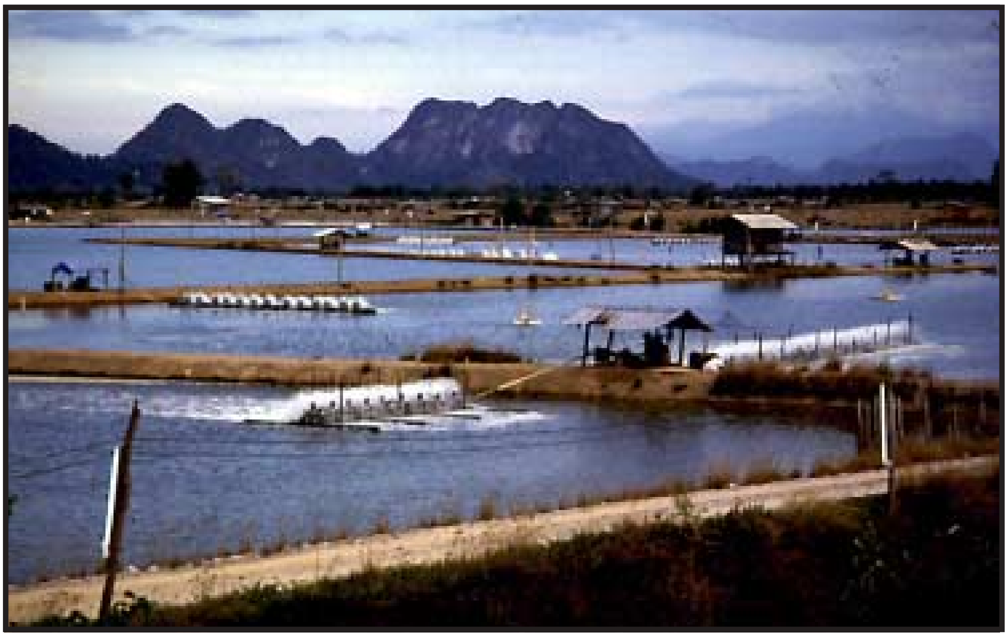
Patrik Rönnbäck

Shrimp aquaculture

State of the art



Report 1

Swedish EIA Centre
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The Swedish EIA Centre

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The report

This report is produced as a special task given to Patrik Rönnbäck, PR Konsult. The opinion presented in the report is the author's own and does not necessary represent the opinion of the EIA Centre or Sida.

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EXECUTIVE SUMMARY

In Asia, penaeid shrimps have for centuries been grown in traditional systems, with low productivity aimed for domestic markets. Export-oriented shrimp aquaculture is a fairly recent industry that took off in the mid 1970s. With improved technologies and the introduction of formulated feeds, the industry boomed in the following decade. In 1975, the shrimp aquaculture industry contributed to 2.5% of total shrimp production, which gradually increased to around 30% in the 1990s. Today shrimp farming makes up only 3-4% of global aquaculture production by weight, but almost 15% by value. Around 80 percent of cultured shrimp come from Asia with Thailand, China, Indonesia and India as the top producers. In the Western hemisphere, Ecuador is the major shrimp-producing country. The giant tiger shrimp – *Penaeus monodon* – accounts for more than half of the total shrimp aquaculture output. Other important commercial species are *P. vannamei, P. indicus, P. merguiensis* and *P. chinensis*.

The commercialisation of shrimp culture has been driven by lucrative profits from export markets and fuelled by governmental support, private sector investment, and external assistance. Despite the negative socio-economics impacts of modern shrimp aquaculture on the livelihoods of coastal communities, many bi-lateral and multi-lateral agencies have supported the development of this industry with large loans.

There are five different shrimp aquaculture practices, ranging from traditional to ultra-intensive techniques, but the most common techniques are extensive, semi-intensive, and intensive. These three categories are divided, according to their stocking densities, and the extent of management over grow-out parameters, i.e., level of inputs. The farmers that exercise extensive methods rely on cheap land and labour, naturally occurring seed stock and feeds, and the lack of regulations which allows the conversion of coastal lands to shrimp ponds. Few input are required so producers can relatively easy enter the industry. Semi-intensive and intensive farming practices require the aquaculturist to implement more control over the environment. Greater capital inputs, control of many grow-out parameters, and technical skills are needed. The potential annual shrimp production (ton per hectare) from these systems are: 0.6-1.5 for extensive; 2-6 for semi-intensive; and 7-15 for intensive. The actual productivity is, however, much lower due to low quality intake water, variable weather conditions, and especially disease problems. In 1999, the global average production was 650 kg shrimps per hectare pond, although most of the production was generated by semi-intensive practices.

Shrimp fishery as well as culture practices are both fraught with environmental problems. For example, the discarded bycatch from shrimp fisheries alone comprise more than half of the total bycatch from all the world's fisheries combined, and consequently shrimp trawling have major impacts on ocean biodiversity and food web interactions. Environmental impacts of shrimp aquaculture arise from: (i) the consumption of resources, such as land, water, seed and feed; (ii) their transformation into products valued by society; and (iii) the subsequent release into the environment of wastes. The direct impacts include release of eutrophicating substances and toxic chemicals, the transfer of diseases and parasites to wild stock, and the introduction of exotic and genetic material into the environment. The environmental impact can also be indirect through the loss of habitat and niche space, and changes in food webs. The deforestation of mangroves to accommodate shrimp ponds is perhaps the most alarming single environmental damage. More than 50% of the world's mangroves have been removed, and the establishment of shrimp ponds has been a major cause behind this loss in many countries. As a paradox, the productivity and sustainability of shrimp aquaculture is directly dependent on the continuos support of mangrove goods like seed and spawners as well as services like water quality maintenance and erosion control.

The rapid expansion of shrimp aquaculture has also created severe social and economic problems for coastal communities. Shrimp aquaculture often utilises common property resources such as mangroves and water. These common property resources contribute greatly to social equity, since net monetary benefits are distributed to large groups of politically and economically marginal people. However, the development of aquaculture ponds transforms mangroves into a single-use private resource, and the opportunity for redistribution of benefits becomes limited. As a consequence, shrimp farming has brought about social displacement and marginalisation of fishermen and agriculturists. The development of shrimp farms also has an impact on local food insecurity coupled to decreased agricultural production, depletion of drinking water, loss of mangrove forest goods, lowered fisheries catch, etc.

Shrimp aquaculture has exhibited a boom-and-bust pattern in many countries, ever since 1988 when the industry first collapsed in Taiwan due to disease problems. Other top-producing countries, like, e.g., Thailand, China, Indonesia and Ecuador, have also experienced a rapid expansion of shrimp farms that collapse within 5-10 years of operation. Diseases that once were restricted to one region are now rapidly spreading over the world as a result of the expansion and globalisation of the shrimp industry. Disease problems have, however, not caused world shrimp production to decrease, simply because of a sequential exploitation pattern, where new shrimp farms are developed at a higher rate than farms are abandoned or left idle.

Deficient environmental management of shrimp farms is the most important underlying determinant to disease outbreaks. The risk of disease problems increases with intensity of farming and farm density in a given area. Wide-scale abandonment of ponds is often due to the proliferation of initially successful farms that ultimately overwhelm the carrying capacity of the environment. The ecological footprint concept is one tool that can indicate the spatial development limitations for shrimp aquaculture. For example, intensive shrimp farms require a mangrove cover – ecological footprint – at least 22 times larger than the pond area to filter the loading of nitrogen and phosphorous.

There are many recommendations on how to make shrimp aquaculture environmentally and socio-economically sustainable. The prevention of disease outbreaks is a critical issue that will improve the financial viability of the shrimp industry as well as reduce many of the environmental and socio-economic concerns. Longer lifetime of individual shrimp ponds would reduce the relative proportion of abandoned and idle ponds, and consequently the boom-and-bust pattern with sequential land exploitation is hampered. The worldwide transfer of shrimps that are potential disease carriers would be reduced if hatcheries could “close” the shrimp’s life cycle and produce their own spawners. As a positive side effect the magnitude of the bycatch problem associated with wild-caught postlarvae, broodstock and spawners is reduced. Many approaches to combat disease also focus on improved pond and water management aimed at ameliorating the impact of shrimp pond effluents on the water quality of the recipient.

Making the proper choice of sites for the ponds is one of the easiest and best ways for shrimp farmers to limit environmental damage and to improve the lifetime of their ponds. There is no defence for large-scale conversion of mangroves to accommodate shrimp ponds. First, mangrove soils are not suitable for aquaculture purposes. Secondly, the opportunity cost of converting mangroves is very high in terms of (i) the substantial natural production of fish and shellfish supported by this system, and (ii) the impacts on the livelihood of coastal communities dependent on mangrove goods and services. Shrimp farmers must also be trained to acknowledge the importance of viable mangrove ecosystems for sustainable shrimp aquaculture production. Mangrove restoration programs should be initiated in areas where shrimp aquaculture development has caused significant damage to this ecosystem. The rehabilitation of mangroves in abandoned shrimp farms should receive high priority.

There are two types of shrimp aquaculture production systems that may be sustainable: (i) extensive, integrated systems that have been practised for hundreds of years in some cases; and (ii) intensive, ”closed” hatchery and grow-out systems that enables the farmer to better control the farming environment. The extensive, integrated systems would rank high in terms of socio-economic sustainability, because they are usually small-scale, labour-intensive businesses owned by local people. The crop diversification in integrated systems also provides an insurance against production failures. The major drawback is that these systems usually involve some mangrove conversion, although their impact on lost mangrove goods and services has to be further assessed. In addition, the productivity per unit area can never compete with that of more intensive systems not affected by disease, and consequently large coastal areas would be required to supply the international shrimp demand.

The re-circulation of water in “closed” systems reduces the amount of wastes discharged and provides an opportunity to locate the ponds away from coastal areas. Although the inland location of ponds spares mangroves, it creates new land and water management conflicts. The environmental impacts of specific concern relates to the salinisation of soil and water, water pollution caused by pond effluents, and the competition between agriculture and aquaculture for fresh water supply. The potential to generate employment opportunities for local people is limited in these “closed” systems. Rather, these capital-intensive systems require high level of skilled management, which is usually reserved for outsiders. An advantage with “closed” practices is the potential to relocate shrimp farms to industrialised countries, where the larger part of the market is and where the price would better reflect the external production costs.

The formulation of policies directed to assure the sustainability of an economic activity like shrimp aquaculture should involve many different actors, and include consumers, aquaculture entrepreneurs, local communities and government representatives. Governments and financial institutions that support shrimp aquaculture development have to place conditions on the use of former common property resources by the industry. These conditions must secure that local people, instead of being displaced and marginalised, gain access to employment as well as become equity holders of the enterprise. Economic incentives and disincentives can also be effective in inducing behavioural changes towards the environment and generate revenues to finance environmental and social policy programmes. Governments should withdraw misdirected subsidies and tax breaks, or at least require environmental planning and performance as preconditions to the approval of loans, credits, subsidies, etc. Efforts must also be made to train aid agencies and international financial institutions, with the ambition to direct their support towards sustainable coastal seafood production systems.

Shrimp aquaculture will never be able to provide a net input to global seafood production. Today, 2 times more protein, in the form of fishmeal, is used to feed the shrimps than is ultimately harvested. Furthermore, shrimp aquaculture also reduces wild fish supplies through habitat modifications, discarded bycatch in fisheries for shrimp postlarvae, and other ecological impacts. The development of more efficient feeding techniques and formulation of feeds that contain less fishmeal will most likely lower the amount of fish meal protein needed to produce a given amount of shrimp, although shrimp aquaculture will still continue to constitute a net loss to global seafood production. New initiatives by governments and donor agencies are needed to further encourage farming of low trophic level fish with herbivorous diets. Instead of favouring the rapid expansion of high-valued carnivorous species like shrimps and salmon, the focus should be on species like carps, tilapia, catfish, milkfish and molluscs, which have great potential to live up to the promises of the Blue Revolution.

Patrik Rönnbäck at PR Miljökonsult was contracted as consultant for the delivery of a state of the art report on shrimp aquaculture. As a Systems Ecologist, the author has conducted research on the Ecological Economics of coastal fisheries and shrimp aquaculture in Asia and Africa. The report is a desk study, using available, up to date information on penaeid shrimp farming. The basis for the report is an extensive literature review, but for the sake of readability only the most relevant literature has been cited in the report. Furthermore, a number of key informants in developing as well as industrialised countries have been contacted to gain access to the latest information for certain aspects.

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1. INTRODUCTION TO SHRIMP AQUACULTURE

1.1. Background

Capture fisheries landings have plateaued at around 85-95 million tonnes (FAO, 1999a), and most ocean fisheries stocks are now recognised as over or fully exploited (NRC, 1999). This fact, together with ever increasing population growth, has provided impetus for rapid growth in fish and shellfish farming, or aquaculture. Global aquaculture production more than doubled in weight and value between 1986 and 1996, and it currently accounts for more than 25% of all fish consumed by humans (FAO, 1999b). Aquaculture, which is sometimes referred to as the Blue Revolution, is in many ways analogous to the Green Revolution in modern agriculture. As the Green Revolution was acclaimed as the means to end world hunger, the Blue Revolution holds the promise of increasing income and assuring the availability of affordable protein to the poor in the third world.

The potential of aquaculture to improve the nutrition and incomes of the poor has been impeded by the emphasis on the cultivation of high-valued carnivorous species destined for export markets in Europe, U.S.A. and Japan. The primary motives are generating high profits for producers and input suppliers and enhancing export earnings for national treasuries (Stonich and Bailey, 2000). This is particularly true for industrial shrimp farming.

When the Food and Agriculture Organisation first compiled production statistics on shrimp in 1950, production came solely from wild catches (FAO, 1995). In Asia, shrimps had for centuries been traditionally grown in low-density monocultures, in polyculture with fish, or in rotation with rice in the *bheries* of West Bengal and *pokkalis* of Kerala in India (Shiva and Karir, 1997). The shrimp production in these systems was low-yielding and aimed for domestic markets. It took until the mid-1970s, when fishermen and hatchery operators began supplying large quantities of penaeid shrimp postlarvae to farmers, before shrimp culture took off. With improved technologies and the introduction of commercial formulated feeds, the industry boomed during the 1980s. Small-scale intensive farms in Taiwan produced dozens of shrimp millionaires, and large-scale extensive farms in Ecuador recaptured their entire investment in the first year (Rosenberry, 1999).

Table 1. Global shrimp production for 1991-97: total fisheries catch, total warm-water fisheries catch (excluding Pandalidae and Crangonidae), total shrimp aquaculture production and the relative importance of aquaculture. Source: FAO (1999 a, b)

	WILD-CAUGHT SHRIMPS		AQUACULTURE	Relative proportion	
	Total (1000 x t)	Warm-water (1000 x t)	(1000 x t)	Total	Warm-water
1991	2 025	1 720	832	29%	33%
1992	2 085	1 754	890	30%	34%
1993	2 083	1 755	848	29%	33%
1994	2 246	1 921	890	28%	32%
1995	2 301	1 952	952	29%	33%
1996	2 448	2 084	949	28%	31%
1997	2 535	2 167	942	27%	30%

In 1975, the shrimp aquaculture industry contributed to 2.5% of total shrimp production, which gradually increased to around 30% of total shrimp supply in the 1990s (Table 1). During the 1990s, the relative importance of farmed shrimp to total supply has stagnated and even been reduced. Today shrimp farming makes up only 3-4% of global aquaculture production by weight, but almost 15% by value (FAO, 1999b). Almost 80 percent of cultured shrimp come from Asia with Thailand, China, Indonesia and India as the top producers (Table 2). In the Western hemisphere, Ecuador is the major shrimp-producing country.

