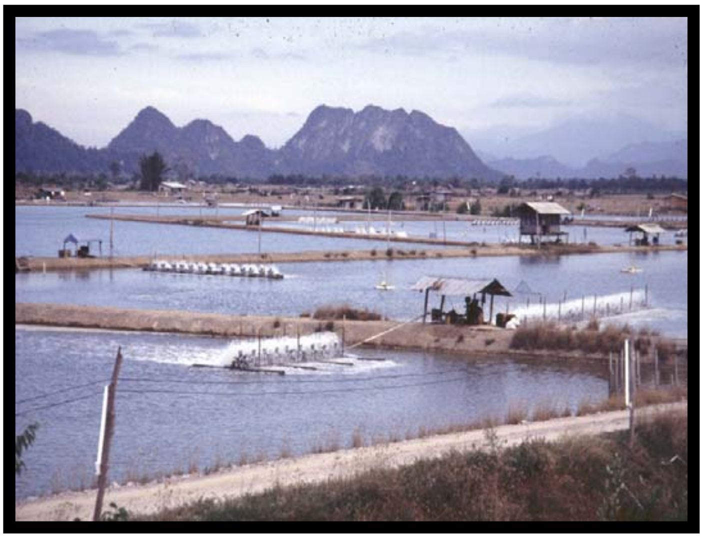
ENVIRONMENTALLY SUSTAINABLE SHRIMP AQUACULTURE



Prepared for the Swedish Society for Nature Conservation by

Patrik Rönnbäck

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SUMMARY

The aquaculture industry has been severely criticised for the environmental and socio-economic problems generated in its backwaters. The adoption of better farming practices can to a large extent be self-regulated by the shrimp industry. 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.

This report suggests a number of criteria that would improve the environmental sustainability of the industry. Environmental impacts such as mangrove conversion, seed bycatch, introduction of alien species and diseases, water use, supplementary feeding, nutrient loading, and chemical and antibiotic use are analysed with the ambition to ameliorate some of the environmental concerns. Two types of production systems that would rank high in terms of environmental sustainability are identified: (i) extensive, integrated systems that have been practised for hundreds of years in some locations; and (ii) intensive, "closed" systems that enables the farmer to better control the farming environment. The advantages as well as drawbacks with these systems are reviewed in detail. At present these systems contribute only marginally to global shrimp aquaculture output, although this may change given adequate regulations and financial incentives. It must, however, be emphasised that in the foreseeable future shrimp aquaculture will continue to constitute a net loss to global seafood production.

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INTRODUCTION

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 polycultures 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.

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 last decade, 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, 1999a). 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. The giant tiger shrimp – *Penaeus monodon* – accounts for more than half of the total shrimp aquaculture output (Rosenberry, 1999). Other important commercial species are *P. vannamei, P. indicus, P. merguiensis* and *P. chinensis*.

The shrimp aquaculture industry has in many countries been severely criticised for the environmental and socio-economic problems generated in its backwaters (Beveridge et al., 1997; Primavera, 1998; Naylor et al., 2000; Rönnbäck, 2001). 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. There are many recommendations on how to make shrimp aquaculture environmentally and socio-economically sustainable (Macintosh and Phillips, 1992; Primavera, 1998; Troell et al., 1999; Kautsky et al., 2000a,b; Naylor et al., 2000; Rönnbäck, 2001; Rönnbäck et al., 2001). This report reviews the environmental impacts that arise from shrimp aquaculture, whereafter a number of criteria that would improve the environmental sustainability of the industry are suggested. There are two types of shrimp aquaculture production systems that would rank high in terms of sustainability: (i) extensive, integrated systems that have been practised for hundreds of years in some regions; and (ii) intensive, ”closed” hatchery and grow-out systems that enable the farmer to better control the farming environment (Primavera, 1998; Kautsky et al., 2000b; Rönnbäck, 2001). The advantages as well as drawbacks with these systems are reviewed in detail.

