RESOURCE USE AND WASTE PRODUCTION AT A SEMI-INTENSIVE, BLACK TIGER PRAWN *PENAEUS MONODON* FARM.

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RESOURCE USE AND WASTE PRODUCTION AT A SEMI-INTENSIVE, BLACK TIGER PRAWN *PENAEUS MONODON* FARM.

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RESOURCE USE AND WASTE PRODUCTION AT A SEMI-INTENSIVE, BLACK TIGER PRAWN *PENAEUS MONODON* FARM.

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VITA

Puan Pengseng, son of Heng and Ploy Pengseng, was born in Klongtom, Krabi Thailand on May 27, 1967. He graduated in animal science (fisheries) with first class honors from Rajamangala University of Technology Tawan-ok, Bangpra Campus, Chonburi, Thailand in 1989. In 1990, he was awarded a grant for development of faculty from Rajamagala University of Technology Issan, Surin Campus, to pursue graduate studies and earned his Master Degree in Fisheries from Kasetsart University, Bangkok, Thailand in 1993. He was an instructor at Rajamangala University of Technology Issan, Surin Campus from 1993 to 1997 and at Walailak University, Nakhon Si Thammarat from 1997 until present. He obtained an assistantship and tuition waiver from Auburn University to enroll in the doctoral program in fall 2004. He earned his Ph.D. degree from the Department of Fisheries and Allied Aquaculture, Auburn University on August 4, 2007. He is married to Laksana Kanchanapongkit, daughter of Wittaya and Malai, and is the proud father of two daughters, Pattarawadee and Paradee.

DISSERTATION ABSTRACT

RESOURCE USE AND WASTE PRODUCTION AT A SEMI-INTENSIVE, BLACK TIGER PRAWN *PENAEUS MONODON* FARM.

Puan Pengseng

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A study of resource use and waste production was conducted at the Aqualma shrimp farm in Madagascar . This farm has 685 ha of grow-out ponds where black tiger prawn *Peneaus monodon* are produced by semi-intensive production techniques. The farm has consistently produced around 3,000 mt/year since it began operations more than 10 years ago.

Three typical production ponds, each roughly 10-ha in area and slightly above 1 m average depth, were selected for measurement of all management inputs and outputs. These budgets allowed calculation of amounts of nutrients applied via the water supply source, and in fertilizers and feeds as well as quantities of nutrients assimilated by the ponds or discharged in effluents. This study revealed that effluents discharged during a

single crop contributed 433 kg nitrogen, 288 kg phosphorus, 3,967 kg organic carbon, and 7,994 kg 5-day biochemical oxygen demand (BOD_5) per crop. Based on these estimates, the annual discharge of the farm was 65,702 kg nitrogen, 43,704 kg phosphorus, 601,293 kg organic carbon, and 1,211,628 kg BOD_5. Although these are large amount of unused nutrients, the Mahajamba Bay that receives the farm effluents has a large volume (4.8×10^9 m^3). The total annual quantities of effluent nutrients, if introduced in a single dose and mixed thoroughly into the bay, would cause concentration increases of 0.0136 mg/L nitrogen, 0.0091 mg/L phosphorus, 0.125 mg/L organic carbon, and 0.252 mg/L BOD_5. The daily increase would be too small to measure. Of course, the bay assimilates wastes by natural processes, and wastes are flushed out by tidal action and freshwater flow. It seems unlikely that the farm is a serious pollution threat to the bay.

Phosphorus not discharged in effluent was adsorbed by bottom soil causing an increase in soil phosphorus concentration in the upper 10-cm layer of the bottom. Physical, chemical, and biological processes in ponds converted much of the nitrogen and organic carbon to gaseous form (ammonia, nitrogen, carbon dioxide, and methane). The increases in soil nitrogen and soil carbon during the crop were small.

Resource use and waste generation by the farm were assessed per tonne of shrimp production. The total land required for the production of 1 tonne of shrimp was 0.96 ha, including grow-out area, land for farm infrastructure, and land for producing plant meals for feed. The production of 1 tonne of shrimp required 2.067 tonnes of feed containing 0.908 tonne of crude protein (143.5 kg nitrogen), and 0.672 tonne fish meal. About 3.024 tonnes wet weight of marine fish were used to make the fish meal needed in feed for 1 tonne of shrimp. Water use was 90,855 m^3/tonne, and the energy use for pumping this water into the farm was estimated to be 868.8 kW·hr/tonne of shrimp produced. Nutrient inputs in feed and fertilizer were 163.2 kg nitrogen/tonne and 31.8 kg phosphorus/tonne. The percentage recovery of these two nutrients in shrimp was 18.9% for nitrogen and 8.2% for phosphorus. Only 3.7% of total organic carbon input to ponds was recovered in shrimp. The amount of liming material applied to the ponds was equivalent to 655 kg $CaCO_3$/tonne

Unused nutrients in the production of one tonne of shrimp were equivalent to the annual waste contribution of 54.1 people for nitrogen, 68.6 people for phosphorus, and 20.6 people for BOD_5. The farm, however, produced enough shrimp to supply the average annual consumption of nearly 2,000,000 Americans who eat about 1.54 kg of shrimp per year.

Style manual or journal used Journal of World Aquaculture Society

Computer Software used Microsoft Word 2003, Microsoft Excel 2003, SigmaStat 2.03, and Sigma Plot 8.0

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INTRODUCTION

Catch statistics complied by the Food and Agricultural Organization (FAO) of the United Nations reveal that world capture fisheries production has been stagnant at between 90 and 100 million tonnes[1/] since the late 1980s. About 70% of the capture fisheries is used for direct human consumption. This global harvest supplies between 3 and 4 kg of edible aquatic animal meat per person per annum. More importantly, it supplies about 20% of mankind's total protein need (Botsford et al. 1997). It is widely believed that most natural fisheries stocks currently are harvested at, or above, sustainable levels (Botsford et al. 1997; Pauly et al. 1998, 2003). Indeed, many upper trophic level stocks have been depleted greatly. The total global harvest has been maintained by shifting to smaller, formerly less desirable species that occupy lower trophic levels within the food web (Pauly et al. 2000). Chamberlain and Rosenthal (1995) predicted that natural stocks will supply only half the global demand for fish by 2025.

The expanding shortfall of food fish has fueled the global expanding of aquaculture.In 2004, aquaculture reached 59 tonnes with a farm gate value of U.S. $ 70 billion. Developing countries dominate aquaculture production and trade contributing over 80% of production and more than 50% of the value of aquaculture in international trade (FAO/NACA/UNEP/WB/WWF 2006). Tomasso and New (1999) estimated that

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[1/] Tonne refers to tons

world production from aquaculture must triple in volume from current levels over the next two decades if anticipated global needs for food fish are to be met. Chamberlain and Rosenthal's prediction became a reality sooner than expected, since aquaculture productions reached 50% of global food fisheries production in 2006. The economic star of the aquaculture industry is on the rise, but this economic growth has not been conflict-free as has been illustrated for shrimp farming.

Shrimp farming probably has been the fastest growing sector of export aquaculture in the world for the past 20 years. According to FAO statistics, 1.9 tonnes of shrimp were produced by aquaculture in 2004. The marine shrimp capture fishery was about 3.0 tonnes during the same year. Rapid expansion of shrimp farming has not been without controversy. There are rising concerns over environmental and social impacts of this activity. Major issues include the ecological consequences of conversion of natural ecosystems, particularly mangroves and other coastal wetlands, to shrimp farms. There also is concern about salinization of groundwater and agricultural land, excessive use of marine fish meal in shrimp feeds, pollution of coastal waters by pond effluents, loss of biodiversity arising from collection of wild brood stock and seed, and social conflicts within coastal communities. The sustainability of shrimp aquaculture has been questioned by some. Moreover, self-pollution of coastal waters used by shrimp farms combined with major shrimp disease outbreaks have resulted in significant economic losses in several producing countries (Primavera 1993, 1997, 1998; Boyd and Clay 1998; Naylor et al. 1998, 2000.

Some of the criticism of shrimp farming is justified while other complaints are of questionable validity. A major valid criticism is degradation of the natural environment, and most notably, eutrophication of receiving waters. Eutrophication is defined broadly as the process by which water becomes enriched with phosphorus, nitrogen, and possibly other nutrients causing excessive growth of aquatic plants.Coastal shrimp farms discharge effluents that contain high concentrations of nitrogen, phosphorus, and organic matter. There is concern that wastes from shrimp farms may accumulate in the coastal environment and the rate of eutrophication will be accelerated (McNevin 2004)

Some progressive shrimp farms have initiated programs to improve their environmental performance. A large shrimp farm in Madagascar has been working with Auburn University to improve production practices (Gomes 2003) and to monitor the effects of effluents on the bay into which the farm discharges water (McNevin 2004). Although the monitoring effort did not reveal evidence of increasing eutrophication as a result of farm effluent, farm management personnel agreed to further collaboration with Auburn University to improve the environmental effect. The main objective of the present research was to determine quantities of nitrogen, phosphorus, and organic matter discharge by the farm to surrounding waters. The secondary objective was to estimate the efficiency with which water, land, and other resources are used by the farm.

LITERATURE REVIEW

The rapid increase in world production of cultured shrimp and its equally rapid decline because of epidemics of viral disease of shrimp in countries like Ecuador, China, and Indonesia have left environmental, social and financial problems in its wake. This has not prevented development of new shrimp farms along stretches of coastline and further intensification of existing farm areas.

Shrimp farming has the capacity to dramatically impact coastal areas. Extensive and semi-intensive farms have significant requirement for land. Although intensive culture requires less land, the quantities of nutrients discharged into coastal waters in farm effluents may be proportionately greater than for less intensive production. Change in land use patterns, eutrophication, salinization, loss of biodiversity, and social transformations also have occurred (Lin, 1989; Chua et al. 1989; Csavas 1993; Liao 1990; Macintosh and Phillips 1992; Panvisavas et al. 1991; Primavera 1991, 1992, 1993, 1995). Social transformations have been both positive and negative. The increased income in traditionally poor coastal areas must be balanced against loss of traditional jobs, loss of independence, rising prices, and growing inequity between farmers and non-farmers (Chong 1990; Masae and Rakkaew 1992; Nuruzzaman 1996; Primavera, 1993, 1995).

Changes caused by shrimp farming tend to be irreversible. Thus, if shrimp farms collapse, little is left in its place for the local inhabitants. Agricultural land and sometimes mangroves have been degraded, and often, farmers are left with considerable debt. This leads to loss of land and an inability of failed shrimp farmers to return to their original lifestyle. There is a pressing need for the development and dissemination of information on shrimp culture systems that are both environmentally and economically sustainable.

Although cultivation of marine shrimp has proven a viable endeavor for some investors, it has sparked heated debates that focus on problems such as deforestation, water quality impairment, zoning, displacement of local people, human rights, foreign exchange, consumption, ecolabels, trade, and globalization (De la Torre 2003). From the 1980s until the present, the polarity between the aquaculture industry and environmentalists on issues related to shrimp farming and other types of aquaculture has caused inherent redundancy in stakeholder position. There has been a general concensus of opinion on the part of environmentalists that shrimp farming was unsustainable (Pillay 1992). This opinion was not based on scientific studies but rather on observations and opinions. Environmentalists were concerned about possible negative impact of the use of wild-caught post larvae shrimp on the shrimp fishery. Net loss of animal protein resulting from incorporation of fish meal and oil into shrimp feed to them appeared wasteful. Other major concerns expressed over the years were as follows: degradation of natural habitats (most notably mangrove forests); contamination of coastal waters through discharge of pond effluents and sediment; excessive use of water, salinization of soils; introduction of exotic species and pathogens; antibiotic, drug and other chemical use; displacement of local human communities; net loss of job opportunities; and changes in economic and social values (Bailey 1988; Macintosh and Phillips 1992; Primaversa 1993; Landesman 1994; Shiva 1995; Clay 1996; Boyd 1997; Clay 1997; Primaversa 1997; Boyd and Clay 1998; Naylor et al. 1998; Primaversa 1998; Naylor et al. 2000). Most environmentalists will not consede that well sited and managed shrimp farm could be operated in an environmentally responsibly manner (Moss et al. 2001).

The shrimp farming industry has relied on scientific information to support their position that sustainability can and often is achieved (Boyd et al. 2006). The industry also noted the benefits of shrimp farming which include creation of new jobs, poverty alleviation, improvement of local and regional economic conditions, protection of ecosystems though use of better practice, and enhancement of local fisheries (Aiken 1990a, 1990b; Boyd 1996; Philips 1998; Singh 1999; Teichert-Coddington 1999).

Many environmentalists initially proposed that governments should ban shrimp farming and urged consumers not to eat farmed shrimp. However, environmentalists soon learned that this approach was futile, for shrimp farming is done in response to a strong consumer demand. It also became clear that shrimp culture by responsible methodology is more environmentally-friendly than shrimp fishing (Clay 2004). The emphasis has shifted from denouncing shrimp farming to promotion of better production practices (Boyd 2006). In hopes of responding positively to these issues, there have been attempts by both environmental groups and industry to encourage improved production practices at shrimp farms. Codes of conduct with best management practices (BMPs) have been offered for voluntary adoption by producers (Boyd 1996; Tookwinas et al. 2000; FAO/NACA/UNDP/WD/WWF/ 2006). The Aquaculture Certification Council has developed a certification program for shrimp facilities. Goverments have initiated environmental regulations in a few nations. Nevertheless, these programs often have been met with criticism and controversy (Barnhizer and De la Torre 2003) even though they seek to and significantly decrease environmental degradation by shrimp farming.

Many of the problems associated with coastal shrimp farming relate to alteration of habitats and eutrophication. Eutrophication is defined broadly as the process by which water becomes enriched with plants nutrients, most commonly phosphorus and nitrogen, thereby causing excessive growth of aquatic plants. Research has shown that discharge of nutrients from shrimp ponds can lead to eutrophication of receiving water bodies if the assimilation capacity of the local environment is exceeded (Philips 1995a, 1995b, 1998; Primavera 1998). Boyd and Clay (1998) suggested there is good evidence that about 90% of all the problems associated with shrimp aquaculture have resulted from inadequate site selection and failure to conduct environmental impact assessments. Clay (2004) noted that poor sitting often leads to local water quality degradation because effluents are not mixed thoroughly with estuary water and rapidly transported to the sea. Ironically because most tropical and sub-tropical shrimp farms use the same water body as water source and effluent recipient, the health of the surrounding ecosystem is of critical importance to their sustainability.

Two significant components of the pond environment are the water and bottom soil in which interact continuously to influence the culture environment. The material comprising the pond bottom can be divided into the original pond bottom that was present immediately after construction, and the sediment that accumulate in pond bottom during shrimp culture (Boyd 1995). Pond management activities also influence the culture environment. Management activities include feeding, use of aerators, water exchange, and liming (Briggs and Fung-Smith 1994).

Pond water quality is of major concern in considerations of shrimp health management. Although there are several primary pathogens of shrimp, the majority of shrimp diseases are caused by secondary pathogens that are able to invade shrimp already stressed and weakened by a poor quality rearing environment. Shrimp that are stressed do not grow rapidly, principally because of poor appetite and delayed molting. It is important to maintain a healthy rearing environment for shrimp to maximize production potential and minimize the risk of opportunistic diseases (Funge-Smith and Briggs 1998).

Viral type diseases such as ‘yellow head’ (YBV) and ‘white spot’ (SEMBV) disease appear to be transmitted via influent water and intermediate crustacean hosts, respectively. White spot disease also can be transmitted through the post-larvae (Flegel et al. 1996). These diseases cannot necessarily be prevented by maintaining a high quality rearing environment, but a poor quality environment certainly will increase disease incidence. Yellowhead disease already appears to be changing from a primary pathogen to opportunist type pathogen. In 1993, only 0.05% of the tiger shrimp *P. monodon* carrying the virus were asymptomatic; now this figure has increased to 60% (Flegel et al. 1996). Therefore, better environmental quality will have a more significant effect in preventing yellowhead disease than before.

Sources of nutrients in aquaculture ponds

The main sources of nutrients in shrimp aquaculture are fertilizers and feeds applied to pond to stimulate production of the culture species (Boyd 1999). Estimates of nutrients and suspended organic solids entering coastal waterways from shrimp ponds indicate that most of this material originates from added feeds (Macintosh and Phillips 1992; Briggs and Funge-Smith 1994). Animal manures or other agricultural byproducts may be applied to ponds as organic fertilizer. These materials contain nitrogen and phosphorus that are released into the water as the organic material are decomposed by microbes. Chemical fertilizers such as urea, triple superphosphate, and diammonium phosphate dissolve in water to release nitrogen and phosphorus (Boyd 1999). Although, manure can be as efficient as chemical fertilizers in enhancing fish and shrimp production in ponds, chemical fertilizers have several advantages over manures. They are more widely available, require lower application rates, have a more consistent composition, elicit a more predictable response, and are less harmful to the pond environment than manures. Manures have low nitrogen content and tend to decompose slowly and incompletely leaving large amounts of organic residues in ponds (Boyd 1995).

Feed also contains nitrogen and phosphorus. Some of the nitrogen and phosphorus in feeds enter the water when feces and unconsumed feed decompose, and more is added when ammonia and phosphate are excreted by the culture species. Organic nitrogen and phosphorus are both present in the water as a component of living plankton and soluble organic matter. Inorganic nitrogen is dissolved in the water primarily as ammonia-nitrogen and nitrate. Inorganic phosphorus in water may be contained on suspended mineral (soil) particles or as soluble phosphate (Boyd 1999).

In freshwater ponds, blue green algae and other microorganism fix nitrogen, so the amount of nitrogen required in fertilizers relative to phosphorus is not great as the composition of living aquatic organisms might suggest (Murad and Boyd 1987).

Although the ratio of nitrogen (N) and phosphorus (P) is 7:1 to 10:1 in aquatic organisms, Boyd (1990) concluded that the ideal ratio in fertilizer is about 1:1.5, and excessive use of nitrogen should be avoided. Nitrogen-fixing blue green algae are less abundant in brackishwater ponds than in freshwater ponds (Boyd 1990). Knud-Hansen and Pautong (1993) suggested that in brackishwater ponds a greater N:P ratio (1:1 or 2:1) is needed to stimulate phytoplankton blooms, because less nitrogen is available through nitrogen fixation. Much higher ratios of N:P (10:1 to 20:1) are used in fertilizing regimes for brackishwater ponds when it is desired to enhance diatom abundance in phytoplankton communities (Boyd and Tucker 1998).

