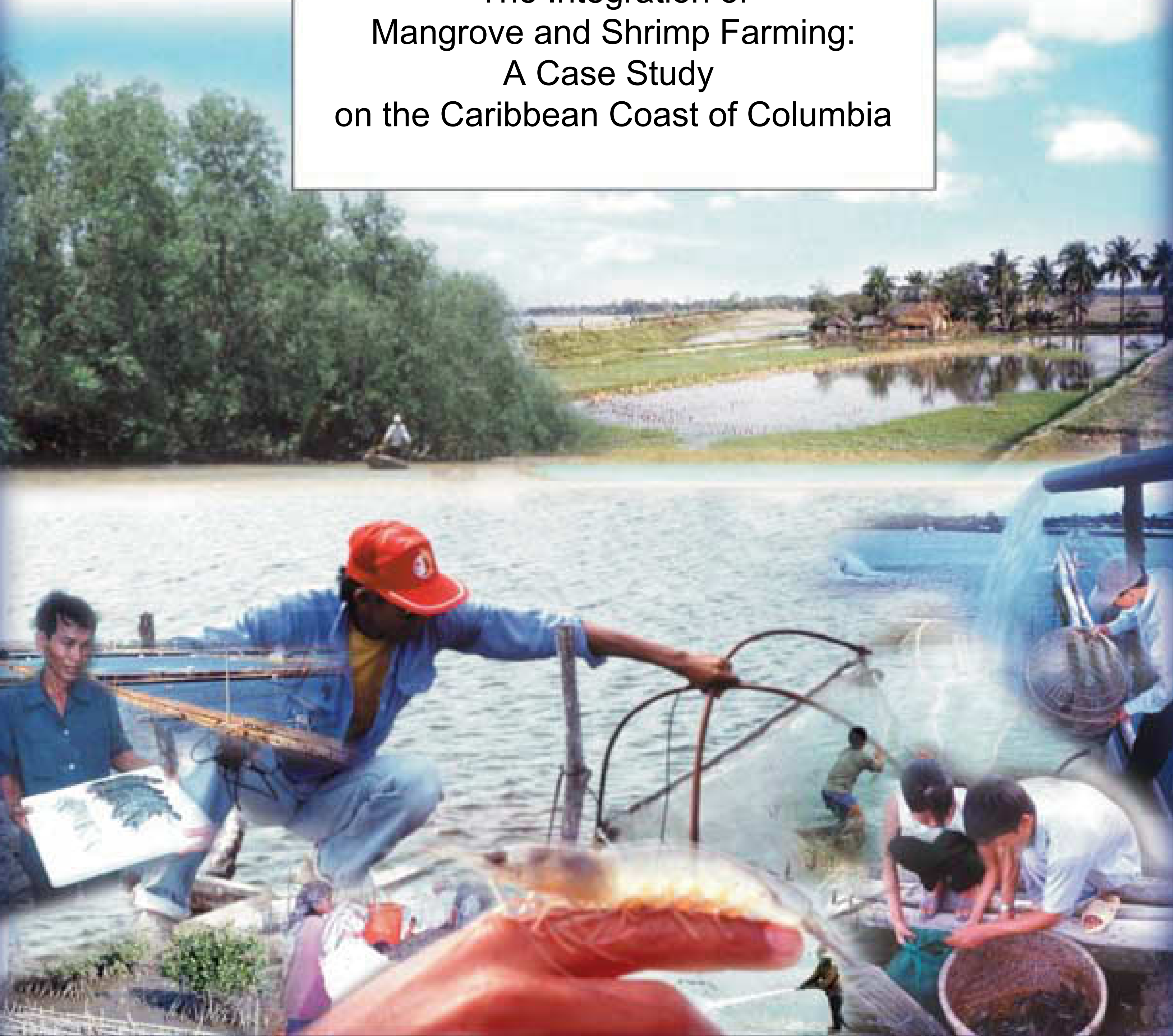
# Shrimp Farming and the Environment

## The Integration of Mangrove and Shrimp Farming: A Case Study on the Caribbean Coast of Columbia



*A Consortium Program of:*

# THE INTEGRATION OF MANGROVE AND SHRIMP FARMING: A CASE STUDY ON THE CARIBBEAN COAST OF COLOMBIA

by

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## Preparation of this document

The research reported in this paper was prepared under the World Bank/NACA/WWF/FAO Consortium Program on Shrimp Farming and the Environment. Due to the strong interest globally in shrimp farming and issues that have arisen from its development, the consortium program was initiated to analyze and share experiences on the better management of shrimp aquaculture in coastal areas. It is based on the recommendations of the FAO Bangkok Technical Consultation on Policies for Sustainable Shrimp Culture[1], a World Bank review on Shrimp Farming and the Environment[2], and an April 1999 meeting on shrimp management practices hosted by NACA and WWF in Bangkok, Thailand. The objectives of the consortium program are: (a) Generate a better understanding of key issues involved in sustainable shrimp aquaculture; (b) Encourage a debate and discussion around these issues that leads to consensus among stakeholders regarding key issues; (c) Identify better management strategies for sustainable shrimp aquaculture; (d) Evaluate the cost for adoption of such strategies as well as other potential barriers to their adoption; (e) Create a framework to review and evaluate successes and failures in sustainable shrimp aquaculture which can inform policy debate on management strategies for sustainable shrimp aquaculture; and (f) Identify future development activities and assistance required for the implementation of better management strategies that would support the development of a more sustainable shrimp culture industry. This paper represents one of the case studies from the Consortium Program.

The program was initiated in August 1999 and comprises complementary case studies on different aspects of shrimp aquaculture. The case studies provide wide geographical coverage of major shrimp producing countries in Asia and Latin America, as well as Africa, and studies and reviews of a global nature. The subject matter is broad, from farm level management practice, poverty issues, integration of shrimp aquaculture into coastal area management, shrimp health management and policy and legal issues. The case studies together provide an unique and important insight into the global status of shrimp aquaculture and management practices. The reports from the Consortium Program are available as web versions (http://www.enaca.org/shrimp) or in a limited number of hard copies.

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[1] FAO. 1998. Report of the Bangkok FAO Technical Consultation on Policies for Sustainable Shrimp Culture. Bangkok, Thailand, 8-11 December 1997. FAO Fisheries Report No. 572. Rome. 31 p.

[2] World Bank. 1998. Report on Shrimp Farming and the Environment – Can Shrimp Farming be Undertaken Sustainability? A Discussion Paper designed to assist in the development of Sustainable Shrimp Aquaculture. World Bank. Draft.

## Abstract

Shrimp aquaculture has been accused of threatening mangrove forests worldwide. In response, the shrimp industry is developing the concept of integrated mangrove–shrimp farm systems. Mangrove and shrimp ponds are known to have mutually supportive functions. Mangrove wetlands can treat effluents from shrimp ponds effectively by removing suspended solids and nutrients. This activity can be expected, in turn, to enhance mangrove productivity. This report describes an integrated mangrove wetland–shrimp farm operating in Colombia since 1996. At this site, shrimp farm effluent is recirculated through an 120 ha mangrove area. Suspended solids are considerably reduced in the effluent, and nutrient concentrations in the adjacent lagoon decrease. Mangrove growth and regeneration in the biofilter are very high, but nutrient cycling in the biofilter is poorly understood. Moreover, the long-term impact of effluents on mangrove ecosystem has to be assessed. This case provides a positive example of responsible aquaculture development in coastal areas, but at the same time reveals the need for further research to develop sustainable practices within the shrimp industry.

# Content

## Abbreviations and Acronyms

| | |
|---|---|
| ADB | Asian Development Bank |
| BOD | Biological Oxygen Demand |
| cm | Centimeter |
| DBH | Stem Diameter at Breast Height |
| FAO | Food and Agriculture Organization of the United Nations |
| h | Hour |
| ha | Hectare |
| kg | Kilogram |
| km | Kilometer |
| $km^2$ | Square kilometer |
| l | Liter |
| m | Meter |
| mg | Milligram |
| NACA | Network of Aquaculture Centres in Asia-Pacific |
| ppt | Parts per Thousand |
| S | Second |
| SRP | Soluble Reactive Phosphorus |
| TAN | Total Ammonia Nitrogen |
| TSS | Total Suspended Solids |
| WWF | World Wildlife Fond |

## Introduction

Historically, high mortality rates and low growth problems in shrimp farming often stem from deteriorated water quality in certain regions of Asia and America (Twilley 1992; Phillips et al. 1993; Primavera 1995; Calderón 1996; Lin and Nash 1996; Qingyin et al. 1997; Flegel 1998; Jiaxin and Zhimeng 1998). Degradation of coastal tropical ecosystems is caused mainly by discharging waters used in the domestic and industrial sectors (Twilley 1992; Calderón 1996; Lin and Nash 1996; Qingyin et al. 1997). The concentration of aquaculture facilities in certain areas and the destruction of mangrove are additional aggravating factors (Twilley 1992; Phillips et al. 1993; Parks and Bonifaz 1994; Rosenthal 1994; Primavera 1995; Calderón 1996; Qingyin et al. 1997). Aquaculture effluents are characterized by high levels of dissolved and suspended solids, the result of waste production in ponds (Beveridge et al. 1991; Pruder 1992; Boyd and Tucker 1998). Previous studies performed on Colombian shrimp farms demonstrate that suspended solid and nutrient concentrations are often higher in effluents then they are in supply waters (Bahamón et al. 1997; Gautier et al. 1998a; Rivera-Monroy et al. 1999). In general, a risk exists of eutrophication in water bodies that receive shrimp farm effluents (Boyd and Tucker 1998). In response, implementation of more sustainable production methods, including effluent and mangrove management, is receiving more attention (Jory 1995; Lin and Nash 1996; Boyd 1997). Legislation to regulate effluent quality and mangrove preservation is currently being developed in many countries (Lin and Nash 1996; Boyd 1997).

Improved farm effluent quality can be achieved through appropriate management decisions applied at different levels. Management considerations include (Wang 1990; Phillips et al. 1993; Hopkins et al. 1995; Boyd and Tucker 1998): (1) site selection, design and farm construction, (2) farm management practices, and (3) effluent treatment. Effluent treatment alternatives include settling ponds (Schwartz and Boyd 1995; Teichert-Coddington et al. 1999) and mollusk culture (Lin et al. 1993; Shpigel et al. 1993; Jimeno et al. 1995; Hussenot et al. 1998) to eliminate suspended solids; and seaweed (Neori et al. 1993) and microalgae cultures (Lefebvre et al. 1996; Hussenot et al. 1998) to absorb nutrients. A relatively new approach is to use natural mangrove areas as a biofilter to remove suspended solids, lower biological oxygen demand (BOD), and absorb nutrients (Twilley 1992; Robertson and Phillips 1995; Wong et al. 1995; Dierberg and Kiattisimkul 1996; Massaut 1999; Rivera-Monroy et al. 1999). Nevertheless, no information exists to document the actual efficiency of such a system in treating shrimp farm effluents in a real situation.

