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# Ecosystem perspectives on management of disease in shrimp pond farming

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## Abstract

This paper reviews and discusses, from an ecological perspective, the causes behind the development and spreading of pathogens in shrimp aquaculture. The risk of disease in shrimp farming often increases with culture intensity and high stocking densities, and when polyculture is replaced by monoculture. High pond densities will facilitate the spread of pathogens between ponds. Shortage of clean water supply and insufficient waste removal lead to overloading of metabolites, environmental degradation, and to the shrimp becoming stressed by bad water quality, and thus more prone to becoming affected by disease. Excessive fluctuations in abiotic factors like oxygen, salinity, and temperature may also increase stress and susceptibility to disease. The location of farms in mangrove environments can lead to acidification that may directly, or indirectly, through release of heavy metals from the sediments, lower disease resistance. The use of hatchery-reared larvae will increase genetic uniformity and thus disease risk in comparison to the collection of wild larvae where selection has already favored the most viable individuals. Global and regional transportation of seed larvae and broodstock will facilitate the spread of pathogens. Apart from the above factors, which are all dependant on the farming itself, contamination by pesticides and pollutants from agriculture and industrial activities may lower disease resistance of the shrimp, especially if combined with other environmental factors.

We show that shrimp farming is, to a large extent, dependent on ecological services supplied by nature, and discuss the carrying capacity of shrimp pond farming from an ecosystem perspective, including aspects like culture intensity, pond density and sustainability. Since

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aquaculture is basically a natural ecological process, although in intensive shrimp farming it reaches industrial proportions, it is essential that we do not forget the underlying ecological principles, as this may help us to understand and contribute to the solution of some of the disease problems faced by shrimp farming.

*Keywords:* Ecosystem; Disease; Shrimp pond farming

## 1. Introduction

All populations of organisms, including humans, are limited partially or completely by diseases in their ecosystems (Real, 1996). Disease prevalence in populations and ecosystems is influenced by numerous environmental factors, including infectious organisms such as fungi and viruses, pollutants such as chemical and biological wastes, and shortage of food and nutrients (Dubois, 1965). This complex of factors and their interactions make tracking and assessing the causes and effects of individual diseases extremely difficult (McMichael, 1993). In contrast to shrimp farming, where disease is a relatively new problem, the causes behind human disease outbreaks are rather well known. It is generally accepted that increased densities of humans facilitate the spread of infectious organisms among people (Lederberg and Shope, 1992; WHO, 1992), and that the rapid human population growth and widespread environmental degradation expand world disease problems (WHO, 1996; McMichael et al., 1999). Crowded conditions in urban areas provide ideal environment for the spread of “old” diseases such as cholera and tuberculosis, as well as for many newly emerging diseases such as HIV (McMichael, 1993; Levins et al., 1994). In humans, about 40% of world deaths can be attributed to various environmental factors, especially organic and chemical pollutants (Pimentel et al., 1998), and an additional 37% of deaths is caused by infectious diseases (Real, 1996). The unprecedented increase in pollutants thus stresses humans as well as other organisms and increases disease.

The disease problems in penaeid shrimp aquaculture have escalated since the late 1980s when the industry collapsed in Taiwan. Throughout the last decade, we have become increasingly aware of the socio-economic and environmental unsustainability of the shrimp aquaculture industry. Due to self-pollution and disease problems, the lifespan of most intensive shrimp ponds (i.e. highly managed and high-yielding farms) seldom exceeds 5–10 years in Thailand (Flaherty and Karnjanakesorn, 1995; Dierberg and Kiattisimkul, 1996) and in other countries. The boom-and-bust pattern of this industry is further indicated by the fact that 70% of previously productive ponds has been abandoned in Thailand (Stevenson, 1997). The outbreaks of viral and bacterial diseases have caused devastating economic losses, e.g. US$750 million in 1993 in China and US$210 million in 1995–1996 in India (Primavera, 1998).

The diseases of cultured penaeid shrimp include syndromes with infectious (viral, rickettsial, bacterial, fungal, protistan and metazoan etiologies), as well as a number of noninfectious diseases, which are also of importance for the industry, caused by environmental extremes, nutritional imbalances, toxicants, and genetic factors, (Lightner, 1988a,b, 1996; Lightner and Redman, 1998; Brock 1992; Brock and Lightner 1990).

Snieszko (1973) drew attention to the fact that disease in aquaculture is the result of a complex interaction of the host animal, its environment, and the pathogen itself. Thus, the mere presence of a known pathogen in shrimp does not necessarily equate with disease.