Table 2. Country-wise production statistics for shrimp aquaculture in 1999. Source: Rosenberry (1999)

	Pond area (ha)	Production (t)	Relative prod. (%)	Productivity (kg/ha)	Farming intensity (%)		
					Extensive	Semi-intensive	Intensive
Thailand	80 000	200 000	24,6%	2 500	5	70	25
China	180 000	110 000	13,5%	610	30	65	5
Indonesia	350 000	100 000	12,3%	290	50	25	25
India	130 000	70 000	8,6%	540	75	20	5
Philippines	60 000	40 000	4,9%	670	30	60	10
Vietnam	200 000	40 000	4,9%	200	85	15	0
Taiwan	5 000	20 000	2,5%	4 000	0	50	50
Malaysia	4 000	6 000	0,7%	1 500	30	60	10
Iran	4 000	2 500	0,3%	630	0	100	0
Australia	600	2 400	0,3%	4 000	0	60	40
Other (Eastern hemisphere)	100 450	51 850	6,4%	520			
Ecuador	100 000	85 000	10,4%	850	40	55	5
Mexico	11 700	35 000	4,3%	3 000			
Brazil	6 000	15 000	1,8%	2 500	0	85	15
Nicaragua	6 000	4 000	0,5%	670	25	75	0
Venezuela	2 000	4 000	0,5%	2000	0	100	0
Panama	3 000	2 000	0,2%	670	10	90	0
United States	400	1 500	0,2%	3 750	0	95	5
Other (Western hemisphere)	11 300	27 000	3,3%	2 340			
TOTAL	1 251 450	814 250		651			

1.2. Farming practices

In the wild, the genus *Penaeus* spp. have a life cycle where they spawn at sea and after a few weeks the postlarval shrimp settles in inshore and estuarine waters (Dall et al., 1990). The nursery ground, which for many species is characterised by the presence of mangroves, is the critical habitat that determines most of the recruitment success to fisheries. After a few months in their nursery grounds, the juvenile shrimp start their emigration offshore to complete their life cycle.

The aquaculture production cycle for the shrimp farming industry is depicted in Fig. 1. The shrimp postlarvae, or seed as they are known to the aquaculturist, that are stocked in grow-out ponds originate from four sources. Naturally occurring wild shrimp seed can be allowed to enter traditional ponds with incoming tidal waters or caught by seed fishermen and subsequently stocked in ponds. Shrimp postlarvae can also be produced in hatcheries, which depend upon the continual inputs of wild-caught gravid female spawners or broodstock allowed to maturate in captivity. The development from hatched egg to ready-to-stock postlarvae lasts approximately 3 weeks. In recent years, a nauplii centre industry has emerged in some countries. These centres buy nauplii larvae (1 day old) from hatcheries, grow them into postlarvae, whereafter they are sold to farmers. Shrimp farmers employ a one or two-phase production cycle. With the two-phase cycle, postlarval shrimps are initially stocked in nursery ponds for a few weeks before they are transferred to grow-out ponds. The use of nursery ponds improves managerial aspects like predator control and feed waste minimisation, although the postlarvae suffer increased mortalities when they are harvested for stocking into grow-out ponds. It takes three to six months to produce a crop of market-size shrimps. Northern China, the U.S.A. and northern Mexico produces one crop per year, semi-tropical countries can produce two crops per year, while farms close to the equator have produced three crops annually, although rarely (Rosenberry, 1999).

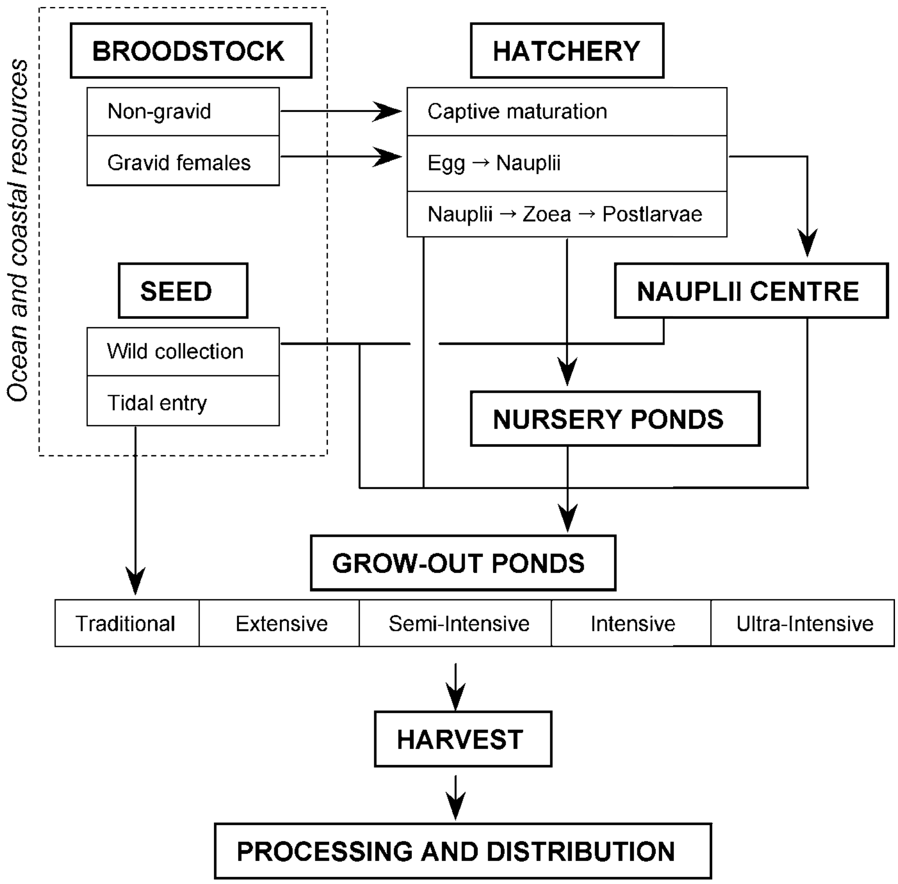

Figure 1. Production cycle for the cultured organism in industrial shrimp aquaculture. Adapted from Fast and Lester (1992)

1.2.1. Species cultured

Although the pioneering R&D for penaeid shrimp farming was conducted in the 1930s on *Penaeus japonicus* (by Motosaku Fujinaga of Japan), the explosive growth of shrimp farming in the later decades has been associated with the tropical giant tiger shrimp *P. monodon*. This species comprised 56% of the total 1999 production, the Asian white shrimps *P. indicus* and *P. merguiensis* came next with 17%, followed by *P. vannamei* (16%), and *P. chinensis, P. stylirostris, P. japonicus* contributed to the rest (Fig. 2).

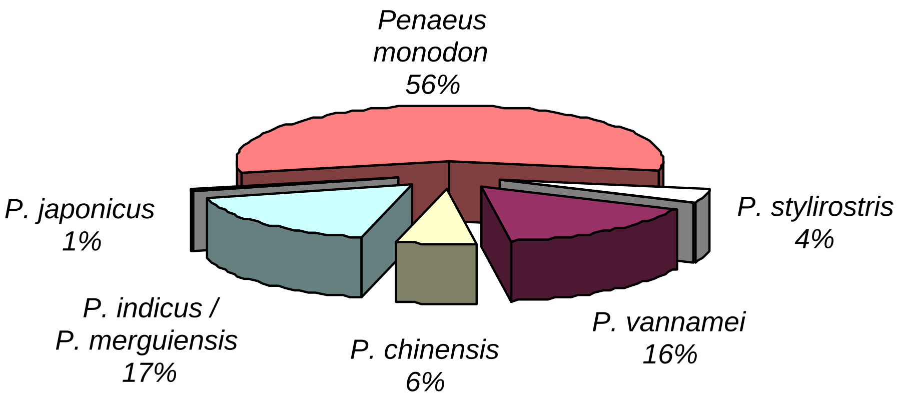

Figure 2. Relative importance of penaeid shrimp species to global aquaculture production in 1999. Source: Rosenberry (1999)

• *Penaeus monodon* – Giant tiger shrimp

Named for its huge size and banded tail, the giant tiger shrimp is the primary species farmed in Asia (excluding China and Japan). This species accounts for more than half of the total world shrimp aquaculture output, and it is the largest and fastest growing of all shrimp species. Even at high stocking densities, *P. monodon* can reach marketable sizes of 20 cm and 35 g in three to six months, and therefore holds the promise for the commercial aquaculturist of a more rapid cash flow than other cultured fish and shellfish (Muir and Roberts, 1982). This species can reach a length of over 33 cm and a weight of over 150 g (Dore, 1994), if allowed to grow to full size.

P. monodon is tolerant to a wide range of salinities, but is highly susceptible to two of the most lethal shrimp viruses – yellowhead and whitespot. Overstocking and pollution have led to widespread mortalities of *P. monodon* from diseases in many Asian nations. It is very difficult to re-establish the industry after such a blow. Other drawbacks with this species is that shortages of wild brood stock often exist, captive breeding is difficult, and hatchery survivals are low (20-30%) (Rosenberry, 1999).

• *Penaeus indicus / P. merguiensis* – Asian white shrimp

P. indicus and P. merguiensis are raised on extensive farms throughout Asia. These species have attracted attention recently because they tolerate low water quality better than *P. monodon*, they can be grown at high densities, and they are readily available as postlarvae in the wild (Rosenberry, 1999). Furthermore, *P. indicus* regularly reaches sexual maturity in the grow-out ponds. Native to the Indo-Pacific region, these closely related shrimp species are among the most commercially important wild-caught shrimp commodities in East Africa, South Asia, Southeast Asia and Australia.

• *Penaeus vannamei* – Pacific white shrimp
P. vannamei is the primary aquaculture species produced in the Western hemisphere. It has the reputation of being a tolerant species, able to adapt to fluctuations in salinity, pH, and dissolved oxygen levels (Rosenberry, 1999). Recommended protein levels for feed are low, 30 percent compared to 45 percent protein feed for *P. monodon*. In addition, *P. vannamei* are easier to reproduce than *P. monodon*. The uniform growth rate of this species is also an advantage in marketing. One major drawback to cultivation is its extreme susceptibility to cold weather, requiring an average water temperature of 28°C. Furthermore, this species has also been subjected to disease problems lately. The dramatic drop in Ecuadorian shrimp aquaculture production – from 130,000 t in 1997 to 85,000 t in 1998 – was due to problems with whitespot virus. In some areas 90% of the production was wiped out (Rosenberry, 1999).

• *Penaeus chinensis* (also known as *P. orientalis*) – Chinese white shrimp
Native to the coast of China and the west coast of the Korean peninsula, *P. chinensis* can grow in very low water temperature (down to 16°C) (Rosenberry, 1999). The species is easy to reproduce, and it is the only farmed penaeid shrimp species that readily mature and spawn in ponds (Rosenberry, 1999). *P. chinensis* dominates the industry in China, the world's largest shrimp producer in 1985-90. Disadvantages for the cultivation of this species include its high protein requirement (40-60%), small size (maximum length of 18 cm), and its meat yield (57%) compared to *P. monodon* and *P. vannamei* (>60%) (Weidner, 1992 cf Clay, 1996). During the late 1980s and early 1990s, the Chinese white shrimp was marketed around the world, but today most of the crop is consumed in China (Rosenberry, 1999).

1.2.2. Grow-out techniques

There are five different shrimp aquaculture practices mentioned in the literature, ranging from traditional to ultra-intensive techniques, but the most common techniques are extensive, semi-intensive, and intensive. These three categories are divided, according to their stocking densities (shrimp/m^2), and the extent of management over grow-out parameters, i.e. level of inputs (Table 3). The farmers that exercise traditional or extensive methods depend on natural advantages to compete in the market place. They rely on cheap land and labour, naturally occurring seed stock and feeds, and the lack of regulations which allows the conversion of coastal lands to shrimp ponds. Few input are required so producers can easily enter the industry. Semi-intensive and intensive farming practices require the aquaculturist to implement more control over the environment. Greater capital inputs, control of many grow-out parameters, and technical skills are needed. Ultra-intensive techniques are characterised by extreme level of inputs. These systems rely on advanced technology for higher survival rates and stocking densities to increase their yield per hectare. Their capital investment is substantially greater, but because the grow-out environment is more controlled, many of the risks associated with climatic fluctuations are reduced. In the most intensive ponds, the systems are nearly closed and water is recycled.

Table 3. Farming practices for extensive, semi-intensive and intensive shrimp aquaculture. Source: Shiva and Karir (1997); Primavera (1998); Rosenberry (1999)

	Extensive	Semi-intensive	Intensive
Pond size (ha)	1-10	1-2	0.1-1
Stocking	Natural + artificial	Artificial	Artificial
Stocking density (seed/m²)	1-3	3-10	10-50
Seed source	Wild + Hatchery	Hatchery + wild	Hatchery
Annual production	0.6-1.5 t/ha/yr	2-6 t/ha/yr	7-15 t/ha/yr
Feed source	Natural	Natural + Formulated	Formulated
Fertilisers	Yes	Yes	Yes
Water exchange	Tidal + pumping <5% daily	Pumping <25% daily	Pumping >30% daily
Aeration	No	Yes	Yes
Diversity of crops	Majority monoculture, some polyculture with fish	Monoculture	Monoculture
Disease problems	Rare	Moderate to frequent	Frequent
Employment	<7 persons/ha	1-3 persons/ha	1 person/ha
Production cost per kg	US $1-3	US $2-6	US $4-8

• Extensive

Extensive shrimp aquaculture is primarily used in areas with limited infrastructure, few highly trained aquaculture specialists, inexpensive land, and high interest rates (Weidner, 1992 cf. Clay, 1996). In that type of environment, individual or family group producers, who generally lack access to credit, are able to set up their operation with few inputs and little technical know-how. They construct impoundments or large ponds in coastal areas where land is inexpensive. Often, mangrove forests or salt flats are used for pond construction.

Producers rely on the tides to provide most of the food for the shrimp and as a means of water exchange. Feed for shrimp is naturally occurring, in some cases fertilisers or manure is added to promote algal growth. The extensive ponds are relatively susceptible to crop losses due to flooding from high tides caused by storms or from excessive rainfall. Low stocking densities (1-3 shrimps per m^2) results in modest yields (maximum 0.6-1.5 t/ha/yr). Extensive systems require minimal management of water parameters, because they usually operate without aerators or pumps for water exchange. Land and labour are the principal inputs, which keeps operational cost at a minimum. Disease outbreaks are rare, due to low stocking densities and no supplementary feeding.

Traditional culture practices differ from extensive methods in that they are completely dependent on the natural tidal entry for seed, food and water exchange. Furthermore, traditional systems are often characterised by polyculture with fish or by rotation with rice, e.g. in the *bheris* of West Bengal and *pokkalis* of Kerala in India (Shiva and Karir, 1997).

• Semi-intensive

Semi-intensive cultivation involves stocking densities beyond those that the natural environment can sustain without additional inputs. Consequently these systems depend on a reliable shrimp postlarval supply, and a greater management intervention in the pond's operation compared to extensive ponds.

Semi-intensive shrimp aquaculture relies on water pumps to exchange up to 25% of pond volume daily. With stocking rates of 3-10 shrimp postlarvae per m^2, farmers are completely dependent on formulated feeds to augment natural food in the ponds. The postlarvae are usually raised in nursery ponds until they are large enough to be stocked at lower densities in grow-out ponds. Maximum annual yields range from 2 to 6 tonnes per hectare.

The risk of crop failure increases with increasing farming intensity, which is mainly due to the impact on water quality exerted by the high stocking densities and supplementary feeding. All of the costs associated with semi-intensive production are much higher relative to those for extensive production, including a more complex system of ponds, installation of a pump system to regulate water exchange, skilled management, labour, purchased feed and seed stock, and increased energy usage. The higher the culture intensity, the higher the capital required and the higher the risks involved. Thus, the increased capital inputs required for semi-intensive culture often preclude its adoption by small-scale producers.

