufficiently known.

11. Various questions on the fate of sediment disposal are emerging. It is necessary to investigate the fate and impact of nitrogen, phosphorus, and other chemical substances during and after of these practices.

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Literature Cited

Alongi, D. M., K. G. Boto, and A. I. Robertson. 1992. Nitrogen and phosphorus cycles. Pages 251–292 *in* A. I. Robertson and D. M. Alongi (eds.), Tropical mangrove ecosystems. American Geophysical Union Press, Washington, DC.

Alvarez, A., B. Vazconez, and L. Guerrero. 1989. Multi-temporal study of mangrove, shrimp farm and salt flat areas in the coastal zone of Ecuador, through information provided by remote sensing. Pages 141–146 *in* S. Olsen and L. Arriaga. (eds.), Establishing a sustainable shrimp mariculture industry in Ecuador. The University of Rhode Island Coastal Resources Center, Providence; Ministerio de Energía y Minas, Ecuador; and US Agency for International Development, Narragansett, RI.

Anonymous. 1995. Pesca y Acuacultura del Estado de Sinaloa en Cifras. Secretaría de Medio Ambiente, Recursos Naturales y Pesca, Delegación Federal de Pesca en el Estado de Sinaloa, Mazatlán, Sinaloa, 42 pp. (in Spanish).

Avnimelech, Y. 1999. Carbon/nitrogen ratio as a control element in aquaculture systems. *Aquaculture* 176:227–235.

Bailey, C. 1988. The social consequences of tropical shrimp mariculture development. *Ocean and Shoreline Management* 11:31–44.

Beveridge, M. C. M., M. J. Phillips, and D. J. Macintosh. 1997. Aquaculture and the environment: the supply of and demand for environmental goods and services by Asian aquaculture and the implications for sustainability. *Aquaculture Research* 28:797–807.

Black, E., R. Gowen, H. Rosenthal, E. Roth, D. Stechg, and F. J. R. Taylor. 1997. The costs of eutrophication from salmon farming: Implications for policy—a comment. *Journal of Environment Management* 50:105–109.

Boto, K. G. 1992. Nutrients and mangroves. Pages 138–145 *in* D. W. Connell and D. W. Hawker (eds.), Pollution in tropical aquatic systems. CRC Press, Boca Raton, Florida.

Boyd, C. E., and J. W. Clay. 1998. Shrimp aquaculture and the environment. *Scientific American* 278:58–65.

Boyd, C. E., and L. Massaut. 1999. Risks associated with the use of chemicals in pond aquaculture. *Aquacultural Engineering* 20:113–132.

Boyd, C. E., P., Munsiri, and B. F. Hajek. 1994. Composition of sediment from intensive shrimp ponds in Thailand. *World Aquaculture* 25:53–55.

Briggs, M. R. P. and S. J. Funge-Smith. 1994. A nutrient budget of some intensive marine shrimp ponds in thailand. *Aquaculture and Fisheries Management* 25:789–811.

Browdy, C. L., and J. S. Hopkins. 1995. Swimming through troubled water. Pages 251 *in* Proceedings of the special session on shrimp farming. 1–4 February 1995. San Diego, California.

Brown, J. J., and E. P. Glenn. 1999. Management of saline aquaculture effluent through the production of halophyte crops. *World Aquaculture* 30:44–49.

Brown, J. J., E. P. Glenn, K. M, Fitzsimmons, and S. Smith. 1999. Halophytes for the treatment of saline aquaculture effluent. *Aquaculture* 175:255–268.

Chua, T. E. 1992. Coastal aquaculture development and the environment, the role of coastal area management. *Marine Pollution Bulletin* 25:98–103.

DeWalt, B. R., P. Vergne, and M. Hardin. 1996. Shrimp aquaculture development and the environment: People, mangroves and fisheries on the Gulf of Fonseca, Honduras. *World Development* 24:1193–1208.

Dierberg, F. E., and W. Kiattisimkul. 1996. Issues, impacts, and implications of shrimp aquaculture in Thailand. *Environmental Management* 20:649–666.

Food and Agriculture Organization. 1999. Aquaculture production statistics 1988–1997. Fisheries Circular no. 815 Rev. 11. FAO, Rome, 203 pp.

Flaherty, M., and C. Karnjanakesorn. 1995. Marine shrimp aquaculture and natural resource degradation in Thailand. *Environmental Management* 19:27–37.

Glenn, E. P., J. W. O'Leary, M. C. Watson, T. L., Thomas, and R. O., Kuehl. 1991. *Salicornia bigelovii* Torr: An oilseed halophyte for seawater irrigation. *Science* 251:1065–1067.

Hopkins, J. S., R. D. Hamilton, P. A. Sandifer, C. L. Browdy, and A. D. Stokes. 1993. Effect of water exchange rate on production water quality, effluent characteristics and nitrogen budgets of intensive shrimp ponds. *Journal of the World Aquaculture Society* 24:303–320.

Hopkins, J. S., P. A. Sandifer, M. R. DeVoe, A. F. Holland, C. L. Browdy, and A. D. Stokes. 1995. Environmental impacts of shrimp farming with special reference to the situation in the continental United States. *Estuaries* 18:25–42.