In this article, we will review ecological and environmental factors that cause disease problems in shrimp farming, and address disease management from an ecosystem perspective. Since aquaculture is basically a natural ecological process, it is essential that we do not forget the underlying ecological principles, as this may help us to understand and contribute to the solution of some of the disease problems faced by shrimp farming.

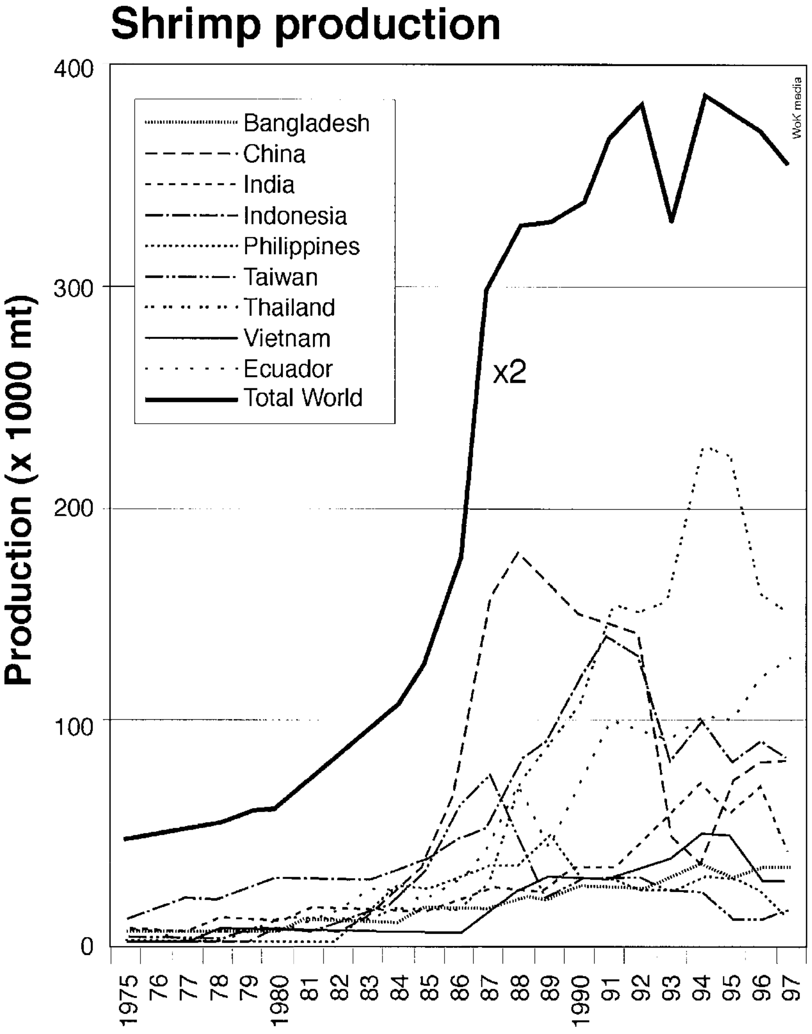

Fig. 1. Shrimp aquaculture production in main producing countries (Source: Primavera, 1997; Rosenberry, 1998).

## 2. Development of shrimp farming and disease problems

Shrimp aquaculture production took off in the 1970s, but due to pollution and disease problems, world production has stagnated and, in many countries, even gone down over the last few years (Fig. 1). In 1997, 1.3 million ha of shrimp ponds produced 660,000 tons of shrimps (Rosenberry, 1997). This corresponds to an annual productivity of 505 kg/ha, which is below the minimum production potential for extensive farming systems (0.6–1.5 tons/ha) (Primavera, 1998). However, many of the top-producing countries have a large percentage of semi-intensive and intensive farming systems (Table 1), which have annual production potential of 2–6 and 7–15 tons/ha, respectively (Primavera, 1998). Already in 1988, shrimp farming collapsed in Taiwan, which had, until then, been the world's leading producer. China then took over as top-producing country, but was soon also struck by disease, which resulted in a major drop in production in 1993. Thailand had, by that time grown, to become the world's leading producer. Although there was, by then, great awareness of the disease risk, and large investments were made to combat disease, Thailand's total production dropped in 1996–1997. A similar boom-and-bust pattern occurred in Indonesia and the Philippines (Primavera, 1997). In contrast, shrimp aquaculture in Ecuador, which started already in 1969, was not struck by large-scale disease problems until 1999. This is probably due to many shrimp disease having evolved in Southeast Asia, and that the geographical positioning of Ecuador results in that pathogens were more likely to first spread to other Asian countries before affecting Latin America. The fact that Ecuador relies on extensive (60%) and semi-intensive (40%) production systems, rather than intensive farming (Table 1), may also render the system less vulnerable to disease outbreaks as will be discussed in Sections 3 and 5. In some countries, the collapse of individual farms does not show in production curves because new farming areas have been taken up at a higher rate than the areas struck by disease were abandoned (Stevensson, 1997). In Thailand, significant disease problems affected one part of the country, while in other areas, production has been expanding, thus compensating for the loss in total country