• Intensive

Intensive grow-out systems have evolved primarily in countries with high land costs, ample supplies of clean sea water, adequate infrastructure, and well-developed hatchery and feed industries. Intensive shrimp farming introduces small enclosures (down to 0.1 ha), high stocking densities (10-50 hatchery-produced shrimps/m^2), around-the-clock management, very high inputs of formulated feeds, and aeration. Aeration – the addition of oxygen to the water – permits much higher stocking and feeding levels. The water exchange rate in intensive ponds is usually more than 30 percent per day.

Frequently conducted in small ponds, intensive farming is also practised in tanks, which may be covered or located indoors. Construction costs range from US $10,000 to $35,000/ha. Sophisticated harvesting techniques and easy pond clean up after harvest permit almost constant production. Yields range from 7 to 15 tonnes per hectare and year, and production costs range from US $5 to $7 per kg of live shrimp. The risk of disease can be serious in intensive culture, especially if water discharge from one pond or farm is taken into another to be reused.

Ultra-intensive shrimp farming, which is still in its experimental stages, takes even greater control of the environment and can produce yields of 10-100 t/ha/year (Rosenberry, 1999). Ultra-intensive production requires huge amounts of water (around 50 percent needs to be exchanged per day), deeper ponds (up to 3 meters), and tremendous investments in technology, equipment, staff expertise, and overall management. Ultra-intensive shrimp farms can be found in Thailand and in the U.S.A. Thus far, these aquaculture systems have, however, not been successful over time (Rosenberry, 1999).

1.3. Country-specific production

Although the majority of the shrimp farms built in the early 1990s were semi-intensive or intensive, much of the world's production still comes from extensive systems. For most countries, the intensity of production increases over time, which is reflected in the increasing productivity for aquaculture ponds on a global scale. Between 1994 and 1999, pond productivity increased from 587 to 651 kg/ha/yr (Rosenberry, 1994, 1999), indicating that production was becoming more intensive. However, the rise of environmental and disease problems in intensive and semi-intensive farms, coupled with generally declining shrimp prices, has led some producers to move into less intensive production methods. High capital and operating costs make intensive shrimp farming a risky proposition.

The productivity estimates presented above are maximum capacities that require good water quality, normal weather conditions and no disease prevalence. On the contrary, low quality intake water, variable weather conditions and especially disease problems, result in much lower annual *in-situ* productivity for extensive, semi-intensive and intensive culture systems (Table 2). For example, in Vietnam, where 85% of all ponds are extensive and 15% semi-intensive, average productivity was only 200 kg/ha in 1998, although extensive and semi-intensive ponds are frequently said to produce 600-1,500 and 2,000-6,000 kg shrimps/ha/yr, respectively (Table 3). In the same year, Thai shrimp ponds only produced 2,500 kg shrimp per ha, although the country has 70% semi-intensive and 25% intensive ponds. Furthermore, these productivity values are only based on the ponds that are in operation. If idle and abandoned ponds were to be included in the analysis, the annual productivity would be much lower for many countries. The relative proportion of abandoned ponds has, for example, been reported to be as high as 70% in Thailand (Stevenson, 1997).

1.4. Financing the expansion of shrimp aquaculture

Shrimp aquaculture is encouraged by prices which are high in absolute terms, in relative terms (vis-à-vis other sources of income), in per hectare terms, and as return on investment. In the early stages of development, the industry also has relatively cheap inputs (land, water and wild larvae). Over time land prices begin to rise as land appropriate for shrimp cultivation is reduced, clean water sources becomes scarce, and wild-caught shrimp larvae cannot meet the demand.

Three financial considerations stand out as having an affect on the economic viability of shrimp farming (Clay, 1996). They are price fluctuations in the shrimp market, the exchange rate, and the economic stability of the producer country. Small farms are more vulnerable to price fluctuations and are likely to be bought out by large producers when prices are too low and profits are driven down. Such trends will probably result in a shrimp aquaculture industry that increasingly is run by large companies, with fewer small independent operators. The most important determinant for economic viability of shrimp farming is, of course, the industry's ability to avoid, or at least minimise, disease prevalence.

The commercialisation of shrimp culture has been driven by lucrative profits from export markets and fuelled by governmental support, private sector investment, and external assistance. Despite the negative socio-economics impacts of modern shrimp aquaculture on the livelihoods of coastal communities, many bi-lateral and multi-lateral agencies have continued to support aquaculture with large loans. International aid to aquaculture increased from US $368 million in 1978-84 to $910 million in 1988-93 (Primavera, 1998).

Multinational corporations and wealthy international investors are both attracted to and actively courted by governments to invest in shrimp production in their countries. To compete with other countries, most international investors are given preferential access to public lands and water, credits, tax holidays, markets, subsidies, licenses, favourable exchange rates, the right to take their money out of the country, and ability to bring inputs into the country tax-free (Gujja and Finger-Stich, 1995).

Another major source of investment in shrimp aquaculture is multi-national companies themselves. Increasingly, shrimp farming is becoming more vertically integrated. Some of the major players (e.g. feed companies, hatcheries, processors, distributors and government agencies) are creating co-operative or joint ventures to produce shrimp. In some cases, the feed companies, processors and distributors are one and the same company or at least subsidiaries of the same company. Under these circumstances, farmers generally own the land and manage the pond. The sponsor supplies the feed, seedstock, training, technical support, processing and marketing, or any combination thereof (Rosenberry, 1994).

Multi-national companies are also helping to promote shrimp production in new countries for their own benefit, for example as reported by Clay (1996). In September 1992, the Thai company Chareon Pokaphand (CP) asked top Cambodian officials for their support to permit foreign investment in the southern province of Kampot. In the same year, CP drafted a proposal for Cambodia to the World Bank to borrow US $100 million to finance the creation of 4,000 intensive shrimp farms. CP proposed to provide all the technical assistance to the project, market all shrimps produced in Cambodia, and sell Cambodians all the equipment, antibiotics and chemicals needed for the aquaculture ponds. CP would have gained tremendously through the project. Not only would they have provided all the inputs, they would have monopolised the sale of shrimp from the country. Feed often represents 50-60% of the operational costs of shrimp production, so profits from feed sales alone would have been staggering. The risk was passed on to the farmer, but if they failed to pay for the seed, feed or equipment, the government would have been responsible. CP would have had only minimal risks. In the end, however, the Fisheries Department of Cambodia rejected the plan, because they did not think it was in the best interest of either the government or their coastal communities.

2. IMPACT ON THE NATURAL ENVIRONMENT

Environmental impacts of shrimp aquaculture arise from the consumption of resources, such as land, water, seed and feed, their transformation into products valued by society, and the subsequent release into the environment of wastes from uneaten food, faecal and urinary products, chemotherapeutants, as well as micro-organisms, parasites and feral animals (Beveridge et al., 1997; Kautsky et al., 2000a). Negative effects may be direct, through release of eutrophicating substances, toxic chemicals, the transfer of diseases and parasites to wild stock, and the introduction of exotic and genetic material into the environment, or indirect through loss of habitat and niche space, and changes in food webs.

In recent years, the ecological, social and economic consequences of converting mangrove ecosystems into shrimp ponds have been widely debated, which is treated separately in chapter 3.

2.1. Feed

Whereas traditional and extensive shrimp aquaculture uses natural production in the ponds or in the incoming waters, semi-intensive and intensive production systems are heavily dependent on formulated feeds based on fish meal and fish oils. These latter systems use 2 times more protein, in the form of fishmeal, to feed the farmed shrimps than is ultimately harvested (Tacon, 1996).

Feed requirements place a strain on wild fish stocks, and currently about 1/3 of the total harvest of capture fisheries is used to produce fish-meal, one third of which is used by the aquaculture industry (Naylor et al., 2000). This may result in over-fishing of small pelagic species, affecting marine food chains, and ultimately marine mammals and top carnivores (Kautsky et al., 2000a; Naylor et al., 2000). Four of the top five, and eight of the top twenty capture species are used for reduction to fishmeal (FAO, 1999a). All are small, pelagic fish, including anchoveta, Chilean jack mackerel, Atlantic herring, chub mackerel, Japanese anchovy, round sardinella, Atlantic mackerel, and European anchovy.

Improved feeds – formulations that use greater amounts of vegetable protein and less fishmeal – are more digestible, appear to last longer in the water and also produce less waste (Boyd and Clay, 1998). Investing in these practices would discourage the overfishing of the seas for shrimp food, and it would save shrimp farmers money on feed, limit pollution and diminish the cost of cleaning up problems later.

2.2. Nutrient loading

Most aquaculture systems are so-called throughput systems (Daly and Cobb, 1989). This means that resources, collected over large areas, are introduced and used in the aquaculture production site, and released back into the environment in concentrated forms as nutrients and pollutants, causing various environmental problems (Folke and Kautsky, 1992). Uneaten food, faecal and urinary wastes may lead to eutrophication and oxygen depletion, the magnitude of which is dependent on the type and size of operation, as well as the nature of the site, especially size, topography and water retention time (Kautsky et al., 2000a).

In semi-intensive and intensive farms, artificial feeds provide most of the nitrogen (N), phosphorous (P) and organic matter inputs to the pond system. Only 17% (by dry weight) of the total amount of feeds applied to the pond is converted into shrimp biomass (Primavera, 1993). The rest is leached or otherwise not consumed, egested as faeces, eliminated as metabolites, etc. Effluent water during regular flushing and at harvest can account for 45% of nitrogen and 22% of organic matter output in intensive ponds (Briggs and Funge-Smith, 1994). Consequently, pond sediment is the major sink of N, P and organic matter, and accumulates in intensive shrimp ponds at the rate of almost 200 t (dry weight) per ha and production cycle (Briggs and Funge-Smith, 1994). During pond preparation between cropping the top sediment is removed and usually placed on pond dikes, from where it continuously leaks nutrients to the environment.

As shrimp biomass and food inputs grow, the water quality in high-density ponds deteriorates over the cropping cycle. Total N and P, silicate, dissolved oxygen and biological oxygen demand increased and water visibility decreased in intensive Thai ponds throughout the grow-out period (Macintosh and Phillips, 1992). Quality of receiving waters may deteriorate if the assimilative capacity of the environment is exceeded. Levels of nitrates, nitrites, phosphorous, sulphide, turbidity and biological oxygen demand increased considerably from 1983 to 1992 in the Dutch canal, the main recipient of shrimp culture effluents in Sri Lanka (Jayasinghe, 1995). The enormous amount of wastes released into the environment has great potential to cause pollution and collapses in shrimp production (through negative feedback). It is well established that the re-use of waste-laden pond water discharge, so-called self-pollution, is a major triggering factor behind disease susceptibility for cultured shrimp. For example, already Lin (1989) reported that self-pollution was a main causative factor behind the mass mortalities in the 1988 Taiwanese shrimp crop.

2.3. Chemical use

Chemicals used in shrimp culture may be classified as therapeutants, disinfectants, water and soil treatment compounds, algicides and pesticides, plankton growth inducers (fertilisers and minerals) and feed additives. Excessive and unwanted use of such chemicals results in problems related to toxicity to non-target species (cultured species, human consumers and wild biota), development of antibiotic resistance and accumulation of residues (Primavera, 1998). Constraints to the safe and effective use of chemicals include misapplication of some chemicals, insufficient understanding of mode of action and efficacy under tropical aquaculture conditions, as well as uncertainties with regards to legal and institutional frameworks to govern chemical use in aquaculture (Barg and Lavilla-Pitogo, 1996).

The antibiotic oxytetracyclin and oxolinic acid were detected above permissible levels in almost 10% of *Penaeus monodon* sampled from Thai domestic markets in

1990-91 (Saitanu et al., 1994). From June 1992 to April 1994, Japanese quarantine stations found anti-microbial residues in 30 shipments of cultured shrimp from Thailand (Srisomboon and Poomchatra, 1995). There are many potential side effects from excessive use of antibiotics, which are now being widely acknowledged in Europe, the U.S.A. and elsewhere. For some types of drugs, the majority of administered antibiotics will ultimately end up in the environment as a result of uneaten treated food and contaminated excrement (Weston, 1996). The continued use of antibiotics and their persistence in sediments tends to lead to the proliferation of antibiotic resistant pathogens, which may complicate disease treatment. The presence of antibiotics in bottom sediments may also affect bacterial decomposition of wastes and hence influence the ecological structure of the benthic microbial communities. Antibiotic use reduces natural microbial activity, which leads to waste accumulation and reduced degradation and nutrient recycling. Consequently, the pond system will increasingly become a throughput system where natural feedback controls and regulators are cut off. This results in loss of buffer capacity and ecological resilience.

2.4. Water use

Aquaculture requires large amounts of clean water to support the farmed animals, replenish oxygen and remove wastes. In land-based systems, aquaculture does not only borrow water and return it in a more degraded form, it consumes water by accelerating its loss from surface to groundwater or the atmosphere. Thus, by creating ponds, especially in areas of poor (sandy/loam) soils or high temperatures, evaporation and seepage is increased and as much as 1-3% of the pond volume may be lost in this way each day (Kautsky et al., 2000a).

Penaeus monodon has been produced at fully marine water in, e.g., Thailand (Kongkeo, 1990). The intensive shrimp farming technology for *P. monodon* developed in Taiwan was, however, based on salinity of 15-25 ppt. Pumping large volumes of underground water to achieve brackish water salinity led to the lowering of groundwater levels, emptying of aquifers, and salinisation of adjacent land and waterways. Even when fresh water is no longer pumped from aquifers, the discharge of salt water from shrimp farms located behind mangroves still causes salinisation in adjoining rice and other agricultural lands (Primavera, 1993; Dierberg and Kiattisimkul, 1996). Salinisation reduces water supplies not only for agriculture but also for drinking and other domestic needs.

2.5. Introduction of alien species and diseases

Worldwide transfers and introductions of the few preferred culture species, among them *Penaeus monodon*, *P. vannamei* and *P. japonicus*, were numerous in the early decades of commercialised shrimp culture. At the peak of Taiwanese shrimp production in 1982-1986, yearly imports from Southeast Asia of 70,000 to 160,000 live *P. monodon* broodstock supported hatchery production (Chin, 1988). Such introductions and transfers may lead to competition with endemic fauna, genetic introgression with local fauna, and introduction of pathogens and parasites.

More recently, the introduction of postlarvae and broodstock from areas affected by the Whitespot Syndrome Virus (WSSV) and Taura Syndrome Virus (TSV) was often followed by the rapid spread of these major shrimp pathogens throughout most of the shrimp-growing regions in Asia and Latin America, respectively (Lightner et al., 1997). A native of Asia, where it has caused multimillion dollar shrimp crop losses, the WSSV was first discovered in mass mortalities of *P. setiferus* in a Texas farm in 1995 (Lightner et al., in press). Every year thereafter it has been detected in wild and cultured shrimp (*P. setiferus, P. vannamei, P. stylirostris* and *P. duorarum*) and other wild decapods in Texas and South Carolina (Lightner et al., in press). The virus was probably introduced by release of untreated wastes from plants processing imported Asian shrimp into coastal waters, and by use of imported shrimp as bait in sports fishing or as fresh food for rearing other aquatic species, e.g., in zoological gardens (Lightner et al., 1997).