In this report, an integrated shrimp farm–mangrove forest system that has been operating by Agrosoledad since 1996 on the Colombian Caribbean coast is described. Shrimp pond discharge is treated through a mangrove wetland (that acts as a biofilter) and is partially recirculated inside the farm. Water quality is monitored in the adjacent estuary, and possible interactions with Agrosoledad's farm and biofilter are analyzed. Based on Agrosoledad's experience, advantages and disadvantages of using a mangrove wetland as a biofilter to treat pond effluent are discussed and recommendations made. The implications of developing coastal shrimp farming on mangrove ecosystems worldwide, and more particularly in Colombia are first discussed.

## Mangrove and Shrimp Farming

Mangrove forests were estimated to cover 160,000 $km^2$ around the globe in the early 1990s (Macintosh and Phillips 1992; Phillips et al. 1993), although about half of the global mangrove forests may have been cleared, with a major impact in especially Asia and Africa (Clay 1996; Boyd 1997). Mangrove destruction usually results from unsustainable short-term exploitation for numerous domestic and industrial uses, including forestry, mining, and industrialization (Mitsch and Gosselink 1993; Macintosh 1998). Before the 1970s, mangrove swamps were considered wasteland. Their importance in protecting inland areas from storms, in preventing coastal erosion, in serving as nutrient sinks, in exporting organic matter to adjacent food chains, and in preserving biodiversity has been studied only recently (Mitsch and Gosselink 1993). Social, economic, and ecological benefits from mangrove are now recognized (Phillips 1995a). Mangrove forests also provide numerous resources and services that are directly beneficial to shrimp farming (Clay 1996; Massaut 1999). Ironically, shrimp farming is accused of threatening mangrove forests and even of being a major cause of their destruction in some countries (Massaut 1999).

Mangrove has been cleared to develop aquaculture projects in some regions, but aquaculture is not the main factor responsible for mangrove destruction around the world (Macintosh and Phillips 1992; Phillips 1995a, 1995b; Clay 1996; Macintosh 1996, 1998). In fact, there is a debate among environmentalists, scientists, and aquaculturists about the impact of coastal aquaculture on mangrove forests (Clay 1996; Lassen 1997; Massaut 1999), and evaluations have differed in their conclusions. Clay (1996) estimated that by the mid-1990s mangrove cleared for shrimp farming could be equivalent to 5% of the global mangrove area, but Macintosh and Phillips (1992), Phillips et al. (1993), Boyd (1997), and Massaut (1999) calculated that it has to be less, without giving any more precise estimate. Clay (1996) also estimated that shrimp farming could be responsible for about 10% of total mangrove clearings (as a global average). But in a few countries, shrimp ponds represent 20–50% of total mangrove clearings, as in Thailand or the Philippines (along with milkfish ponds in this case). Shrimp ponds may even occupy 20–50% of the total area previously covered in mangrove, as in Ecuador (Macintosh and Phillips 1992; Phillips et al. 1993; Phillips 1995b; Clay 1996; Dierberg and Kiattisimkul 1996; Menasveta 1997). The Asian Development Bank (ADB) and NACA (ADB/NACA 1998) reported that 42% of the land used for extensive shrimp culture in Asia was previously mangrove forest. The most significant negative impact on mangrove forests from the development of shrimp culture has been attributed to extensive systems (Phillips 1995a; Menasveta 1997; ADB-NACA 1998). Semi-intensive and intensive shrimp farms are usually located in supratidal zones, while traditional extensive aquaculture has been developed mostly in intertidal zones (Phillips 1995a; Menasveta 1997; ADB-NACA 1998).

Aquaculture's effects on mangrove include cutting trees and clearing land, water-logged soil and hydrological changes due to the construction of canals and roads, and the spread of disease to wild shrimp (Clay 1996; Massaut 1999). Other environmental impacts related to the development of extensive shrimp culture in mangrove forests include coastal erosion, saline intrusion into agricultural lands, decrease in shrimp postlarvae and mud crab, increased malarial incidence in coastal areas, acidification of soils and waters, and declining yields in shrimp ponds (Phillips et al. 1993; Phillips 1995a; Macintosh 1998). Several authors have pointed out the irony that mangrove destruction itself is sometimes the main reason for the unsustainability of shrimp farming, because of erosion, loss of natural productivity, water acidity, and contamination (Macintosh and Phillips 1992; Phillips et al. 1993; Clay 1996; Macintosh 1996; Massaut 1999). As a consequence, some extensive shrimp farm developments have been abandoned (Macintosh and Phillips 1992; Dierberg and Kiattisimkul 1996; Lin and Nash 1996; Clay 1996) and some environmental activists have criticized such occurrences publicly, calling them "slash and burn" exploitation (Saw 1996). But, Boyd and Schmittou (1999) suggest this marginal phenomenon has been distorted in a typical example of undocumented misinformation disseminated by some environmentalists (Saw 1996; Lassen 1997).

Mangrove clearance has significant economic and social effects (Macintosh and Phillips 1992; Phillips et al. 1993; Phillips 1995b; Clay 1996). The most important economic impact of mangrove destruction is the loss of fisheries, but other products and services are also negatively affected (Phillips et al. 1993; Phillips 1995b; Macintosh 1996, 1998). The economic value of mangrove ecosystems has not been precisely measured because of the technical difficulty, but it is clearly higher than the income provided by extensive shrimp farming (Phillips 1995a, 1995b; Clay 1996; Hambrey 1996). Hambrey (1996) calculated that, due to their very low investment requirements, traditional activities such as mud crab fisheries and charcoal or pole production have a higher profit margin than any form of aquaculture developed in mangrove areas.

Therefore, the development of extensive shrimp culture in mangrove areas is considered nonproductive and should be banished, in some analysts' views (Phillips 1995a, 1995b; Clay 1996; Hambrey 1996).

Macintosh (1998) pointed out, "Since loss of ecological attributes of mangroves is a factor contributing to unsustainable coastal aquaculture in Asia, it follows that mangrove conservation, including the restoration of destroyed or degraded mangrove habitats, may improve ecological conditions and reduce the risk of aquaculture failure for environmental reasons." Regulations have been developed in many countries to protect mangrove, but they are seldom enforced (and sometimes penalties are not strong enough deterrents). Regulations usually do not take into consideration the local conditions (Macintosh 1996, 1998; Massaut 1999). Techniques for mangrove restoration in shrimp farms have been published (FAO 1994; Macintosh 1996, Lewis and Marshall 1998; Massaut 1999), but the effects of mangrove reforestation on aquaculture sustainability have still to be demonstrated (Macintosh 1998).

Semi-intensive shrimp farming is considered more "environmentally friendly" than extensive systems that waste land area and intensive systems characterized by higher waste production (Macintosh 1998). But Macintosh also noted that semi-intensive farming managed in a linear fashion (where resources are pumped in, used up, and pumped out) results in environmental problems in the surrounding ecosystems. Best Management Practices (BMPs) and codes of practice–including mangrove reforestation and conservation and effluent treatment–have been recently promoted by aquaculturists and environmentalists (Lin and Nash 1996; Boyd 1997; Boyd and Schmittou 1999; Massaut 1999). Teichert-Coddington (1995) recommended pond management practices to reduce the amount of wastes being discharged. Dierberg and Kiattisimkul (1996) and Macintosh (1998) considered waste recycling necessary to enhance the sustainability of shrimp farming.

Because of the necessity of preserving mangrove and of recycling aquaculture wastes, researchers have proposed that mangrove forests and shrimp farms, which have mutually supportive functions, be integrated (Phillips 1995a, 1995b; Robertson and Phillips 1995; Dierberg and Kiattisimkul 1996; Boyd 1997). Mangroves support coastal shrimp aquaculture by providing buffer zones, nursery areas, coastal productivity enhancement, sedimentation, and nutrient cycling (Phillips et al. 1993; Phillips 1995b; Boyd 1997; Macintosh 1998). Cultured shrimp ponds are a source of nutrients that stimulate mangrove productivity and contribute to the food chain in adjacent waters (Phillips 1995a, 1995b; Boyd 1997). Expected benefits of integrated systems include enhancing coastal fisheries, minimizing contamination of the coastal environment, and providing a higher-quality water supply for shrimp farming (Boyd 1997).

Integrated mangrove–shrimp farming systems have the advantage of combining mangrove conservation with the high income potential of aquaculture (Macintosh 1998). One approach is to transform current extensive shrimp farming into "silvo-fishery" systems (Macintosh 1998). Indonesian "tambak" is a traditional form of integrated system in which extensive aquaculture is sustained by mangrove productivity (Hambrey 1996; Macintosh 1998). Binh et al. (1997) demonstrated that integrated mangrove–shrimp farms (mangrove covering of 30–50% of the pond area) in Vietnam have higher economic returns than farms where mangrove had been cleared.

Another way to integrate shrimp ponds and mangrove areas is to discharge pond effluents into mangrove forests to limit the risk of eutrophication of the adjacent waters (Twilley 1992; Robertson and Phillips 1995; Massault 1999; Rivera-Monroy et al. 1999). Mangrove wetlands could be use as a biofilter to remove suspended solids, lower BOD, and absorb nutrients (Nedwell 1975; Robertson and Phillips 1995; Wong et al. 1995; Dierberg and Kiattisimkul 1996; Massault 1999; Rivera-Monroy et al. 1999). Processes involved in removing suspended solids and nutrients in wetlands include sedimentation, decomposition of organic matter, uptake of nutrients by plants and bacteria, nitrification-denitrification, and absorption of ions by soil (Nedwell 1975; Robertson and Phillips 1995; Boyd and Tucker 1998; Rivera-Monroy et al. 1999). Although how mangrove forests work as sinks for phosphorus and nitrogen is poorly understood

(Massault 1999), several authors have reported their effectiveness in removing nutrients from effluents (Nedwell 1975; Tam and Wong 1993; Corredor and Morell 1994; Wong et al. 1995; Alongi 1996). Mangrove forests' ability to remove water contaminants can be used for domestic or industrial effluent treatment (Tam and Wong 1993; Corredor and Morell 1994; Wong et al. 1995). Mangrove wetlands are actually used in Colombia for hydrocarbon and heavy metal removal from oil refinery and tannery effluents (Malaver 1999; Sanchez, personal communication). Rajendran and Kathiresan (1996) and Macintosh (1996) reported from experiments conducted in India and Thailand, respectively, that applying effluent and waste sludge from shrimp ponds had a positive effect on mangrove seedling growth. Based on theoretical calculations, Robertson and Phillips (1995) estimated that 2–22 ha of mangrove wetlands are required to remove the amount of nutrients produced by 1 ha of shrimp pond depending on the intensity of the farming. These calculations did not take into account nutrient loss through denitrification, sedimentation, and soil absorption (Boyd and Tucker 1998; Rivera-Monroy et al. 1999). Considering denitrification, Rivera-Monroy et al. (1999) calculated that 0.04–0.12 ha of mangroves could remove the amount of dissolved inorganic nitrogen produced by 1 ha of shrimp pond.