Table 1

Percentage distribution between extensive, semi-intensive and intensive farms in main shrimp producing countries (compiled from Rosenberry, 1998)

| Country | Extensive | Semi-intensive | Intensive |
|---|---|---|---|
| Bangladesh | 90 | 10 | 0 |
| China | 50 | 45 | 5 |
| India | 92 | 8 | 0 |
| Indonesia | 70 | 15 | 15 |
| Philippines | 40 | 50 | 10 |
| Taiwan | 10 | 40 | 50 |
| Thailand | 5 | 15 | 80 |
| Vietnam | 80 | 15 | 5 |
| Ecuador | 60 | 40 | 0 |

Extensive aquaculture does not involve feeding of the organism; semi-intensive aquaculture involves supplementation of natural food by fertilization and/or the use of feeds; intensive aquaculture is highly managed with culture species maintained entirely by feeding with nutritionally complete diets.

output. Such a sequential exploitation pattern within and between countries has often masked the problems (Huitric, 1998).

The high return on investments in the early stage of shrimp farming development led to a rapid increase in the number of farms, obviously to a level beyond the carrying capacity of the environment in many countries. In most instances, the profit margin was such that any operation that lasted for more than 2 years was financially profitable, and the cost of establishing operations in other areas, if the old ones collapsed, was sufficiently low as not to be a deterrent (Lundin, 1995).

## 3. The role of pond environmental factors in disease outbreak

Viral and bacterial diseases, together with poor soil and water quality, are the main causes of shrimp mortality (Liao, 1989; Chamberlain, 1997), although deficient environmental management of shrimp farms is another important determinant (Flegel, 1996). Chemical and biological pollution by farms includes disposal of pond effluents and sludge in coastal waters; salinization of soil and water; misuse of chemicals, including antibiotics and pesticides; and introduction of exotic shrimp species and diseases (Primavera 1993; Flaherty and Karnjanakesorn, 1995; Macintosh and Phillips, 1997).

Under some conditions, the host and its pathogen may be co-existing with little or no adverse effect. In penaeid shrimp, we have examples of normally innocuous epicommensal organisms on shrimp gills causing disease when host populations are crowded and environmental conditions are stressful (such as high BOD combined with low dissolved oxygen conditions) (Lightner and Redman, 1998). Examples are common in which bacteria that may be part of the shrimp's normal microflora are found causing disease in stressed shrimp, and there are viruses which seem to cause little or no disease in some shrimp species, genetic strain, or life stage of the same species (Lightner, 1996). Thus, apparently healthy shrimp have constant low levels of bacteria, especially *Vibrio* spp., present in the hemolymph (Lightner, 1988a,b; Gomez-Gil et al., 1998), although their mechanisms of defense seem capable of controlling these bacteria under normal circumstances (Lightner, 1988a,b). It is also interesting to note that Baculovirus and White Spot virus can be present in shrimp ponds without causing major losses (D. Fegan, personal communication).

The risk of disease seems to increase with intensity of farming and thus, density of shrimp in the pond. Disease occurrence in shrimp ponds in Hainan, China was closely associated with excessive stocking and poor water quality (Spaargaren, 1998). In the Philippines, the Infectious Hypodermal and Hematopoietic Necrosis Virus (IHHNV) prevalence in various wild populations of *Penaeus monodon* has been correlated with shrimp culture intensification and mangrove status (Belak et al., 1999). Lower viral incidence in wild shrimp 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 (the probable source of pathogens) and severely degraded mangroves. In areas with high pond density, the emitted chemical and biological pollutants are recirculated among farms, and consequently, the degree of self-pollution increases. Higher levels of bacteria and *Vibrio* are also usually found in shrimp ponds than in mangrove sediments (Smith, 1998). Declining environmental suitability results in an increased incidence of disease with time, which ultimately may lead to failure of the shrimp crop (Chanratchakool et al., 1995). In order to reduce disease risk, the grow-out period in shrimp farming is often shortened, resulting in harvesting of smaller shrimp. Sometimes, cultivation continues until first signs of disease appear when the crop is immediately harvested and can still be marketed, but at lower quality (Thongrak et al., 1997).