Another major shrimp virus, the Infectious Hypodermal and Hematopoietic Necrosis Virus (IHHNV) is believed to have been introduced to the Americas from Asia through the importation of live *P. monodon* in the early 1970s (Lightner et al., 1997). In the Philippines, IHHNV prevalence in various wild populations of the giant tiger shrimp has been correlated with shrimp culture intensification and mangrove status (Belak et al. 1999). Lower viral incidence in wild shrimp has been found in sites with primary mangroves and no major aquaculture industry, whereas higher levels have been observed in areas with intensive shrimp farms and severely degraded mangroves. Wild populations had significantly lower overall IHHNV incidence of 51% compared to total infection in captive *P. monodon* reared from second- and third-generation hatchery fry. Disease occurrence in tiger shrimp ponds in Hainan, China was closely associated with excessive stocking and poor water quality (Spaargaren 1998), and levels of *Vibrio* bacteria were ten times higher in shrimp pond sediments compared to mangrove habitats (Smith, 1998).

2.6. Discarded bycatch from wild shrimp fry and spawner fishery

The farming of shrimp depends on postlarvae collected from the wild or reared in hatcheries from eggs of wild-caught broodstock or spawners, thereby putting additional pressure on marine fisheries. The quantity of bycatch associated with such wild catches is directly proportional to the natural abundance of the target species for culture. In India and Bangladesh where the collection of wild *Penaeus monodon* seed supports major fishery operations, up to 1000 fish and other shrimp fry are discarded for every penaeid shrimp collected from littoral and estuarine waters (reviewed by Primavera 1998). Given a yearly seed collection of one billion *P. monodon* in Southeast Bangladesh, the amount of bycatch destroyed is staggering and could have major consequences for biodiversity and capture fisheries production (Deb et al. 1994).

Although the development of hatcheries for cultured shrimp species may have reduced dependence on wild seed (and their mangrove nurseries), it has also increased demand for wild-caught mature (spawners) and immature (broodstock) adults. The same low abundance of larval *P. monodon* applies to adult stages. In South East Asia, the giant tiger shrimp only comprise 0.1-0.9% of total recorded trawl landings, excluding bycatch discarded at sea (reviewed by Kautsky et al., 2000a). Because it is so rare, wild collection of *P. monodon* broodstock and spawners may lead to large amounts of bycatch. Overexploitation of the adults and larvae of both target and incidental shrimp species could be the cause of declining wild shrimp stocks in some locations. In West Bengal, India, where shrimp seed collection constitutes a significant fishery, the contribution of adult shrimp to fisheries landings decreased from 14.4% in 1970-1971 to 8.1% in 1989-1990 (Banerjee and Singh, 1993).

3. MANGROVES AND SHRIMP AQUACULTURE

3.1. Mangrove loss due to aquaculture development

Mangrove forests, which today cover an area of 181,000 km^2 spread over more than 100 countries (Spalding et al., 1997), have experienced widespread deforestation and degradation during the last decades. More than 50% of the world's mangroves have been removed (World Resources Institute, 1996), and for the Asia-Pacific region an annual deforestation rate of 1% is considered to be a conservative measure (Ong, 1995). Malaysia lost 12% of its mangroves from 1980 to 1990, and in Thailand 50% were lost between 1975 and 1991 (Spalding et al., 1997). The establishment of shrimp aquaculture ponds has been the main cause behind mangrove loss in many countries (Hamilton et al., 1989; Primavera, 1998). The Philippines lost 67% of their mangroves from 1951 to 1988, of which the development of brackish water ponds accounted for approximately half of the loss (Primavera, 1993). In Vietnam, a total of 102,000 ha of mangrove were converted into shrimp farms between 1983 and 1987 (Tuan, 1997 cf. Primavera, 1998). Most of the 180,000 ha shrimp ponds in Ecuador (1996 figures) and more than a third of the total 11,500 ha of shrimp farms in Honduras were developed in mangroves (DeWalt et al., 1996). Of the 204,000 ha of mangroves lost in Thailand in 1961-93, 32% were converted into shrimp farms (Menasveta, 1996), although other authors claim much higher losses caused by the Thai shrimp industry.

Other direct impacts behind mangrove loss include overexploitation of forest resources by local communities, and conversion into large-scale development activities such as agriculture, forestry, salt extraction, urban development and infrastructure. In addition, indirect degradation of mangrove systems include upstream diversion of fresh water flows, and deterioration of water quality caused by pollutants (heavy metals, oil spills, pesticides, etc.) and nutrients (Saenger et al., 1983; UNEP, 1995).

The loss of mangroves in the tropics has been facilitated by the high level of international financial assistance from the World Bank, Asian Development Bank (ADB) and other development agencies (Siddall et al., 1985). To quote a report of the 1978 Aquaculture Project in Thailand: ”The subproject will involve the large-scale development of mangrove swamps into small shrimp/fish pond holdings…” (ADB, 1978 cf. Primavera, 1998).

One major driving force behind the massive loss of mangroves during the last decades, is the inability among economists to recognise and value all natural products and ecological services produced by this ecosystem (Barbier, 1994; Rönnbäck, 1999, 2000). In part, this trend of undervaluation is due to the difficulty involved in placing a monetary value on mangrove goods and services that are: (1) not traded on markets and thus do not have a directly observable value; and (2) harvested or enjoyed outside of the mangrove system and therefore not readily acknowledged as generated by this system (Hamilton and Snedaker, 1984; Barbier, 1994). Lack of ecological knowledge among valuators is another important determinant to the undervaluation of mangroves (Rönnbäck, 1999; Rönnbäck and Primavera, 2000). Consequently, mangroves are considered as wastelands and are therefore prime candidates for conversion into alternative uses like shrimp aquaculture, which generate directly marketable products.

3.2. Socio-economic value of mangrove goods and services

Mangroves have been classified as ”key-stone” ecosystems, which generate a wide range of natural resources and ecosystem services. Ecosystem services like protection against floods and hurricanes, reduction of shoreline and riverbank erosion and maintenance of biodiversity are key features which sustain economic activities in coastal areas throughout the tropics (Saenger et al., 1983; Rönnbäck, 1999). Mangrove forest products like construction materials, charcoal, tannins, medicines and honey are vital to subsistence economies and provide a commercial base to local and national economies. Fish and shellfish constitute the major value of marketed products from unexploited mangroves, and the support to commercial, recreational and subsistence fisheries is well documented (Matthes and Kapetsky, 1988; Rönnbäck, 1999). For instance, 80% of all marine species of commercial or recreational value in Florida, USA, have been estimated to depend upon mangrove estuarine areas for at least some stage in their life cycles (Hamilton and Snedaker, 1984).

In addition to commercial fisheries, coastal subsistence economies in many developing countries are heavily dependent upon sustainable harvest of fish and shellfish from mangroves. The median fisherman density of about 5.6 fishermen per km^2 in mangrove environments is considerably higher than in other fished systems as is the yield per unit area (Matthes and Kapetsky, 1988). Because a large portion of the world’s human population lives in coastal or estuarine areas, e.g. 70% of the population in South East Asia, the importance of fishery activities as a source of food and income cannot be overstated (Rönnbäck, 1999).

The large-scale deforestation and degradation of mangroves during the last decades has impaired the generation of many life-supporting functions. The loss of protection against storms, floods and erosion is perhaps the most alarming example. Fosberg (1971) suggested that the loss of hundreds of thousands of lives in Bangladesh in 1970 following a hurricane and tidal wave might have been reduced had large areas of mangroves not been converted into rice paddies. Primavera (1995) proposed that thousand of deaths and damage to property in the Philippines, inflicted by typhoons that hits the archipelago every year could be reduced by the presence of a mangrove protective belt. In some areas in the Upper Gulf of Thailand coastlines have been eroding at 28 m per year between 1969 and 1987 (Aksornkoae et al., 1993), owing to a large extent to mangrove losses. The replacement cost of building hard protective structures to replace the coastal protection service once generated by mangroves can be significant. For example, in Peninsular Malaysia, Chan et al. (1993) estimated this cost at US $3 million per km coastline. Furthermore, these single-service artificial seawalls have limited lifetime and need continual maintenance. This stands in sharp contrast to mangrove forests, which form cost-free and self-repairing barriers (Moberg and Rönnbäck, 2001).

The potential life-support value of mangrove fisheries was reviewed by Rönnbäck (1999), who found that each ha mangrove generate 1,100-11,800 kg fisheries catch (3,600 kg as mean). This productivity is, for example, much higher than 10-370 kg/ha/yr proposed for coral reefs (Alcala, 1988). In developing countries, the annual market value of fisheries supported by mangroves range from US $900 to $12,400 per ha mangrove ($3,400/ha as mean). It must be emphasised that this value is based on one mangrove good, i.e. fisheries production, alone. Additional efforts to estimate the economic value of forest resources and ecological services generated by mangroves would further highlight the significant value of this ecosystem and its support to subsistence, local and national economies. The significant economic value of mangroves places serious doubt on the low land purchase price or annual lease fees (sometimes only a few dollars per ha mangrove) paid by logging concessionaires and shrimp aquaculture prospectors.

3.3. Potential to restore degraded mangroves and abandoned ponds

As a result of growing awareness regarding the ecological and socio-economic importance of mangroves, a number of countries have initiated mangrove replantation programs in degraded mangrove systems or abandoned shrimp ponds (Stevenson, 1997). In developing countries, the one-time cost of restoring mangroves range lies on the order of a few hundred US $ per ha (Erftemeijer and Lewis, 2000). The fact that the market value of one single good, i.e. fisheries has been valued at US $900-12,400 per ha mangrove annually (Rönnbäck, 1999), implies that there are substantial economic benefits to be gained by restoring mangroves.

Abandoned ponds located in the intertidal zone can regenerate their mangrove cover if dikes are broken to restore tidal flow and transport of propagules. Mangroves can also be established through afforestation on unvegetated intertidal flats and other areas where they would not normally grow. Perhaps the most impressive mangrove afforestation programme on accreting mudflats has been in Bangladesh (Saenger and Siddiqi, 1993; Siddiqi and Khan, 1996). To protect the lives and properties of the coastal communities from cyclone and storm damage, an afforestation programme was initiated in 1966 and by 1990 an area of 120,000 ha (29% of total mangrove area in Bangladesh) of this newly accreted land has been afforested. While the initial objective of the mangrove afforestation programme was to provide storm protection, a number of other goods and services were generated by this multifunctional system. The fisheries production potential has most certainly increased significantly. Furthermore, it is estimated that the plantations have provided 600,000 m^3 of forest products, and have generated more than 5 million mandays of employment for coastal communities, and thereby contributing substantially to the economy of these communities. The creation and stabilisation of new lands is another aspect of immense importance in a country as densely populated as Bangladesh, where about 10 million people live in the coastal region and offshore islands (Siddiqi and Khan, 1996).

4. SOCIO-ECONOMIC IMPACTS

In December 1996, the Supreme Court of India ordered the closure of all semi-intensive and intensive shrimp farms within 500 m of the high tide line. They also banned shrimp farms from all public lands, and required farms that closed down to compensate their workers with six years of wages in a move to protect the environment and prevent the dislocation of local people. If the 1988 collapse of farms across Taiwan provided evidence of the environmental unsustainability of modern shrimp aquaculture, the landmark decision of India’s highest court focused attention on its socio-economic costs (Primavera, 1998).

4.1. Food security aspects

The global food security needs used to justify the heavy promotion and subsidy of aquaculture development by national and international lending agencies, does not apply to cultured shrimp, which is destined mainly for luxury export markets. Rather, the development of shrimp ponds has a negative impact on food security in coastal areas (Table 4).

Table 4. Bio-physical and socio-economic mechanism that cause negative impact of shrimp aquaculture development on local food security.

DECREASED AGRICULTURAL PRODUCTION
• Loss of agricultural lands
• Land subsidy
• Lowered groundwater levels
• Salinisation of soil and water
DEPLETION OF DRINKING WATER
LOSS OF MANGROVE FOREST PRODUCTS
• Lowered production of honey, fruits, vegetables, etc.
• Decreased accessability to products
LOWERED FISHERIES CATCH
• Loss of fish and shellfish habitat, i.e. mangroves
• Local fish stocks reduced due to overharvesting of shrimp seed, spawners and broodstock
• Limited access to fishing areas
INCREASED DEMAND FOR FISHMEAL
• Overfishing
• Increased market prices for fish and shellfish
• Fish previously consumed by humans are fed to shrimps
SHIFTING OF AQUACULTURE SPECIES
• From domestic food crops to export commodity
HEALTH PROBLEMS DUE TO POLLUTED ENVIRONMENTS

Salinisation of soil and water causes reduced agricultural production and depletion of drinking water. Saline water from ponds seeps directly into water tables and adjacent agricultural areas. In the case of lowered ground-water tables, salt water may intrude into emptied aquifers. Shrimp farms may also indirectly cause salinisation through increased tidal flooding area following mangrove destruction or because water flow in waterways have been obstructed. Decreasing rice production in Bangladesh, Thailand and other Asian countries can be traced to salinisation and declining soil fertility caused by shrimp pond development (Boromthanarat, 1995). For example, when 620 ha of rice paddy was converted to shrimp ponds, an additional 344 ha was lost due to saltwater contamination in Vettapalem Mandal, India (Raj and Dhamaraj, 1996 cf. Clay, 1996). At the rate of 2 kg per family daily, the production of 7.5 million kg of rice from the combined areas could feed 10,000 families.

As mentioned previously, mangroves produce a vast array of forest food items as well as supporting substantial fish and shellfish catches. Conversion of mangroves directly affects food security due to loss of these forestry and fishery resources. Shrimp farm complexes may also block fishermen's access to fishing grounds and landing sites. The substantial bycatch problems associated with fisheries for wild shrimp postlarvae as well as adult shrimp broodstock and spawners, also reduce fish stocks.

Increased demand for fishmeal may result in overfishing and unsustainable fishery practices where juvenile life stages are targeted. High fishmeal prices give rise to more expensive animal protein at the local market for coastal communities. Apart from a direct increase in the market value for fish and shellfish, chicken also becomes more expensive as a result of increased prices of poultry feeds that are based on fishmeal. Some of the fish bycatch used for human consumption and cheap raw fish for the salted fish industry have also been diverted to shrimp farming (New and Wijkstrom, 1990). The entry of shrimp as a commodity has also caused some farmers to shift existing aquaculture practices into producing for export instead of domestic markets.

4.2. Privatising the commons

Shrimp aquaculture often utilises common property resources, such as mangroves and water, whose use was once regulated communally. These common property resources contribute greatly to social equity, since net monetary benefits are distributed to large groups of politically and economically marginal people. However, the development of aquaculture ponds transforms mangroves into a single-use private resource, and the opportunity for redistribution of benefits becomes limited.

All across Asia and Latin America, residential, agricultural and forest lands are being converted into shrimp farms (Primavera, 1998). Even burial grounds have not been spared. The loss of grazing land and other green vegetation has led to a decline in livestock in Sri Lanka (Alauddin and Tisdell, 1996). In India, huge shrimp farm complexes also block access of villagers to fishing grounds and to beaches for landing their boats and drying their nets (Shiva and Karir, 1997). Shrimp farms have taken over lagoon areas in Honduras, and fishermen can no longer fish in these rich fishing grounds (DeWalt et al., 1996).

The commonly repeated scenario is a buying out of small farmers and landowners by big shrimp farmers and companies. The increased value of land once an area opens up to shrimp aquaculture development induces small landowners to sell their land, particularly if they are indebted or have no capital to invest in aquaculture. With the spread of shrimp farming, land prices in Pak Phanang, Thailand rose from US $50-75 per ha in 1985 to $50,000-75,000 per ha in 1991 (Boromthanarat, 1995). Aside from tremendous increase in land value and coercion, saltwater contamination of agricultural land by adjacent shrimp ponds makes selling the only option. Where land and resources are under the control of a small elite, most shrimp production is concentrated in a few large entrepreneurs as in India and Bangladesh. But most shrimp farms are small- and medium-sized in Vietnam where land and other natural resources belong to the State (Sinh, 1994) and in Thailand where land is widely distributed (Kongkeo, 1995).