Nitrogen dynamics in aquaculture ponds

Urea and ammonium fertilizers are used widely in ponds because they are cheaper than nitrate fertilizers (Boyd 1990; Knud-Hansen and Pautong 1990). These fertilizers directly increase total ammonia nitrogen concentrations in pond water as shown for urea and ammonium sulfate in the following equations:

$$CO(NH_2)_2 + H_2O \rightarrow 2NH_3 + CO_2,$$

$$(NH_4)_2\ SO_4 \rightarrow 2NH_4 + SO_4^{2-}.$$

Ammonium-nitrogen exists as un-ionized ammonia (NH_3) and ammonium ion (NH_4^+) in a temperature-pH dependent equilibrium;

$$NH_3 + H^+ = NH_4^+.$$

Un-ionized ammonia is toxic to aquatic animals, and its proportion relative to ammonium increases with increasing pH and temperature. Fertilization of ponds stimulates phytoplankton growth, and as phytoplankton removes carbon dioxide from the water to use in photosynthesis, the pH typically rises. Aquaculture ponds ordinarily typically have daytime pH values between 8.0 and 9.5 (Boyd 1995). Thus, un-ionized ammonia can be harmful to shrimp or other culture species in pond water with total ammonia-nitrogen concentration above 2 or 3 mg/L.

Ammonia-nitrogen is acid-forming because of nitrification in which bacteria oxidize ammonia and ammonium to nitrate. Nitrification consists of two reactions. Bacteria of the genus *Nitrosomanas* oxidize ammonia to nitrite:

$$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + 2H_+ + H_2O.$$

Then, bacteria of the genus *Nitrobacter* oxidize nitrite to nitrate:

$$NO_2^- + 1.5O_2 \rightarrow NO_3^-.$$

Two moles of H^+ are releases per mole of ammonium-nitrogen, and hydrogen ion neutralizes total alkalinity (bicarbonate and carbonate) in the water to reduce pH:

$$CO_3^{2-} + H^+ = HCO_3^-,$$

$$HCO_3^- + H^+ = CO_2 + H_2O.$$

Nitrification is an aerobic process and consumes dissolved oxygen. The oxidation of 1 mg NH_4-N consumes 4.57 mg dissolved oxygen, produces 0.14 mg hydrogen ion, and can neutralize up to 7.14 mg of total alkalinity ($CaCO_3$) (Hunt and Boyd 1981).

Nitrite produced by *Nitrosomonas* normally does not accumulate, for it is rapidly changed to nitrate by *Nitrobacter*. Nitrifying bacteria are chemoautotrophic organisms that use the energy derived from the oxidation of inorganic compounds to synthesize organic matter from carbon dioxide. In other words, they produce organic matter through a non-photosynthesis pathway. The amount of organic matter produced by nitrifying organisms is ecologically insignificant (Boyd and Tucker 1998). Nevertheless, ammonia removal by nitrification is generally beneficial in aquaculture in spite of the resulting oxygen consumption and acidity.

Nitrate in water and soil originates from rainfall, nitrate fertilizer, and nitrification. Nitrate may be absorbed by plants and soil microorganisms, reduced to ammonia, and incorporated into protein. Nitrate also can be lost from ponds though denitrification. There are several pathways of denitrification, but the process is most commonly illustrate by the following equation:

$$6NO_3^- + 5CH_3OH \rightarrow 5CO_2 + 3N_2 + 7H_2O + 6OH^-.$$

Denitrification occurs under anaerobic conditions (Park et al. 1975). Microorganisms that carry out these transformations use oxidized inorganic compounds as terminal electron and hydrogen acceptors in respiration instead of molecular oxygen. Nitrate can be reduced to nitrite, which can then be reduced to hyponitrite ($H_2N_2O_2$). At this point several possibilities exist. Hyponitrite may be reduced to hydroxylamine ($2HN_2OH$), which can be further reduced to ammonia (NH_3), or hyponitrite may be reduced to N_2O or N_2. Nitrogen and nitrous oxide are commonly lost from the soil or water by volatilization. Ammonia also may be lost by volatilization if the pH is high, but in most soils and water where denitrification is proceeding, pH is low because of relatively high carbon-dioxide concentrations.

In highly acidic soils and water, denitrification may occur through purely chemical pathways:

$$RNH_2 + HNO_2 \rightarrow N_2 + ROH + H_2O$$

$$3HNO_2 \rightarrow 2NO + HNO_3 + H_2O$$

Microbial mediated denitrification is of much greater magnitude than chemical denitrification in most soils and water.

Denitrification is an important pathway of nitrogen removal from ponds. It occurs in anaerobic sediment; however, the rate of this process is sometimes relatively low because nitrification and denitrification are coupled in sediment and sediment nitrification is limited by oxygen penetration into sediment (Hargreaves 1998).

The nitrogen stored in soil is contained primarily in soil organic matter. Nitrate and ammonium usually are absorbed by microbes and plants or lost through leaching or pond overflow because of their high solubility. Nevertheless, detectable concentrations of ammonium and nitrate occur in most soils and pond waters.

The ratio of carbon (C) to nitrogen (N) in soils of natural ecosystems is usually established by the C:N ratio of humus, which is about 10:1. In agricultural systems, the C:N ratio may be quite variable because nitrogen input by managed. The C:N ratio is an important soil property. Organic matter with a low or narrow C:N ratio decomposes much faster than organic matter with a high or wide C:N ratio. If a soil contain 5% organic carbon, it usually has around 0.5% organic nitrogen. The total nitrogen concentration in pond soils may be higher because of the presence of ammonia and nitrate (Boyd 1995).

Nitrogen is a macroelement in estuaries, and high concentrations of nitrogen have been observed in eutrophic coastal ecosystems (Nedwell et al. 2000). Total nitrogen comprises total organic-nitrogen, nitrate-nitrogen, nitrite-nitrogen, and total ammonia-nitrogen. Major nitrogen sources in coastal water include: inflow of rivers and tidal estuaries, atmospheric deposition, and pollution. Tidal exchange can introduce marine nitrogen, but this source is relatively unimportant in embankments receiving high nitrogen loads from their watersheds. Denitrification is a major sink for inorganic nitrogen in estuaries (Berelson et al. 1998; Zimmerman and Benner 1994). Nitrogen loss through denitrification can exceed 50% of the total nitrogen input, and it is probably the main reason why nitrogen can sometimes be the limiting nutrient in estuaries (Seitzinger 1884).

Green et al. (1998) reported total nitrogen concentrations in a Central American estuary to be between 0.6 to 2.6 mg/L. Teichert-Coddington et al. (2000) examined a Honduran estuary where a shrimp farm was situated and found total nitrogen concentrations averaging 1.71 mg/L in the dry season and 1.68 mg/L in the wet season.

Meeuwig et al. (2000) found average total nitrogen concentrations from nineteen Baltic estuaries to range from 0.320 to 2.133 mg/L.

Chapman (1996) suggested that total ammonia-nitrogen (TAN) concentrations of 0.04 to 0.1 mg/L TAN in estuaries were optimum. Mallin et al. (2002) found an average TAN concentration of 0.10 mg/L in estuaries of rivers from the Piedmont Plateau range of the United States. Teichert-Coddington et al. (2000) found an average TAN concentration of 0.07 mg/L in the Gulf of Fonseca, Honduras. Scharler and Baird (2003) examined estuaries in the Eastern Cape of South Africa and found TAN concentrations ranging from 0.09 to 0.16 mg/L. Trott and Alongi (2000) researched aspects of channel estuaries receiving shrimp farm effluent in Australia and found TAN concentrations in receiving water of 0.03 to 0.06 mg/L following farm discharge.

Of the numerous forms of nitrogen in coastal water, Liss (1976) noted nitrate as the major form of dissolved inorganic nitrogen. Nitrate is found at low concentrations in ocean surface water, but the concentration increases with depth (Millero 1996). Nedwell et al. (2002) stated that because nitrogen is seen as the limiting chemical factor in phytoplankton growth in estuaries, many of the nutrient standards formulated for estuaries have been designated in terms of acceptable nitrate concentrations. Lietz (1999) found nitrate-nitrogen concentrations as high as 4.38 mg/L in Biscayne Bay, Florida. Teichert-Coddington et al. (2000) examined a Honduran estuary where shrimp farms were situated and found mean nitrate-nitrogen concentrations of 0.069 mg/L in the dry season and 0.058 mg/L in the wet season. Chapman (1996) recommended a safe concentration of 0.1 mg/L NO_3-N in estuaries.

Phosphorus dynamics in aquaculture ponds

Phosphorus is a key nutrient limiting aquatic productivity for most natural waters. Compared to natural waters, aquaculture pond waters often are enriched with phosphorus, and the discharge of ponds may enrich receiving waters with phosphorus compounds and lead to excessive plant growth (Boyd and Tucker 1998). Pond sediments interact with the water column affecting the phosphorus cycle in natural waters (Reddy et al. 1999). This interaction is a major factor in pond aquaculture chemistry (Boyd and Musig 1981; Boyd 1995).

Plants absorb phosphorus as orthophosphate ions, which may be considered as ionization products of orthophosphoric acid. (H_3PO_4):

$$H_3PO_4 = H^+ + H_2PO_4^- \qquad pK_{a,1} = 2.1,$$

$$H_2PO_4^- = H^+ + HPO_4^{2-} \qquad pK_{a,2} = 7.2,$$

$$HPO_4^{2-} = H^+ + PO_4^{3-} \qquad pK_{a,3} = 12.3.$$

The normal pH range in aquaculture ponds is 7 to 9, and orthophosphate exists as a mixture of $H_2PO_4^-$ and HPO_4^{2-} within this range. These two phosphate ions are equally available to plants. Phytoplankton cells and particulate matter or detritus of algal origin are the largest phosphorus fractions in aquaculture pond waters (Boyd and Tucker 1998).

In natural waters, sediments usually are considered a source of phosphorus. However, in aquaculture ponds, bottom soils, and especially aerobic soils, are particularly important as phosphorus sinks (Boyd and Musig 1981). Phosphorus normally reacts with aluminum, iron, and calcium in sediments to form chemical complexes with relatively low solubilities under aerobic conditions. The vital key that affects the solubility of calcium, iron, and aluminum bound phosphates is pH. Aluminum normally reacts with phosphorus under acidic condition while calcium phosphates form in alkaline soil. Iron phosphates in sediment become highly soluble at low pH and low redox potential (Eh) (Rowan 2001; Boyd and Tucker 1998). At high pH values, phosphorus is precipitated as hydroxyapatite. When pH decreases, calcium phosphates increase in solubility (Golterman 1995).

Gibbsite (aluminum hydroxide) is a common aluminum compound in soil (Adams 1971). The solubility of gibbsite is strongly influenced by pH:

$$Al(OH)_3 = Al^{3+} + 3OH^-.$$

A decreasing pH favors solubility of gibbsite and other aluminum oxides and hydroxides in soil. Aluminum ions from the dissociation of gibbsite or other aluminum compounds react with phosphorus to form insoluble aluminum phosphate:

$$Al^{3+} + H_2PO_4^- = AlPO_4 + 2H^+.$$

Boyd and Tucker (1998) summarized literature showing that sediment removed phosphorus from water in the form of iron, aluminum, and calcium phosphate compounds with limited solubility. Solubility of aluminum and iron phosphates increases with decreasing pH while the solubility of calcium phosphate compounds decrease with increasing pH. Formation of iron phosphates depends on the amount of oxygen in sediment. Under aerobic conditions, much of the phosphorus is basically combined with amorphous ferric (Fe^{3+}), oxy-hydroxide gels, or as phosphorus co-precipitated in coatings of ferric oxide surrounding silt or clay particles. Under anaerobic conditions, ferric iron is normally reduced to soluble ferrous (Fe^{2+}) iron, and the associated phosphorus is soluble.

The calcium phosphate series ranges from the least soluble $Ca_5(OH, F)(PO_4)_3$ (apatite) through $Ca_4H(PO_4)_3$ (octocalcium phosphate) and $CaHPO_4$ to the most soluble form $Ca(HPO_4)_2$ (Bohn et al. 2001).

The amount of phosphorus lost to sediment differs among aquaculture ponds (Shrestha and Lin 1996). Boyd (1985) demonstrated that 65 % of phosphorus in feed applied to channel catfish ponds was adsorbed by bottom soil. In earthen raceways for channel catfish culture, 44 to 46% added phosphorus was adsorbed by sediment (Worsham 1975). In eel pond culture, sediment removed 40 to 50% of added phosphorus (Chiba 1986).

According to Masuda and Boyd (1994), total phosphorus concentrations in clayed bottom soils of ponds at Auburn, Alabama, were greater in deep water than shallow water areas. The highest phosphorus concentrations were in the upper 10-cm soil layer of areas more than 0.5 mg/L deep, and phosphorus accumulated above its original concentration to depths of 20 to 40 cm. The average depth to which phosphorus concentration had increased above its original level in bottom soils of ponds at Auburn University was 36.8 cm (Masuda and Boyd 1994).

High phosphorus concentrations were observed in bottom soil of tilapia ponds at Samutprakarn, Thailand (Thunjai 2002). The acid-extractable phosphorus concentration ranged from 78 to 944 ppm with an average of 217 ppm. The water extractable phosphorus concentration ranged between 5 to 31 ppm, and the average was 9 ppm. Thunjai (2002) concluded the high concentrations of phosphorus in pond sediments resulted from applying phosphorus fertilizer to ponds over several years.

Phosphorus in estuarine systems exists in either the particulate phase or the dissolved phase. Particulate matter consists of living and dead plankton, other suspended organic particles , and clay and other suspended mineral matter. The dissolved phase includes soluble orthophosphate, dissolved organic phosphorus, and macromolecular colloidal phosphorus.

Phosphorus concentrations in estuaries vary greatly by location. Mallin et al. (2002) found total phosphorus concentrations between 0.075 and 0.211 mg/L in the Cape Fear estuary in the eastern United State. Lietz (1999) reported a median total phosphorus concentration of 0.02 mg/L in Biscayne Bay, USA, but a maximum value of 0.31 mg/L was observed. In an Australian estuary receiving shrimp farm effluent, Trott and Alongi (2000) found the average concentration of total phosphorus ranged from 0.2 to 0.6 mg/L. Teichert-Coddington et al. (2000) studied a Honduran estuary where a shrimp farm was situated and found total phosphorus concentrations to be about 0.25 mg/L during both wet and dry seasons.

Organic matter in aquaculture ponds

Soil organic matter is a heterogeneous mixture. It is composed of compounds resulting from microbial and chemical transformations of organic matter. The increase or decrease of organic matter in the sediments varies with the rate of in situ production and allochtonous input of organic material that settles to the bottom before being mineralized and the rate of organic matter mineralization in the sediment. The size, shape, and density of particles and water density and viscosity were used to determine the rate of sedimentation of particulate matter (Jiměnez-Montealegre et al. 2002). Small particles such as clay and fine organic matter settled very slowly, while sand and silt settled rapidly (Jørgensen 1989).

Soil organic matter is about 45 to 50% carbon, so a rough approximation of organic matter may be obtained by doubling the soil organic carbon concentration (Boyd et al. 2002). Soil organic carbon concentrations usually are 2 or 3% in the sediment of the S and M horizons, but they usually are lower in original pond bottom soil (P horizon) (Munsiri et al. 1995).

The concentrations of soil organic matter in aquaculture ponds ranged from less than 1% in highly leached mineral soils in extensive ponds to over 20% in ponds constructed on organic soils (Boyd 1995). In terms of their relationship to aquaculture, Boyd et al. (2002) provided the following classification of pond soil organic matter concentration:

Organic carbon (%)	**Comment**
>15	Organic soil
3.1 to 15	Mineral soil, high organic matter content
1.0 to 3.0	Mineral soil, moderate organic matter content, best range for aquaculture
<1	Mineral soil, low organic matter content

Comparing fertilized ponds and unfertilized ponds, fertilized ponds had higher nutrient concentrations and larger organic carbon influxes than unfertilized ponds

(Thunjai 2002). Channel catfish ponds with feeding have larger nutrient and organic carbon influxes than do fertilized sportfish ponds (Boyd 1995). When organic matter and nutrient inputs to ponds are discontinued, dissolved nutrients quickly decline and limit the growth of phytoplankton (Diana et al. 1990).

According to Thunjai (2002), organic carbon averaged 2.22% for seventeen tilapia ponds in Changrai, Thailand. The organic carbon concentration in the samples ranged between 1.08 and 3.08%. Boyd et al. (1994) reported the average organic carbon concentrations in 358 freshwater ponds soil sample from Honduras, Rwanda, Bhutan, and the United States and 346 brackishwater ponds samples from Thailand, Ecuador, Philippines, and Venezuela. The averages for freshwater and brackishwater ponds were remarkably similar, 1.78% and 1.79%, respectively. However, some samples from aquaculture freshwater ponds contained up to 8% organic carbon, and some samples from intensive brackishwater shrimp ponds contained more than 10% organic carbon.

The acceptable range of organic carbon for aquaculture ponds is 0.5 to 2.5%. The best range is 1.5 to 2.5% (Banerjea 1967). According to Boyd (1995), when soil pH is below 7 and organic carbon concentrations are above 2.5% (around 5% organic matter) within the S horizon, natural productivity that supports fish growth decreases in ponds.

Waste assimilation in aquaculture ponds

Ponds have a large capacity to assimilate wastes resulting from aquaculture inputs. As stated above, bacteria mineralize organic matter to carbon dioxide, ammonia, and phosphate. Ammonia is lost to the atmosphere by diffusion and oxidized to nontoxic nitrate by nitrifying bacteria. Nitrate can be denitrified to nitrogen gas, which diffuses into the air. Carbon dioxide is converted to organic carbon by photosynthesis or it diffuses from pond water to the atmosphere. Bacteria can transform carbon dioxide in sediment to methane that also diffuses to the atmosphere. Sediment usually has a large capacity to fix phosphorus in insoluble iron, aluminum, and calcium phosphate. Some of the organic matter in ponds resists microbial decay and accumulates in sediment as stable organic matter. However, ponds may receive greater inputs of nutrients in feed and fertilizer than can be assimilated quickly, and water quality deteriorates. When this happens, the culture species can be stressed by adverse water quality conditions. Stress can lead to lower feed conversion efficiency, increases susceptibility to diseases and in lower survival and production (Boyd 2004)

Semi-intensive aquaculture is a natural progression from extensive techniques. In order to eliminate the constraint of a shortage of natural food organisms in extensive ponds, high quality artificial feed is provided to semi-intensive ponds. This allows greater production of the culture species. The limiting factor in semi-intensive systems is the capacity of the pond environment to provide sufficient dissolved oxygen for the culture species and for the microorganisms that assimilate organic matter and potentially toxic metabolic wastes. This limitation can be overcome by periodically exchanging a proportion of the pond water to flush out excess nutrients and to bring in fresh oxygenated water (Boyd and Tucker 1998). Alternatively mechanical aeration may be used to increase the dissolved oxygen content of pond water (Reed and Robert 1981).