King, S. E., and J. N. Lester. 1995. The value of salt marsh as a Sea defence. *Marine Pollution Bulletin* 30:180–189.

Lin, C. K., P. Ruamthaveesub, and P. Wanuchsoontorn. 1993. Integrated culture of green mussel (*Perna viridis*) in wastewater from an intensive shrimp pond: concept and practice. *World Aquaculture* 44:187–200.

Martínez-Cordova, L. R., M. A. Porchas-Cornejo, H. Villareal-Colmenares, J. A. Calderón-Perez, and J. E. Naranjo-Paramo. 1998. Evaluation of three feeding strategies on the culture of white shrimp *Penaeus vannamei* Boone 1931 in low water exchange ponds. *Aquacultural Engineering* 17:21–28.

New-OBE, M. B. 1999. Sustainable shrimp farming in the dry tropics: Third generation shrimp farming technology. *World Aquaculture* 30:34–43.

Páez-Osuna, F., M. Hendrickx-Reners, and R. Cortés-Altamirano. 1994. Efecto de la calidad del agua y composición biológica sobre la producción en granjas camaronícolas. Informe final CONACYT proyecto 0625-N9110. 445 pp. (in Spanish).

Páez-Osuna, F., S. R. Guerrero-Galván, A. C. Ruiz-Fernández, and R. Espinoza-Angulo. 1997. Fluxes and mass balances of nutrients in a semi-intensive shrimp farm in north-western Mexico. *Marine Pollution Bulletin* 34:290–297.

Páez-Osuna, F., S. R. Guerrero-Galván, and A. C. Ruiz-Fernández. 1998. The environmental impact of shrimp aquaculture and the coastal pollution in Mexico. *Marine Pollution Bulletin* 36:65–75.

Páez-Osuna, F., S. R. Guerrero-Galván, and A. C. Ruiz-Fernández. 1999. Discharge of nutrients from shrimp farming to coastal waters of the Gulf of California. *Marine Pollution Bulletin* 38:585–592.

Phillips, M. J. 1994. Aquaculture and the environment-striking a balance. Pages 29–31 *in* Proceedings of Infofish Aquatech 94, 29–31 August 1994, Colombo, Sri Lanka.

Phillips, M. J. 1998. Tropical mariculture and coastal environmental integrity. Pages 17–69 *in* S. S. De Silva (ed.), Tropical mariculture. Academic Press, London.

Phillips, M. J., K. C. Lin, and M. C. M. Beveridge. 1993. Shrimp culture and the environment: Lessons from the world's most rapidly expanding warmwater aquaculture sector. Pages 171–197 *in* R. S. V. Pullin, H. Rosenthal, and J. L. Maclean (eds.), Environment and aquaculture in developing countries. ICLARM, Manila, Philippines.

Primavera, J. H. 1991. Intensive prawn farming in the Philippines: ecological, social and economic implications. *Ambio* 20:28–33.

Primavera, J. H. 1997. Socio-economic impacts of shrimp culture. *Aquaculture Research* 28:815–827.

Primavera, J. H. 1998. Tropical shrimp farming and its sustainability. Pages 257–289 *in* S. DeSilva (ed.), Tropical mariculture. Academic Press, London.

Primavera, J. H., C. R. Lavilla-Pitogo, J. M. Ladja, and M. R. De la Peña. 1993. A survey of chemical and biological products used in intensive prawn farms in the Philippines. *Marine Pollution Bulletin* 26:35–40.

Rivera-Monroy, V. H., L. A. Torres, N. Bahamon, F. Newmark, and R. R. Twilley. 1999. The potential use of mangrove forests as nitrogen sinks of shrimp aquaculture pond effluents: The role of denitrification. *Journal of the World Aquaculture Society* 30:12–25.

Robertson, A. I., and M. J. Phillips. 1995. Mangroves as filters of shrimp pond effluent: Predictions and biochemical research needs. *Hydrobiologia* 295:649–666.

Rosenberry, B. 1998. World shrimp farming. Shrimp News International, San Diego, California, 328 pp.

Sandifer, P. A., and J. S. Hopkins. 1996. Conceptual design of a sustainable pond-based shrimp culture system. *Aquacultural Engineering* 15:41–52.

Shishehchian, F., F. M. Yusoff, H, Omar, and M. S. Kamarudin 1999. Nitrogenous excretion of Penaeus monodon postlarvae fed with different diets. *Marine Pollution Bulletin* 39:224–227.

Stonich, S. C. 1995. The environmental quality and social justice implications of shrimp mariculture development in Honduras. *Human Ecology* 22:143–168.

Teichert-Coddington, D. R., D. B. Rouse, A. Patts, and C. E. Boyd. 1999. Treatment of harvest discharge from intensive shrimp ponds by settling. *Aquacultural Engineering* 19:147–161.

Tunvilai, D., P. Songsanginda, and K. Chaiyakaj. 1993. Pollution loading of effluent from intensive tiger shrimp culture ponds. Technical paper 4/1993. National Institute of Coastal Aquaculture. Department of Fisheries. Kao Saen, Muang District, Songkhla, Thailand, 79 pp. (in Thai with English abstract).