Issues, Impacts, and Implications of Shrimp Aquaculture in Thailand[1]

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ABSTRACT / Water quality impacts to and from intensive shrimp aquaculture in Thailand are substantial. Besides the surface and subsurface salinization of freshwaters, loadings of solids, oxygen-consuming organic matter, and nutrients to receiving waters are considerable when the cumulative impacts from water exchange during the growout cycle, pond drainage during harvesting, and illegal pond sediment disposal are taken into account. Although just beginning to be considered in Thailand, partial recirculating and integrated intensive farming systems are producing promising, if somewhat limited, results. By providing on-site treatment of the effluent from the shrimp growout ponds, there is less reliance on using outside water supplies, believed to be the source of the contamination.

The explosion in the number of intensively operated shrimp farms has not only impacted the coastal zone of Thailand, but has also resulted in an unsustainable aquaculture industry. Abandonment of shrimp ponds due to either drastic, disease-caused collapses or more grandual, year-to-year reductions in the productivity of the pond is common. To move Thailand towards a more sustainable aquaculture industry and coastal zone environment, integrated aquaculture management is needed. Components of integrated aquaculture management are technical and institutional. The technical components involve deployment of wastewater treatment and minimal water-use systems aimed at making aquaculture operations more hydraulically closed. Before this is possible, technical and economic feasibility studies on enhanced nitrification systems and organic solids removal by oxidation between production cycles and/or the utilization of plastic pond liners need to be conducted. The integration of semi-intensive aquaculture within mangrove areas also should be investigated since mangrove losses attributable to shrimp aquaculture are estimated to be between 16 and 32% of the total mangrove area destroyed betweeen 1979 and 1993.

Government policy needs to devote as much attention to sustainability issues as it has on promoting intensive pond culture. Such a balanced policy would include training and education monitoring and enforcement, rehabilitating abandoned ponds, managing land use within the coastal zone, more community involvement, and government reorganization to eliminate overlapping jurisdictions among agencies.

As integrated aquaculture management becomes more the practice than the exception, less risk of crop failure to the industry and reduced discharge loadings from intensively managed shrimp ponds to receiving waters can be expected. Projected limitations on growing and marketing shrimp in the future, such as scarcity of land and broodstock, continued disease outbreaks, negative publicity, regulatory enforcement, water treatment and solids disposal costs, and increased competition from growers in other Asian countries will also drive the government and the industry towards adopting integrated aquaculture management.

As a result of technological advances, government subsidies, and profitable markets, the culturing of penaeid shrimp has been the leading aquaculture growth industry in Thailand, as well as other South East Asian countries. The black tiger shrimp, *Penaeus monodon* Fabricius, is the most commonly cultured shrimp in South East Asia (FAO 1992).

Since 1991, when 162,000 metric tons of cultured marine shrimp were produced (FAO/NACA 1995), Thailand has maintained its position as the world's leading producer (Csavas 1994a). A total estimate of 282,100 tonnes was produced in Thailand in 1993 (personal communication, Thai Department of Fisheries, 8 Sep-

KEY WORDS: Shrimp aquaculture; Thailand; Historical practices; Environmental impacts; Sustainability; Integrated management; Water treatment; Institutional aspects

[1]The data for this paper was obtained while the senior author was a Visiting Fulbright Researcher at the Coastal Resources Institute (CORIN), Prince of Songkla University, Hat Yai, Songkhla, 90112, Thailand.

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tember, 1994); 70% of that was farm-raised shrimp. With an average annual production increase of 19% during 1987 to 1993, Thailand has also become the world's major exporter of shrimp. The 1992 shrimp product export was valued at $124 million dollars, which comprised close to 1% of Thailand's gross domestic production (FAO/NACA 1995).

Because of Thailand's success, other countries in South and South East Asia (India, Myanmar, Cambodia, Vietnam, Indonesia, China, Philippines, and Malaysia) have instituted programs and incentives to encourage their own shrimp farming industry. As a result, about 82% of the world production of prawns and shrimp occurs in Asia (Csavas 1994b).

Although coastal shrimp aquaculture has been practiced in Thailand for over 50 years, it has only been within the past 9 years that the extent and intensity of aquaculture activities increased to such a level that major legitimate environmental concerns have been raised. Since most of the farm-raised shrimp come from ponds constructed in coastal areas, profound impacts to the coastal zone are occurring. Not only is there a need for an environmental assessment of the impact of shrimp aquaculture in the coastal zone, but the exploration and implementation of political, institutional, and technical solutions for planning new, and restoring abandoned, shrimp farms are essential.

Most research efforts have been concentrated on increasing pond productivity (e.g., disease prevention and control, dietary regimens, aeration); few scientific data are available for quantitative assessment of the environmental impacts. Even the water-quality issues are focused on evaluating the effects of poor-quality source water on shrimp yields rather than on the impacts of discharges released from shrimp ponds on receiving waters. Although there have been some published in-country and international reports regarding environmental impact assessments (MIDAS Agronomics 1995, FAO/NACA 1995, Tiensongrusmee and Philipps 1994, Phillips 1994), they are not circulated widely outside the region or the aquaculture community. Most of the reports rely on surveys, anecdotal information, and historical events upon which to base generalizations. As a result, little to nothing is known about the environmental effects of coastal shrimp aquaculture operations outside the farm (Barg 1992), even though the environmental issues receive a lot of attention from the public, press, government, and nongovernment organizations.

The purpose of this paper is to present the environmental impacts of intensive shrimp aquaculture on Thailand's coastal zone and to offer some recommendations that will lead not only to a more sustainable production of shrimp, but also to a more sustainable use of coastal resources. First we will present a short history of the shrimp aquaculture production and practices in Thailand. Next will follow descriptions of the major impacts that shrimp aquaculture are having in Thailand, with particular emphasis on the water-quality aspect. Recommendations are then suggested that not only are needed to better understand and diagnose the environmental problems associated with shrimp farming, but also to alleviate the impacts and make the industry more sustainable. We conclude with a prediction on the changes that may be expected by the Thai shrimp farming industry into the 21st century and the importance of adopting an integrated coastal zone management strategy.

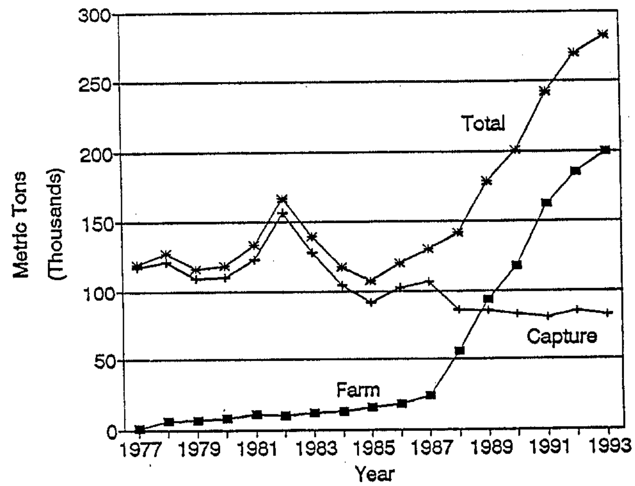


Figure 1. Farm-raised and wild-captured shrimp harvests in Thailand. The data for 1993 are estimates. Source: FAO/NACA (1995).

Evolution of Shrimp Farming Practices in Thailand: The Trend Towards Intensification

Although the rapid rise in farm-raised shrimp production can be attributed to the construction of new ponds, adoption of new farming practices has also contributed significantly to the increase in production levels. A dramatic increase in farm-raised shrimp production occurred in the mid-1980s, which corresponded to the growth of more "intensified" production systems (Kikuchi 1993); the capture industry has remained rather steady during that period of time (Figure 1). After 1989, the farm-raised shrimp production exceeded the captured shrimp, attaining 200,000 metric tons in 1993.