Marine shrimp farmers generally believe that bottom soil quality in ponds deteriorates over time because of sediment accumulation, declining pH, and increasing organic matter concentration. Pond bottom soil management has received more attention in marine shrimp culture than in freshwater fish culture (Limsuwan and Chanratchakool 2004). Discussions with practical aquaculturists indicate a general belief that bottom soils have less importance in fish culture than in marine shrimp culture because shrimp spend much time on the bottom while fish reside more in the water column (Boyd 1995).

Primaversa (1998) reported that only 16.7% of the total amount of feed applied to intensive shrimp ponds in Asia is converted to shrimp biomass. The remainder of the feed is either not eaten, becomes feces, or is transformed to metabolic excretion. The nutrients represent 63 to 82% of nitrogen and 76 to 87% phosphorus applied to intensive ponds as feed (Macintosh and Philips 1992; Phillip et al. 1993; Briggs and Funge-Smith 1994). Gautier et al. (1997) found that at semi-intensive shrimp farms in Columbia, 25% of the dry weight of feed was recovered in harvested shrimp, and 38% nitrogen and 11% phosphorus were recovered from feeds and fertilizers. In semi-intensive shrimp ponds in Hondurus, 45% nitrogen and 21.3% phosphorus supplied by feeds was recovered in harvested shrimp (Boyd and Teichert-Coddington 1994). However, large inputs of fertilizer were made to semi-intensive shrimp ponds in Hondurus. When both fertilizer and feed were considered, only 14% nitrogen and 8.9% phosphorus were recovered in shrimp (Teichert-Coddington et al. 2000).

In semi-intensive shrimp farming, mechanical aeration is not needed, and high rates of water exchange may be used to avoid low dissolved oxygen concentration. In ponds with heavy water exchange, inflowing water may be major source of organic matter, and nutrients and outflowing water may remove large amount of these substances from ponds (Teichert-Coddington et al. 2000).

Studies of freshwater fish culture in the United States revealed that sediment accumulated, and organic matter and nutrient concentrations increased over time in research ponds for sunfish *Lepomis* spp. and channel catfish *Ictalurus punctatus* (Munsiri et al. 1995), commercial channel catfish production ponds (Tucker 1985; Steeby et al. 2004; Silapajarn et al. 2004), and bait minnow *Notemigonus crysoleucas, Carassius auratus,* and *Pinephales promelas* ponds (Tepe and Boyd 2002). Soil management practices had typically not been applied to ponds in those studies, and the most significant problem with pond bottoms was the accumulation of soft sediment in the deeper areas.

A recent study of freshwater ponds for culture of tilapia *Oreochromis* spp. in Thailand (Thunjai et al. 2004) revealed that the composition of bottom soil differed little between ponds less than 5 years old and those over 20 years old. The correlation coefficient between pond age and soil organic carbon concentration was only 0.36. Liming materials had been applied liberally to these ponds and sediment had been removed from some of them. This study suggested that ponds used in semi-intensive production of tilapia could be used for at least 25 to 40 years without severe bottom soil deterioration if pond bottoms are dried between crops, lime is applied, and excessive sediment is removed. Wudtisin (2005) made similar observations regarding sediment composition and management in the bottoms of *Clarius* spp., carp, and freshwater prawn ponds in Thailand.

Phytoplankton and other plants use ammonia-nitrogen, nitrate, and soluble inorganic phosphorus for growth. Nitrogen and phosphorus contained in particulate organic matter or soluble organic matter in the water may be transformed by microbial decomposition to ammonia, nitrogen, nitrate, or phosphate. Because organic phosphorus and nitrogen can be transformed to soluble inorganic forms by microbes, the eutrophication potential of pond effluents increase as the total concentration of nitrogen and phosphorus increases. In ponds with heavy plankton blooms, most of the nitrogen and phosphorus may be contained in plankton and detritus rather than in soluble form. Effluents from a pond with low concentrations of ammonia nitrogen, nitrate, and phosphorus, but with high plankton abundance, may still have a significant eutrophication potential because of nutrients contained in plankton, detritus, and soluble organic matter. When effluents enter natural waters, organic matter contained in them decomposes and releases ammonia nitrogen, nitrate, and phosphate (Boyd 1999).

A major implication of increased nitrogen and phosphorus in estuaries is greater production of phytoplankton and other plant species. Phytoplankton abundance has a dramatic effect on water quality, and particularly on dissolved oxygen concentration. Because plants contain chlorophyll to absorb light for use in photosynthesis, the concentration of chlorophyll a in water may be used as an index of phytoplankton abundance. Chlorophyll a concentrations of 0.1 to 20.2 µg/L was observed by Mallin (2002) in the Cape Fear estuary system. In an estuary of Eastern Cape of South Africa, Scharler and Baird (2003) found chlorophyll a concentrations ranging from 2.2 to 22.8 µg/L. Teichert-Coddington et al. (2000) examined a Honduran estuary where shrimp farms were situated and found chlorophyll a concentrations averaging 74 µg/L in the dry season and 75 µg/L in the wet season.

Suspended soil particles have a dramatic effect on phytoplankton abundance in estuaries. Nutrient inputs to estuaries and oceans from rivers draining disturbed or denuded watersheds often are accompanied by high turbidity that results in light limitation for algal production (Pennock 1985; Peterson et al. 1985; Harding et al. 1986). Many rivers and estuaries with high concentrations of nitrogen and phosphorus do not develop a large algal biomass because deep mixing in a turbid water column prevents adequate exposure to light for photosynthesis (Wofsy 1983; Cole et al. 1992). These turbid aquatic systems eventually deliver their plant nutrients to marine waters where there is sufficient light in the water column, and plant nutrients are consumed until one or more are depleted from surface waters. Although turbid estuaries may not be rich in algal biomass, if there is a large organic fraction in suspended solids, dissolved oxygen depletion can occur.

One characteristic of eutrophic bodies of water is a wide variation in diurnal dissolved oxygen concentration. The increase in dissolved oxygen is attributed to high photosynthetic activity, whereas the decrease in dissolved oxygen is a function of rapid respiration. Photosynthesis occurs when light is available; however, respiration occurs both day and night. Respiration is carried out not only by plants but by bacteria decomposing organic matter and by culture animals as well.

The 5-day biochemical oxygen demand (BOD_5) is used to assess the oxygen demand of organic matter decomposition and nitrification in the water. In a tidally flushed mangrove creek receiving shrimp farm effluent in north Queensland, BOD_5 ranged from 0.5 to 2.0 mg/L (Department of Environment and Heritage 1993). Teichert-Coddington et al. (2000) measured BOD_5 concentrations in a Honduran estuary receiving shrimp farm effluent. Concentrations of BOD_5 averaged 13.0 mg/L in the dry season and 18.2 mg/L in the wet season.

Much of the nitrogen and phosphorus added to ponds will be removed from the water by natural processes. Nitrogen will be lost to the air by volatilization of ammonia and by microbial denitrification. Some nitrogen will be bound in organic matter deposited in the pond bottom, and phosphorus will be absorbed by sediment. Recent studies suggest that about 50% of nitrogen and 65% of phosphorus added in feed could be removed from the water of a pond without water exchange through physical, chemical, and biological processes. Considering that about 25% to 35% of nitrogen and 15% to 25% of phosphorus added in feed is recovered in shrimp at harvest, only 15% to 25% of the nitrogen and 10% to 20% of the phosphorus applied in feed would be lost in effluent at pond draining (Boyd 1985, 1999). Of course, water exchange reduces hydraulic retention time which and consequently to lessens the capacity of ponds to assimilate wastes.

In catfish ponds, if contributions from natural foods are not considered, then recovery of carbon, nitrogen and phosphorus that are added in feed is approximately 25%, 27%, and 30%, respectively (Boyd 1985). Schroeder (1975) suggested that this high recovery in catfish culture is in part the result of using floating feed pellets, most of which are consumed by the fish. Moreover, if organic matter from net photosynthesis is considered, the recovery of organic carbon in the form of fish biomass is only 16%. In Israel, ponds for polyculture of common carp, silver carp and tilapia hybrid (*T. nilotica* x *T. aurea*) were stocked with a total of 20,000 fish/ha. Recovery of organic carbon from net primary productivity in ponds with inorganic fertilization was only 7% (Schroeder 1987).

Schroeder (1987) illustrated that the recovery of carbon from net primary productivity in fish biomass was about 5% in ponds receiving both pellets and fertilizer.

If primary productivity was not considered, about 25% of carbon applied in feed was recovered in fish. Discounting carbon from net primary productivity is more reasonable than including it, because feed pellets usually are the main source of organic matter for fish growth. Nitrogen recovery in these ponds was 10% to 20% of the total nitrogen added as feed, manures, and fertilizer. Phosphorus recovery was 10% to 15% of the total amount added in ponds to which both feed and fertilizers were applied, and 15% to 20% was recovered in pond receiving chemical fertilization alone. The higher recovery of nutrients from catfish ponds in the United States relative to the polyculture ponds in Israel reflects the better fit of floating pellets to the nutritional requirements of the fish.

In the catfish nutrient budget study of Boyd (1985), the waste loads were equivalent to 28.4 mg/L nitrogen, 3.84 mg/L phosphorus, and 703.5 mg/L carbon. None of these variables actually reached such high concentrations. The rate at which the ponds processed added organic matter and nutrients was almost which they were added as part as the rate at which they were added. Thus, equilibrium was reach at much lower concentrations than expected from inputs alone.

Sedimentation of organic matter in uneaten feed, feces, and dead algae from the water column to the pond bottom is a key process in the flow of nutrients in a standing water (static) pond. Usually, the upper few millimeter of the sediment is aerobic and bacteria decompose organic matter to carbon dioxide, water, ammonia, and other inorganic nutrients. Deeper sediment is anoxic and microbial decomposition release potentially toxic metabolites such as reduced organic acids and alcohols, ferrous iron, and hydrogen sulfide. Mixing of sediment can cause these potentially toxic substances to enter the pond water (Boyd 1995).

Only when the ammonia concentration in the water column reaches 1 mg/L does loss of ammonia by diffusion into the atmosphere become significant (Schroeder 1987). The dynamic uptake of ammonia by sestonic algae and bacteria usually keeps ammonia concentrations below 0.5 mg/L. High ammonia concentrations usually are associated with ecological upsets such as rapid die-of of phytoplankton or nitrifying bacteria and sudden thermal destratification or changes of seasons when water temperatures drop below 20 ^{o}C and microbial metabolic rates decrease.

The lack of build-up of nitrogen and phosphorus in the water column, relative to the rate at which they are added to the ponds, is also the result of their transformation by chemical, physical, and biological processes. The lack of build-up of carbon in the water can be attributed to its sedimentation to the pond bottom and to its conversion to carbon dioxide by respiration, both in the water column and on the bottom. Of average, 3 to 4 g organic carbon/m^2 were added to carp pond bottom daily from addition to manure and feed, and gross primary productivity produced 10 g carbon/m^2/day (Scheroeder 1987). About 10 g carbon/m^2/day were respired or fermented into carbon dioxide. Approximately 1 g carbon/m^2 was converted to fish biomass. The remainder of the organic carbon was either decomposed by sediment microorganisms or accumulated in the sediment. If 1 g of organic matter is accumulated and mixed into the upper 10-cm layer of sediment daily for 250 days, the organic matter concentration in the sediment would increase by 0.08%(based on the upper 10-cm layer).

In commercial fish ponds in Israel receiving feeds and fertilizers, approximately 0.3 g phosphorus/m^2 was added daily. Algae contain on the order of 1% to 2% phosphorus. At a gross daily primary productivity rate of 10 g carbon (20 g die algae)/m^2, approximately 0.2 g phosphorus/m^2/day would be absorbed by algae cells (Eren et al.1977). Most of the remaining phosphorus would be adsorbed by the pond bottom. Of course, the phosphorus in algae cells would eventually be deposited on the bottom as dead organic matter or converted to inorganic phosphorus by microbial decomposition and absorbed by soil. Sediments in Israeli fish ponds usually contain 0.1 to 0.3% (1,000 to 3,000 ppm) of phosphorus (Eren et al. 1997). Similar concentrations of phosphorus also were found in catfish pond sediment in the United States (Boyd 1995).

Nitrogen concentrations in ponds on the Auburn University Fisheries Research Station have increased gradually over a period of years (Munsiri et al. 1995). Nevertheless, the increase during a single crop year was too small to measure (Boyd 1985). The absense of a large increase in the nitrogen concentration in pond sediment suggests that much nitrogen is lost through denitrification and ammonia volatilization. Of course, in ponds with significant water exchange, much nitrogen would be flushed out of ponds before it could be fixed at removed by natural purification processes within the pond (Boyd 1999).

The source of organic matter and minerals in intensive, water-recirculation ponds is largely the added feed (Boyd and Tucker 1998). Stocking densities often reach 50 fish/m^2. If harvest weights are 600 g/fish, the average fish biomass at the end of the season is 15 kg/m^2. Daily feeding rates are about 2% of the fish biomass and can exceed a rate of 300 g feed/m^2/day. It is apparent that primary productivity (net approximately 10 g/m^2/day) can contribute only marginal amounts of macronutrients for fish growth. Micronutrients such as vitamins originating with the natural foods may still be significant.

The large capacity of a pond to assimilate nitrogen and phosphorus from feed reduces the local environmental nutrient load. Ponds should be managed to protect internal water quality and maximize their capacity to assimilate organic matter, nitrogen, and phosphorus.

Best management practices

Use of BMPs usually is the most economically feasible and technically practical method of reducing environment impacts in aquaculture or in agriculture in general. For example, BMPs provide a means to prevent overfeeding of fish and thus avoid excessive nutrient loading in ponds. Prevention of overfeeding reduces the environmental impact from effluents released from ponds to receiving waters (Boyd et al. 2003).

Thunjai (2002) pointed out that high soil organic matter, loss of the oxidized layer, and accumulation of soft sediments are the major concerns in bottom soil management in aquaculture. Aquaculture pond bottom soils receive large amounts of nutrients and organic matter from water inflow, eaten and uneaten feed, and fertilizer. It is generally thought that nutrients and organic matter tend to accumulate in bottom soil as pond age increases (Boyd 1992). High nutrient concentrations are not necessarily undesirable in pond soil, but large amounts of organic matter can have adverse effects by encouraging anaerobic condition. Thus, BMPs should be used to prevent excessive accumulation of organic matter in pond soils (Boyd 1995).

According to Boyd and Teichert-Coddington (1994), when ponds bottoms were dried between crops, the decomposition rate of organic matter in pond soil significantly increased. Boyd (1995) suggested that air penetrates into the cracks in the dried pond bottom enhancing oxygenation and improving the decomposition of organic matter. Oxygen supports microbial decomposition by aerobic bacteria. Seo and Boyd (2001) reported that drying and tilling ponds at Auburn, Alabama could decrease the concentration of phosphorus and nitrogen in pond water during the next crop. Thus, pond bottom dry out between crops is an excellent BMP.

Excessive accumulation of sediment in pond bottoms is undesirable. Feed pellets may sinks into soft sediment, soft sediment may result in mechanical obstruction of the gills of shrimp, and harvest is more difficult in ponds with soft bottoms (Boyd 1995). Removal of sediment from selected areas or entire bottoms of ponds was recommended as an aquaculture BMP (Wudtisin 2005).

Wudtisin (2005) stated that liming pond bottoms is one of the methods to improve bottom soils for aquaculture. According to Thunjai (2002), liming material should be applied after each crop to maintain soil pH in the range of 7 to 8. He suggested that agricultural limestone should be applied according to soil pH and total alkalinity of pond water. Soil pH below 7, and alkalinity below 50 mg/L in fresh water ponds and 80 mg/L in brackishwater ponds are indicative of the need for liming. Liming should be practiced routinely, and it also is an excellent BMP.

Pond draining and the discharge of effluents through ditches to streams can sometimes cause erosion and suspension of soil particles (Schwartz and Boyd 1994). Thus, ponds should be drained slowly to reduce water velocities and reduce the potential for erosion. Ditches should be constructed to avoid excessive water velocity and above water areas protected from erosion by grass cover or other means (Wudtisin 2005).

MATERIALS AND METHODS

The site and farm

Ponds for this study were located on a semi-intensive marine shrimp farm, Aquaculture De Mahajamba (Aqualma), located 95 km north of Majunga (Fig. 1) in Northwestern Madagascar. The farm was constructed on a tidal salines behind the mangrove tree. This area consists of clay loam and silty clay loam soils with clay contents of 30 to 40%. The farm is situated between the Masokoenja and Marovoaikely Rivers (Fig. 2). The Marovoaikely River (east side of farm) was the source of water for the culture activity, and 30% of farm effluent was discharged into this river, while the Masokoenja River received the remainder of the farm effluent. Both rivers empty into the Mahajamba Bay.

The farm was developed on a land concession of 3,800 ha. The area for grow-out ponds, nursery and broodstock ponds, reservoir canal, embankments, drains, and other land uses are provided in Table 1. Most production ponds are about 10-ha in area and 1.0-1.2 m in average depth. The farm has an unusually large area devoted to the reservoir canal. One reason is that the site is a narrow island and ponds were constructed in a long band making a lengthy reservoir canal necessary. Moreover, the water supply is quite turbid, and the canal was made especially large to provide retention time for settling of suspended soil particles. A dredge is routinely operated in the canal to remove sediment.

The Mahajamba Bay and estuary (Fig. 3) have collective estimated volume of 4.8 x 10^9 m^3 (McNevin 2004). No other shrimp farms are located on this bay, and the catchment of the bay is not the site of major agricultural of industrial activities. There are no major human population centers on the catchment.