## Mangrove Forests and the Development of Shrimp Aquaculture in Colombia

The area occupied by mangrove forests in Colombia is estimated at 86,311 ha for the Caribbean coast (Sánchez-Páez et al. 1997a) and 292,700 ha for the Pacific coast (Sánchez-Páez et al. 1997b). Five species are reported on the Caribbean coast (Sánchez-Páez et al. 1997a): *Avicennia germinans*, *Conocarpus erectus*, *Laguncularia racemosa*, *Pelliciera rhizophorae,* and *Rhizophora mangle*. Those five species are also present on the Pacific coast, along with *Avicennia tonduzii*, *Mora oleifera*, *Rhizophora harrisonii*, *R. racemosa,* and *R. samoensis* (Sánchez-Páez et al. 1997b; Vieira et al. 1998). Another plant commonly associated with mangrove trees in Colombia is the fern *Acrostichum aureum* (Sánchez-Páez et al. 1997a, 1997b; Vieira et al. 1998). *Acrostichum aureum* colonizes lands between mangrove forests that are partial wetlands and terrestrial vegetation (Vieira et al. 1998).

Sánchez-Páez et al. (1997a) reported a total area of dead mangrove trees of 21,922 ha on the Caribbean coast. About 95% of this mortality is observed in the state of Magdalena, resulting from significant changes in hydrological conditions (Sánchez-Páez et al. 1997a). The rest of the mortality observed along the Caribbean coast is probably due to erosion, sedimentation/accretion, and storms. Several traditional economic activities continue to take place in the mangrove forests: fishing (fish, crab, and mollusks), timber and firewood production, bark extraction for tannin production, and collection of propagules for human consumption and of leaves and fruits for animal feeding (Ulloa-Delgado et al. 1998). Industrial timber production occurs in some places.

Because of the negative impact of human activities on mangrove forests in Colombia throughout the 1960s and '70s, the government developed appropriate legislation to control the exploitation of mangrove trees (Ulloa-Delgado et al. 1998). Cutting mangrove trees without a permit is not allowed. The extraction of mangrove bark used in tannin production has been prohibited by a decree from the Ministry of the Environment. Each state's environmental agency relies on autonomous regional bodies to regulate and control all activities taking place within the mangrove forests (Sánchez-Páez et al. 1997a).

In addition to traditional activities, aquaculture is perceived by the environmental agency as a potential threat to mangrove forests (Sánchez-Páez et al. 1997a; Echavarria et al. 1998). Any aquaculture developers are required to obtain a "culture permit" from the National Institute of Fisheries and Aquaculture (INPA). This permit has included a "plan of environmental management" since 1993, by Decree 1753 of that year (Echavarria et al. 1998). Thanks to this legislation, the destruction of mangrove forests for constructing shrimp farms has been limited to supply and discharge canals, with the ponds built behind the mangrove forest. Actually, Decree 1602 of 1995 from the Ministry of the Environment now prohibits any transformation of mangrove forests into any activity other than forestry, including the construction of aquaculture ponds and canals (Echavarria et al. 1998). Based on a survey administered in 1997, Echavarria et al. (1998) estimated the area of mangrove forest destroyed as a consequence of the development of aquaculture projects as less than 500 ha in the whole country, and less than 100 ha on the Caribbean coast. In fact, most farm managers have known for years that mangrove forests are not suitable for the construction of shrimp ponds. De Nogales and Santos (1995) reported in a Colombian publication the presence of acid-sulfate or acidic soils in mangrove forests; these are harmful to shrimp. The same authors explained that ponds constructed in mangrove areas could not be harvested and dried properly because they are below sea level. Other pragmatic considerations are well known by farm managers: the cost of pond construction is much higher in mangrove forests because of the presence of trees, and heavy equipment cannot be used in mangrove areas because of the low density of mangrove soil.

Despite all these facts, publications by Colombian authors contain erroneous statements that 4,000 ha of mangrove were destroyed in Colombia as a direct consequence of developing shrimp farms (Sánchez-Páez 1994). This would be more than the 3,647 ha of all constructed shrimp farms in Colombia in 1997 (Echavarria et al. 1998). The reason for this misstatement may be unexamined use of previous references from authors who assumed, without historical knowledge of the developed areas, that shrimp ponds were built in mangrove areas (INDERENA 1992). Some recent works (Echavarria et al. 1998) analyze the history of shrimp culture in Colombia and show that shrimp ponds were constructed almost exclusively in elevated areas (former cattle lands) and in salty transition zones characterized by sparse halophytic vegetation. In most cases, mangrove destruction has been limited to the construction of inlet and outlet canals (Echavarria et al. 1998). In many cases, ponds occupy all the area between mangrove forest and terrestrial vegetation, potentially causing confusion on the question of mangrove destruction. Sometimes, mangrove trees also colonize (naturally or by planting) canal and pond banks. It is then impossible to determine the original mangrove limit, and whether any trees were cut to build ponds, without historical knowledge of the developed area. The truth is that farmers respected mangrove borders; the shape of outer ponds is often irregular because their design followed the edge of the original mangrove forest.

## Description of Agrosoledad Farm

Agrosoledad farm is located on the Caribbean coast of Colombia (Figure 1), about 10 km inside an estuarine area influenced by the Sinu River (Figure 2).

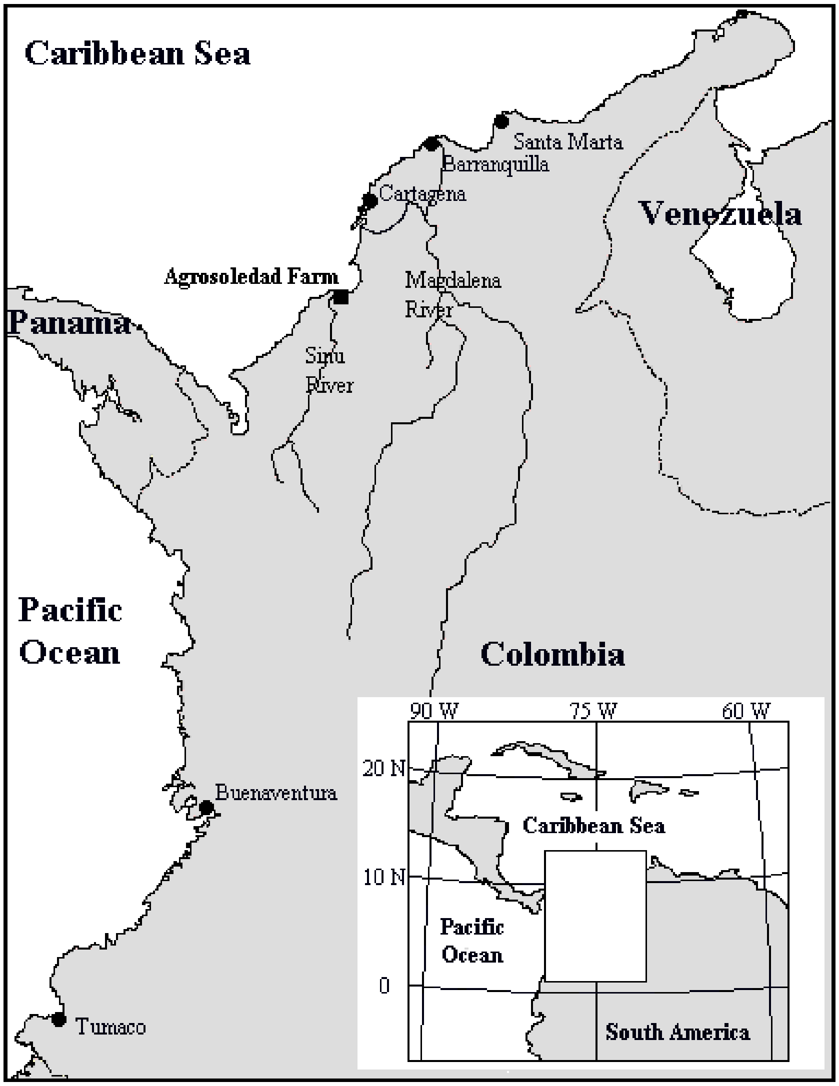


**Figure 1**. Location of Agrosoledad Farm on the Caribbean coast of Colombia

Agrosoledad Company first purchased a 577-ha cattle ranch in 1984. Agrosoledad now owns 1,100 ha, including, from Soledad Lagoon to the south, part of a mangrove forest, former cattle lands, and a dry tropical forest on a hill. Shrimp ponds were constructed 5 m above maximum sea level on former cattle lands, behind the 1 km wide mangrove forest (Figures 3, 4, and 5).