Historically, shrimp culture was probably practiced in Thailand when seawater flooded low-lying coastal

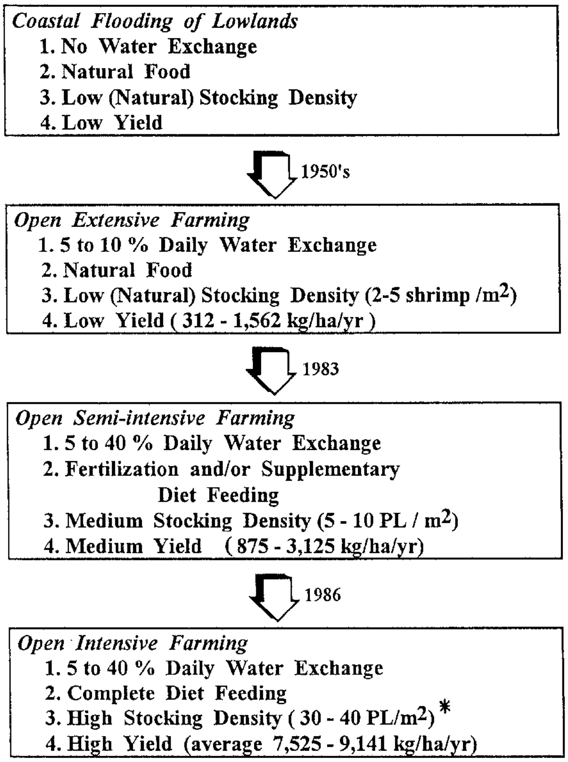


Figure 2. Evolution of shrimp farming practices in Thailand until 1992. Data from FAO/NACA (1995), Tiensongrusmee and Phillips (1994), and Barg (1992). *This is a recommended stocking density by the Thai Department of Fisheries, but postlarvae (PL) stocking densities of 50–100 individuals/m^2 are not unusual (FAO/NACA 1995).

areas, trapping shrimp larvae and adults. The first actively managed shrimp farms occurred in the 1950s in the provinces immediately south of Bangkok at the upper end of the Gulf of Thailand. These were extensive ponds, typically 8–16 ha each (Tiensongrusmee and Phillips 1994) and shallow (50–60 cm) (FAO/NACA 1995).

In the early 1980s, open semi-intensive farming took hold, which required less area (3–5 ha) but more daily water exchange (FAO/NACA 1995) than the extensive system (Figure 2). Inexpensive "push pumps" provided the means for improving the water exchange. The natural food and stock sources of the extensive system were replaced with fertilization or supplementary diet feeding and manipulated stocking densities. Yields improved two to three times with the more managed semi-intensive systems (Figure 2).

Open intensive farming became more common during the mid-1980s, coinciding with the beginning of the rapid increase in farm-raised shrimp after 1987 (Figure 1). By 1994, 80% of Thailand's shrimp farms were intensive farming systems (Rosenberry 1994). The open intensive ponds still required large amounts (5%–40%) of daily water exchange to maintain suitable water quality (Barg 1992), but they were deeper (2–2.5 m) and each pond occupied less area (<1 ha) (FAO/NACA 1995) than either of the previously two managed systems (extensive and semi-intensive). Due to higher stocking densities and more diet feeding, yields increased three- to fourfold over the semi-intensive farming systems (Figure 2). By comparing the shrimp production of 125 kg/ha/crop in 1977 (CORIN 1995), when extensive farming was practiced, to the 2580 kg/ha/crop in 1992 (CORIN 1995), when 80% of Thailand's shrimp farms were intensively managed (Rosenberry 1994), the 20-fold increment in 15 years represents the contribution that intensively managed farms has made to shrimp yields.

Environmental Impacts

Although it is undeniable that the growth of the shrimp aquaculture industry in Thailand has benefitted the social and economic well-being of numerous individuals, there also have been significant environmental impacts (Table 1). We have grouped these into seven major categories: mangrove/wetland destruction; saltwater intrusion; land subsidence; water-quality impairments; sediment disposal; abandoned shrimp ponds; and displaced traditional livelihoods.

Mangrove Destruction

Extent of mangrove replaced by aquaculture farms. As in other areas of the world, perhaps the single largest impact of the rapid rise in intensive shrimp farming in Thailand is the destruction of mangrove wetlands. The rate of the decimation of mangrove forests has been phenomenal in some provinces (Vibulsresth and Murai 1991), although not all of it is due to shrimp farming. However, the replacement of mangroves by shrimp ponds has been documented to be extensive for some localities. For example, no less than 85% of the 69.4 km^2 of mangroves destroyed in the northern part of Pak Phanang District between 1966 and 1991 was due to shrimp farming (CORIN 1992); in Chantaburi Province, nearly all new ponds over the past 10 years have been constructed in mangrove areas (KKBRDSC 1992).

How much of the mangrove forest destroyed throughout Thailand between 1961 and 1986 (or 1989) was due to shrimp pond construction is not known with certainty, but estimates in the literature range from 21% to 64% (Table 2). The differences in the estimates notwithstanding, most have probably overestimated the replacement impact that shrimp farm construction has

Table 1. Major environmental impacts of shrimp aquaculture

Mangrove/wetland destruction
Reduced biodivesity
Reduced catch yields of commercially important species including seed for the shrimp industry
Coastal erosion
Acidification
Loss of detrital material
Loss of forestry products (e.g., charcoal)
Saltwater intrusion
Surface waters
Groundwaters
Soils
Land subsidence
Water quality degradation
Siltation
Eutrophication
Oxygen depletion
Toxicants (i.e., sulfide, ammonia, therapeutants, wastewater treatment chemicals)
Sediment disposal
Saline
Sediment accumulation
Abandoned shrimp farms
Traditional livelihoods displaced
Rice farming
Artisinal fisheries (e.g., mollusc, crab, finfish)
Charcoal production

had on mangroves since it is likely they assumed that every shrimp farm was constructed in a mangrove area. Our estimates, based on shrimp pond construction and mangrove conversion data provided by FAO (1985), Tiensongrusmee and Phillips (1994), and FAO/NACA (1995), assign between 16% and 32% (depending on whether 33% or 67% of the shrimp farm construction was at the expense of mangroves) of the loss of mangroves between 1975 and 1993 to shrimp farm construction. Even less mangrove loss (12%–25%) due to shrimp farming is estimated between 1961 and 1993.

Economic impact. An advantage to locating an aquaculture farm in mangrove habitat is the close proximity to the ocean, where tidal energy and the short length of canals provide cost savings in water exchange, and perhaps a cleaner source of supply water. However, there are clear economic disincentives if shrimp ponds are located in mangrove areas. The most notorious of them is the unsuitability of the acid sulfate sediments common in mangrove areas, which can reduce growth and survival of cultured animals (Poernomo and Singh 1982, Simpson and others 1983). The low pH and the abundance of iron and aluminum ions also result in phosphorus precipitation, thereby lowering the natural food production (algal growth) within the pond (Poernomo and Singh 1982).

If untreated, estimated rates of leaching from dike soils suggest that acidity problems can persist for years (Simpson and others 1983). The remedies are time-consuming and add expense and include trucking in nonacidic soil to cover the pond bottom and constructing dikes; liming (Pedini 1981); successive leaching and drying (Simpson and others 1983); and/or reclamation by a repeated sequence of drying (for oxidation), plowing, flooding, and then flushing with lime application at the end (Poernomo and Singh 1982). Besides the effects of the acid sulfate soils, added expenses are incurred by using heavy equipment in the soft organic substrate for pond construction and in removing mangrove stumps (FAO/NACA 1995).