The capital-intensive nature of high-density shrimp culture has favoured the entry of multinational corporate investors, and national and local élite. They can provide the necessary capital, have easier access to permits, credits, subsidies, and can absorb financial risks. In this context, local communities in coastal areas and small farmers are disadvantaged. Outsiders´ control of large shrimp farms is the primary cause of social imbalance and deteriorating law and order in coastal areas in Bangladesh (Alauddin and Hamid, 1996).

Throughout Asia, Africa and Latin America, coastal communities have organised themselves together with NGOs to protest against the expansion of the shrimp aquaculture industry (reviewed by Primavera, 1998). Protesters have been jailed, threatened, harassed, and had their houses burnt down. Other confrontations have turned even more violent. Shrimp farmers in Bangladesh have hired guards to prevent poaching of shrimp, force landowners to sell their land, and stop protests by villagers – around 100 people have been killed in 5 years.

4.3. Marginalisation of coastal communities

Shrimp farming employs thousands of people as shrimp seed collectors, at hatcheries, farms, and during processing and distribution: 100,000 persons in Ecuador (Hirono, 1989) and 150,000 in Thailand 1993 (Kongkeo, 1995). However, because modern shrimp farming is capital-intensive, rather than labour-intensive, employment of local people is often limited to low-paying, unskilled jobs such as processors, guards or temporary labourers during harvesting and pond preparation. Processing is low-paid and precarious employment done mostly by women and quite often by children. Technical and managerial positions are reserved for outsiders. Funds invested in commercial shrimp culture are generated from outside; the economic benefits to the community are minimal or even negative due to the outflow of profits from the periphery to the centre (Alauddin and Hamid, 1996). In this context, the disparate opportunity costs for the sectors involved should also be acknowledged. The aquaculture entrepreneurs have alternative sites and income sources, whereas municipal fishermen, gatherers of forest products and farmers have no alternative site.

Shrimp farming has brought about social displacement and marginalisation of fishermen and agriculturists instead of improved living standards. Dispossessed and landless fishermen and farmers are forced to seek work elsewhere, migrating to cities and swelling the ranks of the urban unemployed (Alauddin and Hamid, 1996). Shrimp farm development in Satkhira, Bangladesh has displaced nearly 120,000 people from their farmlands (Utusan Konsumer, 1991 in Baird and Quarto, 1994).

The allocation of resources for shrimp farming and the distribution of benefits will, however, depend on the socio-economic context and institutional framework (Barraclough and Finger-Stich, 1996). Where population density is high and artisinal fishing or agriculture common, shrimp farming does not earn as much income for locals as fishing and agriculture. But considerable economic opportunities may be generated in relatively unoccupied areas.

5. BOOM-AND-BUST PATTERN OF SHRIMP AQUACULTURE

Shrimp aquaculture production took off in the 1970s, but due to pollution and disease problems world production has stagnated and in many countries even gone down over the last few years (Fig. 3). Already in 1988, shrimp farming collapsed due to disease in Taiwan, which had until then been the world's leading producer. In only two years production dropped with more than 70% (from 75,000 t to 20,000 t). China then took over as top-producing country, but was soon also struck by disease, which resulted in a major drop in production in 1993. Thailand had by that time grown to become the world's leading producer. Although, the great awareness of the disease risk resulted in large investments to combat disease, Thailand's total production dropped in 1996-97. A similar boom-and-bust pattern occurred in Indonesia and the Philippines. Among the top-producing countries, Ecuador had been spared from large-scale disease problems until 1999, when 90% of the production was wiped out in certain areas (Rosenberry, 1999). This can be explained by two factors. First, Ecuador relies heavily on extensive production systems (Table 2), which makes the system less vulnerable to disease outbreaks. In addition, shrimp disease problems evolved in South East Asia, and due to the geographical positioning of Ecuador, diseases were more likely to first spread to other Asian countries before affecting Latin America. Disease was once a localised problem, but with the expansion and globalisation of the shrimp industry, diseases that once were restricted to one region are now rapidly spreading over the world.

In some countries, the collapse of individual farms do not show in production curves because new farming areas have been taken up at a higher rate than the areas struck by disease were abandoned (Stevensson, 1997). In Thailand, significant disease problems affected one part of the country, while in other areas production has been expanding, thus compensating for the loss in total country output. Such a sequential exploitation pattern within and between countries has often masked the problem with unsustainability. Initially, land is not a significant barrier to the creation of shrimp ponds. In fact, having vast tracts of cheap land appears to be one of the main reasons that shrimp farmers have not invested in more sustainable aquaculture management practices. It is simply cheaper to abandon ponds and move on (Gujja and Finger-Stich, 1995).

5.1. The role of pond environmental factors in disease outbreak

Viral and bacterial diseases together with poor soil and water quality are the main causes of shrimp mortality (Liao, 1989; Chamberlain, 1997), whereas deficient environmental management of shrimp farms is the most important underlying determinant to disease outbreaks (Flegel, 1996).

Under some conditions, the host and its pathogen may be co-existing with little or no adverse effect. For example, apparently healthy shrimp have constant low levels of bacteria, especially *Vibrio* spp., present in the haemolymph (Lightner, 1988; Gomez-Gil et al., 1998), although their defence mechanisms seem capable of controlling these bacteria under normal circumstances. It is also interesting to note that Baculovirus and White Spot virus can be present in shrimp ponds without causing major losses (Kautsky et al., 2000b).

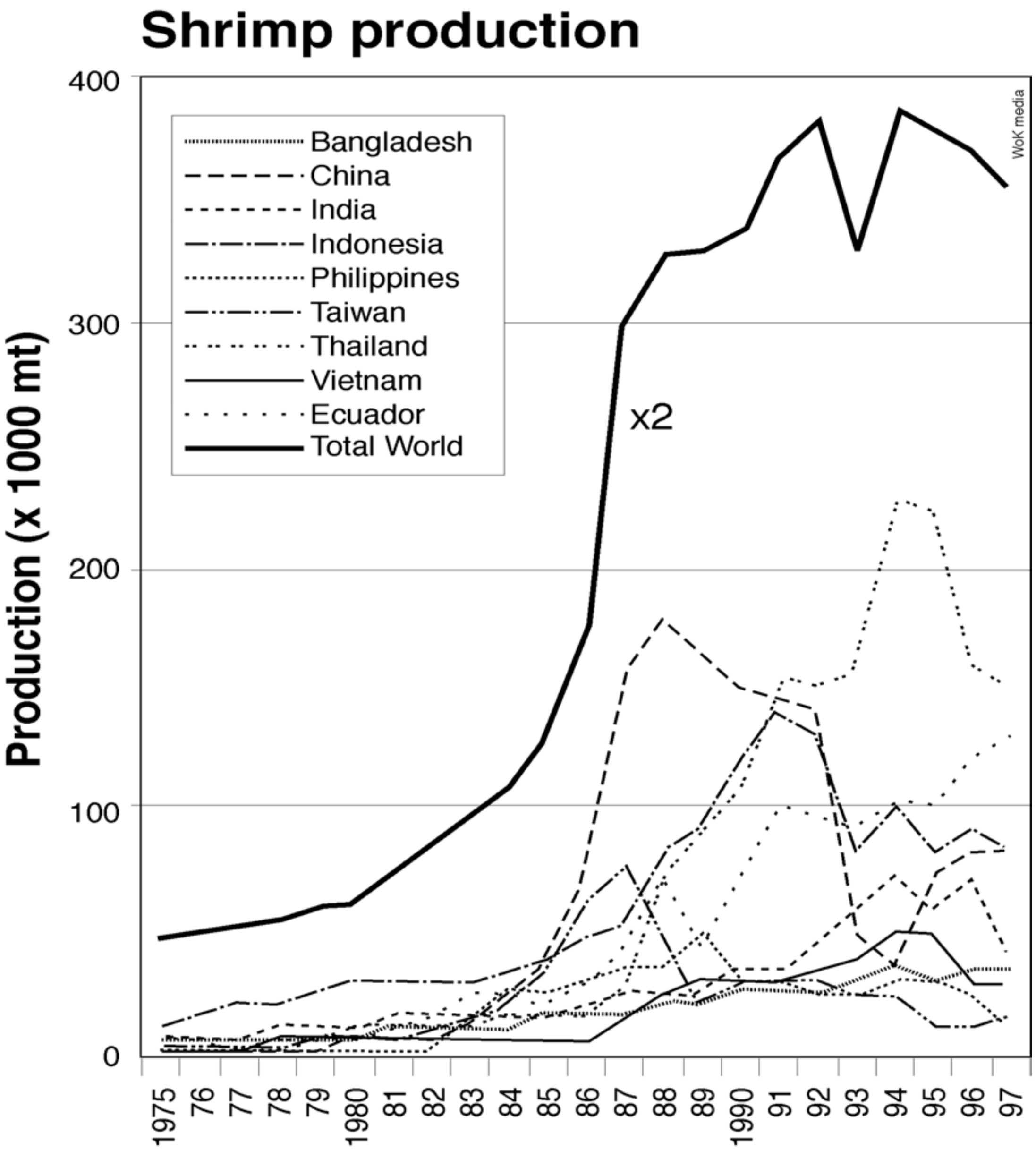

Figure 3. Shrimp aquaculture production in main producing countries. From Kautsky et al. (2000b)

The risk of disease seems to increase with intensity of farming and thus density of shrimp in the pond. Disease occurrence in shrimp ponds in Hainan, China was closely associated with excessive stocking and poor water quality (Spaargaren, 1998). In the Philippines, the Infectious Hypodermal and Hematopoietic Necrosis Virus (IHHNV) prevalence in various wild populations of *Penaeus monodon* has been correlated with shrimp culture intensification and mangrove status (Belak et al., 1999). Lower viral incidence in wild shrimp was found in sites with primary mangroves and no major aquaculture industry, whereas higher levels was observed in areas with intensive shrimp farms (the probable source of pathogens) and severely degraded mangroves. More important than the density of shrimp inside ponds (whether extensive, semi-intensive or intensive) is the farm density in a given area (Dierberg and Kiattisimkul, 1996). This parameter has to be controlled to avoid that the (waste) absorbing or assimilative capacity of the environment is not exceeded. Unproductive ponds can be traced to poorly selected sites, but wide-scale abandonment of ponds is often due to the proliferation of initially successful farms that ultimately overwhelm the system.

There appears to be a clear linkage between environmental conditions and disease outbreak. The development of acid sulphate soils or fluctuations in normal environmental conditions (e.g. oxygen, temperature, and salinity) may indirectly cause production failure by increasing physiological stresses and lowering the immune response. For example, low oxygen levels, which is a common problem in ponds with high shrimp stocking density, increases sensitivity to vibriosis in penaeid shrimp (LeMoullac et al., 1998). In order to reduce disease risk, the grow-out period in shrimp farming is often shortened resulting in that smaller shrimp are harvested. Sometimes cultivation continues until first signs of disease appear when the crop is immediately harvested and can still be marketed, but at lower quality (Thongrak et al., 1997). To minimise the risk of disease triggered by physiological stress, shrimp farmers may restrain from farming during rainy and cold season (low salinity and low temperature, respectively). In some countries, this has reduced the number of crops per annum from two to only one.

6. ECOLOGICAL FOOTPRINT AS AN INDICATOR OF DEVELOPMENT LIMITATIONS IN SHRIMP AQUACULTURE

Contrary to common belief, technical and economic inputs such as construction materials, energy and labour form only a small part of the inputs needed for aquaculture. The main and critical inputs are instead natural resources. Together with nature´s services, they ultimately determine the limits for the local and global expansion of aquaculture. For example, the productivity and sustainability of the shrimp industry is directly dependent on the continuos support of natural resources and ecosystem services from viable mangrove ecosystems. Mangroves provide shrimp seed, broodstock and spawners as well as feed inputs, water quality maintenance and control against natural disturbances like erosion, storms and floods (Beveridge et al., 1997; Rönnbäck, 1999). However, as a paradox, shrimp aquaculture development constitutes a major threat to mangroves. The magnitude and type of resource use and impacts of aquaculture are very much dependent on which species is cultured, the farming methods used, and the intensity of farming.

One way to identify human demands for natural resource and ecosystem services is by estimating the functional ecosystem area – the ecological footprint – required to support human activities. The concept has proven useful in illuminating the non-valued (or monetised) and often unrecognised work of nature that forms the basis for economic activities such as industrial aquaculture. When problems beset aquaculture operations, solutions focus on the pond unit, not realising that the farm is part of a much larger ecosystem with which it interacts. This unvalued work of nature sets the limits to culture levels without compromising biodiversity or causing pollution or disease problems. Many aquaculture developments, such as intensive shrimp farming, have encountered problems or even failed because they exceeded the carrying capacity of the environment.

An illustration of the footprint concept is provided by a study on semi-intensive shrimp farming in a coastal mangrove area in Colombia. This study estimated that the spatial ecosystem support or "footprint" required to produce food inputs, nursery areas and clean water, as well as to process wastes was 35-190 times the surface area of the farm (Fig. 4) (Larsson et al., 1994; Kautsky et al., 1997). The mangrove nursery area required to produce the shrimp seed for stocking was the largest support system covering up to 160 times the pond area, based on farming practices where 10-50% of stocked postlarvae are wild-caught. If located close to the farm, the same mangrove area could also supply natural food inputs (4.2 m^2 per m^2 shrimp pond area) and absorb polluting nutrients (4.8 m^2 per m^2 pond area) in the farm effluents. Feed pellets form a major input to a shrimp farm, and a marine area of 14.5 m^2 was needed to catch the fish, and an additional agricultural area of 0.5 m^2 for the vegetable ingredients used in feed pellet manufacturing. Finally, 7.2 m^2 was needed for providing clean lagoon water to the ponds, and 0.8-2.5 m^2 of forest area per m^2 shrimp pond area to sequester the CO_2 of fossil fuel burning at the farm.