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**		
	Total	**Warm-water**		**Relative proportion**	
	(1000*t)	**(1000*t)**	**(1000*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%

Table 2. Country-wise production statistics for shrimp aquaculture in 1998. Source: Rosenberry (1999)

	Pond area (ha)	**Production (t)**	**Relative prod. (%)**	**Productivity (kg/ha)**	**Farming intensity (%)**		
					Extensive	**Semi-intensive**	**Intensive**
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			
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			
TOTAL	1 251 450	814 250		651			

ENVIRONMENTAL IMPACTS

Shrimp aquaculture is fraught with environmental problems that 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 (Kautsky et al., 2000a; Rönnbäck, 2001). 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 different environmental impacts are reviewed below, and the guidelines for improved sustainability presented in Table 3.

Mangrove conversion

The deforestation of mangroves to accommodate shrimp ponds is perhaps the most alarming environmental damage caused by shrimp aquaculture development (Rönnbäck, 2001). 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 (Hamilton et al., 1989; Primavera, 1998). Apart from the direct conversion of mangroves into shrimp ponds, this ecosystem is also indirectly degraded as a result of altered hydrodynamic regimes due to the construction of access roads and water canals. As a paradox, the productivity and sustainability of shrimp aquaculture is directly dependent on the continuous support of mangrove goods like seed and spawners as well as services like water quality maintenance and erosion control (Beveridge et al., 1997; Rönnbäck, 1999; Kautsky et al., 2000b). The industry thus challenges its own life-support system. It has been estimated that the spatial mangrove ecosystem support, or "ecological footprint", required to produce food inputs, nursery areas and clean water, as well as to process wastes, was up to 160 times the surface area of the farm (Larsson et al., 1994; Kautsky et al., 1997).

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 (Kautsky et al., 2000b; Rönnbäck, 2001). 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.

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 (Rönnbäck, 2001). 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). 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.

Bycatch problems associated with seed inputs

The shrimp seed (postlarvae) that are stocked in grow-out ponds can originate from four different sources (Rönnbäck et al., 2001). Naturally occurring wild shrimp seed can be allowed to enter traditional ponds with (i) incoming tidal waters or (ii) 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 broodstock. The broodstock can be separated into (iii) gravid female spawners and (iv) immature brooders allowed to maturate in captivity.

The fisheries for wild shrimp seed as well as broodstock are fraught with bycatch problems. The seed are caught in coastal waters using fine-meshed nets that inevitably trap large quantities of other invertebrates and fish, which are usually sorted out and discarded on land. 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 (reviewed by Primavera, 1998). The amount of bycatch destroyed globally is staggering and could have major consequences for biodiversity and capture fisheries production. Although the development of hatcheries for cultured shrimp species have reduced the dependence on wild seed, it has increased demand for wild-caught broodstock. 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). Broodstock fisheries can thus lead to large amounts of bycatch with implications for biodiversity and capture fishery production. However, since the bycatch is discarded at sea, the negative impact is less detrimental compared to wild seed fisheries where the entire bycatch is usually killed (Rönnbäck et al., 2001). Broodstock fisheries are also less wasteful, because some of the bycatch is kept and landed by the fishermen.

Closure of the hatchery cycle by improved breeding and domestication programs would reduce the demand for wild-caught shrimp postlarvae and broodstock, 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.

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.

The introduction of postlarvae and broodstock from areas affected by the Whitespot Syndrome Virus (WSSV) and Taura Syndrome Virus (TSV) has often been 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). 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 import of live *P. monodon* in the early 1970s (Lightner et al., 1997). In the Philippines, IHHNV prevalence in various wild populations *P. monodon* 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.

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 could enable the hatcheries to produce their own broodstock, and greatly reduce the need for shrimp transfer between regions and countries. The industry should thus focus their production on shrimp species, which at present, or at least within short, can easily be fully domesticated at hatcheries. Naturally, environmentally responsible shrimp aquaculture cannot involve any genetically modified organisms (GMO).

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, 1997). 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.