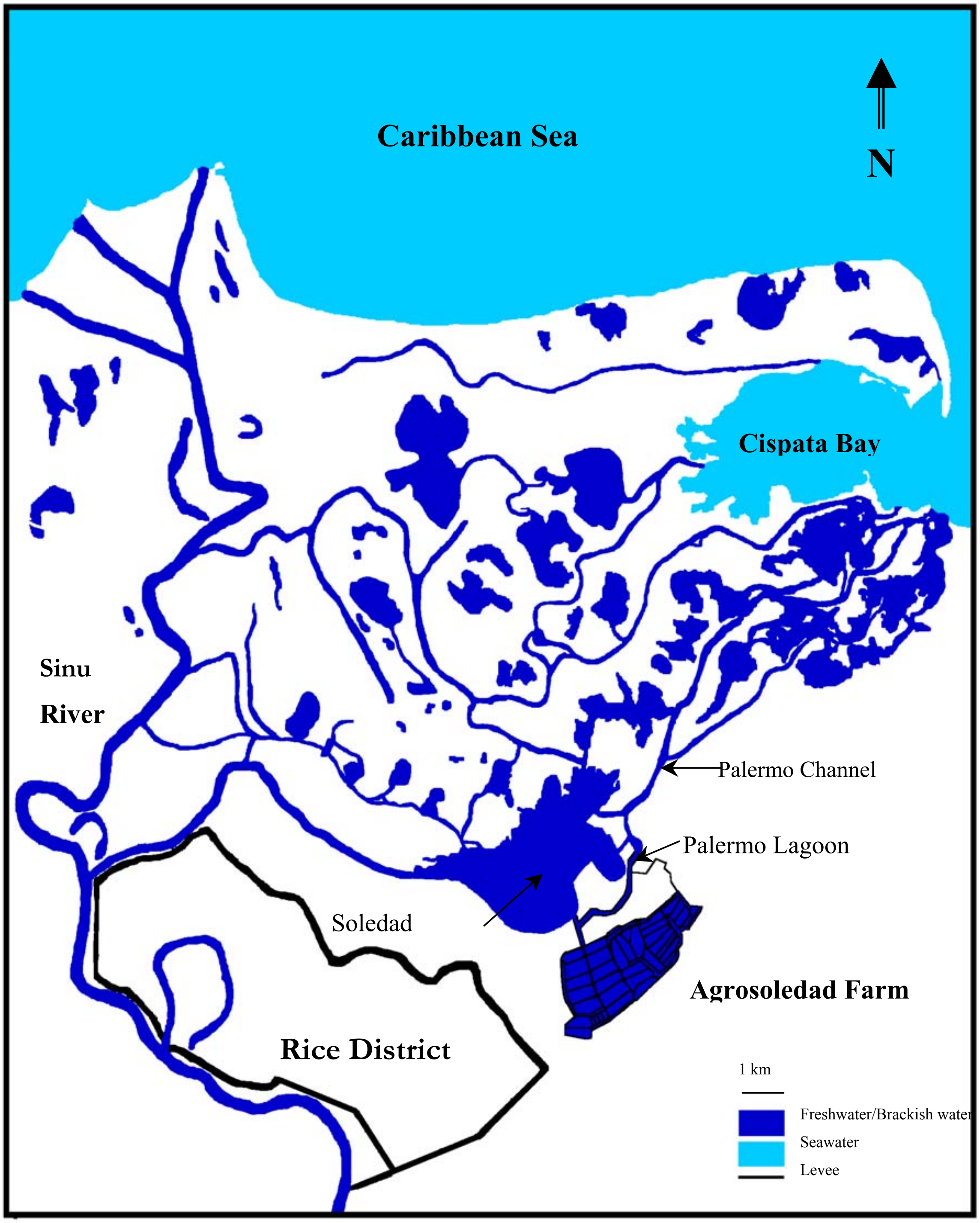


**Figure 2.** Location of Agrosoledad Farm in the Sinu Estuary. (Arrows indicate sampling stations used in water quality monitoring by Agrosoledad's laboratory. Limit between seawater and brackish water indicated is arbitrary and shifts depending on the season.)

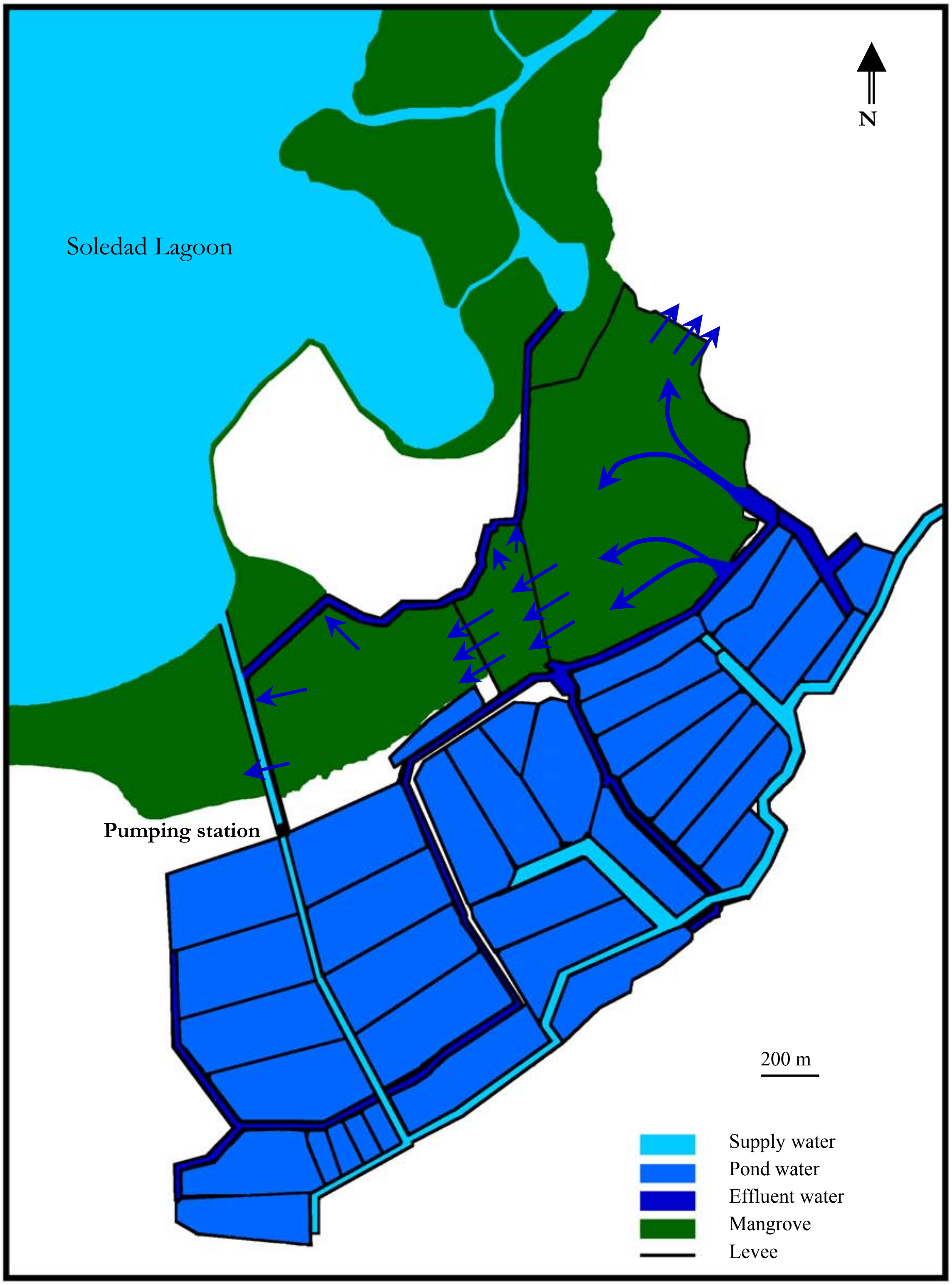


**Figure 3**. Integrated shrimp farm–mangrove system at Agrosoledad Farm. Arrows indicate water flow through the biofilter.

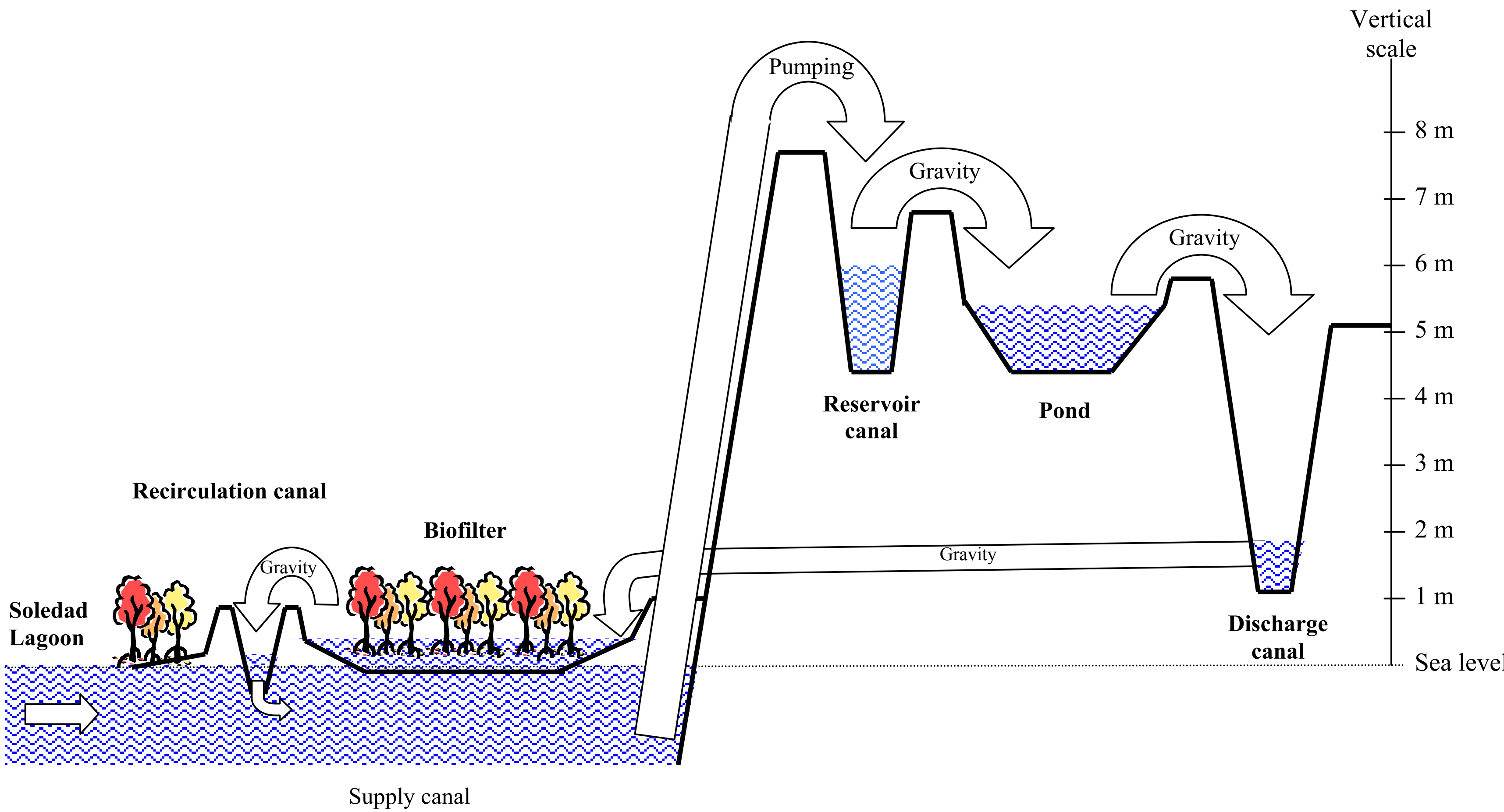


**Figure 4**. Schematic cross section of the integrated shrimp farm-mangrove system at Agrosoledad showing construction design and water flow. Proportions along the longitudinal axis are not to scale.

**Figure 5**. View of Agrosoledad Farm taken from the south (see Figure 3) showing ponds constructed on former cattle lands, behind a 1 km wide mangrove wetland used as a biofilter. We can observe Soledad Lagoon, from which Agrosoledad Farm pumps its renewal water, and in the background, the Sinu Estuary colonized by a dense mangrove forest.