There appears to be a clear linkage between environmental conditions and disease, although the precise nature of the relationship is complex and has to be established (Snieszko, 1973; Chanratchakool et al., 1995). The development of acid sulfate soils, and associated release of toxic levels of aluminum, precipitation of iron, and alterations of water chemistry (e.g. calcium and magnesium) may indirectly cause production failure by increasing physiological stresses and lowering the immune response (Simpson and Pedini, 1985; Abbot, 1994; Stevensson, 1997). Fluctuations in normal environmental conditions (e.g. oxygen, temperature, salinity) have a significant effect on the virulence of *Vibrio harveyi*, with salinity being more lethal to shrimp than temperature (Shivappa, 1997). Low oxygen levels, which are a common problem in ponds with high shrimp stocking density, increase sensitivity to vibriosis in penaeid shrimp (LeMoullac et al., 1998). White Spot virus disease seems to be triggered or aggravated by changes in sea water quality including, among others, hardness, temperature and dissolved oxygen (D. Fegan, personal communication). Other experiences from Thailand have shown that a sudden change in pH or low dissolved oxygen levels can precipitate an outbreak of Yellow Head Virus disease, and pollution from outside, such as insecticide residues, that have a very high direct toxicity on shrimp may be important at sublethal levels as predisposing factors for disease (Flegel, 1996). Other studies have shown that salinity reductions cause physiological stress in crustaceans and lower their tolerance to pollutants, indicating that toxicants in combination with environmental factors may act synergistically (e.g. Tedengren et al., 1988). Clearly, physiological stress seems to be one of the most important factors triggering the disease outbreak.

## 4. Local–regional–global interactions and diseases

Mangrove forests provide critical habitat for biodiversity, including wild shrimp larvae used to stock farms and recruitment areas for broodstock and spawners used in hatcheries (Primavera, 1993; Rönnbäck, 1999). During the last decades, mangroves have experienced widespread deforestation and degradation, and as a consequence, more than 50% of the world's mangroves have been removed (World Resources Institute, 1996). The conversion into shrimp aquaculture ponds constitutes the main threat to mangroves in many countries (Primavera, 1997; Naylor et al., 1998). For example, between 1951 and 1988, the Philippines lost 67% of their mangroves, of which the development of brackishwater ponds accounted for approximately half of the loss (Primavera, 1993). The removal of mangroves, as well as overfishing of shrimp larvae and adults, reduce the availability of shrimp seed and broodstock. This may aggravate a need to import or transport these over long distances, which, as discussed below, increases risk of transmission of pathogens (Lightner and Redman, 1992; Beveridge et al., 1997; Deb, 1998). Worldwide transfers and introductions of the few preferred culture species, among them *P. monodon*, *Litopenaeus vannamei* and *Marsupenaeus japonicus*, were significant in the early decades of commercialized shrimp culture. At the peak of Taiwanese shrimp production in 1982–1986, yearly imports from Southeast Asia of 70,000–160,000 live *P. monodon* broodstock supported hatchery production (Chin, 1988).

Disease has usually been a localized problem, but with the expansion and globalization of the shrimp industry, diseases that have been restricted to one region are now rapidly spreading over the world. The introduction of postlarvae and broodstock from areas affected by the White Spot Syndrome Virus (WSSV) and Taura Syndrome Virus (TSV) was often followed by the rapid spread of these major shrimp pathogens throughout most of the shrimp-growing regions in Asia and Latin America, respectively (Lightner et al., 1997). A native of Asia, where it has caused multimilllion dollar shrimp