Production methods

The farm produces black tiger prawn *P. monodon.* The grow-out ponds are stocked at 4.5-11.2/m^2. Stocking densities vary because of different target sizes at harvest for shrimp sold in different markets. Liming materials and fertilizers are used to establish phytoplankton blooms in grow-out ponds before stocking with PL stage from nursery ponds. It is noteworthy that the farm uses only farmed-reared broodstock in its hatchery, and all ponds are stocked only with hatchery-reared PL stage. Shrimp in grow-out ponds are provided a high-quality feed (42-44% crude protein). Water exchange is conducted at an average rate of about 12% of pond volume daily. Shrimp production on the farm averages about 1,800 kg/ha per crop with 2.2 crops per pond each year. In some ponds, about 50% of the volume may be discharged to facilitate partial harvests if shrimp biomass becomes too high near the end of crops. Water levels are restored following partial harvests. All ponds are completely drained for harvest. The bottoms of empty ponds are allowed to dry, sediment is removed manually from internal drainage canals, liming material is spread over from bottoms, and soil is tilled to a depth of 15 cm with a tractor-drawn, disk harrow. The fallow period between crops usually is 2-3 weeks. The farm has been in operation since 1995 and has consistently produced about 3,000 tonnes of shrimp per year.

Study ponds

Three ponds ranging from 9.82 to 10.00 ha in water surface area and 1.01 to 1.11 m in average depth (Table 2) were selected for determination of quantities of nitrogen, phosphorus, organic carbon, and BOD_5 in their effluents. Two ponds (G74 and G75) were relatively new, having been used previously for three crops. The other pond (G09) had been used for 20 crops.

Seventeen additional ponds were selected and used in the investigation of soil quality. These ponds and ponds G09, G74, and G75 represented the range of fertilizer, feed, and lime inputs for ponds on the farm. Records of all inputs to ponds were available for use in this study.

Nutrient, organic carbon, and BOD_5 budgets

Water samples were taken from ponds immediately after filling, and samples of inflow and outflow were collected weekly from each pond. When ponds were drained for harvest, water samples were collected at midpoints of successive 20% volume increments during drawdown. Water samples for total phosphorus and total nitrogen analyses were subjected to sulfuric acid-potassium persulfate oxidation as described by Gross and Boyd (1998). Phosphate in the digestates was measured by the ascorbic aid method (Clesceri et al. 1998). Nitrate in the digestates was determined by the ultraviolet spectrophotometric method (Gross et al. 1999). The 5-day biochemical oxygen demand (BOD_5) analyses were conducted by the direct method without sample dilution or bacteria and nutrient enhancement as described by Xinglong and Boyd (2005). Dissolved oxygen in BOD_5 tests was measured with YSI Model 52 bench top dissolved oxygen meter with stirring, BOD-bottle probe (YSI, Yellow Springs, OH, USA). Organic matter was analyzed using the sulfuric acid-potassium dichromate, heat-of-dilution method described by Ruttanagosrigit and Boyd (1989).

The amounts of water used for filling ponds were estimated from average depths and water surface areas. Inflow and outflow during water exchange were estimated by solving weir equations for the depths of water passing over inflow and outflow structures (Yoo and Boyd 1994). Volumes of water released during different stages of draining were estimated from the pond depth-volume relationship.

The farm laboratory was not equipped for conducting chlorophyll a analyses or measuring primary productivity. Thus, the amount of organic carbon fixed by gross primary productivity was estimated from data provided in a previous study Boyd (1973).

Nutrient inputs in shrimp stocked, fertilizer, and feed and nutrient outputs in harvested shrimp were estimated from the quantities of these variables applied to or removed from ponds (farm records) multiplied by the respective nutrient concentrations. Feed and fertilizer samples were collected and shipped to Auburn University for analyses. Concentrations of phosphorus and nitrogen in fertilizers were determined at the State Chemical Laboratory, Alabama Department of Agriculture and Industries, Auburn, Alabama. Feed samples were dry-ashed at 450 ^{o}C for 8 h in a muffle furnace, the ash was taken up in 1.00 N nitric acid, and the extract was passed though a Whatman number 40 filter paper (Anonymous 1974). Phosphorus in the filtered extracts was measured by the vanadomolybdophosphoric acid yellow color method (Jackson 1958). The concentration of nitrogen in feed was determined with a Leco Nitrogen Analyser Model FP-2000 (Leco, St. Joseph, Michigan, USA) at the U.S. Agricultural Research Service, Aquatic Animal

Health Research Unit, Auburn, Alabama. Concentrations of phosphorus, nitrogen, and organic carbon in shrimp from the farm were obtained from an earlier study (Gomes and Boyd 2003).

Budgets were constructed for total nitrogen, total phosphorus, organic carbon, and BOD_5 in which inputs and outputs were totaled separately. The quantity (kg) of a variable (X) in effluent that resulted from aquaculture loads activities was estimated as follows:

$$\text{Aquaculture load}_X = \text{Outflow burden}_X - \text{Inflow burden}_X.$$

The amounts of variables that were lost from the system in gaseous form though physical, chemical and biological processes or stored in the sediment could not be determined separately in the budgets. However, the amounts of a variable that could not be accounted for in the budget was either lost from the pond as a gas or stored in the bottom. This quantity was termed pond assimilation, and it was calculated by the equation:

$$\text{Pond assimilation}_X = \text{Input}_X - \text{Output}_X.$$

Soil sampling and analyses

Three types of soil samples were obtained from ponds G09, G74, and G75 at the beginning of the crop on the day after stocking and at the end of the crop on the day before final harvest. Cores of 30-cm length were taken at three places in each pond (Fig. 4). At each place, three cores were taken to secure an adequate quantity of soil for analyses. Workers waded into the ponds to places about 80 cm to 100 cm deep. They inserted 5-cm diameter, clear plastic, core liner tubes (Wildlife Supply Company, Buffalo, New York USA) into the bottoms. A wooden mallet was used to hammer the tubes downward to a depth of 35 to 40 cm. The top of tubes were beneath the water, and they were sealed with plastic caps. Tubes were carefully withdrawn from the soil, and the bottoms also were capped. Tubes were held upright during transport to a work area where water was siphoned from tubes and the cores pressed upward with a core removal tool. A 2-cm core ring was placed on the upper end of the core liner, and segment was pushed upward into the ring (Munsiri et al. 1995). A wide spatula was inserted between the top of the core liner tube and the core ring to cut off the 2-cm core segment. This process was repeated to remove consecutive, 2-cm-long core segments from the upper 30-cm portion of the core. Core segments from the three cores at each location were combined to assure enough soil for analyses.

Samples were collected from one of the two internal drainage areas and the central mesa of each pond (Fig. 5). The samples were taken with 5-cm diameter core liner tubes as described above, but the tube was only inserted to a depth of 10 to 15 cm. A 5-cm core ring was used to obtain a 5-cm core segment. Core segments were combined to provide a composite sample from the drainage area and one from the central mesa for each pond.

Three composite samples from the upper 5-cm layer of each pond bottom also were collected to provide a representation of the entire bottom (Fig. 6). The same methodology described above was used to secure the samples.

Soil samples were dried at 60 ^{o}C in a forced air draft oven. They were placed in plastic bags and shipped to Auburn University. A soil crusher (Custom Laboratory

Equipment Company, Inc., Orange City, Florida, USA) was used to pulverize the samples. The samples were then sieved though a 40-mesh (0.425 mm) sieve.

Soil pH was measured with a glass electrode in 1:1 soil-distilled water mixtures (Thunjai et al. 2001). Free carbonates were measured by digesting soil samples in 1.00 N hydrochloric acid and measuring amounts of carbon dioxide evolved (Jackson 1958). The calcium carbonate equivalent of the carbon dioxide was estimated. Total nitrogen concentration was determined with a Leco Model FP-2000 nitrogen analyzer (Leco, St. Joseph, Michigan USA). Soil phosphorus analyses were conducted by placing 1.00 g of dry soil in a 125-ml Erlenmeyer flask and extracting for 1 hour on an oscillating plateform shaker (150 oscillations/min). The extract was passed though a Whatman Number 40 filter paper, and phosphate was measured by the ascorbic acid procedure (Boyd and Tucker 1992). The concentration of organic carbon in soil was determined by sulfuric acid-potassium dichromate oxidation according to the Walkley-Black method (Nelson and Sommers 1982).

Data analysis

Data were computer analyzed by t-test, analysis of variance, histogram, contrast, and simple linear regression. The statistics packages Sigma Plot 8.0 and Sigma Stat 2.1 were used (SPSS 1997). To analyze data different means were declared significant at alpha level 0.1 unless otherwise indicated.

RESULTS

Salinity, temperature, and dissolved oxygen

This study was initiated at the beginning of the rainy season. Salinity in ponds was slightly above 20 ppt at the beginning of the study, but steadily declined to about 5 ppt (Table 3; Fig. 7). This was the result of rainfall and freshwater inflow into the estuary causing the salinity of the source water to decline. Beginning at week 19 of the study, salinity began to increase because of less rainfall and freshwater inflow at the end of the rainy season. The black tiger prawn grows well within this range of salinity (Lester and Pante 1992).

The rainy season also was a period of high air temperature and warm surface water. Pond water temperature ranged from about 28.5 ^{o}C to 31.9 ^{o}C during the crop (Table 3; Fig. 8). This temperature is ideal for rapid growth of black tiger prawn (Lester and Pante 1992).

Dissolved oxygen concentrations in pond waters were maintained above 3.5 mg/L throughout the study by heavy water exchange (Table 3; Figure 9). Thus, the minimum dissolved oxygen concentrations in the ponds were above 50% of saturation and high enough that shrimp did not experience conditions bringing about stress (Boyd and Tucker 1998). The high water exchange rate also flushed ammonia, carbon dioxide, and other metabolic wastes from ponds.

Budgets

Data on inputs of water, PL stage, fertilizer, lime, and feed and outputs of water and shrimp for the three ponds are provided in Table 4. The composition of fertilizer, liming material, feed, and shrimp are provided in Table 5.

Means for total nitrogen, total phosphorus, organic carbon, and BOD_5 (Table 6) reveal that concentrations of these variables were greater in pond outflow than in pond inflow. The increase in concentration of these variable resulted from aquaculture activities. The total nitrogen concentrations require explanation, because they are relatively high even in the incoming water. The ultraviolet spectrophotometric screening method for measuring total nitrogen in water (Gross et al. 1999) was found to consistently give erroneously high results (McNevin 2004). Nevertheless, the error was systematic for all samples, and the differences in total nitrogen between inflow and outflow of ponds are therefore reliable. The desirability of adopting a new method for total nitrogen was discussed with the farm management. The response was that the farm was in a remote place and acquisition of new instruments, reagents, and other items require many months. Thus, it was not possible (during the study) to change the method of total nitrogen analysis.

Data on inputs, outputs, and concentration of variables were used to estimate aquaculture loads and pond assimilation of total nitrogen (Table 7), total phosphorus (Table 8), organic carbon (Table 9), and BOD_5 (Table 10). The differences in inputs and outputs represent the amount of each variable transformed to gaseous form by process within the pond, e.g., ammonia volatilization, denitrification, respiration and carbon dioxide evolution, etc., or adsorbed by or deposited in bottom soils (pond assimilation).

The nutrient load to the environment caused by aquaculture activities in the ponds is the reason for increase in amounts of variables discharged in effluents relative to the amounts of these variables introduced to ponds in inflow to fill ponds, maintain water levels, and conduct water exchange (aquaculture loads).

Soils

Core samples clearly show that concentrations of total nitrogen (Fig. 10), available phosphorus (Fig. 11), organic carbon (Fig. 12), and calcium carbonate (Fig. 13) were concentrated in the upper 10-cm bottom soil layer. This resulted from aquaculture inputs and of mixing of the upper 10-cm soil by layer tilling between crops. Soil pH also was distinctly greater in the upper 10 to 15-cm soil layer (Fig. 14). Results from core samples did not clearly reveal changes in concentrations of the soil variables between the beginning and end of the crop. However, the findings suggest that sampling to evaluate changes in bottom soil quality variables associated with aquaculture should focus on the upper 10 to 15 cm layer.

A comparison of concentrations of measured soil variables in the drain sections and central areas of the study ponds (Fig.15) revealed only one difference ($P < 0.05$). This difference was for the total nitrogen in pond G75. A number of comparisons were different at $P = 0.1$ and 0.2. This suggests that bottom samples should be collected in a manner that results in samples which are descriptive entire pond bottom. Such samples can be obtained by the sampling scheme outlined in Fig. 6.

When samples over the entire pond bottom were considered, total nitrogen, available phosphorus, and calcium carbonate usually increased ($P < 0.05$) during the crop cycle (Fig. 16). Organic carbon decreased in G74, increased in G75, but did not differ between the beginning and end of the crop in G09. There were no significant changes in pH during the crop (Fig. 16).

A fairly wide range in concentration of each measured variable was obtained for the set of twenty ponds (Fig. 17). The soil concentrations (Y) were regressed versus total cumulative inputs of each variable to individual ponds. Total nitrogen concentration increased with nitrogen input into ponds in feed and fertilizer ($R^2 = 0.199$; $P = 0.049$). There was no correlations between soil concentrations and inputs for phosphorus ($R^2 = 0.028$; $P = 0.482$), organic carbon ($R^2 = 0.034$; $P = 0.437$), or calcium carbonate ($R^2 = 0.018$; $P = 0.567$). Moreover, soil pH was not correlated with input of liming material ($R^2 = 0.001$; $P = 0.911$).

DISCUSSION

Water quality in ponds G09, G74, and G75 was adequate for good shrimp growth throughout the study, and shrimp production ranged from 1,700 to 2,320 kg/ha with mean of 2,089 kg/ha. Water exchange for the ponds varied from 8.4 to 12.9% of pond volume with an average of 10.7%. This is the reason that adequate concentrations of dissolved oxygen were maintained in these ponds despite production being higher than normally achieved in semi-intensive culture without mechanical aeration. In semi-intensive shrimp ponds without water exchange, shrimp production usually is 1,000 to 1,500 kg/ha per crop (Boyd and Tucker 1998).

Ponds are constructed and used to provide somewhat controlled environment for culture of aquatic organisms. However, only10-20% of the space and water actually is necessary for the animals. The remaining 80 to 90% of the space and water in ponds serves primarily for nutrient assimilation water treatment (Boyd et al. 2007). Natural treatment is provided through bacterial decomposition of organic matter, nitrification of ammonia to nitrate, denitrification nitrate to nitrogen gas, and loss of carbon dioxide, gaseous nitrogen, un-ionized ammonia, and methane to the atmosphere. Organic matter containing nitrogen and phosphorus accumulates on the pond bottom, and bottom soil at this site strongly adsorbs phosphorus from water. Water exchange improves water quality in ponds, but it flushes out nutrients before they can be assimilated by natural processes, Water exchange transfers the process of natural assimilation from the pond to the outside environment. This allows ponds to produce a greater biomass of the culture species, but it increases the potential for eutrophication in waters receiving pond effluents.

Nitrogen

As mentioned in the results section, the total nitrogen concentrations in inputs and outputs of water were erroneously and systematically high, but the differences were accurated. For this reason, the total inputs and total outputs of nitrogen in water are overestimates, but become of the systematic nature of the error, these discrepancies do not influence the veracity of the estimates of effluent nitrogen loads or nitrogen assimilation by ponds.

Feed was a much greater source of nitrogen than urea, and only a small amount of nitrogen was introduced in PL stage (Table 7). The amount of harvested nitrogen in shrimp (641.6 kg) was 18.7% of that added in urea, feed, and PL stage, and 22.6% of the nitrogen input in feed input alone. The amount of nitrogen lost through ammonia volatilization and denitrification plus that contained in organic matter accumulated in soil was 2,351.1 kg (236.5 kg/ha). The total nitrogen load in pond effluent resulting from aquaculture was 433.1 kg (43.57 kg/ha).

Phosphorus

Feed was by far the largest input of phosphorus to the ponds, accounting for about three times as much phosphorus as found in inflowing water (Table 8). The amount of phosphorus added in triple superphosphate fertilizer and shrimp PL stage was quite small. The removal of phosphorus from ponds in effluent was about ten fold greater than the amount of phosphorus in harvested shrimp. Phosphorus removal in shrimp was 6.15% of total phosphorus input, 7.7% of phosphorus added in triplesuperphosphate, feed, and PL stage, and 8.4% of feed phosphorus alone.

The recovery of applied phosphorus in harvested shrimp was much less than the recovery of applied nitrogen. In fish culture, however, the recovery of these two elements is typically about equal (Boyd and Tucker 1998). The reason for this difference is that fish contain bones composed of calcium phosphate while shrimp do not have bones. The percentage phosphorus in live fish usually is about 0.5-0.75% (Boyd et al. 2007) while live *P. monodon* contained only 0.26% phosphorus (Table 5). Another reason for low nutrient recovery; shrimp molts frequently and molted shell also contain P, N etc. Even it is impossible to deter mine this, it is worth while to discuss.

Increased phosphorus concentration in natural waters usually is more important than increased nitrogen concentration as a cause of eutrophication (Wetzel 2001). Thus, on a unit of production basis, shrimp farms have a greater potential than fish farms for causing eutrophication in receiving waters.

Phosphorus is not lost to the atmosphere though chemical, physical, or biological process as is nitrogen. Phosphorus applied to pond and not discharged in effluent or harvested in shrimp will be sequestered in the pond bottom (Boyd 1995). The phosphorus retained in soil may be adsorbed by the soil, bound in iron, aluminum, or calcium phosphates, or contained in soil organic matter. Phosphorus uptake by bottom soil during the crop was 36.6% of the total phosphorus input, 48.2% of phosphorus added in fertilizer, feed, and PL stage, and 49.8% of that applied in feed alone. The total amount adsorbed (321.8 kg) was equivalent to 32.4 kg/ha.

It is interesting to note that in channel catfish ponds without water exchange in which effluent resulted only from heavy rainfall and pond drainage for harvest, about 67% of feed phosphorus was adsorbed by bottom soil (Boyd 1985). This difference between ponds with water exchange and static ponds illustrates that water exchange increases the pollution potential of pond aquaculture of shrimp.

Effluents from the ponds contained 287.8 kg phosphorus attributable to aquaculture. This is equal to 29.0 kg/ha.