An 800 m long and 20 m wide supply canal has been dug through the mangrove (Figure 3). Planting young propagules mitigated loss of mangrove trees. Supply water is pumped (installed pumping capacity is 6.4 $m^3/s$) 7.5 m up, to an elevated canal (Figures 3 and 4). This canal serves as a reservoir to exchange pond water by gravity. Exchanged pond water is discharged into drainage canals that bring water into a separate 1-km-long effluent canal, which then brings water into the mangrove wetland. The mangrove acts as a biofilter (Figures 3 and 4).

Shrimp production first started in 1987, with ponds covering an area of 88 ha. Production area has been progressively extended, up to 234 ha (in 1998). Pond size ranges between 1.8 and 11.5 ha. Agrosoledad raises *Litopenaeus vannamei* shrimp under typical semi-intensive conditions (Clifford 1994). Postlarvae supply is covered by local hatcheries, which produce a Colombian strain developed by the industry as a response to the Taura syndrome (Suarez et al. 1999). The average yield is about 2,000 kg/ha/cycle. An average of 2.4 127-day cycles are completed each year, allowing an appropriate time of about 20 days for soil preparation between each crop.

Agrosoledad also dedicates resources to several other economic and conservation activities. For example, 100,000 hardwood trees were planted over more than 100 ha, and 50 ha native dry forest has been preserved. Part of the property is dedicated to thatch palm and fruit production, and other parts to sheep and cattle ranching. Altogether, those activities represent 130 permanent positions, plus about 50 daily workers, in addition to about 50 additional workers for harvesting shrimp. Moreover, Agrosoledad has developed social programs to help the surrounding population. Six schoolteachers are paid by the company, which also supports schools with funding and ecological training. Agrosoledad also employs a health-care worker to work with local populations. In addition, the company supports projects ranging from an agricultural cooperative to horticulture and freshwater aquaculture units, and infrastructure constructions, among others.

## Historical Evolution of the Sinu Estuary

The historical evolution of the Sinu Estuary provides a more complete understanding of the current ecological conditions. The history of the Sinu Estuary has been studied in detail by Mogollón (personal communication). Cispata Bay (Figure 2) was a deep seawater bay until the late 19th century. Deforestation along the Sinu River valley during the 19th century caused erosion and silting of the Sinu Estuary. As a result, the Sinu River formed a large freshwater delta between 1890 and 1930, displacing seawater from the southern part of Cispata Bay to the north. This phenomenon allowed the development of rice culture in the Sinu Delta, which lasted until the late 1950s or early 1960s. In 1945, the Sinu River opened a new route to the Caribbean Sea, about 10 km west of the estuary (Figure 2). Since around 1950, the previous Sinu Estuary has grown more saline, and a new mangrove forest has been progressively colonizing the estuary. The area that was Sinu Estuary is now colonized by a 7,383-ha riverine mangrove forest dominated by *Rhizophora mangle* (Sánchez-Páez et al. 1997a; Ulloa-Delgado et al. 1998). *Avicennia germinans* and *Laguncularia racemosa* are also abundant, but *Pelliciera rhizophorae* and *Conocarpus erectus* are scarce (Sánchez-Páez et al. 1997a). In Soledad Lagoon, the average height of *Rhizophora mangle* is 12 m, and reproduction is very successful (6,700 propagules are found per ha) (Sánchez-Páez et al. 1997a). Taking advantage of the high productivity of this mangrove forest, about 400 families currently live off fishing (fish, oysters, mussels, and snails) and timber production (Sánchez-Páez et al. 1997a).

Ecology of the Sinu Estuary is now regulated by the relative balance of seawater and freshwater, from both runoff and the Sinu River (Figure 2). Depending on the season, water salinity ranges from 32 to 0 ppt (Figure 6). During the rainy season, from May to October, runoff can cause a drastic drop in salinity, possibly to 0 ppt in case of heavy rainfall. During the dry season, from December to April, salinity progressively increases, sometimes creating marine conditions (Figure 6).

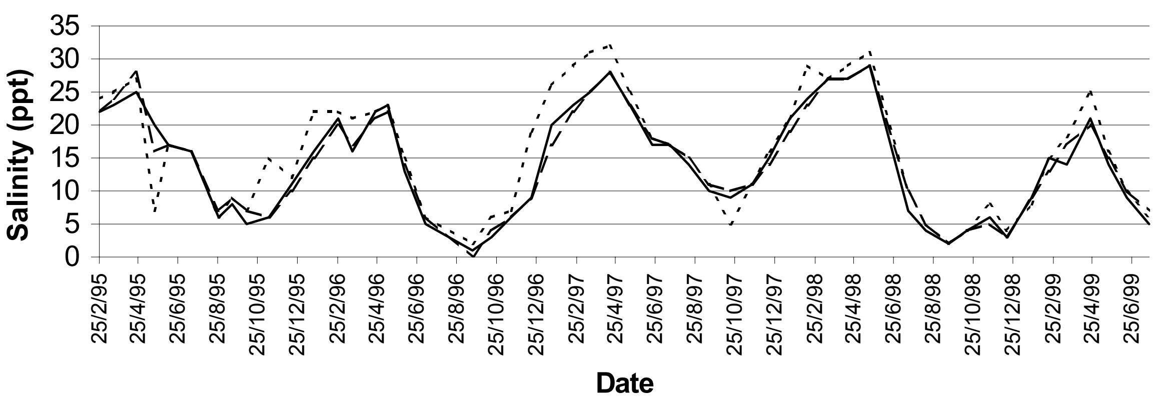


**Figure 6**. Changes in water salinity in Soledad Lagoon (continuous line), Palermo Lagoon (dashed line) and Palermo Channel (dotted line) between 1995 and 1999. Refer to Figure 2 for station location. Source: Agrosoledad.

## Functions of the Recirculation System

In 1964, a 2000-ha rice-growing district (Figure 2) was created by the Colombian government to mitigate the social impact of the salinization of the estuary. The rice district was rehabilitated in 1988 with funds from the World Bank, allowing the construction of irrigation and discharge facilities. The rice district discharges its waste waters into the Soledad Lagoon (Figure 2), from which Agrosoledad Farm also pumps its intake water.

In 1994, Agrosoledad Farm experienced, for the first time, a problem of off-flavor in its raised shrimp, resulting in financial loss (harvest had to be delayed or sale price of shrimp was lowered). The off-flavor was perceived as earthy or musty, and the cause is thought to be the presence of some blue-green algae or actinomycetes in pond waters (Lovell and Broce 1985). The algae probably belonged to the genera *Oscillatoria* and *Anabaena* identified at the farm. Those algae were also present in Soledad Lagoon. The phenomenon appeared during the rainy season, when salinity dropped to very low values (Figure 6).

Blue-green algae usually flourishes in tropical brackish water environments when salinity is low (Lovell and Broce 1985) and particularly in case of eutrophication (Boyd and Tucker 1998). Runoff from the rice district was suspected as the main nutrient source to Soledad Lagoon, but no study was done to confirm this hypothesis. (Note that the only information available about water quality in Soledad Lagoon is generated by Agrosoledad farm). Shrimp farm effluent could also contribute to the enrichment of the lagoon in nutrients. It also posed a risk of self-pollution by introducing blue-green algae into shrimp ponds via the pumped intake waters. The best remedy to the situation was then to recirculate waters inside the farm as soon as salinity dropped below 10 ppt. Recirculation provided several advantages: avoiding introducing blue-green algae from Soledad Lagoon into the farm, preventing the discharge of blue-green algae into the lagoon in case of bloom at the farm, and avoiding contributing to the eutrophication of the lagoon. But pond effluent had to be treated to avoid self-pollution as defined above. Then Agrosoledad's staff proposed the idea of using an 120-ha mangrove forest, included in the property, as a biofilter to treat pond effluents. Based on the principles of wetland treatment, this mangrove filter was expected to remove algae and nutrients by sedimentation and absorption-consumption, respectively.

## The Water Recirculation System

Pond discharge waters are collected into a 1-km-long canal that brings the effluent into the biofilter (Figures 3 and 4). An area of 120 ha has been closed by levees, and water flow through the biofilter is controlled by concrete structures. Several exits (Figure 7) distributed all around the biofilter direct water flow and recirculation, and allow the discharge of effluent into Soledad Lagoon (Figure 3).

**Figure 7**. View of one exit from the biofilter showing the water flowing into the recirculation canal. The water level in the biofilter is about 30 cm higher than in the canal.

In the recirculation configuration, northeastern and southwestern exits are closed, as is the entrance of the supply canal (Figure 3). Water goes out through the northern exits into the recirculating canal and then the supply canal (Figures 3 and 4). An estimated 80% of treated water is recirculated using this configuration. When farm staff wants to discharge treated waters into Soledad Lagoon and recirculate only a small proportion of it, the supply canal is kept open as well as the northeastern and southwestern exits (Figure 3). In this case, treated waters flow through additional mangrove–an estimated 260 ha–before going back into Soledad Lagoon.

A survey was conducted in September 1999 to quantify the flora in the biofilter, according to the sampling methods recommended by FAO (1994), Sánchez-Páez et al. (1997a), and Ulloa-Delgado et al. (1998).

Various plots ($25m^2$) were sampled in four different areas within the biofilter. One plot was sampled in a reforestation area, where 50,000 young *Rhizophora mangle* seedlings had been planted by Agrosoledad's personnel in 1995 and 1996 (Figure 8).

**Figure 8**. About 50,000 young Rhizophora mangle seedlings were planted in the biofilter by Agrosoledad's personnel between 1995 and 1996. They are now between 2 and 4 m high, and seem to be very healthy.

Species composition, density, height, and diameter were evaluated (Table 1). Results were compared with values given by Sánchez-Páez et al. (1997a) and Ulloa-Delgado et al. (1998) for Soledad Lagoon (Table 2) and the Sinu Estuary. This survey indicates that the biofilter's flora is composed of mangrove trees of *Rhizophora mangle* (46%) and *Conocarpus erectus* (13%), and by the fern *Acrostichum aureum* (41%).

*Conocarpus erectus* occupies 11 ha in the middle of the biofilter and colonized edges along levees. Its population is very dense and regeneration is especially successful with 200,000 plantules/ha (Table 1). In contrast, *Conocarpus erectus* is scarce in the Sinu Estuary (Sánchez-Páez et al. 1997a; Ulloa-Delgado et al. 1998). This species typically colonizes transition zones between true mangrove and terrestrial vegetation (Chapman 1976).