In order to reduce the problems associated with water use, shrimp aquaculture ponds need to invest in re-circulating systems that aim at closing the cycle at the pond level. The need for water input is thus reduced. Developing the methodology for farming shrimps in fully marine waters could reduce the dependence on fresh water sources to achieve brackish water salinity in ponds. In large river deltas and in inland areas it may, however, be more important to develop the methodology for farming shrimps in low salinity waters to minimise the risk of salinisation of adjacent soil and water.

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 fishmeal and fish oils (Table 4). These latter systems use more than 2 times more protein, in the form of fishmeal, to feed the farmed shrimps than is ultimately harvested (Tacon, 1996). Consequently, these systems constitute a net loss to global seafood production.

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, 1999b).

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). The use of fishmeal should also be restricted to trimmings of fish processed for human consumption, in order to reduce the net loss to global seafood production. 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.

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.

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; Troell et al., 1999); and the use of mangroves as biofilters for pond discharge prior to the release of effluent to estuarine waters (Robertson and Phillips, 1995). Furthermore, the use fertilisers should be restricted to organic products.

Chemical and antibiotic 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). Recently, the Swedish National Food Administration found residues of the highly toxic antibiotic chloramphenicol in shrimps imported from Vietnam. Following an alert in August 2001, it only took three months and the control of around ten shipments before the Swedish authorities detected this problem. 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.

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.

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.

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.

Table 3. Defining the local/regional and global criteria for improved environmental sustainability in shrimp aquaculture.

LAND USE	
local	• Do not convert mangrove ecosystems or agricultural land into shrimp ponds
	• Reduce the negative indirect impact on mangroves caused by access roads and water canals
	• Initiate mangrove restoration programs where aquaculture development has caused significant damage to this ecosystem
	• Minimise land use by good management
	• Place pond in areas with low population density to minimise land and water use conflicts
	• Use feasibility studies prior to development to minimise risk of arising resource use conflicts
	• Avoid overcrowding of ponds that exceeds the environmental carrying capacity (use e.g. the "ecological footprint" concept)
global	• Locate ponds in consumer countries
SEED AND INTRODUCTION OF ALIEN SPECIES AND DISEASE	
local	• No use of gentically modified organisms (GMO)
	• Use hatchery produced seed
	• Close cycle in shrimp hatcheries by domesticating shrimps
	• Farm only native species
global	• No transport of seed and broodstock between countries
WATER USE	
local	• Reduce water exchange rates and thus water input requirement
	• Site-specific methodlogical considerations: – develop the farming of shrimps in fully marine waters to reduce the dependence on fresh water sources – develop the farming of shrimps in low salinity waters to minimise the risk of salinisation of adjacent soil and water
FEED	
local	• Use culture system that utilise natural or stimulated production in the ponds or incoming waters
	• Minimise the food conversion ratio (FCR) through proper management
global	• Develop and use formulated feeds not based on fishmeal and fish oil, or at least drastically reduce content of these
	• Use fish meal based on trimmings of fish processed for human consumption
NUTRIENT LOADING	
local	• Use only certified organic fertilisers
	• Reduce water exchange rates and thus the amount of effluent discharge
	• Reduce nutrient concentrations in effluents by investing in settling and biological treatment ponds, including integrated farming with e.g. seaweeds and filter feeders
	• Improve feeds and management to reduce the food conversion ratio (FCR)
	• Remove salt from sludge and use as fertiliser
CHEMICAL AND ANTIBIOTIC USE	
local	• Reduce the need for chemicals and antibiotics by improved pond and water management that limit the risk of exceeding the local carrying capacity of the environment
global	• Minimise or refrain from chemical use
	• Refrain from antibiotic use
	• Use probiotics

SUSTAINABLE FARMING PRACTICES

The most common farming techniques are extensive, semi-intensive, and intensive practices. 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 4). The farmers that exercise 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. 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.

Table 4. 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/m^2)	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,
Pond construction cost		US $10-35,000/ha	US $25-250,000/ha
Production cost per kg	US $1-3	US $2-6	US $4-8

The above farming practices have all been severely criticised for their environmental unsustainability. 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. The potential as well as drawbacks with these systems are outlined in Table 5. It is important to acknowledge that neither integrated nor “closed” systems can fulfil all the general sustainability criteria outlined in Table 3. Rather, specific sustainability criteria should be formulated for each system.