Organic carbon

The largest input of organic carbon was organic matter production through photosynthesis by phytoplankton in pond water (Table 9). Although this finding is logical and can be supported by results of previous studies (Boyd and Tucker 1998), the selection of the value for gross carbon fixation in the ponds requires justification. It was impossible to measure chlorophyll a concentration or gross primary productivity at the farm in order to assess phytoplankton abundance or carbon fixation rate. The Secchi disk visibility in ponds of this study typically ranged from 25 to 40 cm. This is similar to Secchi disk visibility in channel catfish ponds that had an average gross primary productivity of 2.55 g carbon/m^2 per day (Boyd 1973). As Secchi disk visibility in aquaculture ponds usually results largely from turbidity caused by plankton in the watercolumn, it was assumed that the photosynthetic rate in the ponds of the present study were similar to those reported by Boyd (1973).

Feed also was a major input of organic carbon accounting for slightly more than half of the estimated input by photosynthesis (Table 9). Inflowing water was the source of about 10% the total organic carbon input, while less than 1% of the input was from PL stage.

The amount of organic carbon harvested in shrimp was 3.7% of the total carbon input, 4.1% of organic carbon input in feed, photosynthesis, and PL stage, and 12.2% of organic carbon input in feed alone.

The discharge of organic carbon in effluent was much less than the amount of organic carbon entering the ponds suggesting that much organic carbon was transformed to inorganic carbon, in carbon dioxide, by respiration by plankton, shrimp, and bacteria, converted to methane by methane bacteria and lost to the air, or stored in the pond bottom as soil organic matter. This fraction was 80.5% of the total carbon input. The amount of organic carbon in effluent attributable to aquaculture was 3,967 kg per pond (399.1kg/ha).

Biochemical oxygen demand

The concentration of BOD_5, rather than the concentration of organic carbon, normally is used as a measure of potential oxygen demand that will be exerted by effluent in receiving waters (Boyd and Tucker 1998). In this study, it was not possible to isolate and quantity the source of BOD_5. However, the difference in BOD_5 between inflow and outflow of ponds revealed that ponds discharged 7,994 kg (804 kg/ha) of BOD_5 that can be attributed to shrimp culture.

The organic carbon load was about 50% of the BOD_5 load. Oxidation of organic carbon to carbon dioxide can be expressed as:

$$\text{Organic C} + O_2 = CO_2.$$

Based on the stiochiometric relationship in the above equation, 32 g oxygen are needed to oxidize 12 g of organic carbon, or 1 mg/L organic carbon has an oxygen demand of 2.67 mg/L. The fact that oxygen demand of organic carbon is 2.67 times its concentration suggests that the total biochemical oxygen demand (BOD) should be 2.67 greater than the organic carbon concentration. However, the BOD_5 or 5-day BOD usually represent only about two-thirds of the total oxygen demand of organic matter because a much longer incubation time would be required for measuring the total BOD (Boyd and Tucker 1998). In this study, the estimate of 804 kg/ha BOD_5 is 75.4% of the theoretical total BOD loads of 1,066 kg/ha (399.1 kg organic x 2.67). Thus, the measured BOD_5 load agrees reasonably well with the theoretically expected load based on organic carbon.

Inferences from soil analyses

The amount of nitrogen lost from ponds in gaseous form (NH_3 and N_2) and stored in soil organic matter was estimated at 2,351.1 kg/pond (236.5 kg/ha) (Table 7). Soil samples were taken before the bottoms dried thoroughly. The dry bulk density of soil in the upper 5-cm layer averaged 0.5 g/cm^3 (0.5 tonne/m^3) at time of sampling. The 0-1.5-cm layer weighed 250 tonnes/ha (250,000 kg, and an input of 236.5 kg (236,500,000 mg) of nitrogen should increase its total nitrogen concentration by 946 mg/kg. The measured increase in soil nitrogen was 310 mg/L (Fig. 16). The other two-third of the difference represented nitrogen lost to the air through ammonia volatilization or denitrification.

Following the approach used for nitrogen, the estimated amount of phosphorus added to the soil (Table 8) would cause an increase in soil phosphorus of 129.6 mg/kg. The measured increase in phosphorus concentration of the upper 5-cm layer was 165 mg/kg (Fig. 15). Thus, the estimated and measured phosphorus uptake by the soil layer agree reasonably well.

The organic carbon budget (Table 9) suggests that an increase of up to 22,484 mg/kg (2.24%) of organic carbon might occur. However, the measured concentrations of carbon (Fig. 16) revealed a decrease in G74, a slight increase in G75, and no change in G09 (actually a numerically, but statistically insignificant decrease). This lack of clear increase in bottom soil organic carbon suggests that the large difference between the inputs and outputs of carbon is the result of carbon used in respiration by the pond biota. The finding is not surprising because Munsiri et al. (1995) presented data showing that bottom soil organic carbon concentration in aquaculture pond soils reaches an equilibrium within 1-2 years. Afterward, if the input of organic carbon and pond management procedures remain about the same, soil organic carbon concentrations remain rather constant.

The input of lime to ponds was equivalent to 1,385 kg $CaCO_3$/ha (1,108 kg lime/ha x 1.25). If all this lime accumulated in the soil, the calcium carbonate concentration of the soil should increase by 5,540 mg/kg (0.55%). The measured increase in pond G09 was about 0.6% while in pond G74, the increase was about 0.35% (Fig. 16). There was no increase in calcium carbonate in pond G75.

The soil study revealed considerable variation within and between ponds associated with area location and depth of samples. There was no strong tendency of increasing concentrations of nitrogen, phosphorus, and organic carbon caused by cumulative management inputs in older ponds. Soil pH was within an acceptable range as a result of liming, but soil pH was not increased in older ponds.

Daily water exchange, draining for harvest, removed of sediment from drainage sections after each crop, and drying to stimulate aerobic decomposition has minimized the accumulation of nutrients and organic matter in pond soils. Liming has neutralized acidity, and tilling has mixed the soil to avoid excessive accumulation of liming material and associated high pH near the soil surface.

Study of pond bottom soil quality requires a large effort for sampling, analyses, and data interpretation. It seems more reasonable to develop budgets of inputs and outputs of management variables in aquaculture production facilities, and estimate the assimilation and uptake by bottom soils.

Pollution potential of farm

All grow-out ponds on the farm are operated in basically the same manner as the three study ponds, and the farm averages 2.2 crops of shrimp per pond each year. Thus, the average aquaculture loads given in Table 11 (nitrogen, 43.6 kg/ha; phosphorus, 29.0 kg/ha; organic carbon, 399 kg/ha; BOD_5, 804 kg/ha) can be multiplied by 1,507 ha/year (685 ha production ponds x 2.2 crops/year) to estimate the loads of these potential pollutants released into the Mahajamba Bay system by the farm. The resulting annual quantities are 65,702 kg nitrogen, 43,704 kg phosphorus, 601,293 kg organic carbon, and 1,211,628 kg BOD_5.

The Mahajamba Bay system has a volume 4.8 x 10^9 m^3 (McNevin 2004). If the entire aquaculture load of these variables was released in a single dose and thoroughly mixed with the water of the bay system, concentration increases would be 0.0136 mg/L nitrogen, 0.091 mg/L phosphorus, 0.125 mg/L organic carbon, and 0.252 mg/L BOD_5. These are small concentrations, and the daily additions are much less. The bay system assimilates these substances by the same physical, chemical, and biological processes that have been described above as operating in ponds. There also is considerable flushing of the bay by tidal action and by freshwater during the rainy season. It seems highly unlikely that the shrimp farm is a serious pollution treat to the bay. A water quality monitoring effort of the bay by McNevin (2004) suggested that the bay system was not becoming eutrophic. Moreover, the study by McNevin did not reveal general on point pollution problems in the mixing zone where farm effluents enter the bay.

Shrimp farms and other types of aquaculture operations are not all isolated facilities, discharging into a large, well-flushed bay. Sometime farms discharge into small, relatively-closed water bodies or many farms discharge into a common water body. There also may be other sources of pollution to the same water into which aquaculture facilities discharge. Facilities operate at different production intensities, and estimating pollution loads on an area as done here may be misleading.

Resource use efficiency and waste generation

There has been much discussion about resource use in shrimp farming and other types of ponds in aquaculture. However, there is relatively little data from actual aquaculture operations for which thoroughly evaluate this issue. The same also may be said for waste generation by aquaculture in general.

Boyd et al. (2007) suggested a series of indicators for assessing the efficiency of resource use and the amount of waste generated by aquaculture. It is of interest to use data from the present study to quantify the indicator.

Feed use

The feed conversion ratio (FCR) is the weight of feed divided by net production of the aquaculture species. The average FCR for shrimp culture in the three ponds was 2.067. Thus, it required 2,067 kg of feed to achieve a net production of 1 tonne of shrimp.

The dry matter ratio (DMR) is an indicator of efficiency with which nutrients in feed are converted to animal biomass:

$$\text{DMR} = \text{FCR} \times \frac{\%\,\text{DM in feed}}{\%\,\text{DM in culturespecies}}.$$

Black tiger prawn had an average dry matter concentration of 27.1%, and the feed was about 10% moisture. The value of DMR was 6.86 indicating that 6,860 kg dry matter of feed would be needed to produce 1 tonne dry matter of shrimp.

The waste production ratio (WPR) is the ratio of the waste generated to the net production of live weight of the cultured species:

$$\text{WPR} = (\text{DMR} - 1) \times \frac{\%\,\text{DM in culture species}}{100}.$$

The WPR for shrimp production at Aqualma was 1.59. This means that 1,590 kg waste (dry weight) would result from the production of 1 tonne of live shrimp.

The protein recovery ratio (PRR) is the weight of feed crude protein necessary to produce a unit of shrimp biomass. It is estimated as:

$$\text{PRR} = \text{FCR} \times \frac{\%\,\text{Feed protein}}{100}.$$

The feed used in study ponds has a crude protein concentration of 43.94%. Thus, PRR was 0.908, or it required 908 kg feed crude protein to produce 1 tonne of shrimp.

The protein efficiency ratio (PER) is a index of the recovery of feed crude protein as crude protein in the culture species:

$$\text{PER} = \text{FCR} \times \frac{\%\,\text{Feed protein}}{\%\,\text{Protein in culture species}}.$$

The feed contained 43.94% crude protein and the culture species contained 19.31% crude protein. The PER for this shrimp cultured in the study ponds was 4.703. It required 4,703 kg of feed crude protein to produce 1 tonne of crude protein in shrimp.

The fish meal ratio (FMR) is the ratio of fish meal in feed to production of the culture species:

$$\text{FMR} = \text{FCR} \times \frac{\%\,\text{Fish meal in feed}}{100}.$$

For the present study, feed contained 32.5% fish meal and the FMR was 0.672. It took 672 kg fish meal in feed to produce 1 tonne of shrimp.

The conversion of live fish to marine fish meal is about 4.5 to 1 (Boyd et al. 2007). The live fish equivalence (LFE) of fish meal in feed may be estimated as:

$$\text{LFE} = \text{FMR} \times 4.5.$$

Substituting the FMR of 0.672 into the equation reveals a LFE of 3.02. Thus, 3.02 tonnes of live fish were used to make the fish meal needed in feed to produced 1 tonne of shrimp. This statistic shows that for Aqualma the amount of live fish used to make fish meal for the shrimp feed is three times greater than the quantity of shrimp produced. Both aquacultured shrimp and marine fish used to make fish meal are included in FAO estimates of world fisheries production. In aquaculture, if the use of wild fish to make fish meal for feed exceeds the production of a species, a decrease in world fisheries production results. Of course, one may argue that per tonne some catch fishery species eat as much or more wild fish than used in feed for aquaculture species. In the case of wild shrimp, this argument cannot be made, for shrimp do not eat wild fish. Moreover, for piscivorous species the argument in meaningless, because wild fish consumed by other wild fish are not included in the FAO statistics.

Water use

According to Boyd (2005), use of brackishwater or sea water is not a consumptive water use. Nevertheless, water had to be pumped from the estuary into the farm water supply system, and this required energy. Because of the high water exchange rate, 90,855 m^3 of water were required to produce 1 tonne of shrimp. The discharge of effluent was slightly less, 90,348 m^3/tonne, but energy was not required to discharge the water.

The reason for the slightly smaller discharge than inflow was related to the balance between rain falling directly into ponds, pond evaporation, and seepage from ponds. However, this difference was not subjected to analysis because the estimation of seepage and evaporation was not a study objective.

Land use

Data on land use (Table 1) reveals that the farm water surface and associated infrastructure occupies 1,175 ha of which 685 ha are in production, and grow out ponds. Thus, 0.715 ha of additional land is necessary for each hectare of water surface area for grow out of shrimp. Moreover, land was needed to produce plant meal used in shrimp feed. The shrimp feed contained about 15% soybean meal and 25% wheat middlings. Wheat middlings are a by-product, but land must be dedicated to soybean meal production. According to Boyd et al. (2007), average soybean meal yield is 2,231 kg/ha in the United States. The land requirement for soybean meal is:

$$\text{Land requirement, ha/t} = \frac{(\%\,\text{ingredient}/100)(\text{FCR})\,(1{,}000\,\text{kg animals})}{\text{Meal yield, kg/ha}}.$$

Thus, the feed needed to produce 1 tonne of shrimp would contain the soybean meal from 0.139 ha.

Average production for the study ponds was 2,089 kg for each hectare of water surface area. Another 0.715 ha of land was necessary for infrastructure to support each hectare of grow-out, water surface area. It follows that each tonne of production required 0.82 ha on the farm. An additional 0.13 ha was required for the soybean meal for the feed for 1 tonne of shrimp. The total land used to produce 1 tonne of shrimp at Aqualma was 0.96 ha/tonne. Of course, both the coastal land devoted to ponds and the agricultural land needed to produce plant meals for shrimp feed can be used over and over again.

Nutrients

The inputs of nitrogen and phosphorus to the study ponds in fertilizer and feed were 340.9 kg/ha (Table 7) and 66.4 kg/ha (Table 8), respectively. Nitrogen and phosphorus use was 163.2 kg/tonne and 31.8 kg/tonne, respectively. The percentage material recovery in shrimp was 18.9% for nitrogen and 8.2% for phosphorus.

Lime use can be expressed as the calcium carbonate index (Boyd et al. 2007). The equation for calculating this index is:

$$\text{CaCO}_3\text{ index, kg/t} = \frac{\text{Liming material, kg} \times \dfrac{\%\,\text{NV}}{100}}{\text{Production, t}}\,.$$

NV = Neutralizing value

Lime used averaged 1,111 kg/ha, and the material had a neutralizing value of 125%. The $CaCO_3$ index was 664.8 kg/tonne.

Energy use

The use of energy in aquaculture is important, but little information has been collected about this variable. At Aqualma , mechanical aeration was not used, and the major energy cost was pumping water. A total of 90,855 m^3 of water was used per tonne of shrimp. Assuming that the pumps operated 12 hr per day to effect water exchange, the pumping time for the average crop period was 1,848 hr. This would be a discharge of 0.0137 m^3/sec for each tonne of shrimp. The pump power can be calculated as:

$$P = \frac{\gamma QH}{E}\ .$$

where P = power required by pump (kW), γ = specific weight of water (9.81 k N/m^3), Q = discharge (0.0137 m^3/sec), H = pumping head (3 m), and E = pump efficiency (0.85). Substitution into the equation gives P = 0.47 kW. The pump operated 1,848 hr, so the energy use for pumping was 868.8 kW·hr/tonne.

Waste loads

The waste loads were calculated already (Table 11). They were 13.8 kg phosphorus/tonne, 20.4 kg nitrogen/tonne, 380.3 kg BOD_5/tonne, and 192.6 kg organic carbon/tonne.

It is interesting to put the waste loads in terms of human population equivalents. According to Tchobanoglous et al. (2003), humans in developing countries contribute 18,469 g BOD_5/year, 3,614 g nitrogen/year, and 201 g phosphorus/year to waste water. The production of 1 tonne of shrimp at Aqualma produced waste equivalent to the annual contribution of 20.6 people for BOD_5, 68.6 people for phosphorus, and 54.1 people for nitrogen. The entire farm produces about 3,000 tonne shrimp/year. Thus, depending upon the variable chosen, the farm has an annual pollution load equivalent to 61,800 to 205,800 people.

The waste load appears rather large when express in human population equivalents. But, the average person in the United States eats 1.54 kg of shrimp per year (Annonymous 2004), and the farm produces enough shrimp for nearly 2,000,000 people.

Boyd et al. (2007) provided estimates of resource use efficiency and waste production for pond culture of channel catfish, cage culture of tilapia, and raceway culture of trout. These estimates were based on average FCRs, production rates, and inputs rather than actual farm data, but they allow a rough comparison with black tiger prawn production at Aqualma (Table 12). It is obvious from data in Table 12 that pond culture of black tiger prawn uses more protein, fish meal, water, and land than the other three species and production system. However, waste production by black tiger prawn in ponds with water exchange is not much greater than for cage culture of tilapia or raceway culture of trout. Culture of channel catfish in static ponds generates much less wastes than pond culture of black tiger prawn or the other two species.

Although the present study suggests that production of shrimp by aquaculture consumes considerable resources and generates pollution, shrimp fishing also has negative impacts. According to Wikipedia (http://en.wikipedia.org/wiki/Trawling), shrimp are fished mainly by trawling. In trawling, a net is pulled through the water or dragged across the sea bed to capture fish, shrimp, and other organisms. Trawl nets may be non-selective, capturing both marketable and undesirable species of both legal and illegal sizes. The part of the catch that cannot be used is called the bi-catch. The bi-catch is thrown overboard, and most of the organisms die. Shrimp trawling has a particularly large bi-catch often 10-15 times greater than the weight of the shrimp captured. The destruction of sea turtles in the bi-catch of shrimp trawling has been a particularly contentious issue. Trawls with turtle exclusion devices (TEDs) are available, but they are not employed in many nations.

Shrimp trawling involves towing nets over the seabed at a speed of several miles per hour. This action creates furrows in the seabed, it turns over rocks and other structure, and it destroys benthic organisms.

Shrimp fisheries in many regions of the world have been over exploited. This results in an increase in fishing effort with greater negative effects on the seabed and more energy use for boat operations.