*Rhizophora mangle* is the most common species in the biofilter. Its population in the biofilter is denser than in Soledad Lagoon (Table 2). The natural regeneration rate (13,600 plantules/ha) is twice the value reported by Sánchez-Páez et al. (1997a) in Soledad Lagoon (Tables 1 and 2). Nevertheless, similar densities of both trees and young seedlings were reported in other areas of the Sinu Estuary (Sánchez-Páez et al. 1997a; Ulloa-Delgado et al. 1998). The growth rate of planted *Rhizophora mangle* (Plot 4) cannot be calculated, since initial data are not available. Nevertheless, estimated growth seems to be much higher than what Ulloa-Delgado et al. (1998) observed in reforestation trials in Cispata Bay (average of 20 cm/year). The maximum growth rate reported by Ulloa-Delgado et al. (1998) for another area on the Colombian Caribbean coast is 103 cm/year, about the same as in Agrosoledad's biofilter. This observation is in agreement with the results of Rajendran and Kathiresan (1996), who reported a positive effect of shrimp pond effluent on mangrove seedling growth.

*Acrostichum aureum* is the second most important plant in the biofilter. It occupies a large part of the eastern part of the biofilter (Figure 3) and grows along with *Rhizophora mangle* (Table 1). This fern usually establishes itself in mangrove forests where light is available, and starts forming communities where mangrove trees have been felled (Chapman 1976). Once the *Acrostichum aureum* population has grown dense, subsequent regeneration of mangrove is difficult (Chapman 1976).

**Table 1**. Flora characteristics of sampled plots in Agrosoledad's biofilter in September 1999

| Area[1] | Species[2] | Mean DBH[3] (cm) | Max DBH[3] (cm) | Mean height (m) | Max height (m) | Density (plants/ha) |
|---|---|---|---|---|---|---|
| 1 | Ce<1m | | | | 1 | 200,000 |
| | Ce>1m | | | 3.5 | 4 | 19,000 |
| 2 | Rm <1m | | | | 1 | 13,600 |
| | 1<Rm<3m | | | 2.2 | 3 | 1,200 |
| | Rm>3m | 11.6 | 38.2 | 8.6 | 15 | 1,400 |
| | Aa | | | | | 2,800 |
| 3 | Aa | | | 3 | | 1,000 |
| 4 | Rm | 2.8 | 4 | 3.2 | 3.9 | 14,400 |

[1] Plot distribution is shown in Figure 3. Plot 4 corresponds to reforested area; other plots are natural mangrove areas.
[2] Ce: *Conocarpus erectus*, Rm: *Rhizophora mangle*, Aa: *Acrostichum aureum*.
[3] DBH: Stem diameter measured 30 cm above the highest root resulting in a deformation of the stem (FAO 1994).

**Table 2**. *Rhizophora mangle* characteristics in Soledad Lagoon

| Category | Mean DBH (cm) | Max DBH (cm) | Mean height (m) | Max height (m) | Density (plants/ha) |
|---|---|---|---|---|---|
| H<1m (regeneration) | | | | 1 | 6,700 |
| DBH<5cm | | | 3.3 | 4.5 | 171 |
| 5<DBH<15cm | 10.6 | 16.1 | 7.3 | 14 | 327 |
| DBH>15cm | 22.5 | 45 | 12 | 15 | 355 |

Source: Sánchez-Páez et al. 1997a

Abundant fauna can be observed in Agrosoledad's biofilter, including primates, birds, reptiles, fish, crabs, and insects–a typical mangrove-associated fauna ecosystem (Sánchez-Páez et al. 1997a). Curiously, a very large bird community (thousands of birds) settled in the middle of the biofilter, in the 11-ha *Conocarpus erectus* area (Figure 9). The main species are egrets (*Egretta* and *Nyticorax*), herons (*Pilherodius pileatus*, *Ardea cocoi*, and *Tigrisoma*), neotropic cormorant (*Phalacrocorax olivaceus*), white ibis (*Eudocimus albus*), and anhinga *(Anhinga anhinga leucogaster*); even wood stork (*Mycteria americana*) appears from time to time.

**Figure 9.** Thousands of birds, mainly egrets and herons, roost in the middle of the biofilter, in *Conocarpus erectus* trees.

The installed pumping capacity is 6.4 $m^3$/s, and pumps are run 15 h/day on average. Thus, pumped volume is estimated to be 345,600 $m^3$/day on average. Pond management includes daily water exchange of about 10 cm of the water column. Based on pond water exchange calculations, the flow rate through the biofilter would be equal to 234,000 $m^3$/day, i.e. 68% of the volume of water pumped daily. Field measurements in the canal bringing water into the biofilter performed in September 1999 indicated a flow rate through the biofilter of 308,850 $m^3$/day, or 81% of the volume of water pumped daily. The difference between these two values could be due to an underestimation of pond water exchange rate and/or to seepage into the pond banks. The latter is plausible, because Agrosoledad's soil is loamy and seepage can be an important source of water loss (Boyd 1995). Seepage into the pond bottom could also explain why only 81% of the volume of pumped water is measured in the discharge canal. Based on data from Sánchez-Páez et al. (1997a), evaporation is estimated to account for the loss of only 257 $m^3$/day, or 0.7% of the volume of water pumped daily.

Estimations based on topographic data indicate that the area of the biofilter is about 120 ha and the average depth is 52.4 cm. Therefore, biofilter volume is estimated as 628,800 $m^3$. Resulting hydraulic residence time (Boyd 1995) in the biofilter is estimated as about two days. This value would be a good estimation if the biofilter had only one exit, which is not the case (Figure 3). As a consequence, residence time is actually much less than two days for water that leaves through the northeastern exits (Figure 3), and much more than two days for water that passes through the whole biofilter on its way to the southwestern exits. The biofilter: shrimp pond area ratio is 0.51. This is an intermediate value between two ranges predicted by prior research: 2–22 ha (Robertson and Phillips 1995) and 0.04–0.12 ha (Rivera-Monroy et al. 1999). This ratio represents the area of mangrove required to assimilate nutrients produced in 1 ha of shrimp ponds.

## Water Quality in the Integrated Mangrove-Shrimp Farm System

Colombian Law 99 of 1993, which created the Ministry of the Environment, defined the principles for applying taxes on waste discharge, including waste waters from any discharge identified point sources, as specified by Decree 901 of 1997. Autonomous regional corporations have the responsibility to apply tax legislation in each department, based on effluent quality monitoring. In the case of aquaculture, the parameters involved are Biochemical Oxygen Demand (BOD in mg/l) and Total Suspended Solids (TSS in mg/l), also measured in other countries (Boyd 1997).

Initial measurements of Agrosoledad Farm's effluent performed by both the Autonomous Regional Corporation and the independent laboratory Cartagena Waterworks indicated that BOD and TSS values were, respectively, 70% and 51% lower in the biofilter effluent (sampled at the northeastern exits) than in supply water. Treatment efficiency of the biofilter must also be evaluated by comparing water quality at the entrance and the exit of the biofilter, because an increase in TSS typically results from ponds with shrimp feeding (Boyd and Tucker 1998). Major sources of TSS in ponds are suspended soil particles and particulate organic matter resulting from phytoplankton and detritus (Boyd and Tucker 1998). In fact, Gautier et al. (1998a) earlier measured an increase in TSS of 200–300% in pond discharge (over that in supply waters) from Colombian farms along the Caribbean coast. In this study, the TSS concentration in water drained from Colombian farms (about 50–100 mg/l) was actually lower than the values reported by Lin and Nash (1996) and Dierberg and Kiattisimkul (1996) in Asian shrimp ponds stocked at a similar density. Nevertheless, results obtained by Gautier et al. (1998a) justify implementing treatment methods to remove TSS from pond effluents in Colombian farms (Boyd and Tucker 1998). In a previous study of Agrosoledad's biofilter, Gautier et al. (1998b) demonstrated that 95% of TSS entering the biofilter was removed. In that study, measurements were done at the southwestern exit of the biofilter (Figure 3), allowing a longer residence time than in the monitoring performed by the environmental authority. Nevertheless, it is interesting to note that TSS removal measured by Gautier et al. (1998b) in

Agrosoledad's biofilter is higher than the removal rates of 78–88% reported by Schwartz and Boyd (1995) for a constructed wetland and similar residence times of one to four days. The percentage of TSS removed at Agrosoledad is also more than the values of 71–88% reported by Teichert-Coddington et al. (1999) for a settling pond, but in that study residence time was only six hours.

Nutrient discharge is another concern because of the risk of eutrophication in receiving waters (Boyd and Tucker 1998). Generally, aquaculture pond effluents are richer in nutrients than supply waters (Ziemann et al. 1992; Samocha and Lawrence 1995; Boyd and Tucker 1998). However, Ziemann et al. (1992), Gautier et al. (1998a), and Rivera-Monroy et al. (1999) observed no increase in nitrate-nitrogen concentration in shrimp pond effluents. Rivera-Monroy et al. (1999) observed an increase in total ammonia nitrogen (TAN) concentration in Colombian shrimp farms. But Gautier et al. (1998a) also observed in Colombian shrimp farms that any increase in certain nutrients in pond effluents depended mainly on the intensity of inorganic fertilization. Slight fertilization, as practiced at Agrosoledad Farm, did not cause any increase in nutrient concentration in pond discharge (from that of supply water) (Gautier et al. 1998a). Nevertheless, fed ponds usually produce a large amount of organic wastes that are progressively transformed into inorganic nutrients through bacterial activity (Boyd and Tucker 1998). Therefore, the absence of increased inorganic nutrient concentration in pond effluent does not necessarily imply no risk of eutrophication in receiving natural waters.

Agrosoledad's staff has been monitoring nutrient concentrations on a monthly basis at three stations (Figure 2): Soledad Lagoon, Palermo Lagoon, and Palermo Channel. Soledad Lagoon station’s water is representative of natural water that supplies the farm (Figure 3), but could be influenced by the rice district's effluent (Figure 2). Palermo Lagoon station is representative of an area directly influenced by the farm effluent. Palermo Channel station is representative of natural waters with no direct influence from either Agrosledad Farm or the rice district (Figure 2). Inorganic nitrogen and soluble reactive phosphorus (SRP) concentrations are highly variable in all three stations (Figures 10, 11, and 12). No consistent concentration difference can be observed among stations for any of these parameters.