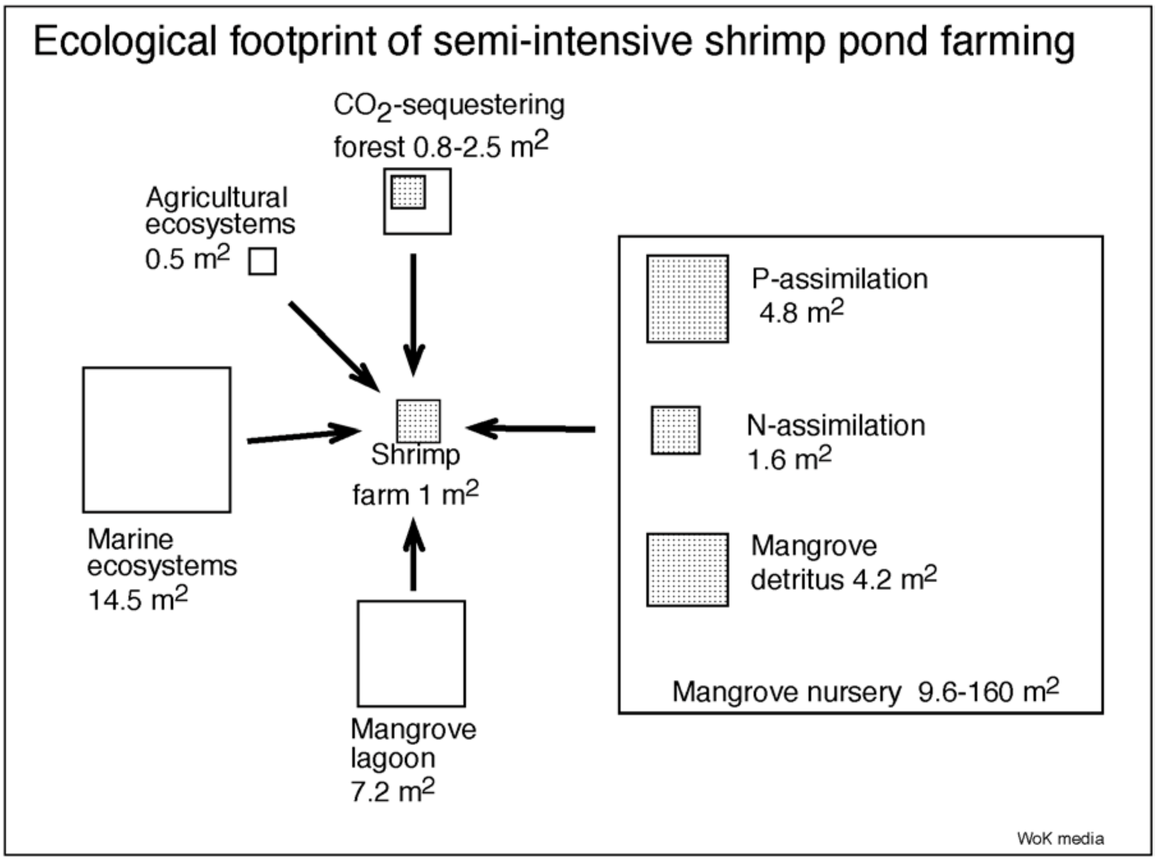

Figure 4. Ecosystem support areas required to sustain a semi-intensive shrimp farm in a coastal mangrove area of Colombia, assuming that 10-50% of shrimp seed are wild caught (m^2 of support area needed per m^2 of pond area). From Kautsky et al. (1997)

The size of the ecological footprint will change with the intensity of farming and the extent to which the seed is wild-caught and hatchery-produced. For example, a higher stocking density will require more food inputs and also produce more wastes. For an intensive shrimp farm, that produces 14 t of shrimps per ha annually, the marine area needed for feed production increases about five times (Kautsky et al., 2000b), and the area needed for nutrient absorption about eight times, compared to semi-intensive production (Robertson and Phillips, 1995).

7. THE FUTURE OF SHRIMP AQUACULTURE

Various ways to make shrimp aquaculture environmentally and socio-economically sustainable have been suggested, for example by Macintosh and Phillips (1992), FAO/NACA (1995), Barraclough and Finger-Stich (1996), Clay (1996), Primavera (1998), Troell et al. (1999); Kautsky et al. (2000b).

The prevention of disease outbreaks is a critical issue that will improve the financial viability of the shrimp industry as well as reduce many of the environmental and socio-economic concerns. Longer lifetime of individual shrimp ponds would reduce the relative proportion of abandoned and idle ponds, and consequently the boom-and-bust pattern with sequential land exploitation is hampered. Many approaches to combat disease also focus on improved pond and water management aimed at ameliorating the impact of shrimp pond effluents on the water quality of the recipient.

Careful site selection and planning would avoid large-scale mangrove deforestation and degradation in the development phase. Mangroves could also be used as a biofilter to improve water quality in the recipient. Mangrove restoration programs should be initiated in areas where shrimp aquaculture development has caused significant damage to this ecosystem.

There are two general pond management strategies that may be sustainable. The "ecological" strategy implies that the cultivation is done at lower intensity and that efforts to farm shrimp are more in tune with ecosystem processes and functions, e.g., by creating large mangrove buffer zones, and adapt the farming to the local carrying capacity. This strategy may also incorporate the use of integrated aquaculture techniques, where resources and wastes are re-circulated within the farm instead of depleting or overloading the environment (Troell et al., 1999). Another pond management strategy is more of a "technological" alternative, which tends to drive development towards completely artificial super-intensive systems that are isolated from the environment. This strategy invest in high-tech recirculating or so-called ”closed” system, which allows shrimp ponds to be located in inland areas away from the intertidal coastal zone. In the context of sustainable shrimp aquaculture, we must also analyse the sustainability of shrimp trawling, which is by far the dominant supplier of shrimps to the global market.

7.1. Best management practices and disease prevention

Best environmental management practices aim at an on-going minimisation of shrimp aquaculture’s environmental damage through cost-effective measures. Best management practices also constitute a critical instrument in disease prevention, since the environmental quality of both the ponds and the surrounding waters has a strong influence on disease prevalence.

Improved control and regulation of the worldwide transfer of shrimp postlarvae, broodstock and spawners is a vital step needed to reduce the spread of disease between regions, countries and continents. Only native species should be cultured to avoid the introduction of alien species and minimise the spread of disease. Closure of the hatchery cycle by improved breeding and domestication programs could enable the hatcheries to produce their own broodstock and spawners, and greatly reduce the need for shrimp transfer between regions and countries. By improving the hatchery technology, the demand for wild-caught shrimp postlarvae, broodstock and spawners would probably also be weakened, and consequently the bycatch problems associated with these fisheries are ameliorated. It should, however, be emphasised that this could cause huge social impacts, as wild postlarval collection is a major source of income and employment in many coastal regions.

In the local pond environment, the most realistic approach to combat diseases at present will be combining careful site selection with good pond management and the use of prophylactic agents. The most important factor is to prevent, or at least reduce, the risk of exceeding the assimilative capacity of the pond as well as the surrounding environment by regulating the density of shrimp ponds in any given area. The ecological footprint concept can help to indicate the spatial development limitations for shrimp aquaculture, and thus lower the risk for self-pollution and subsequent disease prevalence. Several methods have been proposed to ameliorate the impact of shrimp pond effluents on the water quality of the recipient: improved pond design (Dierberg and Kiattisimkul, 1996); construction of waste-water oxidation-sedimentation ponds, reduction of water exchange rates (Hopkins et al., 1995); reduction of nitrogen and phosphorous input from feed (Jory, 1995); removal of pond sludge; a combination of semi-closed farming systems with settling ponds and biological treatment ponds using polycultures (Dierberg and Kiattisimkul, 1996); and the use of mangroves as biofilters for pond discharge prior to the release of effluent to estuarine waters (Robertson and Phillips, 1995). Prophylactic agents that can be used to limit disease prevalence include immunostimulants and probiotics. Probiotics are bacterial-enzyme preparations that work on the principle of competitive exclusion of harmful bacteria by the introduced ”good” bacteria. The control of diseases and pests through the use of chemicals should be a last resort only after environmental conditions, nutrition and hygiene have been optimised.

7.2. Shrimp farm development and mangrove conservation

Shrimp aquaculture, the predominant cause of recent mangrove loss, is the major threat to remaining mangroves in many developing countries. Lessons from Asia and Latin America on how (not) to develop shrimp farms and conserve mangrove may be instructive to countries embarking on coastal aquaculture. For example, Africa with its favourable physical environment is becoming increasingly attractive to Asian aquaculture entrepreneurs who have both technical expertise and capital.

The proportion of a mangrove area that can be clear-cut without affecting the health of the ecosystem, including support to fisheries, erosion control, flood protection, etc., needs to be clearly established with the aid of additional research. As mentioned previously, mangroves also act as a biofilter for shrimp pond effluents and in the process water quality is improved. The value of this service should be compared with the cost involved in nitrogen and phosphorous reduction in conventional water treatment systems. The overall waste treatment function of mangroves has been estimated at US $6,700/ha/yr (Costanza et al., 1997). The filtering capacity of mangroves can only be used successfully if the density of shrimp ponds is sufficiently low and ponds are located either towards the landward edge of the forest or on terrestrial areas inland. The ratio of mangroves to shrimp ponds is very high – for intensive culture systems a mangrove cover at least 22 times larger than the pond area is needed to filter the nitrogen and phosphorous loading (Robertson and Phillips, 1995). This implies that a maximum of 4% of the forest can be converted into ponds. Unfortunately, large-scale conversion, where the area of ponds greatly exceeds that of remaining mangroves, has been the rule and consequently water quality quickly deteriorates, which can trigger self-pollution and disease outbreaks.

Some aquaculture entrepreneurs practice the concept of ”no net mangrove loss”, i.e., for each hectare of mangrove converted during development, one ha of new mangrove is planted. Adjacent sand and mud flats is the usual location for this mangrove afforestation. The choice of mud flats for the mangrove planting has the advantage of avoiding conflicting claims over land ownership and development, as would arise in efforts to restore mangroves in abandoned shrimp farm areas or former logging areas. However, these intertidal mudflats represent a rich and productive ecosystem in themselves, providing an important habitat that supports high densities of intertidal benthic invertebrates and fulfilling a range of key ecological functions (Erftemeijer and Lewis, 2000). During low tides, the intertidal mudflats serve as important feeding grounds for large concentrations of migratory shorebirds, while in many areas the mudflats are exploited by humans for bivalves and crabs, contributing substantially to their income and food. Consequently, the planting of mangroves on mudflats would represent a form of "habitat conversion", where one valuable habitat is transformed into another. Even if the afforestation is successful, the net gains in such a situation are likely to be less than in the case of restoration efforts in degraded former mangrove areas and abandoned shrimp ponds.

7.3. Integrated mangrove-aquaculture systems

Aquaculture ponds may not necessarily preclude the presence of mangroves. Dikes and tidal flats fronting early Indonesian *tambak* were planted with mangroves to provide firewood, fertilisers and protection from wave action (Schuster, 1952). Present-day versions of integrated forestry-fisheries-aquaculture can be found in the traditional *gei wai* ponds in Hong Kong (Lee, 1992), mangrove-shrimp ponds in Vietnam (Binh, 1994), aquasilviculture in the Philippines (Baconguis, 1991), and the *tambak tumpang sari* or *tambak empang parit* in Indonesia. The basic design of the various models is the planting of mangroves and other trees on a central platform occupying 60-80% of total area and a peripheral canal for growing fish, crabs and shrimp (reviewed by Primavera, 2000).

The annual shrimp productivity of the different systems generally lies in the order of 100-400 kg per ha, although the *gei wai* ponds in Hong Kong only generate 15-40 kg shrimps per ha due to pollution from surrounding urban areas. On a global scale, the relative importance of these integrated systems is, however, minimal. The average global shrimp productivity, which is dominated by non-integrated farming practices, was 500 kg per ha pond in 1996 and 650 kg/ha in 1998 (Rosenberry, 1997, 1999). This implies that the more high-yielding integrated mangrove-aquaculture systems has the potential to significantly contribute to global shrimp aquaculture production, if more pond were to be converted into integrated practices. Furthermore, these integrated systems also produce a variety of other forest as well as fish and shellfish products. Besides generating additional income for the farmer, the integration of trees, fish and shellfish with shrimps also provides an insurance against production failures by diversifying the number of organisms cultured.

These integrated mangrove-aquaculture systems are labour-intensive rather than capital-intensive, and consequently they offer coastal communities the possibility for income and employment. Most integrated farms are also small-scale businesses owned by families or village co-operatives. This stands in sharp contrast to the capital-intensive nature of high-density shrimp aquaculture ponds, which are usually owned by multinational corporate investors, and national and local élite. Therefore, the integrated systems rank high in the context of socio-economic sustainability criteria. Given the small-scale nature of these integrated systems, regional processing plants, marketing channels, etc. that can serve a large number of small producers and still be viable economically need to be developed.

The environmental criteria for sustainability are also improved in these integrated systems. For example, the presence of mangrove trees results in a much tighter nutrient recirculation in the ponds, and consequently the environmental impact of effluent discharge is lowered. One major drawback with many types of integrated mangrove-aquaculture is, however, the exclusion of most biophysical interactions between the pond environment and surrounding ecosystems. The construction of dikes completely obstructs natural tidal flows and consequently the mangrove habitat function for wild fish and shellfish is lost, which have implications for coastal fisheries.

7.4. Inland shrimp farming in ”closed” systems

Extensive shrimp culture requires an intertidal location (for water management) which is often associated with clearcutting of wide mangrove stands. On the other hand, intensive systems located inland spare mangroves, but jeopardise water supplies and agricultural land because of salt water contamination. From a farmer’s perspective, the relocation of ponds away from mangroves can be beneficial. Many mangrove areas are characterised by high organic matter content, abundant sulphates, iron and anaeroby, all of which are prerequisites for pyrite formation, which during aeration produces acid sulphates that can reduce growth and survival of the cultured animals.

With shrimp farming practices coming under increased criticism for mangrove destruction, the shrimp industry has endorsed ”sustainable” shrimp farming practices. Although the extent to which mangrove destruction by shrimp farming has slowed down is open to debate, recent innovations in shrimp culture technology are raising new land and water management concerns. In Thailand, low salinity shrimp farming, which relies on salt water trucked in from the coast, has facilitated the establishment of shrimp farms in predominantly rice growing areas 100 km or more inland from the coast (Flaherty et al., 2000). This activity developed during the 1990s, but in 1998 its rapid expansion into the rich farmland of Thailand’s central region came under intense public and governmental scrutiny. The Thai government subsequently banned inland shrimp farming in designated fresh water areas. Nevertheless, concern continues to grow about the capacity and willingness of the government to enforce the ban, the manner in which fresh and brackish water areas have been designated, and the possibility that the ban on inland farming may be relaxed (Flaherty et al., 2000).

The environmental impacts of specific concern for inland shrimp farming relates to the salinisation of soil and water, water pollution caused by shrimp pond effluents, and competition between agriculture and aquaculture for fresh water supply. Proponents claim that the use of ”closed” systems will insure that low salinity farming can be undertaken without harm to the surrounding environment. The general scheme of ”closed” is similar to some conventional waste water treatment facilities, which include sedimentation ponds, biological treatment and aeration (Lin, 1995). The treated water is stored in a reservoir pond before being returned to shrimp grow-out ponds. Water treatment ponds may incorporate fish, bivalves and algae to assimilate nutrients and particulate matter from the pond water. While the concept of water recycling is ecologically sound, the efficiency of the system is still far from perfect in many locations (Lin, 1995; Funge-Smith and Briggs, 1996). In the case of inland shrimp farming in Thailand, the likelihood of no effluents being discharged into the open environment has been questioned (Flaherty et al., 2000). It was argued that there is no guarantee that shrimp farmers will invest in better systems, as most are small-farmers who do not have enough land for waste treatment facilities irrespectively of their willingness and ability to pay for these improvements. Furthermore, even with the adoption of more ”closed” systems, chemical residues would still contaminate the soil on site, and salt content in the area would continue to accumulate. Finally, the wastewater management standards set by the Thai government are widely ignored due to the limited capacity to enforce compliance.

7.5. Wild-caught or farm-raised shrimp

Cultured shrimp only contribute to around 30% of global shrimp production, which is dominated by wild-caught shrimps (Table 1). This fact, together with the ecological and socio-economic problems associated with shrimp aquaculture, has generated discussions of the potential for shrimp-importing countries to actively select for wild-caught shrimps. Apart from the general problem associated with separating shrimps based on their origin, whether fished or farmed, there are a number of aspects worth considering in the context of advantages and drawbacks with the two different production systems (Table 4). It must also be acknowledged that most ocean fisheries stocks are over or fully exploited, and consequently wild-caught shrimps cannot be expected to meet the current market demand.

The primary advantage of well managed shrimp aquaculture over fisheries include predictability of supply and reduced time from harvesting to processing. Aquaculturists are able to estimate the volume of their harvest more readily than fishermen who are dependent on fluctuating wild harvests. When shrimps ponds are ready to be harvested they can be collected all at once and sent for processing. Shrimp fishermen, on the other hand, often stay out on the open seas for several weeks before returning with their harvest. Furthermore, shrimp farmers do not incur the high fuel costs that often make up more than half of the expenses of shrimp fishermen.