Intact mangrove stands provide a diverse array of "free" services (i.e., coastline stabilization; nursery grounds for fish, crabs, and shirmp; nutrient and sediment traps; BOD removal; organic matter production; water conservation), which would need to be replaced at higher costs if mangroves were exploited. A particularly valuable function that mangroves can provide to a fish farmer is treatment of wastewaters high in organic matter, nutrients, and solids, which are predominant in intensively managed shrimp farms (Tables 3 and 4). If effluents from shrimp ponds were distributed in nearby mangrove forests prior to return of pond water to the estuary, water rich in particulates, nutrients, and BOD from shrimp ponds will be renovated, thereby improving the discharge water quality to the receiving estuary. For example, Nedwell (1975) observed that mangrove sediments had high denitrification potentials, particularly in areas near sewage discharges. The high capacity of mangrove sediments for denitrification is particularly attractive for economically removing the nitrate-laden pond waters released during harvesting, assuming efficient nitrification is promoted within the production/treatment system on the farm.

Since such external costs associated with the removal of mangroves for culture ponds are usually not considered (Primavera 1993), primarily because they have yet to be established (FAO/NACA 1995), most economic analyses favor higher returns for intensive shrimp farms than from intact mangrove (FAO/NACA 1995). However, the economics may be substantially affected when mangrove long-term sustainability, its multipurpose uses (i.e., erosion control, sediment traps, wood production, nursery/breeding grounds), and unsuitability of the acid sulfate sediments are considered in the analysis (FAO/NACA 1995). Dixon (1989) suggested that the annual value of mangroves is between $500 and $2500/ha when fishery and forestry benefits are included. Primavera (1993) reported even higher values for intact/managed mangroves ($11,600/ha/y). Unfortunately

Table 2. Estimates of amount and percentage of mangrove forests displaced by shrimp farms in Thailand

Years	Land use	Area (ha)	Mangroves displaced by shrimp farms (%)	Source
1961–86	Mangrove	−171,464	—	Aksornkoae 1993
1961–86	Mangrove	−88,006	—	Chancharaswat 1991
1961–89	Mangrove	−187,340	—	Kongsaengchai 1991 (cited in Tiensongrusmee and Phillips 1994)
1961–86	Shrimp farm	+109,737	64	Aksornkoae 1993
1961–89	Shrimp farm	—	50	MIDAS Agronomics 1995
1961–86	Shrimp farm	+37,993	43	Chancharaswat 1991
1961–89	Shrimp farm	+444,785	38	FAO/NACA 1995
	Shrimp farm	—	25	GESAMP 1991
1980–89	Shrimp farm	—	21	Macintosh and Phillips 1992
1961–93			12–25	This manuscript
1975–93			16–32	This manuscript

Table 3. Average nutrient, oxygen demand, total suspended solids, and chlorophyll *a* concentrations in discharge waters of intensively managed shrimp ponds with different stocking densities of *Penaeus monodon* Fabricius (black tiger shrimp)[a]

	Chaiyakam et al. (1992)		Tunvilai et al. (1993a)				
Stocking density (No/m^2)	30	75	30	40	50	60	70
Ponds (N)	22	38	1	1	1	1	1
Sampling period (months)	20	20	3.9	3.9	3.9	3.9	3.9
NO_2-N	<0.01	0.01	0.02	0.01	0.06	0.08	0.08
NO_3-N	0.02	0.03	0.07	0.06	0.15	0.15	0.15
TAN	0.11	0.61	0.98	0.98	6.36	7.87	6.50
Total N	nd	nd	3.55	4.04	14.9	20.9	17.1
Total P	nd	nd	0.18	0.25	0.53	0.49	0.32
COD	27.6	39.0	nd	nd	nd	nd	nd
BOD_5	5.4	7.1	10.0	11.4	28.9	33.9	28.8
TSS	184	214	92	114	461	797	498
Chl *a* (μg/liter)	76	140	70	110	350	460	350

[a]All units in mg/liter unless otherwise noted. TAN = total ammoniacal nitrogen. nd = no data.

Table 4. Mass loadings for nutrients, oxygen demanding substances, total suspended solids, and chlorophyll *a* from intensively managed *Penaeus monodon* Fabricius (black tiger shrimp) ponds in Thailand based on a 109-day grow-out cycle (nd = no data)

	Songsangjinda and Tunvilai (1993)		Tunvilai et al. (1993a)	
Ponds (N)	94		5	
Stocking density (N/m^2)	ave. 35		30–70	
Pond area (ha)	ave. 0.575		0.285	
Units	g/m^2	kg/pond	g/m^2	kg/pond
(NO_2 + NO_3)-N	0.87	5.0	0.07–0.23	0.20–0.65
TAN	6.4	37.0	0.98–7.9	2.8–22.4
Total N	20.6	118	3.6–20.9	10.1–59.5
SRP	0.33	1.9	nd	nd
Total P	3.4	19.4	0.18–0.53	0.51–1.51
COD	845	4860	nd	nd
BOD_5	135	777	10.0–33.9	28.5–96.5
TSS	5810	33,400	92.4–797	263–2270
Chl *a*	1.2	6.9	0.07–0.46	0.20–1.31

the tasks of assigning external costs for the replacement of mangrove areas with shrimp ponds is complicated by the assertion that much of the shrimp pond construction in the mangrove areas was done in degraded mangrove habitats (FAO/NACA 1995).

Environmental implications to outside ecosystems and communities. Not only would utilizing mangrove buffer areas improve the economic outlook of the shrimp industry, since many of the costs inherent in shrimp farming (e.g., canal dredging, pumping, aeration, water treatment, disease control/prevention) are directly related to water quality, but it would also benefit nearby ecosystems. Justification of mangrove conversion to shrimp ponds is frequently made on the grounds that pond effluent provides the necessary organic matter and nutrients to receiving waters that the mangroves used to contribute; thus, the nutrient export function of former mangal areas has been effectively replaced and even surpassed (FAO/NACA 1995). There are two major constraints to this argument.

The first is that although carbon is certainly exported from mangrove stands, on a net basis this may not be true for nutrients. The importance of the allochthonous contribution by mangroves to the total estuarine carbon budget (from both allochthonous and autochthonous sources) was demonstrated by Twilley (1988), who found that mangroves accounted for 39% of the total organic matter supplied to an estuary in southwest Florida. Moreover, the form of the organic carbon may be particularly significant to the estuary. Organic matter from mangroves, in the form of detritus and dissolved organic carbon, may be a more appropriate substrate for secondary production and ecosystem maintenance in an estuary than phytoplankton since seagrass, coral reef, and demersal fish communities could be adversely affected by phytoplankton standing crops due to shading effects and differences in the carbon food source. In addition, while the evidence for net nutrient transport from mangroves to estuaries is equivocal (Twilley 1988, Robertson and Blaber 1992), there can be little doubt that shrimp pond effluent contains abundant labile nutrients and organic matter, both of which are outwelled to estuarine and coastal waters where they can stimulate phytoplankton production.

The second major drawback in substituting shrimp ponds for mangrove habitat is that there is evidence that mangroves and marshes provide critical substratum and protective cover for at least some species of juvenile shrimp (Boesch and Turner 1984, Robertson and Blaber 1992). Although no data exist that show unequivocally a significant drop in penaeid prawn catches caused by reduction of mangrove habitat (Robertson and Blaber 1992), the loss of mangroves may affect the number of wild broodstock, which is the major source of seed for the hatcheries and is becoming an important constraint of the industry (Csavas 1994a). Consumption of detritus, even if it is microbially enriched, is apparently not as important a food source for natant species such as fishes and penaeid shrimp as was originally thought (Boesch and Turner 1984, Stoner and Zimmerman 1988).

Management plan. The demise of mangrove habitat for shrimp pond construction has widespread ecological and socioeconomic implications (Table 5). Primavera (1993) suggested a management strategy for mangroves that would accommodate both the preservation and wise utilization of mangroves. She designated mangrove areas into one of four zones: undisturbed (preservation–conservation) for research, education, recreation, and genetic, species, and community diversity; sustained yield for timber, nipa, fish, and shellfish; conversion zones (preferably on previously altered sites) for agriculture, aquaculture, and salt production; and a reforestation zone.