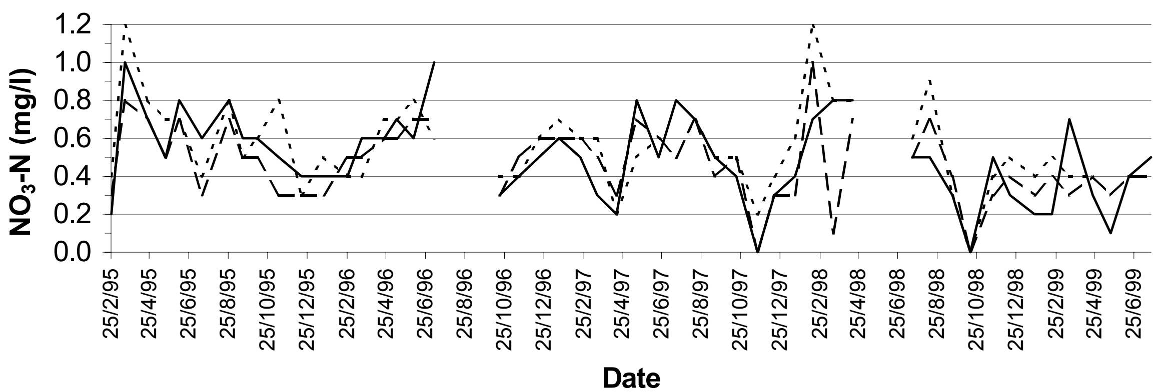


**Figure 10**. Changes in Nitrate-Nitrogen ($NO_3$-N) concentration in Soledad Lagoon (continuous line), Palermo Lagoon (dashed line) and Palermo Channel (dotted line) between 1995 and 1999. Refer to Figure 2 for station location. Source: Agrosoledad.

Mean values of nitrate-nitrogen (Figure 10) and TAN (Figure 11) are much higher than concentrations reported by Teichert-Coddington (1995) in Honduran estuaries and rivers. In contrast, the mean concentration of SRP is lower than the values reported by the same author.

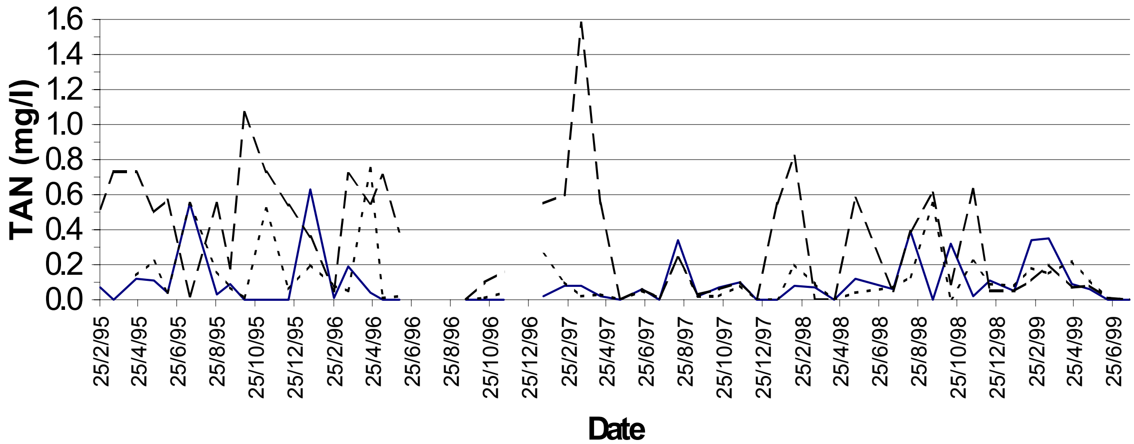


**Figure 11**. Changes in Total Ammonia-Nitrogen (TAN) concentration in Soledad Lagoon (continuous line), Palermo Lagoon (dashed line) and Palermo Channel (dotted line) between 1995 and 1999. Refer to Figure 2 for station location. Source: Agrosoledad.

On average, nutrient concentrations seem to decrease slightly over time (Figures 10, 11, and 12), but time-series analysis did not show any evidence of significant change. Time-series analyses have been performed with Systat® (Berk and Steagall 1995) to analyze possible seasonal trends in estuarine water quality parameters. An identical seasonal pattern was observed in salinity variations in all studied stations (Figure 13). Salinity starts decreasing in May, drops to the minimum value in August or September, and increases quickly through November and December to reach the maximum value in March and April. Nitrate concentrations show neither seasonal trend nor high variations over the year (Figure 13).

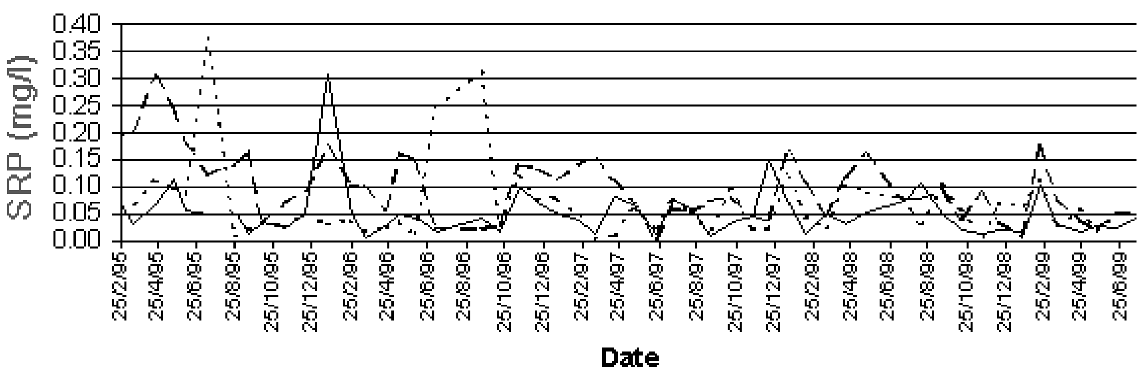


**Figure 12**. Changes in Soluble Reactive Phosphorus (SRP) concentration in Soledad Lagoon (continuous line), Palermo Lagoon (dashed line) and Palermo Channel (dotted line) between 1995 and 1999. Refer to Figure 2 for station location. Source: Agrosoledad.

This result suggests a continuous cycling of nitrate within the estuary. Ammonia and phosphorus concentrations vary highly over the year, though following a pattern different from the salinity trend, in both Soledad Lagoon and Palermo Channel stations (Figure 13).

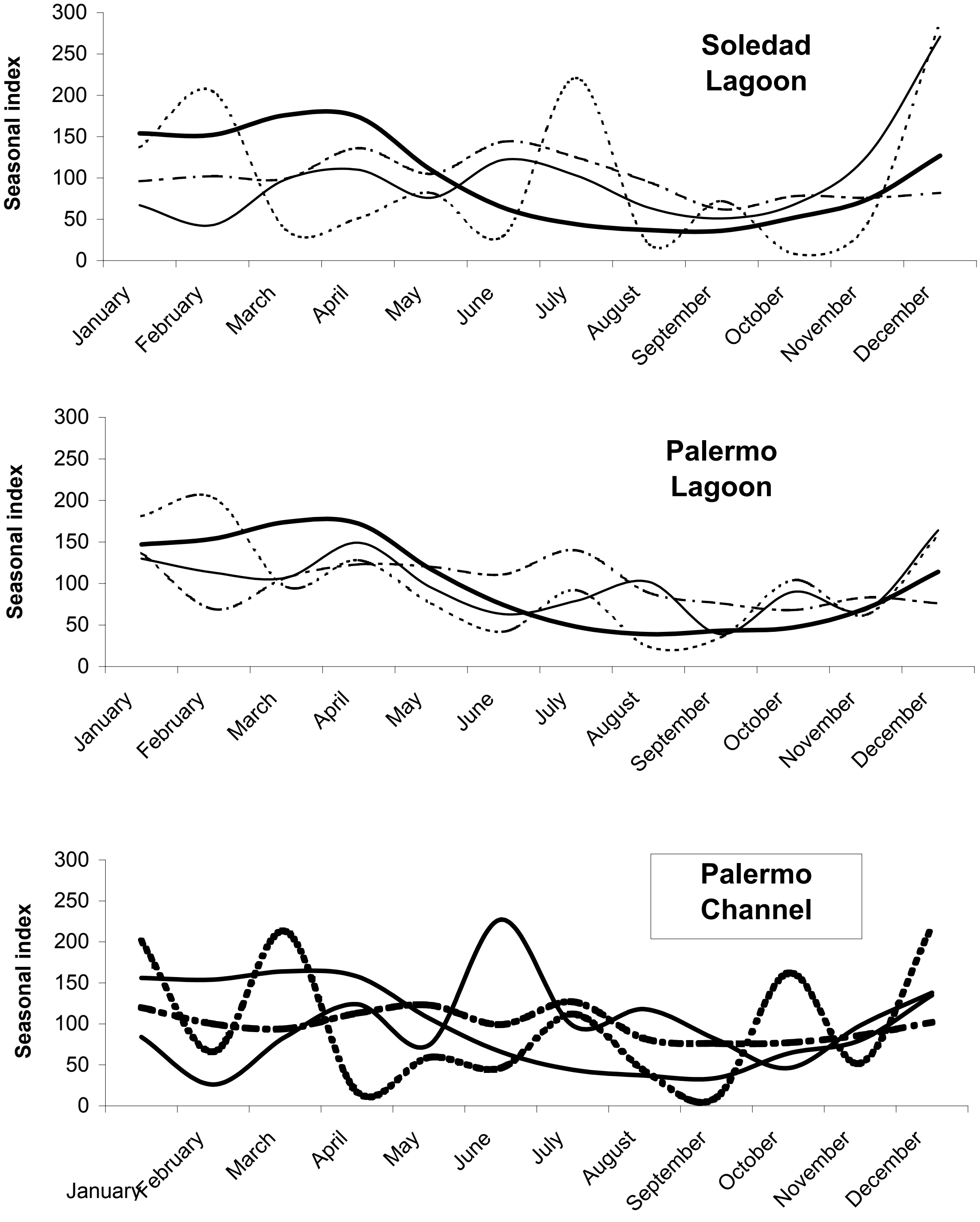


**Figure 13**. Seasonal indices of water salinity (thick continuous line), Soluble Reactive Phosphorus (thin continuous line), Total Ammonia Nitrogen (dotted line) and Nitrate-nitrogen (dashed line) concentrations in Soledad Lagoon, Palermo Lagoon, and Palermo Channel, as determined by a time-series analysis. Seasonal indices express variation proportions over the year (Berk and Steagall 1995). Refer to Figure 2 for station locations

These results suggest some external input that could be related to freshwater runoff, but one that provides varying influence. It is not possible to identify potential sources without more information about the environment in the Sinu Estuary. Ammonia and phosphorus concentrations are more stable at Palermo Lagoon station than at the other stations (Figure 13). Although ammonia and phosphorus concentrations do not follow the salinity trend exactly, they tend to be higher during the dry season and lower during the rainy season in Palermo Lagoon. This trend suggests a continuous source of added nutrients, with their concentration in the lagoon related to possible dilution by freshwater from rainfalls and rivers, as Teichert-Coddington (1995) found for a Honduran estuary. Since neither significant change over time nor clear seasonal pattern in nutrient concentrations was determined by a time-series analysis, it is valid to compare mean values from different periods of time. Nutrient concentrations were compared among the three studied stations, both before and after biofilter implementation at Agrosoledad. Comparisons of mean values among stations produced the same results before and after biofilter implementation (Table 3). TAN concentration was significantly higher (one-way ANOVA, $P<0.05$) in Palermo Lagoon than in the other stations (Table 3), while nitrate-nitrogen concentration was the same in all stations. SRP concentration in Palermo Lagoon was significantly higher than in Soledad Lagoon, but no significant difference was noticed with Palermo Channel station. These results provide additional evidence to support the hypothesis of TAN and SRP contamination in Palermo Lagoon, perhaps from the farm's effluent. That TAN and SRP concentrations are still higher in Palermo Lagoon than in other stations, even after the implementation of the biofilter, could be related to the fertilization of water in the biofilter by guano, which is relatively rich in organic matter, nitrogen, and phosphorus (Hussenot et al. 1989). Actually, Gautier et al. (1998b) observed increases in inorganic nitrogen and phosphorus in Agrosoledad's biofilter and attributed these increases to the input of guano by the large bird community that roosted in the biofilter.