Shrimp farming and other types of aquaculture have negative environmental impacts as discussed above. However, there is a growing opinion among both the environmental and scientific communities that aquaculture is less harmful to the environment than fishing (Clay 2004). Moreover, many of the negative impacts of aquaculture can be lessened or prevented through application of good management practices.

Table 1. Use of land conceded to the shrimp farm.

Land use	Area (ha)
Ponds	
- Grow-out	685
- Nursery and broodstock	115
Reservoir canals	250
Embankments	50
Drains	50
Other land uses (pumping station, work shop, offices, living quarters, staging area, recreational area, etc.)	25
Protected mangrove forest	2,625
Total	3,800

Table 2. Features of ponds used in study.

Variable	Ponds			Average ± SD
	G09	G74	G75	
Water surface area (ha)	9.82	10.00	10.00	9.94 ± 0.103
Average water depth (m)	1.05	1.01	1.11	1.057 ± 0.050
Water volume (m^3)	103,100	101,000	111,000	105,033 ± 5,273

Table 3. Averages and standard deviations (SD) of water quality and water exchange rate data for three shrimp ponds.

Variable	Ponds G09	 G74	 G75	Average ± SD
Dissolved oxygen (mg/L)				
Minimum	4.0	3.6	3.6	3.7 ± 0.2
Average	7.8	6.8	7.3	7.3 ± 0.5
Maximum	14.6	10.0	11.0	11.9 ± 2.4
Water temperature (^oC)				
Minimum	28.5	28.5	28.5	28.5 ± 0.0
Average	30.7	30.7	30.7	30.7 ± 0.0
Maximum	31.9	31.1	31.9	31.6 ± 0.5
Salinity (ppt)				
Minimum	2.8	7.2	4.5	4.8 ± 2.2
Average	17.6	14.9	19.7	17.4 ± 2.4
Maximum	35.0	32.0	36.5	34.5 ± 2.3
Weekly water exchange (% pond volume)				
Minimum	1.7	0.5	1.9	1.4 ± 0.8
Average	11.0	10.2	13.3	11.5 ± 1.6
Maximum	26.1	26.3	36.5	29.6 ± 5.9

Table 4. Averages and standard deviations (SD) of management inputs and outputs for three study ponds.

Variable	Ponds			Average ± SD
	G09	G74	G75	
Inputs				
Water (m^3)	1,949,128	1,297,345	2,412,585	1,886,353 ± 560,263
Triple superphosphate (kg)	73	68	65	69 ± 4.0
Urea (kg)	1,300	1,200	1,150	1,217 ± 76.4
Lime (kg)	13,290	8,580	11,250	11,040 ± 2,362.0
Shrimp PL stage (kg)	1,463	577	1,592	1,211 ± 552.5
Feed (kg)	44,445	31,580	45,200	40,408 ± 7,654.9
Crop length (days)	163	139	160	154 ± 13.07
Outputs				
Shrimp (kg)	22,778	16,995	22,514	20,762 ± 3265.3
Effluent (m^3)	1,938,777	1,287,245	2,401,485	1,875,836 ± 559,780

Table 5. Carbon, nitrogen, and phosphorus of shrimp feed, fertilizer, lime, and shrimp.

Variable	Carbon (%)	Nitrogen (%)	Phosphorus (%)
Urea	20	45	-
Triple superphosphate	0	-	20.10
Feed	52.1	7.03	1.60
Shrimp	12.4	3.09	0.26
Lime, $Ca(OH)_2$ [1]	0.0	0.0	0.0

[1] Neutralizing value = 125%

Table 6. Averages and standard deviations(SD) for concentrations of total nitrogen (TN), total phosphorus (TP), organic carbon (OC), and 5-day biochemical demand (BOD_5) in inflow and outflow of three shrimp ponds.

Variable	TN (mg/L)	TP (mg/L)	OC (mg/L)	BOD_5 (mg/L)
G09				
Inflow	2.26 ± 1.31	0.09 ± 0.05	6.9 ± 0.75	2.0 ± 0.36
Outflow	2.68 ± 1.73	0.25 ± 0.53	9.1 ± 1.45	6.1 ± 0.05
G74				
Inflow	3.23 ± 2.05	0.12 ± 0.07	4.9 ± 2.09	1.9 ± 0.36
Outflow	3.49 ± 2.17	0.31 ± 0.46	10.2 ± 4.42	6.2 ± 0.54
G75				
Inflow	3.05 ± 1.29	0.14 ± 0.07	6.6 ± 4.21	2.5 ± 0.36
Outflow	3.15 ± 1.78	0.27 ± 0.32	10.6 ± 4.71	6.9 ± 0.54

Table 7. Averages and standard deviations (SD) for inputs and outputs of total nitrogen for three shrimp ponds.

	Ponds			
Variable	G09 (kg)	G74 (kg)	G75 (kg)	Average ± SD (kg)
Inputs				
Water	4,405.0	4,190.4	7,358.4	5,317.9 ± 1,770.3
Urea	585.0	540.0	517.5	547.5 ± 34.4
Feed	3,124.5	2,220.1	3,177.6	2,840.7 ± 538.1
Shrimp PL stage	45.2	17.8	49.2	37.4 ± 17.1
Sum	8,159.7	6,968.3	11,102.7	8,743.6 ± 2,128.1
Outputs				
Effluent	5,195.9	4,492.5	7,564.7	5,750.9 ± 1,609.6
Harvested shrimp	703.8	525.1	695.7	641.6 ± 100.9
Sum	5,899.7	5,017.6	8,660.4	6,392.6 ± 1,676.6
Assimilated or stored in soil	2,260.0	1,950.7	2,842.3	2,351.1 ± 452.7
Aquaculture load	790.9	302.1	206.3	433.1 ± 313.5

Table 8. Averages and standard deviations (SD) for inputs and outputs of total phosphorus for three shrimp ponds.

Variable	Ponds G09 (kg)	 G74 (kg)	 G75 (kg)	Average ± SD (kg)
Inputs				
Water	175.4	155.7	337.8	223.0 ± 99.9
TSP[1]	14.7	13.7	13.1	13.8 ± 0.8
Feeds	711.1	505.3	723.2	646.5 ± 122.5
Shrimp PL stage	3.8	1.5	4.1	3.1 ± 1.4
Sum	905.0	676.2	1,078.2	886.5 ± 201.6
Outputs				
Effluent	484.7	399.0	648.4	510.7 ± 126.7
Harvested shrimp	59.2	44.2	58.5	54.0 ± 8.5
Sum	543.9	443.2	706.9	564.7 ± 133.1
Assimilated or adsorbed by soil	361.1	233.0	371.3	321.8 ± 77.1
Aquaculture load	309.3	243.3	310.6	287.8 ± 38.5

[1] TSP = triple superphosphate

Table 9. Averages and standard deviations (SD) for inputs and outputs of total organic carbon for three shrimp ponds.

Variable	Ponds			Average ± SD (kg)
	G09 (kg)	G74 (kg)	G75 (kg)	
Inputs				
Water	7,819	3,695	9,275	6,924 ± 2,887
Shrimp PL stage	672	265	731	556 ± 254
Feed	23,156	16,453	23,549	21,053 ± 3,988
Photosynthesis (estimated)	40,817	40,800	40,800	40,806 ± 10
Sum	72,464	61,213	74,355	69,344 ± 7,104
Outputs				
Effluent	10,257	7,633	14,799	10,897 ± 3,626
Harvested shrimp	10,455	7,800	10,333	9,529 ± 1,498
Sum	20,712	15,433	25,132	20,426 ± 4,856
Assimilated or stored in soil	51,752	45,780	49,223	48,918 ± 2,998
Aquaculture load	2,438	3,938	5,524	3,967 ± 1,543

Table 10. Averages and standard deviations (SD) of 5-day biological oxygen demand (BOD_5) for three shrimp ponds.

	Ponds			
Variable	G09 (kg)	G74 (kg)	G75 (kg)	Averages ± SD (kg)
Water for filling and water exchange	3,898	2,465	6,032	4,132 ± 1,795
Water discharged for water exchange and harvest	11,827	7,981	16,570	12,126 ± 4,302
BOD_5-load	7,929	5,516	10,538	7,994 ± 2,512

Table 11. Averages and standard deviations (SD) for amounts of phosphorus (P), nitrogen(N), 5-day biological oxygen demand (BOD_5), and organic carbon (OC) discharged per tonne of shrimp production for three shrimp ponds.

Variable	Ponds			Average ± SD
	G09	G74	G75	
P (kg/tonne shrimp)	13.4	14.3	13.5	13.8 ± 0.5
N (kg/tonne shrimp)	34.4	17.8	9.0	20.4 ± 12.9
BOD_5 (kg/tonne shrimp)	348.1	324.6	468.1	380.3 ± 76.9
OC (kg/tonne shrimp)	106.0	231.6	240.2	192.6 ± 75.1

Table 12. Comparisons of resource use efficiency and waste generation in four kinds of aquaculture.

Variable	Pond culture of catfish[1]	Cage culture of tilapia[1]	Raceway culture of trout[1]	Black tiger prawn (Aqualma)
FCR[2]	2.2	1.8	1.2	2.067
DMR[3]	7.61	6.23	4.15	6.86
WPR[4]	1.72	1.61	0.82	1.59
PCR[5]	0.62	0.58	0.54	0.908
PRR[6]	4.13	4.14	3.46	4.703
FMR[7]	0.04	0.11	0.30	0.672
LFE[8]	0.20	0.49	1.35	3.02
Total water use (m^3/tonne)	6,000	667	60,000	90,855
Land use (ha/tonne)	0.54	0.40	0.09	0.96
Energy use kW·hr/tonne	1,000	-	-	868.8
Waste production (kg/tonne):				
Total nitrogen	6.3	65.1	50	20.4
Total phosphorus	0.45	9.1	13.9	13.8
BOD_5	9.3	-	315	380.3

[1] From Boyd et al. (2007)
[2] FCR = feed conversion rate
[3] DMR = dry matter ratio
[4] WPR = waste production ratio
[5] PCR = protein conversion ratio
[6] PRR = protein recover ratio
[7] FMR = fish meal ratio
[8] LFE = live fish equivalece

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Figure 1. Map of Madagascar showing the location of Aqualma shrimp farm.

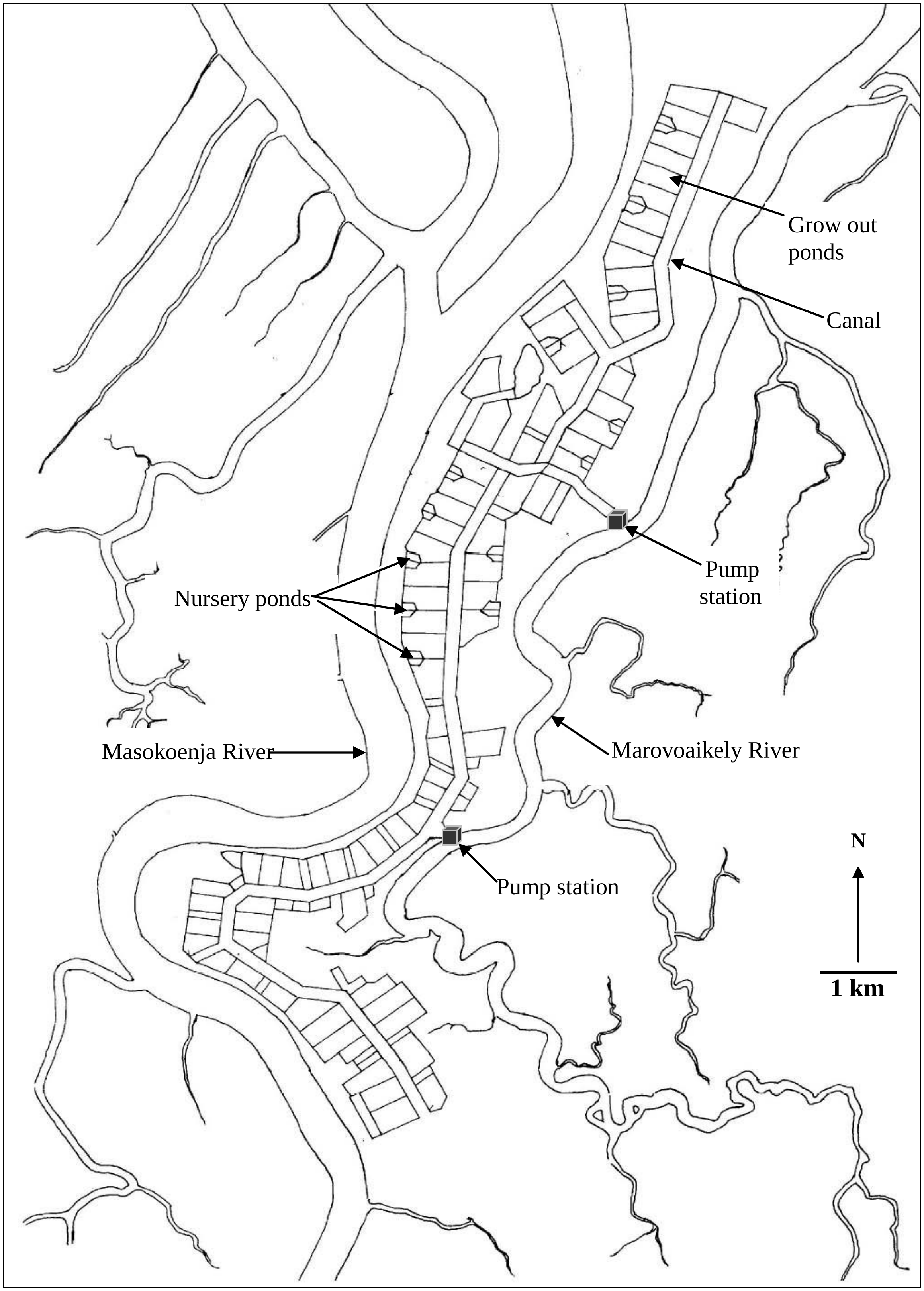


Figure 2. Map of Aqualma shrimp farm.

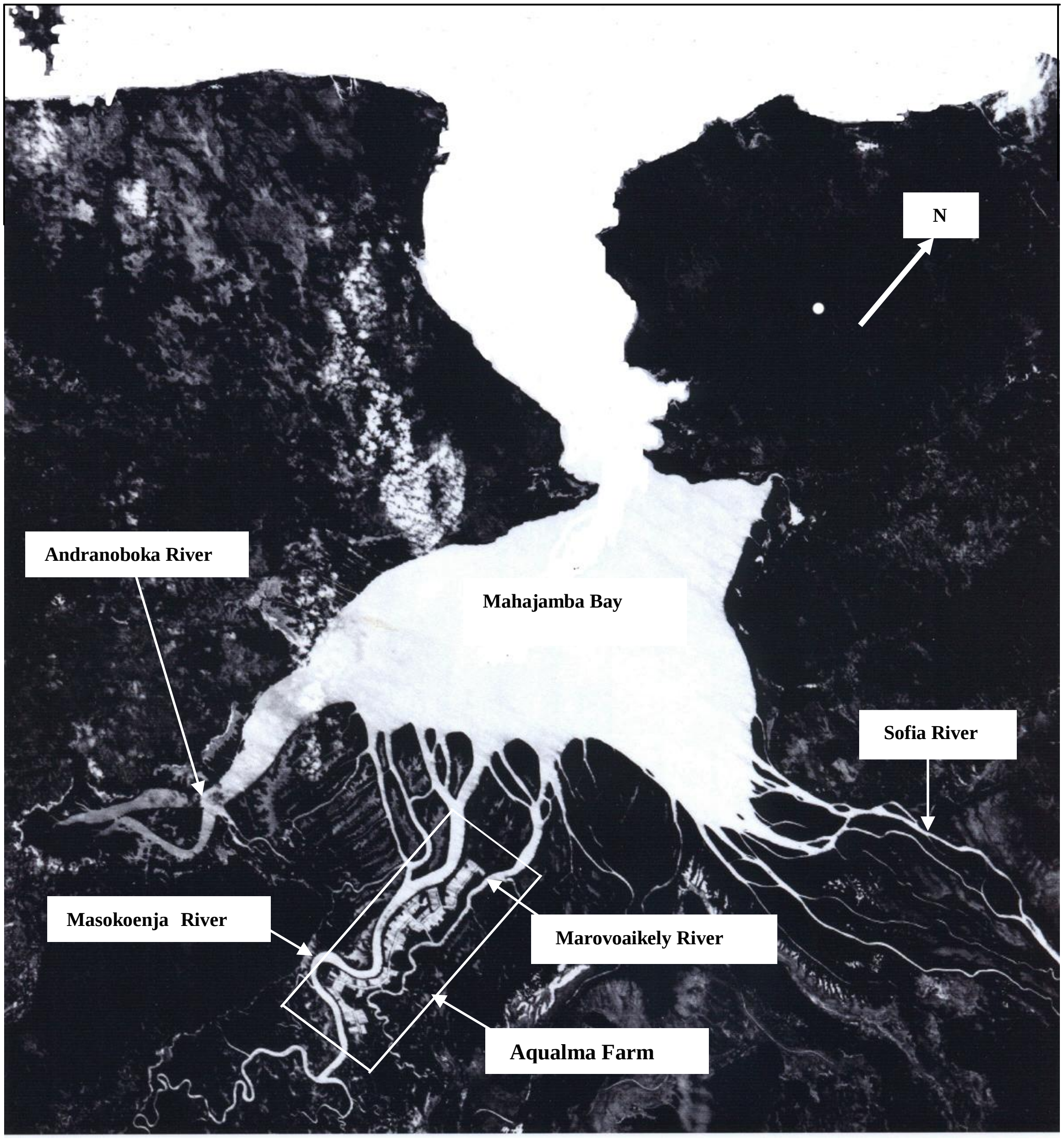


Figure 3. Satellite view of the Mahajamba bay, estuary, and Aqualma shrimp farm.