Table 5. The advantages (+) and drawbacks (-) with integrated mangrove-aquaculture in relation to inland "closed" farming systems.

INTEGRATED MANGROVE-AQUACULTURE SYSTEMS	INLAND INTENSIVE "CLOSED" SYSTEMS
(+) Labour-intensive	(-) Capital-intensive
(+) High diversity of cultured species	(-) Usually monoculture focus
(+) Low water exchange rates	(+) Minimal water exchange rates
(+) Tight nutrient recirculation	(+) Tight nutrient recirculation if successful
(+) Low nutrient concentration in effluents	(+) Very low nutrient concentration in possible effluents
(+) Low susceptibility to disease	(-) More susceptible to disease
(+) Minimal chemical use	(-) Regular use of chemicals
(-) Seed are usually wild-caught	(+) Seed are hatchery produced
(+) Local seed source	(-) May involve shrimp transfer between regions
(+) Natural or stimulated pond production as main feed input	(-) Depend solely on formulated feeds
(-) Low productivity result in the requirement of large coastal areas to meet consumer demand	(+) Minimal land use due to high productivity (+) Ponds can be located away from coastal lands
(-) May conflict with mangrove conservation	(-) May cause salinisation of adjacent soil and water inland
(+) Stimulate plantation of mangroves if located in idle shrimp or salt ponds	(-) Can systems be fully "closed"? (-) Many countries lack regulations and have limited capacity to enforce set management standards
(-) Obstruct the flow of goods and services generated by natural mangrove ecosystems	(+) Ponds can be located in consumer countries

Ecological alternative: 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), silvofisheries (*tambak tumpang sari*, *tambak empang parit, and hutan tambak*) in Indonesia (Fitzgerald, 1997), mangrove-shrimp ponds in Vietnam (Binh, 1994), and aquasilviculture in the Philippines (Baconguis, 1991) (Table 6). 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. 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 higher yielding integrated mangrove-aquaculture systems have the potential to significantly contribute to global shrimp aquaculture production if more ponds 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. For instance, Indonesian silvofisheries ponds produce more than 2000 kg fish per ha annually (Sukardjo, 1999 in Primavera, 2000). 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.

The integrated mangrove-aquaculture systems are labour-intensive rather than capital-intensive, and consequently they offer coastal communities the possibility for income and employment (Primavera, 1998; Rönnbäck, 2001). 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 (Rönnbäck, 2001). 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. Farming is in tune with ecosystem processes, which make the system less susceptible to disease outbreaks. Consequently, the need for chemical use is reduced. Seed are usually wild-caught or allowed to enter the ponds with incoming tides, which limits the risk introducing alien species and diseases along with shrimp transfer. One major drawback with many types of integrated mangrove-aquaculture is, however, that these systems involve some mangrove conversion, although their impact on lost mangrove goods and services has to be further assessed. 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.

At the moment, the shrimp produced in integrated mangrove-aquaculture systems only make a marginal contribution to global aquaculture output. The area cover of these systems lies in the order of 10,000 ha, although the exact coverage has not been assessed (Table 6). Assuming a total coverage of 10-20,000 ha and a productivity of 100-400 kg shrimps per ha annually, gives a total output of 1,000 to 8,000 ton per year. This is only 0.1-0.8% of global aquaculture production that amounts to 950,000 ton per year (Table 1). The relative importance of integrated mangrove-aquaculture systems could, however, be increased by either modifying other existing systems into integrated practices or by encouraging the use of integrated techniques whenever new shrimp ponds are developed. The productivity per unit area integrated pond can never compete with that of more intensive systems not affected by disease, and consequently large coastal areas converted would be required to supply the international shrimp demand with shrimps farmed in integrated systems. The development of new ponds should therefore not be located in areas where land use conflicts are likely to arise. The conversion of mangroves and agricultural land should be discouraged. Available coastal land that can be set aside for shrimp aquaculture development must be determined in regional or national feasibility studies. Naturally, these studies must acknowledge environmental and social concerns. Existing semi-intensive and intensive ponds located in the intertidal zone could be modified into integrated mangrove-aquaculture systems. This would improve the sustainability of these systems, but most individual farmers are still unlikely to take this step willingly, and consequently certain types of regulatory approach or financial incentives have to be developed. A straightforward initial step would be to plant mangroves in abandoned or idle shrimp ponds and convert these into integrated systems.