Beginning in 1987, the government of Thailand approved a similar mangrove management plan, designating its remaining mangrove areas into either a preservation zone (42,678 ha), economic zone A (199,689 ha), or Economic zone B (130,081 ha) (MIDAS Agronomics 1995), which correspond to Primavera's undisturbed, sustained yield, and conversion zones, respectively. Although a reforestation zone is not specifically identified as a discrete zone under the Thai mangrove zonation scheme, the government has funded a national Mangrove Rehabilitation Project. Unfortunately, only 5% of the original target of planting 8000 ha/yr has been achieved since the start of the project in 1992 (MIDAS Agronomics 1995).

Saltwater Intrusion

The impact of the exponential rise in shrimp farming on whole ecosystems is not limited to only mangroves. New pond construction frequently occurs behind mangrove zones where freshwater wetlands and rice-growing areas are affected by surface and subsurface saltwater intrusion generated by the new ponds. Not only is the productivity and land use changed by salinization, but freshwater supplies used for irrigation and potable water are also affected.

The tendency to encroach into freshwater environments is not limited to just the areas near the ocean. There is a trend in Thailand to extend the range of new shrimp ponds by locating in areas where brackish water exists only part of the time, such as upstream riverine environments that reach mid-level salinity ranges (12–18 ppt) only during strong tides and/or during the dry season. The farmers begin their produc-

Table 5. Matrix of ecological and socioeconomic values and problems of brackishwater shrimp pond culture compared with intact or managed mangrove systems in Thailand[a]

	Mangrove system	Shrimp farming		
		Ext	S-Int	Int
VALUES				
Traditional livelihoods	+	±	–	–
Communal ownership of resources	±	–	–	–
Mangrove products	+	–	–	–
Biodiversity	+	±	–	–
Coastal protection	+	–	–	–
Nearshore fisheries production	+	–	–	–
Domestic food supply	+	–	–	–
Foreign exchange	±	+	+	+
Income	+	+	+	+
Employment	+	+	+	+
Competition for land and credit	–	+	+	+
PROBLEMS				
Water quality degradation	–	–	+	+
Sediment disposal	–	–	+	+
Water and soil salinization	–	–	+	+
Abandonment	–	+	+	+
Spread of shrimp diseases	–	–	+	+
Public health risks	–	–	+	+
Coastal erosion and land subsidence	–	+	+	+

[a]Modified after Primavera (1993) to fit what the authors believe to be conditions in Thailand. + denotes presence; – denotes absence or loss. Ext = extensive; S-Int = semi-intensive; Int = intensive.

tion cycles by supplying full-strength seawater, usually brought in by tanker truck, to partially fill up the pond volume. After the postlarvae are placed in the ponds, water from nearby low or nonsaline sources is gradually added to the ponds, thereby acclimating the juvenile shrimp to lower and lower salinities. During the third and fourth months of the growout period, when water quality deteriorates due to the increased feeding and metabolic activities of the shrimp, the low-salinity pond water is exchanged with fresh waters. By the time harvesting occurs, the pond water salinity is reportedly just a few parts per thousand or less (MIDAS Agronomics 1995).

Land Subsidence

On some farms, groundwater is pumped to the culture ponds to dilute saltwater in the belief that brackish water is best for rearing shrimp; occasionally the abstraction of groundwater results in land subsidence.

Water Quality Impairments

Besides the salinization of freshwater resources, the water-quality issues are focused on siltation, eutrophication, oxygen depletion, and toxicity from sulfide, ammonia, and xenobiotics (e.g., therapeutants and wastewater treatment chemicals) released into receiving waters.

Depending on stocking density, pond effluent discharged from intensively operated farms usually contains high, but variable, concentrations of nutrients, suspended solids, oxygen demanding substances, and chlorophyll *a* (Table 3). Moreover, given that the daily exchange of pond water with outside water can be as much as 40% for semi-intensive and intensive systems (Barg 1992; Lin and others 1993) in order to remove excess nutrients and organic matter, the loadings to receiving waters can be significant (Table 4). Nutrient budgets carried out on intensive shrimp ponds in Thailand indicated that 66% and 94% of the total N and total P inputs, respectively, are either released in the discharge waters or deposited in the pond bottom (Briggs and Funge-Smith 1994).

Since the pond is emptied during harvesting at a time when the nutrient, suspended solids, and BOD concentrations are likely to be at their highest, significant loadings can be experienced during that brief harvest period. For example, nutrient, biochemical oxygen demand, and total suspended solids exported during harvest ranged 23% to 71% of the loadings measured during several 4-month growout periods in one study (Table 6), except for total ammoniacal nitrogen (TAN), which was nearly the same (82%–104%).

Another source of loading generally not accounted for is sediment disposal. Although some aquaculturists advise against it (Boyd and others 1994), collecting and disposing of accumulated sediment deposits between production cycles is considered to be essential in promoting good water quality for successive shrimp production cycles in intensive ponds. Based on the 40,000 ha of intensive shrimp ponds currently in operation in Thailand, approximately 16.2 million metric tons of dry sediment are produced each year (Briggs and Funge-Smith 1994). Depending on whether the sediment is disposed of legally (drying, excavating, and mounding on the property) or illegally (flushing ponds with high-pressure hoses to drainage canals), the nutrient, oxygen demand, and solids loadings can exceed those during the growout and harvesting periods (Table 6). Specifically, if postharvest bottom pond sediment is improperly disposed, then loadings can double, as in the case for total N, or even increase by more than 9- to 10-fold for total P and 13- to 18-fold for suspended solids (Table 6).

Depending on the stocking density, total loadings

Table 6. Comparisons of nutrient, oxygen demand, total suspended solids, and chlorophyll *a* loadings for discharge waters and accumulated sludge during two to three successive 4-month grow-out and harvest periods from intensively managed *Penaeus monodon* Fabricius (black tiger shrimp) ponds at two stocking densities in Thailand[a]

	Discharge waters		Harvest drainage		Pond sediment		Total	
	LD	HD	LD	HD	LD	HD	LD	HD
NO_2-N	0.71	3.3	0.4	1.6	nd	nd	nd	nd
NO_3-N	2.7	9.0	1.0	2.7	nd	nd	nd	nd
TAN	18.4	71.1	19.1	58.4	nd	nd	nd	nd
Total N	178	223	78	141	199	304	455	668
SRP	2.0	2.6	1.2	0.6	nd	nd	nd	nd
Total P	15.7	24.9	8.2	10.7	214	285	238	321
BOD_5	474	494	211	222	nd	nd	nd	nd
TSS	6650	9658	4034	6866	185,000	199,000	196,000	215,000
Chl *a*	4.6	9.9	2.0	5.9	nd	nd	nd	nd

[a] LD = Low density stocking at 50–60 individuals/m^2; HD = high density stocking at 80–100 individuals/m^2. All units are kg/ha/cycle. Data from Briggs and Funge-Smith (1994), Funge-Smith and Briggs (1994a). nd = no data.

from the combined sources of water exchanged during the 4-month production cycle, harvest drainage, and pond bottom sediment removal (if disposed of improperly) are 238–321, 455–668, and 196,000–215,000 kg/ha/cycle for total P, total N, and total suspended solids, respectively. The total P and total N numbers compared favorably with the estimates of Lin and others (1993) of 154 kg P/ha/cycle and 478 kg N/ha/cycle based on low stocking densities (30–50 individuals/m^2) and a food conversion ratio of 2.0. Since most shrimp farmers average slightly more than two production cycles per year, then these numbers could easily be doubled for calculating annual loadings.

These represent substantial loadings to Thai coastal environments. Briggs and Funge-Smith (1994) estimated that the 40,000 ha of intensive shrimp ponds currently cultivated produce the waste equivalent of 3.1–3.6 million people for nitrogen and 4.6–7.3 million people for phosphorus, which is between 5% and 11% of the Thai population. This is equivalent to increasing the population of the coastal zone by 50%–100% without any sewage treatment (MIDAS Agronomics 1995).