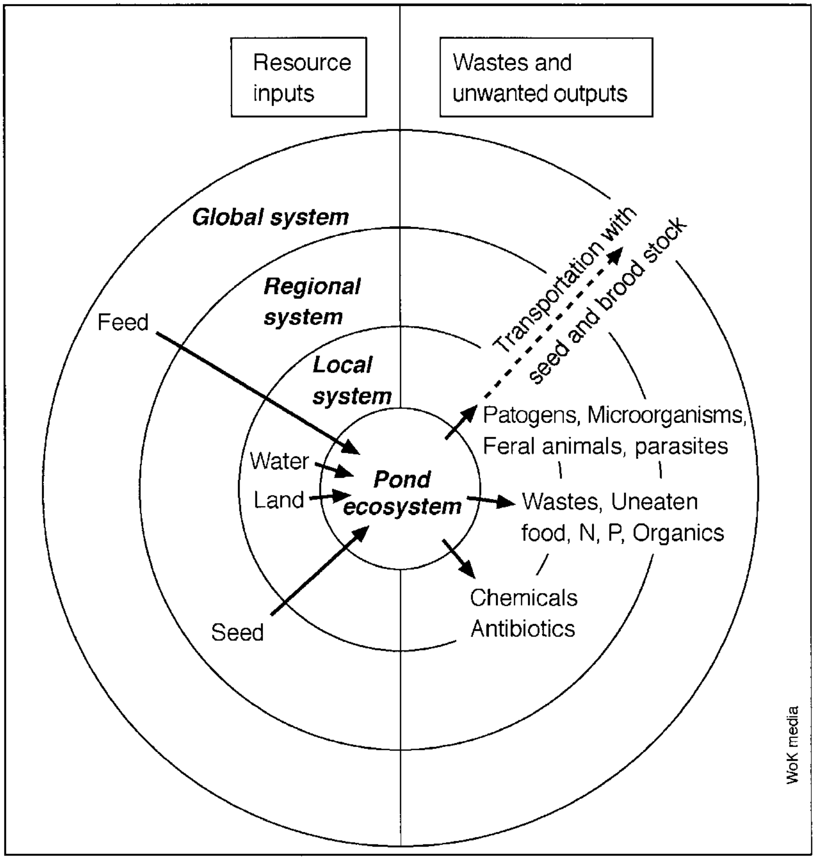

Fig. 2. Interactions between shrimp farming and the environment at the local, regional and global spatial scales.

crop losses, the WSSV was first discovered in America in mass mortalities of *L. setiferus* in a Texas farm in 1995 (Lightner et al., in press). Every year thereafter, it has been detected in wild and cultured shrimp (*L. setiferus*, *L. vannamei*, *L. stylirostris* and *Farfantepenaeus duorarum*) and wild decapods in Texas and South Carolina (Lightner et al., in press). Shrimp farming interacts with the environment across spatial scales regarding the need for resource inputs and the production of wastes and other unwanted outputs (Fig. 2). Usually, we mainly consider and manage impacts at the local level. However, the dependence on ecosystems extends far beyond the cultivation site (Folke et al., 1998), and it is therefore important that effects are evaluated also at the regional and global levels. It is comparatively easy to manage the pond itself since the farmer is usually aware of alarming signs and any measures taken give a direct feedback on production. Changes in local resource availability (clean water, land, seed, spawners, etc.), or impacts from wastes on the surrounding environment may also be noticed and can be directly linked to the activity. Regional and global effects are less obvious because the supporting ecosystems or the resource base may be situated far away. Often, the links to shrimp farming are not directly evident, or there are time lags, where the resources are slowly exhausted or where pollutants are successively accumulated before the threshold levels are reached and serious environmental problems develop. By then, it is usually too late or too expensive to solve the problem. Regional effects will often have a profound social and economic impact, especially if the farming area has to be abandoned. Another problem is that regional and global effects tend to threaten the supporting ecosystem in other nations, which makes it even more difficult to control.

## 5. The pond ecosystem and use of chemicals in shrimp farming

Aquaculture is basically a natural ecological process, although in intensive shrimp farming, it reaches industrial proportions. The rapid development towards high-yielding monocultures has unfortunately made some of the existing ecological links and dependencies less obvious. Furthermore, the high profits enable the farmer to replace some of the free ecosystem services and resource inputs that he earlier relied on, e.g. by long-range pumping of water, increased inputs of formulated feeds, medicines, energy, etc. Thus, ponds no longer need to be placed in mangroves, which is beneficial to the environment and reduces the problems of acidic soils for the farmer. Other ecosystem services and resources, however, may be difficult to replace for technological reasons or simply because we are unaware of them. To be successful in replacing ecosystem services, we need thorough ecological knowledge and good pond management, apart from capital. One sign of incomplete ecological understanding is that when problems appear, we usually routinely apply end-of-the-pipe solutions, i.e. antibiotics, chemicals, etc. Clearly, substantial gains can be made if we understand the cause of the problems better and take advantage of nature's services in a sustainable way.