On the other hand, it is interesting to notice decreases in TAN (t-test, $P=0.065$) and SRP (t-test, $P=0.012$) concentrations in Palermo Lagoon after the biofilter implementation compared with before (Table 3), even if the difference in TAN was not significantly different at $\alpha=0.05$. Although other parameters seem to decrease in other stations after the implementation of the biofilter, no difference was significant (t-test, $P>0.05$). These results tend to confirm that Agrosoledad's effluent does affect TAN and SRP concentrations in Palermo Lagoon. The decreases in TAN and SRP indicate that the biofilter has had a positive effect in reducing nutrient contamination in Palermo Lagoon. Palermo Lagoon's higher TAN and SRP concentrations compared to Soledad Lagoon's and Palermo Channel's (Table 3) indicate that the influence of Agrosoledad's effluent does not extend to either Soledad Lagoon or Palermo Channel and that the carrying capacity of the Sinu Estuary is not exceeded by Agrosoledad's effluent. Nevertheless, nutrient decrease in other stations could just stem from microalgae growth, as demonstrated by Teichert-Coddington (1995).

The hypothesis that Agrosoledad's effluent contaminates the estuary with nutrients must be analyzed more carefully through a complete study of the nutrient flux along the discharge canal. Data show no evidence of nutrient contamination of Soledad Lagoon by either the rice district or Agrosoledad farm. No significant decrease in nutrient concentrations were found that could explain the disappearance of blue-green algae blooms in the estuary since 1997. Possible eutrophication of the estuary, assumed to occur during blue-green algae bloom events between 1994 and 1996, cannot be confirmed by available data. Information about phytoplankton abundance should be included in the analysis to evaluate possible eutrophication of the estuary. Nevertheless, occurrence of blue-green algae blooms is probably a very complex phenomenon that results from a range of causal factors that include human activities among others. High mangrove productivity is often associated with nutrient input from both estuarine and upland sources, including freshwater runoff (Mitsch and Gosselink 1993).

**Table 3**. Comparison of Total Ammonia Nitrogen (TAN), Nitrate-Nitrogen ($NO_3$–N) and Soluble Reactive Phosphorus (SRP) concentrations in 3 stations in the Sinu Estuary (Figure 2) before and after the implementation of the biofilter in Agrosoledad.

| | TAN | | | $NO_3$-N | | | SRP | | |
|---|---|---|---|---|---|---|---|---|---|
| | Soledad Lagoon | Palermo Lagoon | Palermo Channel | Soledad Lagoon | Palermo Lagoon | Palermo Channel | Soledad Lagoon | Palermo Lagoon | Palermo Channel |
| Before biofilter implementation | | | | | | | | | |
| Mean | $0.14^{b}$ | $0.56^{a}$ | $0.19^{b}$ | $0.61^{a}$ | $0.51^{a}$ | $0.65^{a}$ | $0.05^{b}$ | $0.16^{a}$ | $0.08^{ab}$ |
| S.E. | 0.06 | 0.08 | 0.06 | 0.06 | 0.06 | 0.07 | 0.01 | 0.02 | 0.03 |
| Max | 0.55 | 1.07 | 0.55 | 1.00 | 0.80 | 1.20 | 0.11 | 0.30 | 0.37 |
| Min | 0.03 | 0.02 | 0.01 | 0.20 | 0.30 | 0.30 | 0.01 | 0.03 | 0.01 |
| After biofilter implementation | | | | | | | | | |
| Mean | $0.14^{b}$ | $0.34^{a}$ | $0.13^{b}$ | $0.49^{a}$ | $0.48^{a}$ | $0.54^{a}$ | $0.05^{b}$ | $0.08^{a}$ | $0.06^{ab}$ |
| S.E. | 0.03 | 0.06 | 0.03 | 0.03 | 0.03 | 0.03 | 0.01 | 0.01 | 0.01 |
| Max | 0.63 | 1.58 | 0.75 | 1.00 | 1.00 | 1.20 | 0.31 | 0.18 | 0.31 |
| Min | 0.01 | 0.01 | 0.01 | 0.10 | 0.10 | 0.20 | 0.01 | 0.00 | 0.00 |

Letters in supercript indicate homogeneous groups among stations for each parameter, measured with Systat®. Bonferroni-adjusted one-way ANOVA tests were conducted at $\alpha$=0.05 performed with Systat®.

## Costs and Benefits of the Integrated Mangrove –Shrimp Farm System

Construction of the biofilter cost about 100,000,000 Colombian pesos (in 1995), or about $100,000 U.S. Considering the large area the biofilter covers, the system is very inexpensive in comparison with the cost of a constructed wetland as proposed by Schwartz and Boyd (1995). It is difficult to estimate the value of the benefits, however. Probably the most significant benefit of the system is the BOD and TSS removal from pond effluent. Since $BOD_5$ and TSS values are lower in farm's effluent than in supply water (natural water from Soledad Lagoon), the environmental authority does not charge any contamination tax to Agrosoledad. Another potential financial benefit of the recirculation system is the possible prevention of blue-green algae bloom in the estuary, which may cause an off-flavor to develop in shrimp.

Nevertheless, the uncontrolled water fertilization by the very large bird community settled in the biofilter is a concern. The farm could take advantage of this natural fertilization to reduce the amount of inorganic fertilizer it adds to ponds (and thereby reduce cost) by circulating the water more efficiently. On the other hand, too much fertilization by guano and recirculation of those waters could result in eutrophication of supply water, with dangerous consequences for pond water quality (Boyd and Tucker 1998). Nutrient monitoring in the estuary suggests that Agrosoledad's effluent contaminates the estuary with inorganic nitrogen and phosphorus. Nevertheless, no negative impact of Agrosoledad's effluent on water quality has been detected in the estuary so far. Moreover, a decrease in nitrogen and phosphorus concentrations in the estuarine area directly influenced by Agrosoledad's effluent was measured after the implementation of the biofilter. This observation indicates that the biofilter may act as a sink for nutrients, contrary to the expected results from the enrichment of water by guano in the biofilter. This situation illustrates the need for more studies of nutrient cycling in mangrove wetlands before researchers can predict expected results of using mangrove for effluent treatment.

Another positive aspect of the presence of a large and diverse bird community in the biofilter is its possible commercial potential via ecotourism. Agrosoledad farm, and more generally the Sinu Estuary, have great potential for developing ecotourism because of the richness and diversity of such natural resources. Moreover, Sinu Estuary is not only a natural ecosystem but also a site of human activities (fishing, timber cutting, shrimp farming, and rice culture). This is a good opportunity for developing programs of both ecological education and integrated coastal management. Agrosoledad Farm can be used internationally as an example of integrated shrimp farm–mangrove forest to promote a positive image of the Colombian shrimp industry, or the shrimp industry in general. Finally, Agrosoledad's biofilter provides a good opportunity for developing applied research projects on the use of mangrove wetlands as biofilters.

## Recommendations

Agrosoledad's integrated system is an original approach to aquaculture, and many factors are still poorly understood. Before recommendations about the application of such a system to shrimp farming can be produced, more studies are required. Ecological studies are needed to understand and quantify the mechanisms involved in effluent treatment by mangrove forests. For example, the effects of shrimp pond effluents on mangrove ecosystems should be evaluated. A positive impact of shrimp pond effluents has been observed on growth and regeneration of mangrove trees in Agrosoledad's biofilter after four years, but long-term effects have yet to be assessed. Not only mangrove trees, but also the associated fauna, need to be considered. For instance, the potential consequences of particle sedimentation in the biofilter on benthic fauna remain unknown. Hydrological studies are needed to describe water circulation in mangrove wetlands and to understand the processes involved in suspended particle movement. Engineering studies are also required, to optimize water treatment through appropriate design and management.

A major issue is the risk of eutrophication of adjacent waters. Despite the fact that mangrove forests are described as nutrient sinks in the literature, available data from Agrosoledad’s biofilter do not yet support this hypothesis. The fluxes of various nutrients, including inorganic and organic forms, have to be studied to establish a balance for the treating system. Water sampling stations should include entrances to and exits from the biofilter. Nutrient input from birds and retention by soil and plants must also be quantified. Potential contamination of the estuary has to be assessed by monitoring water quality in the farm's effluent and along its path in the estuary. Parameters to be considered include organic and inorganic nitrogen and phosphorus, BOD, pH, dissolved oxygen, total suspended solids, and phytoplankton (Teichert-Coddington 1995; Boyd 1997; Boyd and Tucker 1998). Other major sources of contaminants into Soledad Lagoon (mainly the rivers and the rice district) must be quantified, to evaluate the risk of eutrophication and to develop integrated management of the ecosystem overall. Rivers could be the primary source of discharged nutrients into the estuary, as demonstrated by Teichert-Coddington (1995) in the Gulf of Fonseca in Honduras.

A general consideration about Agrosoledad's experiment centers on the difficulty of using natural ecosystems for water treatment; the lack of control can lead to unpredictable results. As a consequence, any theoretical calculation, as proposed by Robertson and Phillips (1995) and Rivera-Monroy et al. (1999), or specific observations such as those made at Agrosoledad, cannot be used as general references. In particular, it is not possible to make any recommendation about an appropriate ratio of mangrove-to-shrimp pond area while the nutrient assimilation capacity of different kinds of sediments and plants remains unknown.

Developing such an integrated system within the shrimp industry will require great effort to adapt a general system plan to each particular situation. Moreover, although integrated systems seem promising, their long-term environmental and economic viability has to be demonstrated (Robertson and Phillips 1995; Macintosh 1998). Another front for future research is the assessment of mangrove carrying capacity and mangrove forests’ ability to sustain coastal aquaculture at a regional level (Phillips 1995b; Macintosh 1998).

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