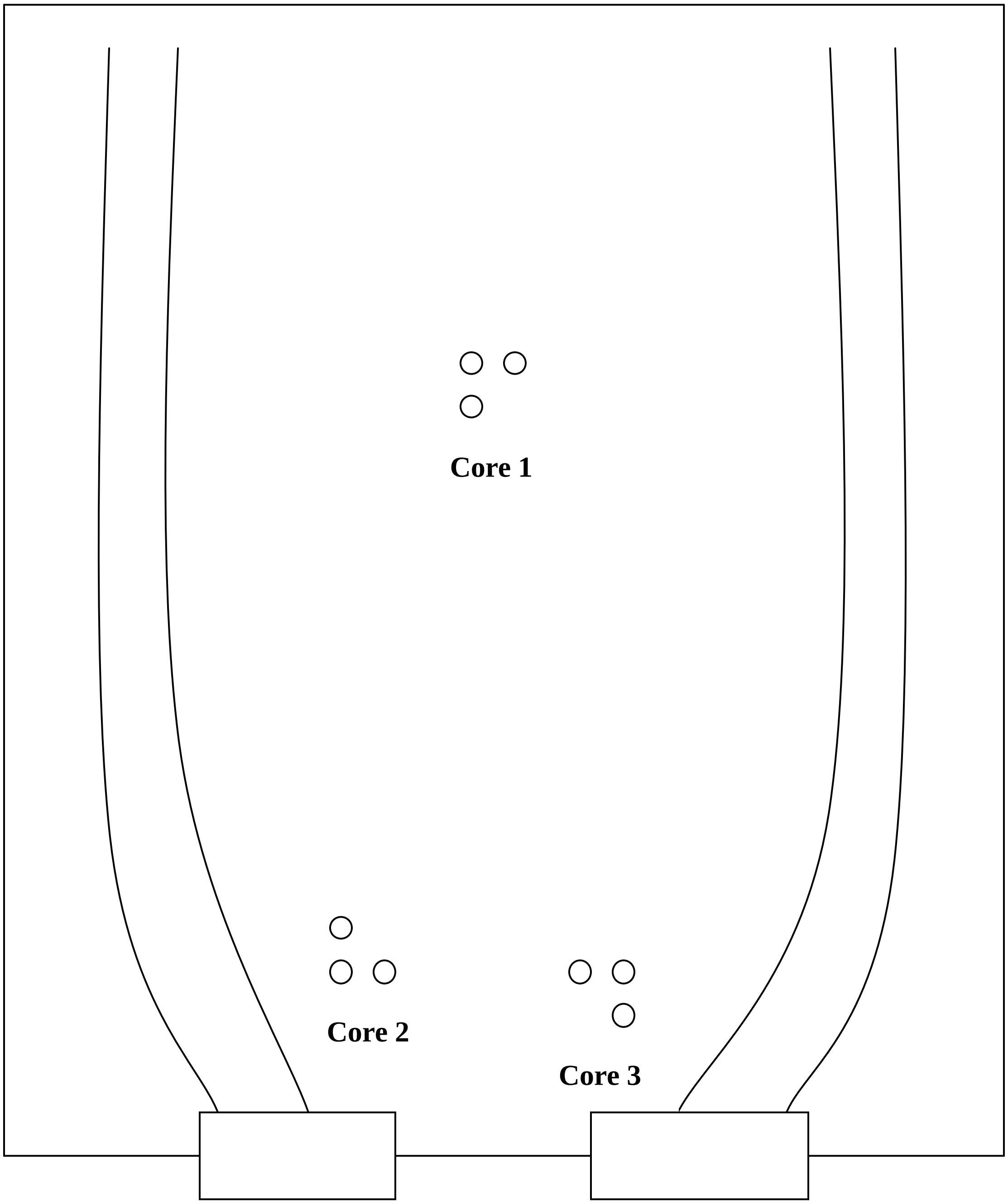


Figure 4. Soil core sampling locations for studying the distribution of nutrient with depth. Core were taken to 30-cm depth and cut into 2-cm long segments.

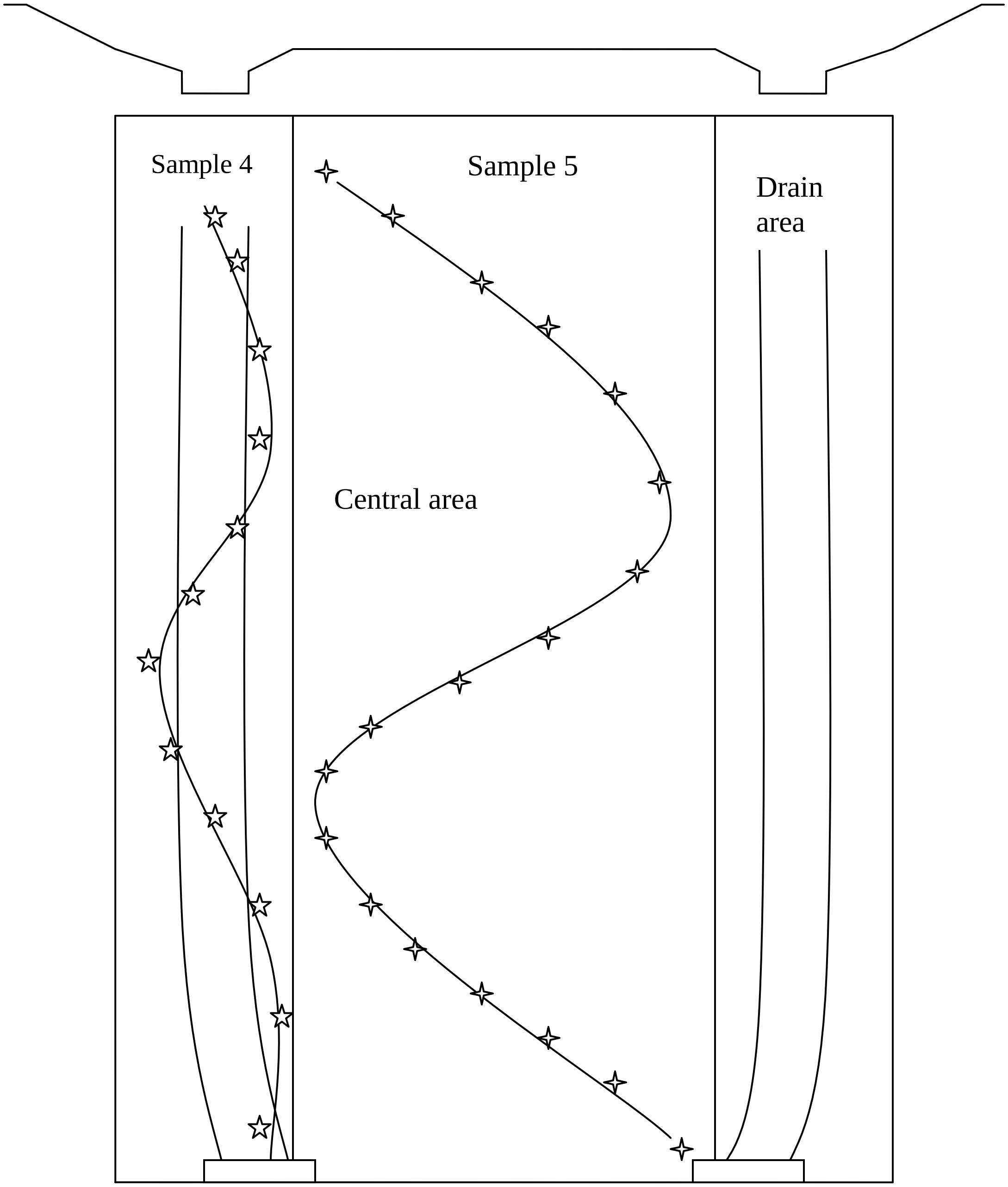
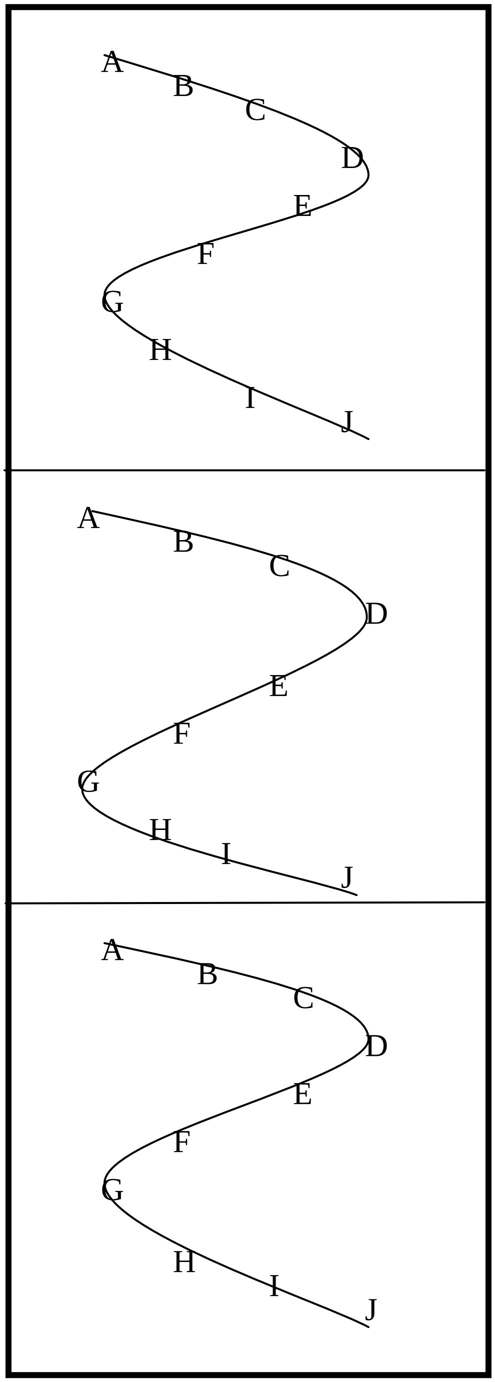


Figure 5. Soil sampling locations for comparing drain section with central area. Samples taken to 5-cm depth.



Combined samples
A-J for composite
sample No.1

Combined samples
A-J for composite
sample No. 2

Combined samples
A-J for composite
sample No. 3

Figure 6. Sampling scheme for obtaining three samples from the bottom of each pond before filling with water and soon after draining for harvest. Samples were taken to 5-cm depth.

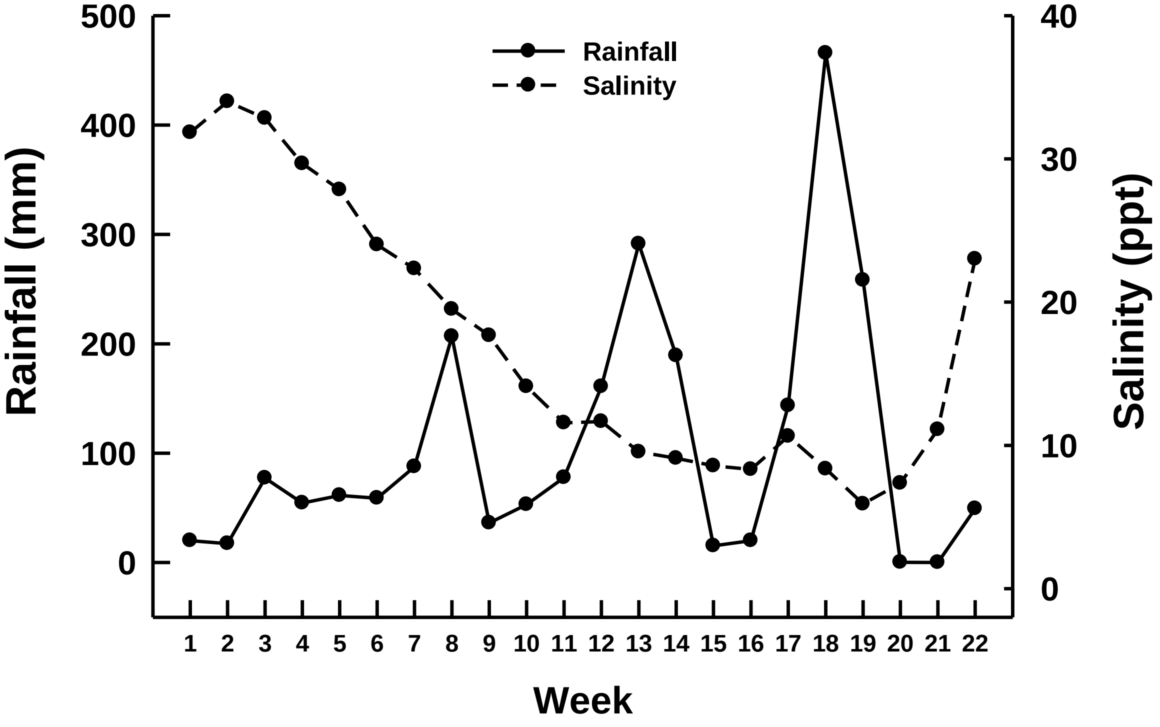


Figure 7. Weekly rainfall (mm) and average weekly salinity (ppt) for three study ponds.

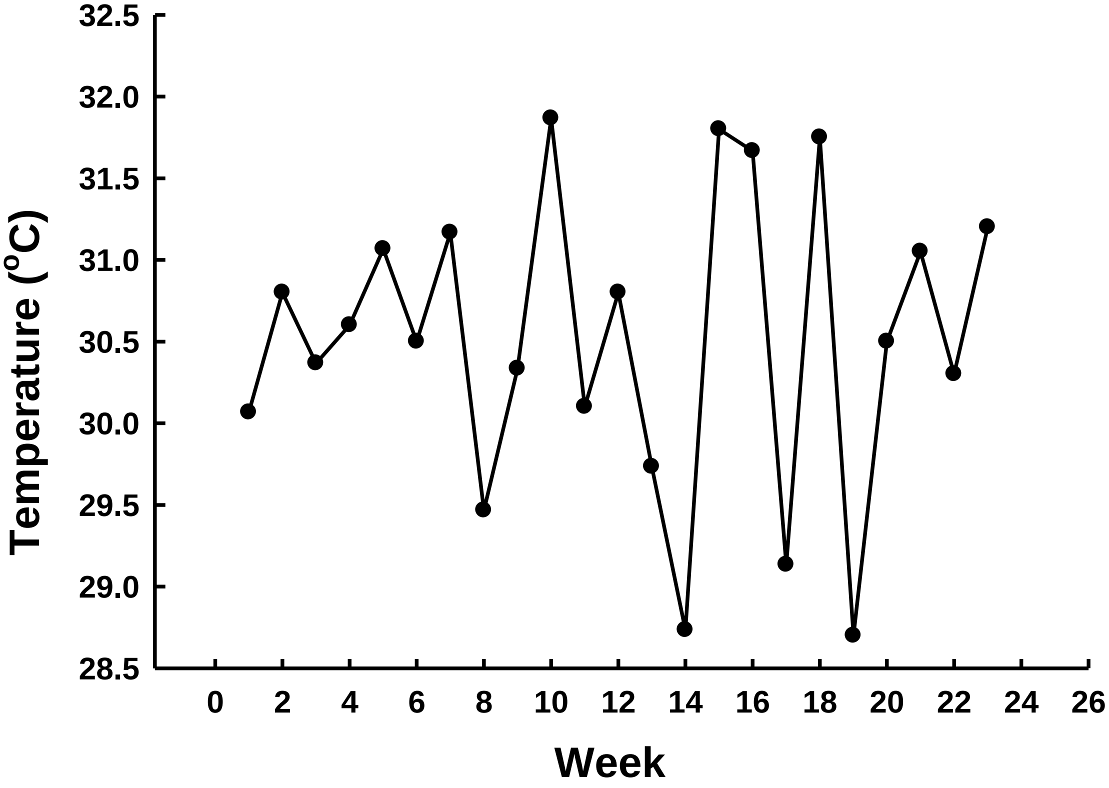


Figure 8. Average surface water temperature (^{o}C) of the three study ponds.

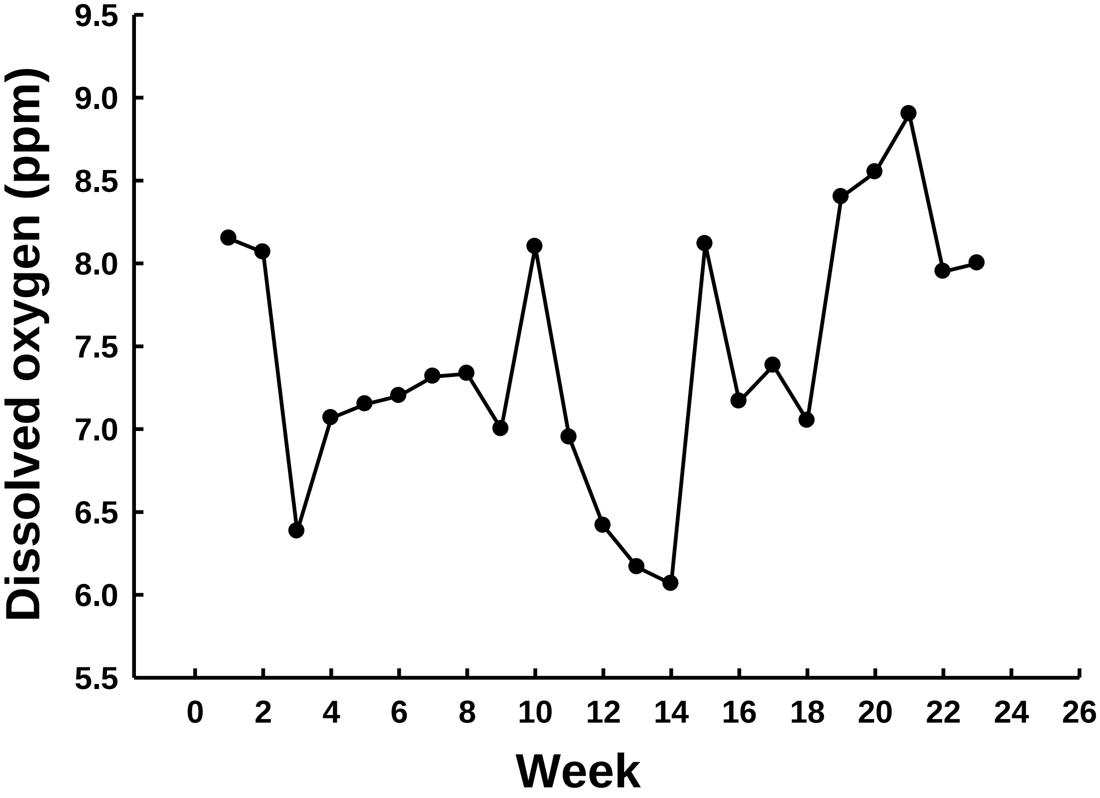


Figure 9. Average weekly dissolved oxygen concentrations (mg/L) measured 10-cm above the bottom at 0600 hr in the three study ponds.