In general, the more intensive the farming system, the less will the processes in the pond resemble a natural ecosystem, which is kept in dynamic balance by recycling and feedback mechanisms. In semi-intensive and extensive farming, all, or part of the wastes is recycled into micro-algae production that is used as food by the shrimp. A balanced normal bacterial composition may also keep the pond healthy and reduce risks for rapid spread of pathogenic microbes. With increased shrimp density, management becomes more difficult and the farmer may attempt to sterilize the pond environment with antibiotics, chlorine, formaldehyde, etc. (Primavera et al., 1993; Barg and Lavilla-Pitogo, 1996). Furthermore, the use of hatchery-produced shrimp larvae makes the system less tolerant to disease outbreaks because these larvae have been raised in a relatively sterile environment compared to wild-caught larvae. A sterile pond may increase disease risks substantially, since any microbe which enters the system might easily take over. To reduce this risk, experiments are now made to introduce probiotics, i.e. "friendly microbes", in the farming environment to suppress and outcompete pathogenic ones (Moriarty, 1998).

An extensive range of chemicals, such as disinfectants, therapeutants, antibiotics, vitamins, immunostimulants, and bioremediation products, have been used to treat pond soil and water (Primavera et al., 1993; Barg and Lavilla-Pitogo, 1996; Tonguthai, 1996). The use of chemicals usually increases with farming intensity, but their environmental impacts are virtually unknown. Disinfection by chlorine is widely used as a disease-preventing measure in intensive shrimp farming with 50,000 tons of chlorine used annually in Thailand alone (Gräslund, 1998). Chlorine kills bacteria and viruses, but also small crustaceans and other invertebrates that could act as vectors for the disease-causing organisms, besides controlling phytoplankton and macroalgae abundance (Boyd, 1996; Dierberg and Kiattisimkul, 1996; Kongkeo, 1997). The impacts of chlorination have received limited investigation, in spite of widespread use and the potential interactions of chlorine with organic substances that may lead to formation of halogenated hydrocarbons (Gräslund et al., 1999).

Another issue is the use of antibiotics in shrimp farming. Although, in general, use of antimicrobials in aquaculture is rapidly decreasing in industrialised countries, e.g. Norway), statistics are doubtful elsewhere, and there are considerable constraints to the promotion of safe and effective use of drugs and chemicals in developing countries (Barg and Lavilla-Pitogo, 1996). This includes misapplication of some chemicals (e.g. the excessive prophylactic use of antibacterials), and insufficient understanding of mode of action and efficacy under tropical aquaculture conditions, as well as uncertainties with regard to legal and institutional frameworks to govern chemical use in aquaculture (Barg and Lavilla-Pitogo, 1996).

This uncertainty worries us as there are many potential side-effects from excessive use of antibiotics, which are now being widely acknowledged in, e.g. Europe and the USA.

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 appearance of drug residues in non-target organisms, human health issues and ecological impacts associated with antibiotic uses raise concern (Daily and Ehrlich, 1996; 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.

## 6. The dependence of shrimp farming on ecosystem support

When problems appear in shrimp ponds or fish cages, people tend to look at what is going on inside the pond or cage, without realizing that the farm is an integral part of a much larger surrounding ecosystem. The surrounding ecosystems provide the feed, seed, clean water and other necessary natural resources and ecosystem services including waste assimilation. This unperceived work of nature sets the limits as to how much can be cultured without running into pollution or disease problems. However, failure to acknowledge these life support functions of surrounding ecosystems is one explanation to the boom-and-bust pattern of shrimp aquaculture (Rönnbäck, 1999).

While a natural ecosystem can maintain its main functions reasonably well within its boundaries, any managed cultivation ecosystem will heavily depend on well-functioning infrastructure and management, controlling the flows in and out. Intensive and semi-intensive shrimp farms are throughput systems (Folke and Kautsky, 1992). Thus, they show similarities to other man-made systems such as most modern agriculture, which have "footprints" extending far beyond their physical boundaries and are dependent on surrounding ecosystems for the import of resources as well as their capacity to take care of wastes (Folke et al., 1998).

In order to identify the demands for natural resources and ecosystem services of shrimp farming, we have previously estimated the ecosystem area, the "ecological footprint", that is functionally required to support the activities of a semi-intensive shrimp farm in Colombia with an annual production of 4 tons/ha (Larsson et al., 1994; Kautsky et al., 1997). This study estimated that the spatial ecosystem support or "footprint" required to produce food inputs, nursery areas, clean water, and waste processing was 35–190 times the surface area of the farm. The mangrove nursery area required to produce the shrimp larvae that are stocked in the pond was the largest support system, being 10–160 times the pond area, based on current practice that 10–50% of stocked seed is wild-caught (Larsson et al., 1994). If situated close to the farm, the same mangrove area could also, e.g. supply clean water and absorb polluting nutrients in the farm effluents. The ecosystem area needed for absorbing nutrients is at least 2.8 $m^2/m^2$ shrimp pond area (Robertson and Phillips, 1995). Another major input to a shrimp farm are the ingredients in the feed pellets. We calculated that the marine area needed to catch the fish component in feed pellet was 14.5 $m^2/m^2$ semi-intensive shrimp pond (Larsson et al., 1994).