Although there are examples of eutrophication of lacustrine waters as a result of fish farming, few examples are reported from coastal waters (GESAMP 1991). Thus the impact of these loadings on Thailand's coastal waters is the subject of speculation (FAO/NACA 1995). Aquacultural interests (NACA 1994) state that the contribution by shrimp aquaculture is small in comparison to other sources (e.g., domestic wastewater, agricultural). Moreover, they claim that the added nutrients from shrimp farms help to increase the productivity of Thailand's coastal waters, thereby contributing to an increase in the fisheries yield of the Gulf of Thailand.

On the other hand, others point out that coastal areas that have poor flushing characteristics, such as embayments, become eutrophic from the shrimp farm discharges, which alters habitats (coral reefs, seagrasses) and community structure (e.g., eradication of demersal fisheries). Futhermore, "red tide" outbreaks, a common occurrence in many South East Asian countries, may be partially caused by shrimp pond effluent, although no direct linkage has been demonstrated (GESAMP 1991).

Most of the suspended solids originating in shrimp pond effluent are mineral particles eroded from pond sides by aerator-induced water currents (Boyd and others 1994, Funge-Smith and Briggs 1994b). Thus, particles exported in the discharge waters from ponds will not decompose in the receiving waters, which can lead to shoaling of offshore waters and siltation of canals and river mouths.

Pond Sediment Disposal

The sediment that accumulates within the production ponds during each rearing cycle [185–199 t dry wt/ha or 139–150 m^3/ha (Funge-Smith and Briggs 1994a); 200–836 t dry wt/ha or 151–629 m^3/ha (Tunvilai et al. 1993b)] is removed or allowed to oxidize after each production cycle as a maintenance measure to safeguard against deteriorating water quality during the next production cycle (Tacon and others 1995). Sediment removal is almost exclusively done in Thailand, which has led to water pollution (if disposal is done in an illegal manner), salinization of soils and water, and a solid waste disposal problem. The tendency to dispose of sediment illegally is exacerbated by its lack of utility; pond sediment is not suitable for agricultural and horticultural fertilizer because of its low organic content, large volume, and high salt content. Even designated sediment discarding areas are not commonly used for sludge disposal: only 36% of the farmers surveyed in Hua Sai and Ranot districts disposed pond sediment in designated areas (Tiensongrusmee and Phillips 1994).

Instead of following the usual practice of sediment removal and disposal, Boyd and others (1994) argue for spreading the dry sediment back over the areas of the pond bottoms from which it was eroded to promote oxidation of the low percentage of organic matter (1.9%–7.5%) typically found in pond bottom sediment (Lin and others 1993, Funge-Smith and Briggs 1994c, Boyd and others 1994). Prior to reflooding, compaction to reduce erodability by water currents would occur.

Abandoned Shrimp Ponds

Continued, widespread semi-intensive and/or intensive culturing of shrimp within a country usually results in a catastrophic collapse of the industry primarily by viral and bacterial diseases, either throughout the country or within a region (Lin 1989; Phillips and others 1993; Wigglesworth 1994). As with disease-causing collapses in other countries, the cause or combination of causes for the failure are unknown (Kikuchi 1993). Although the relationship between poor water quality and disease proliferation if not understood (Phillips 1994), the most frequently cited reason for crop failure is the poor water quality.

For the Samut Sakhorn and Samut Prakan provinces in the Upper gulf of Thailand, which underwent catastrophic collapses in 1989, poor water quality originated from both industrialization within the watersheds of major rivers draining into the Upper Gulf of Thailand and from self-pollution by the farms themselves. Regarding the latter, poor pond siting, construction, and management are believed to have contributed to water quality problems (Kikuchi 1993, Phillips 1994). The reliance by farmers on technical information from feed and chemical suppliers and the poor flushing characteristics of the drainage canals were also believed to be major contributors to the decline of the shrimp industry in the Upper Gulf of Thailand.

A collapse can also be more gradual as pond productivity generally declines at a rate of 3%–8% per production cycle (Tiensongrusmee and Phillips 1994, Funge-Smith and Briggs 1994a, Primavera 1993). The exact reason has not been identified, although deterioration of pond sediment quality, the loss of essential minerals from pond soil, and poor pond management (which lead to low oxygen and high ammonia concentrations) are common explanations.

Given that the average lifetime of an intensive shrimp pond is estimated to be 7 years before disease outbreaks make the enterprise unprofitable, abandonment of the ponds is a common phenomenon. The total area of abandoned shrimp ponds in Thailand is unknown, but estimates range from 4500 to 16,000 ha (MIDA Agronomics 1995). Frequently, the individual farmer or private company moves to a new, unspoiled location and begins shrimp farming operation anew, a term known as "shifting aquaculture" (MIDAS Agronomics 1995).

Rehabilitation of abandoned ponds has been coincidental—some are used again as extensive, semi-intensive, or intensive shrimp ponds; others are converted to salt ponds; a small percentage is used for growing other aquaculture species such as shellfish or crabs. Those near encroaching urban and/or industrial areas are sold to developers, but most lay idle.

Farming Practices that Promote Sustainability

Two Key Ingredients: Site Selection and Pond Management

Sustainability in any aquaculture industry depends on two major factors: site selection and pond management. An overriding factor in determining how much a farm is at risk may be the location of the farm vis-à-vis other farms in the immediate area. In other words, the density of farms within an area may be more important than whether the farms are operated as semi-intensive or intensive systems, provided of course that appropriate pond management is practiced. Although intensification usually results in a deteriorating pond water and sediment quality, there is no evidence to suggest that intensified operations will put the farmer more at risk of crop failure. There are many examples (Thailand, China, Indonesia) where shrimp aquaculture collapses in South East Asia occurred predominantly within semi-intensive ponds (Tacon and others 1995).

To date, no way has been found for making areally concentrated semi-intensive or intensive aquaculture operations ecologically sustainable in Thailand. Part of the answer may lie in deployment of water treatment and minimal water use systems, especially in locations where there are numerous farms which use common discharge canals and source waters.

Water Treatment and Minimal Water Use Systems

Water treatment in open farming systems. To reduce the risk of cross-contamination of disease organisms and pollutants among farms, more and more of the larger commerical farms, as well as some individual farmers, are constructing water-treatment ponds at the front end of their farming operations to treat incoming water supplies. The usual practice is to settle out particulates and add either chlorine or benzalkonium chloride (BKC) in the treatment pond(s). Pond effluent is generally not treated before discharge to receiving waters.

Partially closed farming systems. Since the sustainability of shrimp farming is widely believed to be mainly linked to water quality issues, it is surprising that there have been few attempts toward developing and utilizing minimal water use systems. The employment of partially closed recycle operations in Thailand, where ponds are operated with as little makeup water originating outside the farm as possible (termed semiclosed intensive farming in Figure 3), is rare. The shrimp farmer must be willing to sacrifice some of the growout pond area for treatment ponds in order to treat not only the initial outside water, but also the internally recycled water. The water treatment methods are usually limited to settling ponds, although biological treatment ponds using polyculture (finfish, mollusks, and seaweeds) have also been used (Lin and others 1993, Phillips 1994).

Two semiclosed, integrated intensive farms were examined as to their effectiveness in maintaining high water quality. The first was a small-sized farm in Samut Songkram Province (Wanuchsoontorn and others 1993). After an initial chlorine treatment of outside water in a reservoir, water entered four growout ponds (0.58 ha each), then exited via mussel-inhabited drainage canals to an aeration pond, followed by two sedimentation ponds in series, a biological treatment pond (sea bass), and finally an additional treatment reservoir before being recirculated to the growout ponds (Figure 4).

The production ponds were stocked at a low density (30 individuals/m^2), far below the typical stocking densities practiced by Thai farmers. This probably resulted in the rather low average total ammoniacal nitrogen (TAN) in the production ponds (0.11 mg/liter), which was further reduced by 78% to (0.02 mg/liter) during transit through the various treatment ponds. Nevertheless, 45% of the pond volume was still discharged during the growout period (Figure 4), presumably due to TAN buildup in the latter part of the growout period. Nitrate + nitrite concentration was low (0.09 mg N/liter) in the growout ponds, and remained so throughout the treatment system (Wanuchsoontorn and others 1993). This system existed for only one production cycle; there is no record of the system having been adopted commercially in Thailand (MIDAS Agronomics 1995).