Table 5. Comparison of advantages (+) and drawbacks (-) with farmed and wild-caught penaeid shrimps.

SHRIMP AQUACULTURE	SHRIMP TRAWLING
(-) Inability to raise larger shrimp	(+) Ability to harvest high-value large shrimp
(-) High construction costs with increasing intensity	(+) Lower initial and operational costs
(+) Less fuel used per unit of production	(-) Fuel intensive: Š50% of production costs
(-) Dependent on wild stocks that provide seed and spawner input	(-) Completely dependent on vagaries of wild stocks
(-) Declining yields due to poor water quality	(-) Problems with overfishing and environmental impacts
(+) Fresher harvest, can arrive at markets hours after harvest	(-) Can land 2-3 weeks old shrimp
(+) Potential to supply shrimp throughout much of the year since production cycles not as fixed as for wild stocks	(-) Sharp seasonal fluctuations in landings
(-) Very suscepible to disease and environmental problems	(+) Not as susceptible to disease and environmental problems
(-) Due to monoculture operations the economic sustainability of the industry is highly vulnerable in the case of crop failures	(+) Lower risk of "crop failures" since crop is composed of several shrimp and fish species
(-) Environmental problems • Mangrove destruction and degradation • Salinisation of groundwater and soil • Substantial discarded bycatch in seed and spawner fishery • Effluents contain nutrients, chemicals and other pollutants	(-) Environmental problems • Trawl damage sea floor • Substantial bycatch problems
(-) Social impacts • Marginalisation of coastal population • Food insecurity for local communities • Privatisation of common lands • Conflicts	

Shrimp fishermen have at least one market advantage which growers cannot yet match. Part of the trawler catch is high-value large shrimp that seldom, if ever, can be produced in ponds. In many instances, shrimp farmers are forced to harvest early, due to the need to forestall cash crises or to avoid disease outbreaks. Because penaeid shrimp sales generate most of the revenues from mechanised trawling in developing countries, shrimps effectively subsidise commercial fish harvesting efforts by these vessels (Rönnbäck, 1999). The fact that trawl catches include many fishery species lowers the risk of ”crop” failure relative to shrimp aquaculture, which usually only farm one species. Shrimp fishermen have lower costs associated with their production. They do have to maintain their boats and equipment, but do not have to make large capital outlays for facility construction, seed stock, and feeds.

The major drawback with shrimp fisheries is the environmental impacts. People has since long been aware of how trawling damages underwater vegetation and harms both the seabed and numerous ocean species. As nets and boats became more powerful and efficient during the 20th century concerns have grown. While coastal sailboats with small nets still exist, sophisticated trawlers capable of dragging four large nets, staying at sea for weeks at a time, and processing, freezing, and packaging the shrimp before returning to port dominate today’s ocean catches. Trawling affects the bottom-dwelling benthic communities both directly and indirectly.

The direct effects include the damage and often death of both target and non-target species due to physical contact with the trawl or the ”ploughing” of the seabed. Trawl nets can penetrate up to six cm into bottom sediments, and otter boards have been known to dig into the bottom to a depth of 50 cm (Arntz and Weber, 1970; Krost et al., 1990 cf. Clay, 1996). Indirect effects include the suspension of sediments, toxic chemicals and nutrients as well as the trawl bycatch, which affects biodiversity and food web interactions. The most easily measured environmental impact of shrimp wild-capture fisheries is the bycatch. The discarded bycatch from shrimp capture fisheries is estimated at 10 to 11 million tonnes (Alverson et al., 1994) or more than half of the bycatch from all fisheries combined. Bottom trawl fisheries have a staggering discard rate of 200,000 individuals per ton target species, the highest in the world. In contrast, high seas drift net fisheries which is now under a United Nations moratorium, reports a discard rate ranging from a mere 50 to 300 individuals per ton of target species. Nowadays, some countries require devices and fishing techniques that reduce the impact of shrimp trawls on specific species, particularly endangered species. In the U.S.A., for example, trawlers are required to use turtle excluder devices in their nets.

8. POLICY OPTIONS

The formulation of policies directed to assure sustainability of an economic activity like modern shrimp aquaculture should involve many different actors, including consumers, aquaculture entrepreneurs, local communities and government representatives.

8.1. Consumers, industry representatives and local communities as actors

Boycotts and eco-labelling are consumer-driven market mechanisms that can act as a means to modify production processes. Eco-labelled shrimp grown in ecologically and socially responsible farms can command premium prices from generally affluent and environmentally aware consumers. Certification of such shrimp should be undertaken by an internationally acclaimed organisation, although representatives from the government, the aquaculture industry and independent third parties should be approached in the certification process. These groups need to agree on general principles, which can be adapted to specific local conditions.

Policy formulation can also be self-regulated by the industry itself. For example, shrimp farmers can readily undertake self-regulation when they acknowledge the connection between sustainability and long-term profitability. Sectoral codes of conduct on pond design, effluent disposal, groundwater use, etc. are industry initiatives that are consultative, less confrontational than boycotts, and less politically controversial than green taxes (Riggs, 1996).

It is of critical importance that various sectors of local communities are consulted in drawing up codes of conduct as well as during environmental impact and social feasibility assessment and zoning projects (Gujja and Finger-Stich, 1996). However, the groups most vulnerable to the negative effects of shrimp culture generally do not participate in the formulation and implementation of public policies related to aspects like environmental impact assessment (EIA), location of shrimp ponds, farm activity regulation, etc. (Barraclough and Finger-Stich, 1996).

8.2. Government initiatives

8.2.1. Regulatory approach

The December 1996 ruling of the Indian Supreme Court on shrimp projects followed a 1-year moratorium on new shrimp farms declared by the Honduran government to allow public environmental assessment of changes to fish stocks, mangrove cover and biodiversity, and another moratorium on new farms and non-renewal of old licenses announced by the Costa Rican government (Primavera, 1998). In response to shrimp crop failures in 1990, the Thai government announced a set of shrimp farm regulations which required: (i) all farms to register; (ii) farms > 8 ha to set up treatment and sedimentation ponds; (iii) a limit of 10 mg/l biochemical oxygen demand on effluents; (iv) a ban on the release of salt water into public fresh water sources; and (v) a ban on the flushing of mud or silt into natural water sources (Lin, 1995). However, the Thai shrimp farm regulations are hardly monitored and numerous violations can be seen (Dierberg and Kiattisimkul, 1996).

The regulatory approach is surrounded with problems because the targeted sectors, i.e., shrimp farmers, are usually powerful and disregard or circumvent the laws (Alauddin and Hamid, 1996; Barraclough and Finger-Stich, 1996). Shrimp farms less than 50 ha do not require an EIA in Malaysia, and consequently entrepreneurs develop much larger projects in phases to circumvent the need for an EIA (Choo, 1996). Furthermore, there is little will or ability to enforce legislation. The Philippine Fisheries Code of 1970 disallows ownership of mangrove forests placing them under the joint administration of the government fisheries and forestry department, but illegal cutting by members of local political, military or economic elite continues (Primavera, 1993). Government officials tasked to oversee the Ecuadorian shrimp industry are also shrimp producers and exporters with personal economic and political interests (Meltzoff and LiPuma, 1986). Official laws, decrees and regulations forbidding the use of mangroves and agricultural land in shrimp pond construction are often ignored. Another difficulty with regulation is the vague delineation of government agencies responsible for enforcement of specific laws, as well as the level of authority whether local, state/provincial/regional or national. Resources used by shrimp culture such as water and wild postlarvae are readily appropriated because ownership is not clearly defined.

8.2.2. Economic approach

Economic incentives/disincentives may be more effective than traditional regulatory approaches in inducing behavioural changes towards the environment and generating revenues to finance environmental policy programmes (van Houtte, 1995; Primavera, 1998). These may take the form of taxes, penalties and credits for effluent disposal, groundwater abstraction, chemical use, etc.

Such fees should reflect the economic rent of the resource used, for example ground water and mangrove areas converted to pond. Green taxes based on the polluter pays principle can be promoted to mitigate the environmental and socio-economic damage of shrimp farms by correcting water quality problems, financing alternative water supplies in salt-contaminated areas, rehabilitating mangroves and other damaged landscapes, and compensating local populations for the loss of livelihoods (Barraclough and Finger-Stich, 1996). Toward this end, a more comprehensive economic analysis of shrimp culture is needed to incorporate ”externalities” in the final valuation of the product. A cost-benefit analysis (CBA) commissioned by the Indian Supreme Court concluded that shrimp culture caused more economic harm than good, the damage outweighing the benefits by 4 to 1 (63 billion Rupees vs. 15 billion Rupees annual earnings) in Andhra Pradesh and by 1.5 to 1 in Tamil Nadu (Shiva and Karir, 1997). The damage included mangrove loss, salinisation and unemployment.

A number of other CBAs have performed trade-offs between mangrove conservation and conversion into alternative uses like shrimp aquaculture ponds, but their outcome varies greatly (Primavera, 1998; Rönnbäck and Primavera, 1999; Rönnbäck, 2000), and up to date there is no general consensus on the external environmental and socio-economic costs that can be attributed to shrimp aquaculture development. Many CBAs have been criticised for underestimating the true value of mangroves (Barbier, 1994; Rönnbäck and Primavera, 2000). A common feature is the inability to estimate economic values for some goods and most ecosystem services, due to insufficient ecological information or erroneous assumptions. Since cost-benefit analyses usually account for the foregone benefits of not converting mangroves into aquaculture ponds, but only partially cover the foregone benefits of not preserving the mangroves, these analyses becomes biased. Another critique relates to the fact that most trade-off analyses are based on monetary values. Comparisons based solely on monetary values can be misleading, because these values are directly or indirectly based on consumer preferences, and generally derived in terms of small or marginal changes. There is need to expand the concept of economic valuation to include also sustainability aspects and fairness of revenue distribution and not focus entirely on economic efficiency (Costanza and Folke, 1998). In conclusion, we must question the scientific value of resource valuation in its present form and the current use of this ”tool” as the basis for management plans and policy decisions.

Past government policies of export-led development, declaration of coastal land as public resources, and market interventions through loans, subsidies and tax breaks that were used to stimulate industry expansion have also led to environmental destruction. To reverse direction, government can withdraw such subsidies and tax breaks or require environmental planning and performance as preconditions to the approval of loans, credits and subsidies, and access to resources utilised in shrimp culture.

9. CONCLUSIONS

Financially strapped national governments have, often with the assistance of international donor agencies, promoted the development of export-oriented shrimp aquaculture regardless of the environmental and socio-economic consequences. Increased globalisation has enabled producers to transfer production among countries in the event of unacceptable social conflicts, environmental degradation or epidemic disease outbreaks.

The adoption of better farming practices can to a large extent be self-regulated by the shrimp industry. For instance, abandoning shrimp ponds after only a few years due to inappropriate location or poor pond and water management, not only cause considerable environmental and socio-economic damage, it also proves needlessly costly from an economic perspective. Integrated aquaculture, ”closed” systems and other practices that would make shrimp farming more sustainable are already used by some progressive farmers, although there are still hundreds of thousands of farmers that need to adopt more sustainable practices. It is also important to understand that not all investments required for improved environmental and socio-economic sustainability, will be compensated by boosted income for the shrimp farmer. The polluter-pays principle has to be applied so that farmers that does not comply with environmental standards are charged for their own environmental impact. Some sustainability costs will also have to passed on to consumers, who are, after all, the ultimate polluters in the economic system.

10. LITERATURE CITED

Aksornkoae, S., Paphasavait, N., Wattayakorn, G. 1993. Mangroves of Thailand: Present status of conservation, use and management. In: Clough, B. (Ed.), The Economic and Environmental Values of Mangrove Forests and Their Present State of Conservation in the South-East Asia/Pacific Region. International Society for Mangrove Ecosystems, Okinawa, Japan. p. 83-103.

Alcala, A.C. 1988. Effects of marine reserves on coral fish abundance and yields of Philippine coral reefs. Ambio, 17: 194-199.

Aluaddin, M. and Tisdell, C.A. 1996. Bangladesh shrimp industry and sustainable development: Resource-use conflict and the environment. Working Paper no. 1, Shrimp-Rice Farming Systems in Bangladesh Working Paper Series, Univ. Queensland, Brisbane, Australia.

Alversson, D.L., Freeberg, M.H., Pope, J.G. and Murawski, S.A. 1994. A global assessment of fisheries bycatch and discards. FAO Fisheries Technical Paper No. 339. FAO, Rome, 233 pp.

Baconguis, S.R. 1991. Aquasilviculture technology: key to mangrove swamp rehabilitation and sustainable coastal zone development in the Philippines. Canopy International, 17: 1, 5-7, 12.

Banarjee, B.K. and Singh, H. 1993. The shrimp fry bycatch in West Bengal. Bay of Bengal Programme, Madras, India, BOBP/WP/88.

Barbier, E.B. 1994. Valuing environmental functions: tropical wetlands. Land Economics, 70: 155-173.

Barg, U. and Lavilla-Pitogo, C.R. 1996. The use of chemicals in aquaculture: a brief summary of two international expert meetings. FAO Aquaculture Newsletter, 14: 12-13.

Barraclough, S. and Finger-Stich, A. 1996. Some ecological and social implications of commercial shrimp farming in Asia. Discussion Paper. United Nations Research Institute for Social Development & World Wildlife Fund.

Belak, J., Dhar, A.K., Primavera, J.H., de la Pena, L.D., Pettit, P. and Alcivar-Warren, A. 1999. Prevalence of viral diseases (IHHNV and WSSV) in *Penaeus monodon* from the Philippines and its association with mangrove status and shrimp culture systems. In: Alcivar-Warren, A. (Ed.), Proceedings of the Aquaculture and Conservation of Marine Shrimp Biodiversity Symposium Tufts University School of Veterinary Medicine, 10 Dec. 1998.

Beveridge H.C.M., Phillips, M.J. and Macintosh, D.J. 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- 808.

Binh, C.T. 1994. An assessment of integrated shrimp-mangrove farming systems in the Mekong delta of Vietnam. M.Sc. Thesis, Asian Institute of Technology, Bangkok, Thailand.

Boromthanarat, B. 1995. Coastal zone mangement. In: FAO/NACA Regional Study and Workshop on the Environmental Assessment and Management of Aquaculture Development. Network of Aquaculture Centres in Asia-Pacific, Bangkok, Thailand, TCP/RAS/2253, pp. 431-434.

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

Chamberlain G. W. 1997. Sustainability of world shrimp farming. In: Pikitch, E.K., Huppert, D.D.and Sissenwine, M.P. (Eds.), Global Trends: Fisheries Management. American Fisheries Society Symposium 20, Bethesda, Maryland, 1997.

Chan, H.T., Ong, J.E., Gong, W.K. and Sasekumar, A., 1993. The socio-economic, ecological and environmental values of mangrove ecosystems in Malaysia and their present state of conservation. In: Clough, B.F. (Ed.), The Economic and Environmental Values of Mangrove Forests and Their Present State of Conservation in the South-East Asia/Pacific Region, Vol. 1. International Society for Mangrove Ecosystems, International Tropical Timber Organization and Japan International Association for Mangroves, Okinawa, pp. 41-81.

Chin, P.K. 1988. The potential of tiger prawn *Penaeus monodon* broodstock resources in Sabah. In: Singh,T. and Ang, K.J. (Eds.), Marine Prawn Farming in Malaysia. Malaysian Fisheries Society, Serdang, Malaysia, pp. 37-44.