The size of the footprints will change with the intensity of farming and the extent to which the seed is wild-caught or hatchery-reared; e.g. a higher stocking density will require more food inputs and also produce more wastes (Folke and Kautsky, 1992). For an intensive farm producing 14 tons $ha^{-1}$ $year^{-1}$, the marine area needed for feed production increases about five times (Larsson et al., 1994), and the area needed for nutrient absorption about eight times, compared to semi-intensive production (Robertson and Phillips, 1995). For both intensive and semi-intensive farming, feeds are usually imported from other areas, and the dependence on mangrove nursery areas is reduced by investing in shrimp hatcheries. This will reduce the pressure on local ecosystems. However, it should be emphasized that even intensive shrimp farms located far away from the mangroves and totally relying on hatchery-produced seed are still dependent on viable mangrove ecosystems, which support the continual input of spawners and broodstock to hatcheries (Rönnbäck, 1999).

Some services provided by nature, like clean water supply and waste assimilation, must be located close to the farming area. Up to a certain pond density and farming intensity, this may be no problem, but when the dynamic carrying capacity of the local or regional environment is exceeded, the whole activity may collapse, unless costly and space-demanding pipelines and water treatment facilities are built. The footprint concept may help indicate when this carrying capacity level is being approached.

We believe that the footprint concept in its present stage is useful for communicating the importance of viable ecosystems to farmers and policy makers. Although being a static measure, the concept illuminates the hidden requirements for ecosystem support, and puts the scale of fisheries and aquaculture within an ecosystem framework. It also demonstrates that human activities that at first glance may seem separate from nature would not function without ecosystem support (Folke and Kautsky, 1989). This fundamental lesson should be incorporated in aquaculture policies, as well as in policies of any other economic activity.

## 7. Sustainability and costs

Usually, there is a relationship between the sustainability, ecosystem recovery and the intensity of farming. Intensive shrimp farming, which may reach an annual production of 10–15 tons/ha, has often generated pollution and disease problems resulting in that ponds had to be abandoned after only 5 years (Flaherty and Karnjanakesorn, 1995; Dierberg and Kiattisimkul, 1996). Semi-intensive and more traditional farming methods seem to be less sensitive and usually have a much longer lifespan (Gujja and Finger-Stich, 1996), although producing a lower shrimp yield per area. Less intensive farms also tend to need shorter time after collapse before the area can be used again for shrimp farming as it takes less time for the ecosystem to recover (Shiva, 1997). With these prerequisites, semi-intensive and traditional farming may not give lower long-term production. However, in a changing coastal environment with increasing population and pollution pressure, more extensive and traditional farming methods will run greater risks, since they are more directly linked and dependent on nature's services.

One of the arguments raised against lowering of farming intensities is usually that more land and pond area are appropriated to grow shrimp at lower densities. The main factor is, however, the economic situation with a strong global market demand, which creates incentives for farmers, companies, and bankers to aim at a quick return on investments. The mismatch between short-term profits and high yields that result in longer-term environmental impacts and socio-economic costs has been a significant factor in reducing sustainable outcomes of shrimp farming. Furthermore, market prices of farmed products do not cover the costs of deteriorated coastal and marine support areas caused by the farming. We believe that the internalization of such costs in line with the Rio Declaration would create incentives for the industry to redirect into a more sustainable path (Folke et al., 1994). In the long run, this may be a possible solution, although in order to be realistic, it needs to be simultaneously adopted also for other aquaculture and agriculture systems.

## 8. Conclusions and solutions

Management of the pond environment is probably the most important factor for disease prevention in shrimp mariculture (Flegel, 1996). But it is often not sufficient since the pond is an open system impacted by human activities in the surrounding landscape as well as by regional and global transportation.