The second intensively managed farm, a large operation (27 growout ponds at 1.2 ha each), experienced

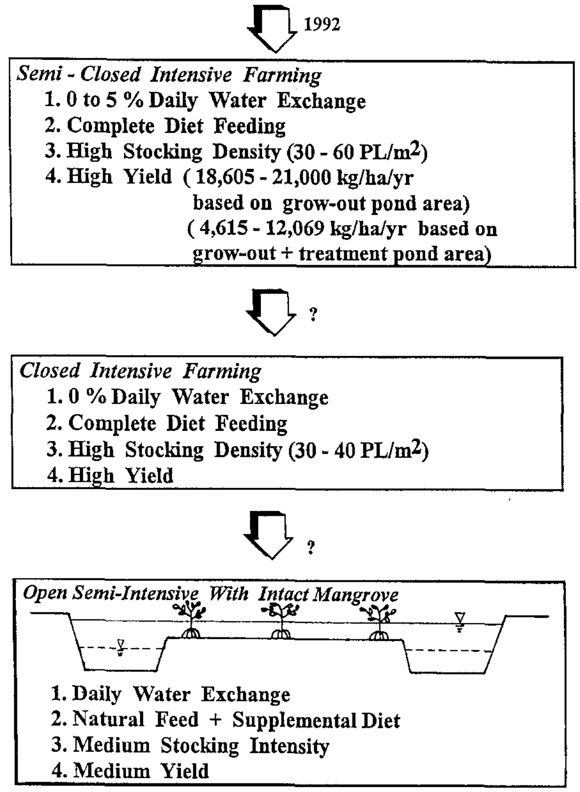
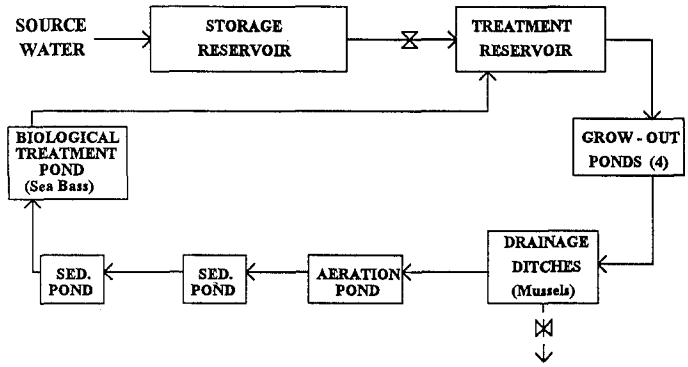


Figure 3. Recent and future shrimp farming practices in Thailand that promote sustainability. Data from S. Phansi (unpublished data 1994) and Wanuchsoontorn et al. (1993).

four of six crop failures from what was reputed to be combinations of turbidity, heavy metals (particularly Cu), cyanide, toxic dinoflagellate blooms (*Peridinium* and *Noctiluca*), and stress-induced yellowhead disease (Phansi unpublished data 1994). Thereafter, a semiclosed system was attempted, which consisted of 27 growout ponds discharging into drainage ditches routed to a sedimentation pond, then a biological treatment pond, and finally a storage reservoir before water was pumped to the growout ponds again (Figure 5). The outside source water was initially treated with chlorine before being pumped to the biological treatment pond, which contained mullet (*Mugil*), *Tilapia,* and milkfish (*Chanos*), as the first cell in the system. Another disinfectant, BKC, was added to discharged production pond water prior to being recirculated to the biological treatment pond.

As expected, the concentrations of TAN increased during the growout period in each treatment and production component (Figure 6) as feeding and shrimp metabolism increased. The lowest concentrations were found in the last treatment unit (the storage reservoir) prior to recycling to the growout ponds, indicating am-



Source : Wanuchsoontorn *et al.* (1993)

Number and Size of Grow-out Ponds	**4 @ 0.53 ha each**
Treatment Area : Grow-out Area	**1.79**
Hydraulic Exchange Rate During Growout	**45 %**
Hydraulic Exchange After Growout	**82 %**
Shrimp Stocking Density	**30 individuals / m²**
Shrimp Survival Rate	**81 %**
Polyculture Organisms	**Sea bass ; green mussel**
Bactericides	**Chlorine ; others (?)**
TAN in Grow-out Ponds	**0.11 mg/L**
Reduction in TAN	**78 %**
Nitrate + Nitrite -N in Grow-out Ponds	**0.09 mg/L**
Reduction in Nitrate + Nitrite -N	**4 %**
Site Disposition	**Closed system abandoned after one cycle**

Figure 4. Schematic and relevant data for an integrated, semiclosed intensive shrimp farm in Thailand.

monium removal did occur throughout the treatment train.

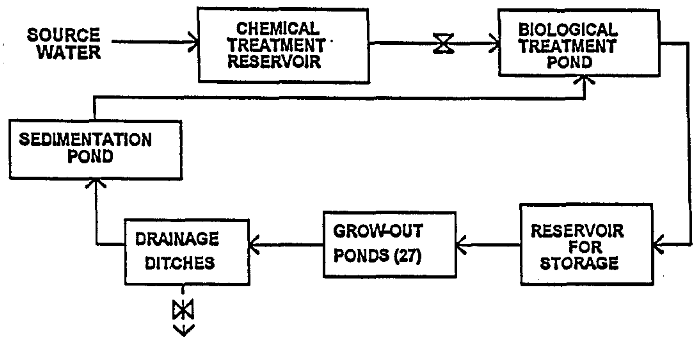
The average growout pond TAN concentrations from weekly sampling during the 20-week production cycle was 0.83 mg/liter (Figure 5). The treatment units (sedimentation, biological, and storage ponds) reduced the TAN concentration in the growout ponds by 67% (to 0.47 mg/liter). Even though the water leaving these units and entering the production ponds is relatively low in ammonium concentrations, the high TAN production in the growout ponds, especially during the later months of the production cycle, necessitated that pond effluent be released periodically to the environment (weeks 12, 17, and 19 in Figure 7).

Given that dissolved oxygen concentrations ranged from 2.9 to 4.7 mg/liter during the night and the diel pH was 7.9–8.5 in the production ponds, a high rate of nitrification should have occurred. However, the nitrate plus nitrite data did not indicate nitrification was occurring (Figure 7), or if it was, denitrification was occurring at an even more rapid rate. Nitrate plus nitrite nitrogen averaged only 0.24 mg/liter in the production ponds, and was only reduced 34% during the treatment process.

The apparent lack of nitrification needs further exploration since it is a common and economical process for reducing ammonium levels in aquaculture wastewaters (Rakocy and Hargreaves 1993). If more nitrification could be achieved in the production ponds and other parts of the treatment train, then low ammonium levels may be maintained throughout the entire production cycle, obviating the need for periodic discharges of high ammonium waters as is presently being done in these semiclosed systems.

Of utmost importance to the shrimp farmer, these examples of semiclosed systems produced yields that were comparable to those obtained in open intensive farming (4615–12,069 kg/ha/yr), even when the treatment pond areas are included with the growout ponds in calculating the yields (Figure 3).

It must be emphasized that these semiclosed farms still exchange about 40%–50% of the growout pond water



Source : S. Phansi (1994)

Number and Size of Grow-out Ponds	**27@1.2 ha each**
Treatment Area : Grow-out Area	**0.74**
Hydraulic Exchange Rate During Growout	**48 %**
Hydraulic Exchange After Growout	**100 %**
Shrimp Stocking Density	**40 individuals/m²**
Shrimp Survival Rate	**82%**
Polyculture Organisms	**Mugil, Chanos, Tilapia**
Bactericides	**Chlorine ; BKC**
TAN in Grow-out Ponds	**0.83 mg/L**
Reduction in TAN	**67%**
Nitrate + Nitrite N in Grow-out Ponds	**0.24 mg/L**
Reduction in Nitrate + Nitrite N	**34%**
Site Disposition	**One cycle completed ; second cycle begun**

Figure 5. Schematic and relevant data for a second integrated, semiclosed intensive shrimp farm in Thailand.