Choo, P.S. 1996. Aquaculture development in the mangrove. In: Suzuki, M., Hayase, S. and Kawahara, S. (Eds.), Sustainable Utilization of Coastal Ecosystems. Proceedings of the Seminar on Sustainable Utilization of Coastal Ecosystems for Agriculture, Forestry and Fisheries in Developing Countries. JIRCAS and Ministry of Agriculture, Forestry and Fisheries, Japan, pp. 63-71.

Clay, J.C. 1996. Market Potential for Redressing the Environmental Impact of Wild Captured and Pond Produced Shrimp. World Wildlife Fund.

Costanza, R. and Folke, C. 1998. Valuing ecosystem services with efficiency, fairness, and sustainability as goals. In: Daily, G.C. (Ed.), Nature's Servives. Island Press, Washington, U.S.A., p. 49-68.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P. and van den Belt, M. 1997. The value of the world's ecosystem services and natural capital. Nature, 387: 253- 260.

Dall, W., Hill, B.J., Rothlisberg, P.C. and Staples, D.J. 1990. The biology of the Penaeidae. Advances in Marine Biology, 27: 1-489.

Daly, H.E. and Cobb, J.B. Jr. 1989. For the Common Good: redirecting the economy toward community, the environment and a sustainable future. Beacon Press, Boston, USA, 482 pp.

Deb, A.K., Das, N.G. and Alam, M.M. 1994. Colossal loss of shell-fish and fin-fish postlarvae for indiscriminate catch of *Penaeus monodon* fry along the Cox's Bazar-Teknaf coast of Bangladesh. In: Wells, P.G. and Ricketts, P.J. (Ed.), Coastal Zone Canada, Cooperation in the Coastal Zone: Conference Proceedings, Vol. 4, pp. 1530-1545. Coastal Zone Canada Association, Bedford Institute of Oceanography, Nova Scotia, Canada.

Dewalt, B.R., Vergne, P. and Hardin, M. 1996. Shrimp aquaculture development and the environment: people, mangroves and fisheries on the Gulf of Fonseca. World Development, 24: 1193-1208.

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

Dore, I. 1994. Shrimp: supply, products and marketing in the aquaculture age. Urner Barry Publishers, Inc., Toms River, New Jersey, U.S.A.

Erftemeijer, P.L.A., Lewis, III, R.R. 2000. Planting Mangroves on Intertidal Mudflats: Habitat Restoration or Habitat Conversion? Paper presented at the ECOTONE-VIII Seminar "Enhancing Coastal Ecosystem Restoration for the 21st Century", Ranong & Phuket, 23-28 May 1999.

FAO. 1995. World Fishery Production, 1950-93. Food and Agriculture Organisation, Rome.

FAO. 1999a. The State of the World Fisheries and Aquaculture 1998. Food and Agriculture Organisation, Rome.

FAO. 1999b. Aquaculture Production Statistics. Food and Agriculture Organisation, Rome.

FAO/NACA. 1995. Report on a Regional Study and Workshop on the Environmental Assessment and Management of Aquaculture Development. Network of Aquaculture Centres in Asia-Pacific, Bangkok, Thailand.

Fast, A.W. and Lester, J. (Eds.). 1992. Marine Shrimp Culture: Principles and Practices. Elsevier Science Publishers, New York.

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

Flegel, T. 1996. A turning point for sustainable aquaculture: The white spot virus crisis in Asian shrimp culture. Aquaculture Asia, July-September, pp. 29-34.

Folke, C. and Kautsky, N. 1992. Aquaculture with its environment: prospects for sustainability. Ocean and Coastal Management, 17: 5-24.

Fosberg, F.R. 1971. Mangroves versus tidal waves. Biological Conservation, 4: 38-39.

Gomez-Gil, B., Tron Mayen, L., Roque, A., Turnbull, J.F., Inglis, V. and Guerra-Flores, A.L. 1998. Species of *Vibrio* isolated from the hepatopancreas, haemolymph and digestive tract of healthy juvenile *Penaeus vannamei*. Aquaculture, 163: 1-9.

Gujja, B. and Finger-Stich, A. 1996. What price prawn? Shrimp aquaculture's impact in Asia. Environment, 38: 12-15, 33-39.

Hamilton, L.S. and Snedaker, S.C. (Eds.). 1984. Handbook for Mangrove Area Management. UNEP and East West Center, Environment and Policy Institute, Honolulu, 126 pp.

Hamilton, L., Dixon, J. and Miller, G. 1989. Mangroves: an undervalued resource of the land and the sea. Ocean Yearbook, 8: 254- 288.

Hirono, Y. 1989. Ecuadorian shrimp industry. In: Proceedings of Shrimp World IV, pp. 151-167. Shrimp World, New Orleans, U.S.A.

Hopkins, J.S., Sandifer, P.A. and Browdy, C.L. 1995. A review of water management regimes which abate the environmental impacts of shrimp farming. In: Browdy, C.L. and Hopkins, J.S. (Eds.), Swimming Through Troubled Water, Proceedings of the Special Session on Shrimp Farming, pp. 157-166. World Aquaculture Society, Louisiana, U.S.A.

van Houtte, A. 1994. The legal regime of aquaculture. FAO Aquaculture Newsletter, 7: 10-15.

Jayasinghe, J.M.P.K. 1995. Country report: Sri Lanka. In: FAO/NACA Regional Study and Workshop on the Environmental Assessment and Management of Aquaculture Development, pp. 357-376. Network of Aquaculture Centres in Asia-Pacific, Bangkok, Thailand, TCP/RAS/2253

Jory, D.E. 1995. Feed managemnet practices for a healthy pond environment. In: Browdy, C.L. and Hopkins, J.S. (Eds.), Swimming Through Troubled Water, Proceedings of the Special Session on Shrimp Farming, pp. 118-143. World Aquaculture Society, Louisiana, U.S.A.

Kautsky, N., Berg, H., Folke, C., Larsson, J. and Troell, M. 1997. Ecological footprint as a means for the assessement of resource use and development limitations in shrimp and Tilapia aquaculture. Aquaculture Research, 28: 753-766.

Kautsky, N., Beveridge, M., Folke, C., Primavera, J.H., Rönnbäck, P. and Troell, M. 2000a. Aquaculture and Biodiversity. In: Levin, S. (Ed.), Encyclopedia of Biodiversity, Vol. 1: 185-198. Academic Press, London.

Kautsky, N., Rönnbäck, P., Tedengren, M. and Troell, M. 2000b. Ecosystem Perspectives on Management of Disease in Shrimp Pond Farming. Aquaculture, 191: 145-161.

Kongkeo, H. 1997. Comparison of intensive shrimp farming systems in Indonesia, Philippines, Taiwan and Thailand. Aquaculture Research, 28: 789-796

Larsson, J., Folke, C. and Kautsky, N. 1994. Ecological limitations and appropriations of ecosystem support by shrimp farming in Colombia. Environmental Management, 18: 663-676.

Lee, S.Y. 1992. The management of traditional tidal ponds for aquaculture and wildlife conservation in Southeast Asia: problems and prospects. Biological Conservation, 63: 113-118.

LeMoullac, G., Soyez, C., Saulnier, D., Ansquer, D., Avarre, J.C. and Levy, P. 1998. Effect of hypoxic stress on the immune response and the resistance to vibriosis of the shrimp *Penaeus stylirostris*. Fish and Shellfish Immunology, 8: 621-629.

Liao, I.-C. 1989. *Penaeus monodon* culture in Taiwan: through two decades of growth. Int. J. Aq. Fish. Tech. 1: 16-24.

Lightner, D.V. (Ed.). 1988. A handbook of shrimp pathology and diagnostic procedures for diseases of cultured penaeid shrimp. World Aquaculture Society, Baton Rouge, LA, USA, 305 pp.

Lightner, D.V., Redman, R.M., Poulos, B.T., Nunan, L.M., Mari, J.L. and Hasson, K.W. 1997. Risk of spread of penaeid shrimp viruses in the Americas by the international movement of live and frozen shrimp. Rev. Sci. Tech. Off. Int. Epiz. 16: 146-160.

Lightner, D.V., Redman, R.M., Poulos, B.T., Tang, K.F.J., Nunan, L.M., Mari, J.L., Pantoja, C.R., Wang, Q., Zhou, J.L., Durand, S., Hasson, K.W. and White, B.L.. In press. The penaeid shrimp viruses TSV, IHHNV, WSSV and YHV: current status in the Ameridas, available diagnostic methods and management strategies. Journal of Applied Aquaculture.

Lin, C.K. 1989. Prawn culture in Taiwan, what went wrong? World Aquaculture, 20: 19-20.

Lin, C.K. 1995. Progression of intensive marine shrimp culture in Thailand. In: Browdy, C.L. and Hopkins, J.S. (Eds.), Swimming Through Troubled Water, Proceedings of the Special Session on Shrimp Farming, pp. 13-23. World Aquaculture Society, Louisiana, U.S.A.

Macintosh, D.J. and Phillips, M.J. 1992. Environmental considerations in shrimp farming. In: de Haan, H. and Singh, T. (Eds.), Proceedings of the Third Global Conference on the Shimp Industry. INFOFISH, Kuala Lumpur, pp. 118-145.

Matthes H. and Kapetsky, J.M. 1988. Worldwide Compendium of Mangrove-Associated Aquatic Species of Economic Importance. FAO Fishery Circular No. 814, FAO, Rome, 238 pp.

Meltzoff, S.K. and LiPuma, E. 1986. The social and political economy of coastal zone management: shrimp mariculture in Ecuador. Journal of Coastal Zone Management, 14: 349-380.

Menasveta, P. 1996. Mangrove destruction and shrimp culture systems. Asian Shrimp News, 3rd Quarter 1: 3.

Moberg, F. and Rönnbäck, P. 2001. Ecosystem services in the tropical seascape: ecosystem interactions, substituting technologies, and ecosystem restoration. Submitted to Ocean and Coastal Management.

Muir, J.F. and Roberts, R.J. 1982. Recent Advances in Aquaculture. Westview Press, Boulder, U.S.A.

National Research Council. 1999. Sustaining Marine Fisheries. National Academy Press, Washington DC.

Naylor, R., Goldburg, R., Primavera, J.H., Kautsky, N., Beveridge, M.C.M., Clay, J., Folke, C., Lubchenko, J., Mooney, H. and Troell, M. 2000. Effect of aquaculture on world fish supplies. Nature, 405: 1017-1024.

New, M.B. and Wijkstrom. 1990. Feed for thought. World Aquaculture, 21: 217-230.

Ong, J.E., 1995. The ecology of mangrove conservation and management. Hydrobiologia, 295: 343-351.

Primavera, J.H. 1993. A critical review of shrimp pond culture in the Philippines. Rev. Fish. Sci., 1: 151-201.

Primavera, J.H. 1998. Tropical shrimp farming and its sustainability. In: S. de Silva (Ed.), Tropical Mariculture. Academic Press, London, pp. 257-289.

Riggs, P. 1996. Trade and environment concerns in the context of aquaculture regulations. Aquaculture Asia, 1: 18.

Robertsson, A.I. and Phillips, M.J. 1995. Mangroves as filters of shrimp pond effluents: predictions and biogeochemical research needs. Hydrobiologia, 295: 311-321.

Rosenberry, B. 1994. World Shrimp Farming, 1994. Shrimp News International, San Diego.

Rosenberry, B. 1997. World Shrimp Farming, 1997. Shrimp News International, San Diego.

Rosenberry, B. 1999. World Shrimp Farming, 1999. Shrimp News International, San Diego.

Rönnbäck, P. 1999. The ecological basis for the economic value of mangrove forests in seafood production. Ecological Economics, 29: 235-252.

Rönnbäck, P. 2000. Fisheries and shrimp aquaculture supported by mangroves: the ecological basis for economic valuation. Paper presented at the thematic session on Rational Use of Estuaries at the International Society for Mangroves (ISME) conference Sustainable use of estuaries and mangroves: Challenges and prospects, 22-28 May, 2000, Recife, Brasil.

Rönnbäck, P. and Primavera, J.H. 2000. Illuminating the need for ecological knowledge in economic valuation of mangroves under different management regimes–a critique. Ecological Economics, 35: 135-141.

Saenger, P., Hegerl, E.J. and Davie, J.D.S. (Eds.). 1983. Global status of mangrove ecosystems. The Environmentalist, 3 (supplement No. 3), 88 pp.

Saenger, P. and Siddiqi, N.A. 1993. Land from the sea: the mangrove afforestation program of Bangladesh. Ocean and Coastal Management, 20: 23-39.

Saitanu, K., Amornsin, A., Kondo, F. and Tsai, C.-E. 1994. Antibiotic residues in tiger shrimp (*Penaeus monodon*). Asian Fisheries Science, 7: 47-52.

Schuster, W.H. 1952. Fish culture in the brackish water ponds of Java. IPFC Spec. Pub. 1: 1-143.

Shiva, V. and Karir, G. 1997. Towards sustainable aquaculture. Research Foundation for Science, New Dehli, India, 133 pp.

Siddall, S.E., Atchue, J.A. III and Murray, R.L. Jr. 1985. Mariculture development in mangroves: a case study of the Philippines, Ecuador and Panama. National Park Service & USAID, Washington D.C.

Siddiqi, N.A., Khan, M.A.S. 1996. Planting techniques from mangroves on new accretions in the coastal areas of Bangladesh. In: Field, C.D., (Ed.), Restoration of Mangrove Ecosystems. International Society for Mangrove Ecosystems, Okinawa, Japan, pp. 143-159.

Sinh, L.X. 1994. Mangrove forests and shrimp culture in Ngoc Hien District, Minh Hai Province, Vietnam. NAGA, ICLARM Quarterly, 17: 15-16.

Smith, P.T. 1998. Effect of removing accumulated sediments on the bacteriology of ponds used to culture *Penaeus monodon*. Asian Fisheries Science, 10: 355-370.

Spaargaren, D.R. 1998. Cultivation of tiger prawns, *Penaeus monodon*, Fabricius, 1798 (Decapoda, Natantia) in Hainan, PR China. Crustaceana, 71: 144-157.

Spalding, M., Blasco, F. and Field, C. (Eds.). 1997. World Mangrove Atlas. The International Society for Mangrove Ecosystems, Okinawa, Japan, 178 pp.

Srisomboon, P. and Poomchatra, A. 1995. Antibiotic residues in farmed shrimp and consumer health. Infofish International, 4: 48-52.

Stevensson, N.J. 1997. Disused shrimp ponds: option for redevelopment of mangroves. Coastal management, 25: 425-435.

Stonich, S.C. and Bailey, C. 2000. Resisting the blue revolution: contending coalitions surrounding industrial shrimp farming. Human Organization, 59: 23-36.

Tacon, A.G.J. 1996. Feeding tomorrow's fish. World Aquaculture, 27: 20-32.

Thongrak, S., Prato, T., Chiayvareesajja, S. and Kurtz, W. 1997. Economic and water quality evaluation of intensive shrimp production systems in Thailand. Agricultural Systems, 53: 121-141.

Troell, M., Rönnbäck, P., Kautsky, N., Halling, C. and Buschmann, A. 1999. Ecological engineering in aquaculture. The use of seaweeds for removing nutrients from intensive mariculture. J. Appl. Phycology, 11: 89-97.

UNEP. 1995. Global Biodiversity Assessment. Cambridge University Press, pp. 387-393.

Weston, D. P. 1996. Environmental considerations in the use of antibacterial drugs in aquaculture. In: Baird, D.J., Beveridge, M.C.M., Kelly, L.A. and Muir, J.F. (Eds.), Aquaculture and Water Resources Management. Blackwell, Oxford, pp. 140-165.

World Resources Institute. 1996. World Resources 1996-97. The World Resources Institute, UNEP, UNDP, World Bank. Oxford Univ. Press, Oxford, 365 pp.