The footprint analysis illuminated that mangroves provide key inputs and support to shrimp farming. Resources such as food, seed and broodstock, and services like clean water supply, all affect the long-term productivity of the farming systems. Extensive and some traditional farming methods are usually directly dependent on these goods and services and often use them in a sustainable way. However, when farming reaches the semi-intensive level, conflicts increase. Still, the farmer may be interested in locating his farms in mangrove areas to reduce water pumping costs and land acquisition prices. However, overexploitation of the mangroves exceeds the environment's carrying capacity for clean water and recycling of nutrient wastes, which may trigger disease problems. The removal of mangroves will eventually also lead to a shortage of wild larvae and adult breeders, which then need to be brought from other areas, increasing the risk for spread of pathogens. The farmers will be driven into capital-intensive high-technology solutions, e.g. relying on hatcheries for larval supply and pumping of water from far distances, which means that the whole business will turn into intensive and super-intensive farming methods. In the long run, this will cut all feedbacks to the environment and make the systems lose resilience, which greatly increases risks for disease and collapse.

The footprint concept may help indicate where these biophysical limits are. It may be possible to go beyond the limits with the help of biotechnology and close management, but this requires the development and application of new technologies, which will cost money and skills. We will become dependent on hatcheries, genetic selection, large inputs of high quality feeds, medicines, water pumping and aeration, pond preparation after each crop, including drying of ponds and sediment removal, liming, etc. The use of hatchery-reared larvae will tend to increase genetic uniformity, and thus disease risk in comparison to the collection of wild larvae, where selection has already favored the most viable individuals. All these will tend to make the system less resilient. Such — getting rid of nature's services — has, in many cases, proven unsustainable in the longer term (Gunderson et al., 1995). If management rules are not strictly followed, or a new disease develops, or antibiotic resistance appears, or the surrounding water quality deteriorates due to pollution, then it may all crash. It must also be remembered that super-intensive systems still rely on good water quality and other ecological goods and services (Folke and Kautsky, 1989).

Concerns about the environmental sustainability of shrimp farming have become more pronounced in the light of large-scale production failures. We argue that many problems experienced in aquaculture have been due to lack of ecological understanding. Aquaculture is basically a natural ecological process, although in intensive shrimp farming, it reaches industrial proportions. Thus, it is essential that we do not forget the underlying ecological principles, as this may help us to understand and contribute to the solution of some of the disease problems faced by shrimp farming. It is also clear that disease and environmental issues are now forcing shrimp farmers to re-evaluate traditional management practices which rely heavily on external resources such as healthy wild shrimp, clean estuarine water, and a large adjoining ecosystem to assimilate wastes (Chamberlain, 1997).

In order to reduce disease problems and increase sustainability of shrimp farming, essentially two different strategies can be taken. One more "conservative", less high-yielding, ecological approach and one using the latest developments in biotechnology aim at highest possible productivity and economic output (Table 2). The "ecological" approach 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 buffer zones that prevent spreading of disease and provide ecological services, and adapt the farming to the local carrying capacity. The use of integrated farming of shrimp with mussels and seaweed, or aquasilviculture, where resources and wastes are re-circulated within the farm instead of depleting or overloading the environment, may be one way of reducing the size of the footprint (Troell et al., 1997, 1999). It must, however, be emphasized that these low-intensity systems require much larger pond areas for a given volume of production compared to intensive systems.

The "technological" alternative tends to drive development towards completely artificial super-intensive systems, which are isolated from the environment. It also involves treatment and recirculation of pond wastes, sterilization of pond environment with antibiotics, ozone, chlorine, formaldehyde, etc., and continued hopes that it may be possible to genetically select for disease resistance, and developing efficient vaccines. This alternative aims at high output but demands very high level of management. The growth period is shortened to reduce disease risk, which gives smaller and lower quality shrimp. It would be very interesting to compare these two approaches in a cost–benefit analysis including environmental costs and sustainability issues to see how we should optimize shrimp production.

Table 2
Alternative approaches to reduce disease problems in shrimp farming

| Ecological solution | Technological approach |
|---|---|
| (1) Lower intensity and pond densities | (1) Isolate farm from the environment |
| (2) Create large buffer zones | (2) Treat and re-circulate pond water |
| (3) Integrate systems for effluent treatment and resource management | (3) Sterilize pond environment |
| (4) Keep farming within carrying capacity of local environment | (4) Use of antibiotics and medicines |
| | (5) Genetic selection for disease resistance |

If super-intensive farming proves successful, we could probably expand shrimp farming in temperate areas. Shrimp farming is today mainly confined to developing countries largely because of lower labor costs and land prices as well as limited enforcement of already weak environmental laws. Extensive and semi-intensive farming techniques made it profitable to farm shrimp in developing countries because nature's ecological services were free (Naylor et al., 1998). Now that advanced technology and high level management are taking over and production costs are increasing in developing countries, we might move some of the farms to USA, Japan or Europe where the larger part of the market is, and where the price of the shrimp would better reflect all costs involved in shrimp farming.

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