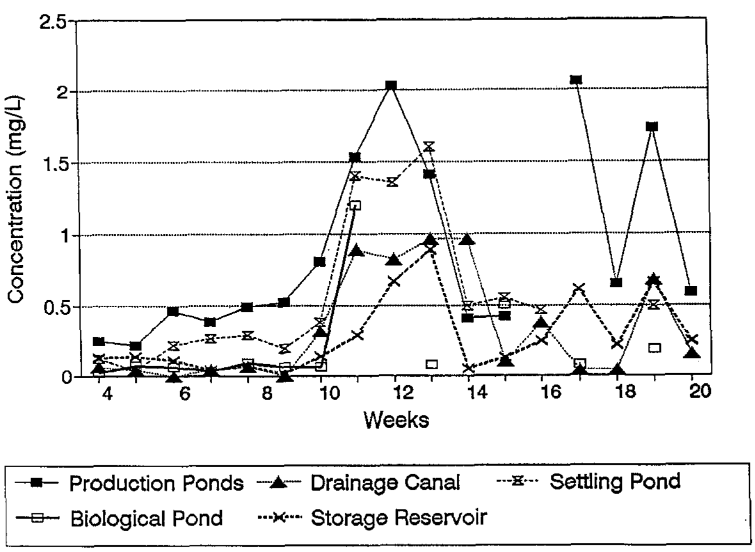


Figure 6. Total ammoniacal nitrogen (TAN) concentrations for production ponds and treatment areas during a 20-week production cycle of a semiclosed intensive shrimp farm.

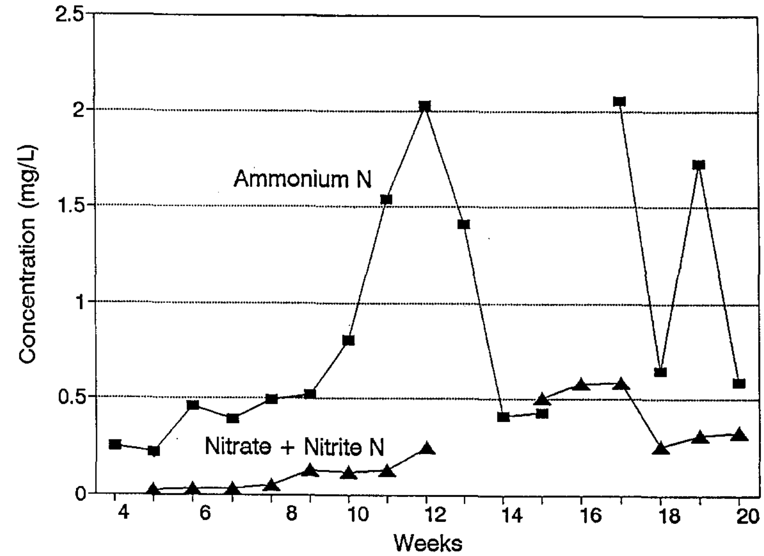


Figure 7. Ammonium nitrogen and nitrate + nitrite nitrogen concentrations in the production ponds during a 20-week production cycle of a semiclosed intensive shrimp farm.

during the production cycle (Figures 4 and 5), particularly near the end when ammonium concentrations build up in the production ponds. In addition, the ponds are still completely drained to outside receiving waters at the end of the production cycle for harvesting. Lastly, bottom sediment is also removed after the end of each cycle. Notwithstanding the periodic and terminal releases of pond water and sediment to the environment, these examples of semiclosed systems are a move in the right direction towards reducing the environmental impact of high nutrient/suspended solids pond water discharge.

Closed water reuse systems. The remaining two shrimp farming practices in Figure 3, closed intensive and open semi-intensive with intact mangrove, have yet to be practiced in Thailand but deserve serious consideration. A closed system would require more capital (and expertise) than the experimental semiclosed intensive farming systems that have been presented above. The two major unit processes that must be the major features if a closed intensive system is to be operational are solids removal and nitrification. Solids removal can improve water quality for shrimp production as well as reduce nutrient discharge to the environment (Hopkins and others 1994). Clarifiers (Rakocy and others 1991), expandable granular media (bead) filters (Malone and Drennan 1992), screen filters (Tetzlaff 1991), and foam fractionation devices (Chen and Malone 1991) have been used for removing suspended solids in aquaculture settings. Various devices have been used to promote nitrification: biofilters employing sand, gravel, shell, or plastic media as substrate configured in submerged, trickling, or reciprocating hydraulic modes; suspended growth processes such as activated sludge and algal uptake have also been used (Rakocy and Hargreaves 1993). Rotating biological contactors, expandable media (sand, plastic beads) and fluidized biofilters are currently considered the most viable treatment options for nitrification (Timmons and Losordo 1994).

Sandifer and Hopkins (1996) proposed a conceptual design for sustainable, closed-cycle shrimp culture. Their design included three production ponds, one oyster–mullet polyculture and water treatment pond, a small phytoplankton inoculation pond, a solids settling basin, and sludge drying beds. A working example of a closed reuse system for shrimp cultivation was presented by Chin and Ong (1994). Besides utilizing two sedimentation units and two aerated biofilters for solids removal and nitrifications, respectively, they also disinfected the water with ultraviolet light. They reported a production equivalent of 22,800 kg/ha/yr (a high yield) with only 20% mortality of the shrimp, but failed to provide an economic analysis of their water treatment and reuse system; it is also not known if the success they had during one growout cycle can be sustained.

One technology that deserves further scrutiny is the use of polyethylene liners. Pond liners have several advantages, especially with respect to closed-cycle aquaculture. They can reduce the volume of sediment generated during a production cycle by preventing erosion of the pond sides, which can contribute as much as 90% of the accumulated total solids (Funge-Smith and Briggs 1994b). In addition, pond liners can facilitate solids collection and disinfection between crops; reduce leaching from acid sulfate or organic-rich soils, which may inhibit shrimp growth or affect survival; prevent seepage losses and groundwater intrusion; and extend the range of new pond siting to otherwise marginal areas (e.g., porous or infertile soil types).

If further research using the black tiger shrimp confirms the conclusions of initial studies using the Pacific white shrimp (Pruder and others 1992) that pond liners do not affect (and may even enhance) shrimp growth and survival, then economic cost–benefit analyses will determine whether the costs of the liner material and its deployment are less than the savings realized by shortened crop-to-crop turnaround time, accessibility to inexpensive land with marginal soils, reduction in water exchange and sediment accumulation, more effective disinfection, reduction in groundwater contamination and salinization, and improvement in some of the effluent quality characteristics (e.g., suspended solids and ammonium). Some effluent parameter concentrations, such as phosphorus, actually increased in the presence of a liner compared to natural substrate (Pruder and others 1992), probably because of the occlusion of effective phosphorus binding sites by the liner.

Semi-intensive culturing integrated with mangrove forests. The last management plan in Figure 3 depicts an open semi-intensive farming system within intact mangroves. Since mangroves are indisputably essential for maintaining shorelines, providing critical habitat for fish and wildlife, and serving as a source of wood products, a serious attempt should be made to integrate shrimp aquaculture with mangroves. Leaving the mangrove soils intact (i.e., unscraped) would also prevent the oxidation of the acid-producing pyrite, as well as help process the nutrients, solids, and oxygen-demanding organic matter that the semi-intensive farm operation will invariably produce.