Table 6. Shrimp aquaculture systems integrated with mangroves in Southeast Asia. Adapted from Primavera (2000).

	HONG KONG	**INDONESIA**	**INDONESIA**	**VIETNAM**	**PHILIPPINES**
Technology	Traditional *gei wai*	Traditional *tambak*	Silvofisheries	Mixed shrimp-mangrove	Aquasilviculture
Year started	mid-1940s	1400s	1976 (trials in 1950s)	mid-1980s	1987
Area cover	250 ha	wide area	wide area (6,600 ha in West Java alone)	widespread (thousands of ha)	< 10 ha experimental
Objectives	shrimp, fish production; mangrove, wildlife conservation	food, fuel, fertiliser, fodder, soil stabilisation	mangrove rehabilitation, conservation; relieve forestry-fisheries conflict	mangrove rehabilitation; relieve land use conflicts	increase income for artisinal fishermen
Cultured species	shrimp, fish (tidal entry)	shrimp, fish (tidal entry) milkfish (stocked)	shrimp, fish (tidal entry) milkfish (stocked)	shrimp (tidal entry)	shrimp, fish (tidal entry) milkfish, crab (stocked)
Feed	natural	natural	natural + formulated	natural	natural + formulated
Productivity	15-40 kg shrimp/ha/yr		200-400 kg shrimp/ha/yr	100-400 kg shrimp/ha/yr	
Problems	declining shrimp yield; industrial pollution; trade-off between wildlife and aquaculture management	pond intensification	difficult management; conflict in choice of mangrove species	declining shrimp yield; illegal mangrove conversion	mangrove tree mortality; development of raw (trash) fish substitutes

Technological alternative: 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 (Rönnbäck, 2001). 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 wastewater 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; Rosenberry, 1999). The technology for “closed” farming systems is still in the experimental phase, and currently the relative contribution to global shrimp aquaculture output is marginal from these systems. 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-scale farmers who do not have enough land for waste treatment facilities irrespectable 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.

There are, however, a number of advantages with these “closed” systems. The nutrient recirculation is high, and although it may be difficult to completely “close” the cycle, the nutrient loading from these systems is relatively low. Furthermore, if these systems can avoid disease problems, they have very high productivity per unit area. This implies minimal land use to supply the consumer market. Perhaps the most interesting 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 (Kautsky et al., 2000b). Furthermore, these countries have generally a much better capacity to enforce that the set aquaculture standards are complied by the individual farmers.

CONCLUSIONS

This report identifies a number of criteria that would improve the environmental sustainability of shrimp aquaculture systems. One major focal point is that the development of new farming areas should not result in any mangrove clearance. Improved pond and water management would reduce water exchange rates, supplementary feed requirements, disease susceptibility, chemical use, etc. Given adequate training and awareness programmes, these managerial aspects should be self-regulated by the industry since they are all cost-effective measures.

Two culture systems – extensive, integrated mangrove-aquaculture and intensive, "closed" practices – that would rank high in terms of sustainability are identified in this report. Each of these systems have a number of advantages as well as drawbacks, and the future investments in these systems has to be viewed in a country-specific context. At present both integrated and "closed" systems contribute only marginally to global shrimp aquaculture output, although this may change given adequate regulations and financial incentives.

It must, however, be emphasised that in the foreseeable future shrimp aquaculture will 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. Aquaculture systems should be affordable to local people and primarily generate products for the local market. Thus, instead of favouring the rapid expansion of high-valued carnivorous species like shrimps in the tropics and salmon in the temperate zone, 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.

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