One approach to integrating shrimp farming areas within mangrove zones is to construct peripheral canals to raise dikes so that a sufficient depth of water could be maintained in the central part of the unscraped pond during high tide. A similar plan was proposed by Pedini (1981) as a partial solution to the acidity generated by exposed sulfate soils in former mangrove areas. He also recommended that the area be cleared of mangrove trees and stumps, which is contrary to our proposal of integrating intact mangroves with shrimp culture (Figure 3).

Institutional Considerations

Although there are numerous technological improvements that could be made toward making shrimp farming and the coastal environment in which it occurs more sustainable, they will only be implemented if there are institutional changes. Up until now, government policy has stressed the promotion of intensive shrimp pond culture more than addressing the problems associated with the environmental impacts or sustainability of the industry, such as encouraging sustainable pond management techniques, emphasizing pollution abatement, or rehabilitating abandoned shrimp ponds to some productive function. Considering the large financial losses imposed by the lack of solutions to these technical problems, it is surprising that significant financial investments are not being made by the government (MIDAS Agronomics 1995).

Government incentives such as low-interest loans and import duty exemptions for equipment have encouraged investment in the development of intensive shrimp aquaculture. The government has also supported technological developments aimed at encouraging investment in intensive shrimp farms. For example, by conducting an active research program in culturing hatchery seed, the government was able to produce shrimp seed on a commercial scale in the mid-1980s (FAO/NACA 1995). Further governmental assistance is rendered by deepening existing, and digging new, irrigation canals (FAO/NACA 1995).

The latest government proposal is to pump seawater from offshore as source water for the ponds, instead of farmers having to rely on the more polluted inshore waters and canals. While such an expensive engineering approach will undoubtedly improve the quality of water entering the aquaculture ponds, it will do nothing to overcome the problems associated with the high intensity shrimp farming (Table 1). In some respects, it will even make matters worse since it will not encourage farmers to reduce stocking, feeding, or adding therapeutants in their ponds; nor will it lead to better discharge water quality or enforcement of water-quality standards.

Thailand's regulations are aimed at shrimp farm siting (i.e., mangrove protection), waste treatment, and sludge disposal (FAO/NACA 1995, Tiensongrusmee and Phillips 1994):

- To protect the coastal environment, the Department of Fisheries (DOF) has limited the total area and production tonnage of shrimp farms to 80,000 ha and 200,000 metric tons, respectively.
- Mangrove conservation and economic zones have been established.
- Farmers who are engaged in shrimp farming operations covering more than 8 ha are required to be registered and licensed and comply with the following restrictions:
  - discharge waters not to exceed a 5-day BOD of 10 mg/liter
  - pond sludge not to be released into natural water sources or public areas (provision of monetary fines and jail sentences for violators)

- saltwater not to be discharged into public fresh waters
- utilize an effluent treatment pond with an area not less than 10% of the culture area

Failure to register a farm covering more than 8 ha disqualifies a farmer from using Department of Fisheries services such as water-quality and chemotherapeutic residue tests, diagnosis of shrimp diseases, certification for export, and reimbursement for natural disasters. In practice, enforcement of the regulations is difficult (MIDAS Agronomics 1995). There is virtually no monitoring and numerous violations can be seen on Thai shrimp farms.

Partly because of the lack of government emphasis, and partly due to economic and social reasons, there is little incentive at the present for the industry to pursue more sustainable practices. Profits from a successful production cycle are such that a farmer can lose three of four crops and still break even. This imparts a "winning the lottery" type of attitude, where chance is considered more important than practicing good site selection and management techniques.

Outlook for the Future: Limited Growth Potential

Intensive shrimp aquaculture will likely continue to grow, but a slower rate than during the 1987–1993 period (see Figure 1); eventually growth will stabilize. Although the 1993 data in Figure 1 are only estimates, that year may signal the beginning of reaching a production asymptote. There are several reasons why a reduced rate of growth for intensively managed shrimp farms can be expected in the future:

Availability of Suitable Land

The demand by aquaculture interests for coastal zone resources will continue in the near future, driven by the looming supply–demand gap resulting from the leveling off of capture fisheries production (Csavas 1994b) and high profit margin expectations. However, competing interests (i.e., urban centers, capture fisheries, tourism, industry, agriculture) and the scarcity of remaining economically and ecologically viable land effectively means less construction of new ponds in the future. For instance, we determined that between 38% and 65% of the 62,800 ha of mangrove areas estimated by NRCT (1977) to be suitable for shrimp farms have been replaced by shrimp farms between 1975 and 1993. In addition, an unspecified amount of the 62,800 ha of mangrove has also been lost to other development pressures such as urbanization, agriculture, and industrialization during that period.

Scarcity of Broodstock

Although the Thai government has successfully produced shrimp seed in hatcheries from broodstock, the availability of wild broodstock is becoming a constraint on the industry (Csavas 1994a).

Disease Outbreaks

Since it is commonly held that severe bacterial and viral infections that can destroy a shrimp crop are directly related to the quality of water in the pond, gradual production declines with the age of the pond and catastrophic collapses from disease will continue to beset the shrimp farming industry until regulatory enforcement and minimal water use systems are in place.

Negative Publicity Affecting Consumer Choice

Most Western nations that buy shrimp from Thailand are unaware of the environmental degradation and social changes that accompanied the rapid growth of farming. If the unsustainable practices of shrimp farming should receive more media coverage in the West, consumers may decide not to buy shrimp products from countries that exploit mangroves, displace traditional livelihoods, and despoil coastal zones by abandoning farms and discharging waste from the ponds.

Regulatory Enforcement

Although the exact extent and severity of the environmental impacts of shrimp aquaculture are, and will continue to be, controversial, it will become increasingly more difficult for the shrimp farming industry to ignore the effects of their activities. Thai governmental sectors and international organizations (lending institutions; NGOs) are becoming more aware of the environmental issues surrounding shrimp mariculture (Kikuchi 1993, Phillips 1994). Thus, more monitoring and regulatory (and voluntary) measures aimed at reducing the environmental impacts of shrimp aquaculture can be expected.

Supply Water, Wastewater, and Sediment Treatment and Disposal

Either by government regulation or economic necessity (to ensure good water quality), more attention to uncontaminated sources of water supply, drainage water treatment, sludge disposal, polyculture, and water recycling will be devoted by the industry in the future. This will inevitably lead to higher capital and operating costs.

Increased Competition from Other Asian Countries

Governments of other Asian countries are following Thailand's lead in promoting farm-raised shrimp as an export commodity. Depending on the rate of growth, shrimp prices could fall during certain times of the year when supply exceeds demand.

Integrated Aquaculture Management for Achieving Sustainability

Although important first steps (e.g., experimentation with recycling systems, mangrove reforestation and management plans, promulgation of water-quality standards) in moving from recognition of the problem to action have occurred in Thailand, a more comprehensive, integrated approach to the problems is required. As practiced now, a sustained shrimp industry in Thailand is unlikely. Thus, integrated aquaculture mangement (a part of a more comprehensive integrated coastal zone management (ICZM) plan), where shrimp farms are protected from harmful environmental change and other coastal zone resource users are protected from shrimp farm impacts, needs to be pursued vigorously in Thailand. Failure to do so will inevitably result in further environmental and economic instability.

Components of a sound management plan would include:

1. training for extension workers;
2. rehabilitation of abandoned shrimp ponds;
3. monitoring and enforcement of existing effluent and pond management standards;
4. devising a coastal zone map which identifies areas that are appropriate for new pond construction;
5. promotion of a research program for determining impacts from, and best management practices/ technologies for, the shrimp industry;
6. requiring environmental impact assessments for new and expanding aquaculture facilities;
7. recognition of the processes and functions of existing natural resources of the estuary that contribute to the sustainability of shrimp aquaculture;
8. less centralized, top-down planning and management with more involvement at the local level; and
9. less overlap and more cooperation between government institutions in data collection, planning, and resource management.

Acknowledgments

This manuscript benefitted from insights provided by Imre Csavas, Regional Aquaculture Officer, FAO Regional Office in Bangkok, and Isara Tanthien, Managing Director, Isaraporn Co., Ltd.

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