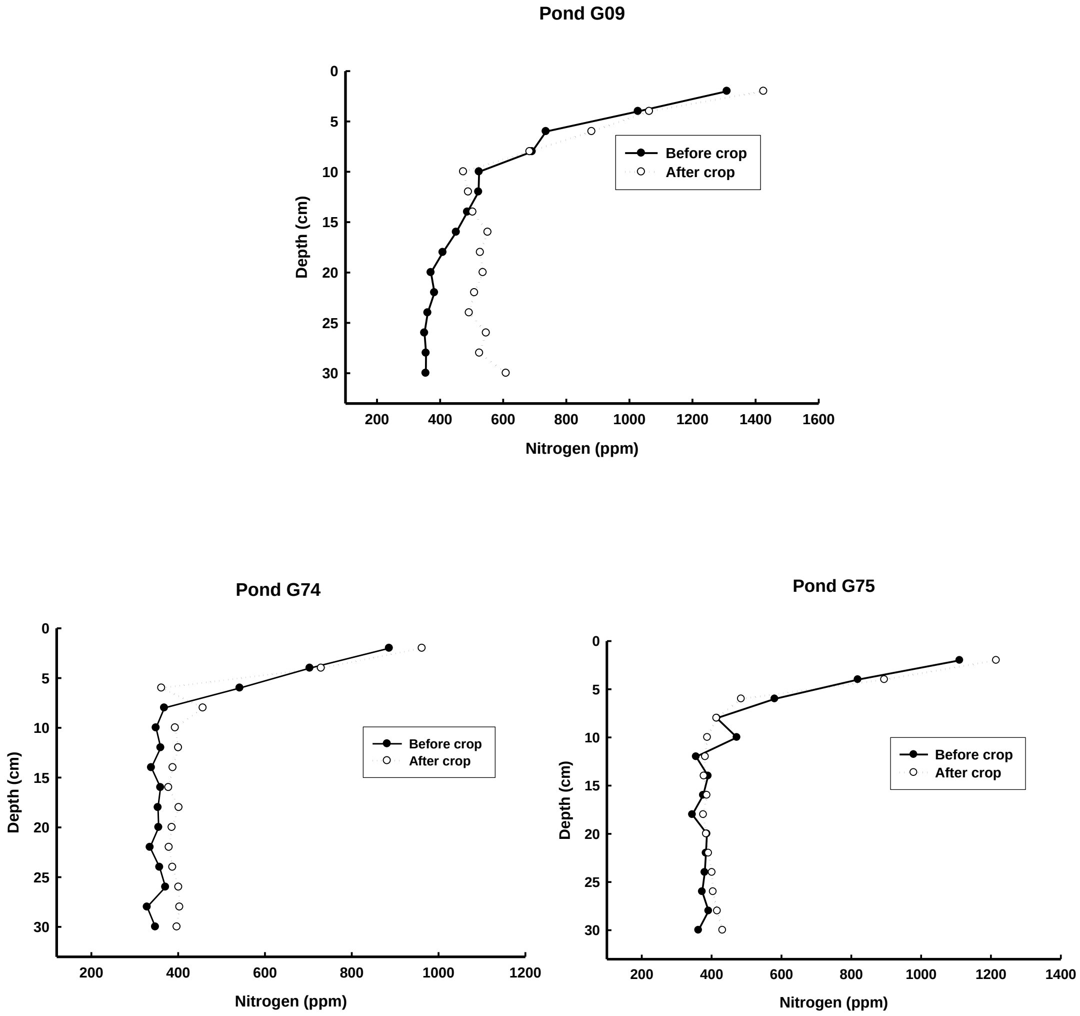


Figure 10. Nitrogen concentrations (ppm) in pond soil at different depths for three study ponds.

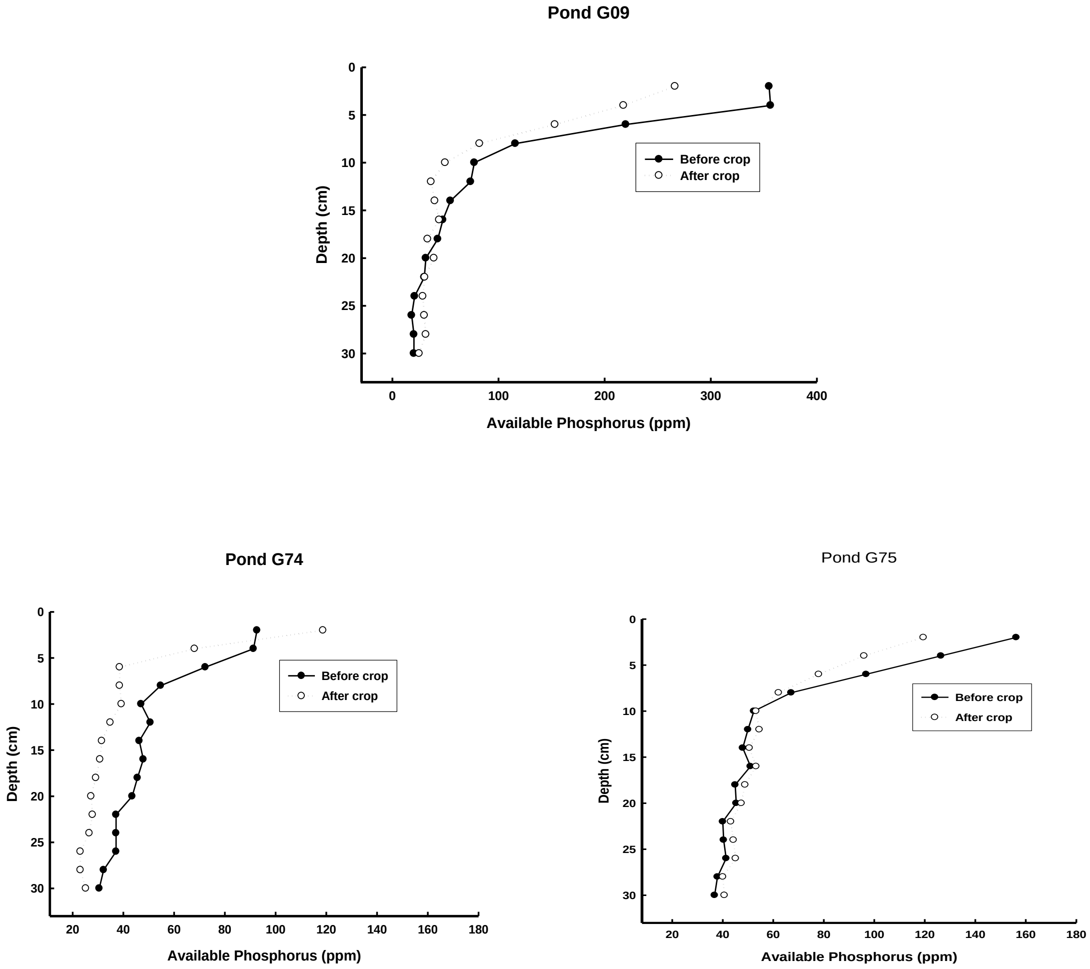


Figure 11. Available phosphorus concentrations (ppm) in pond soil at different depths for three study ponds.

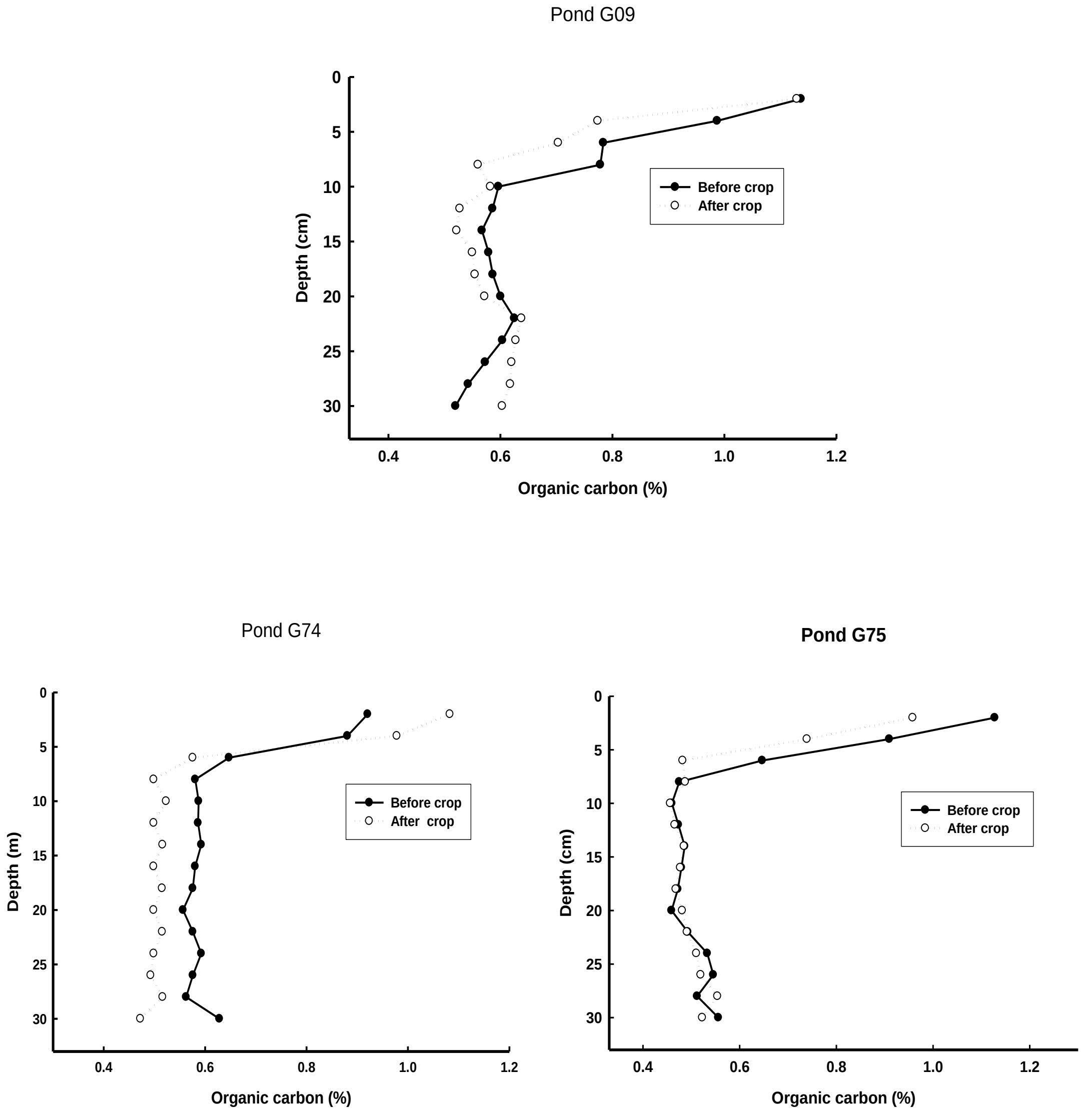


Figure 12. Organic carbon concentration (%) in pond soil at different depths for three study ponds.

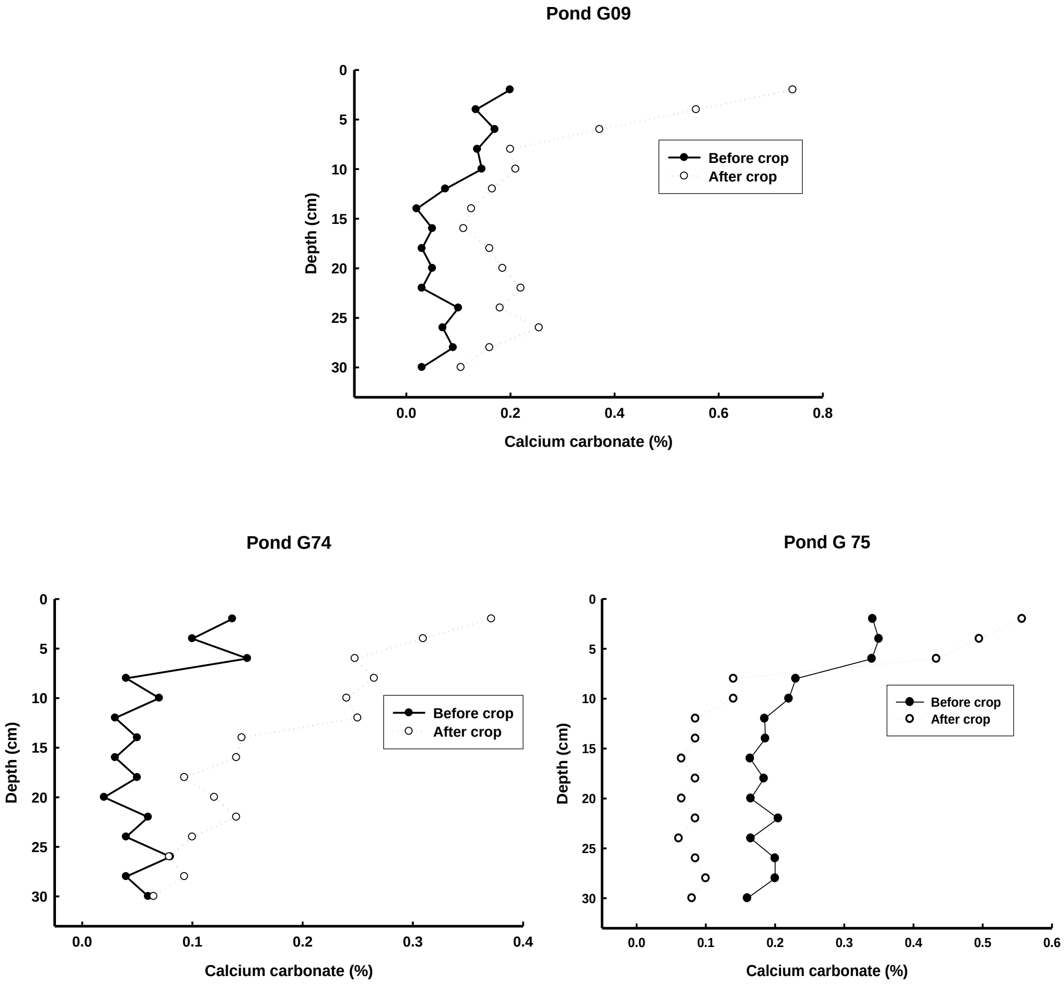


Figure 13. Calcium carbonate concentration (%) in pond soil at different depths before for three study ponds.

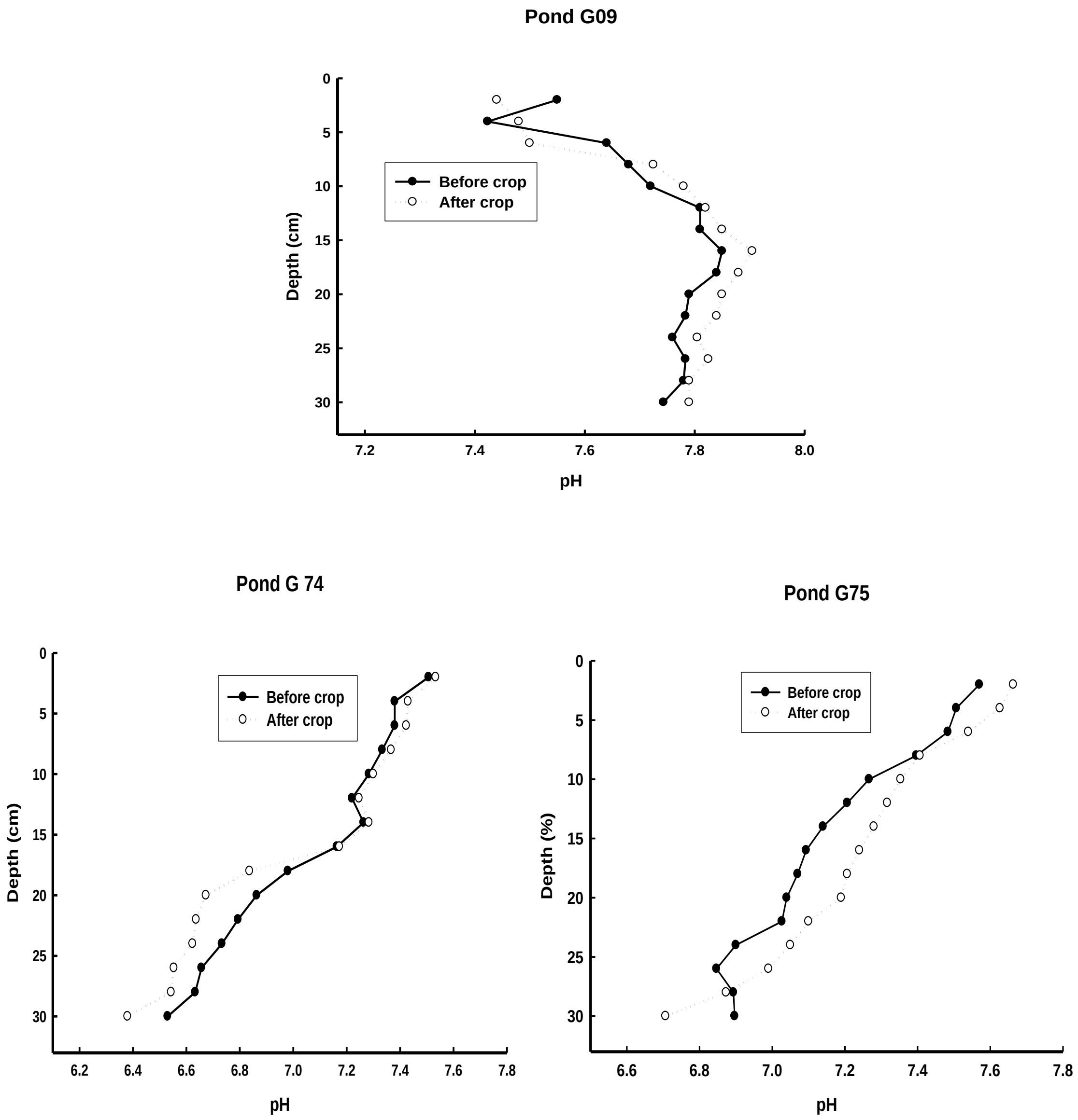


Figure 14. Soil pH at different depths for three study ponds.

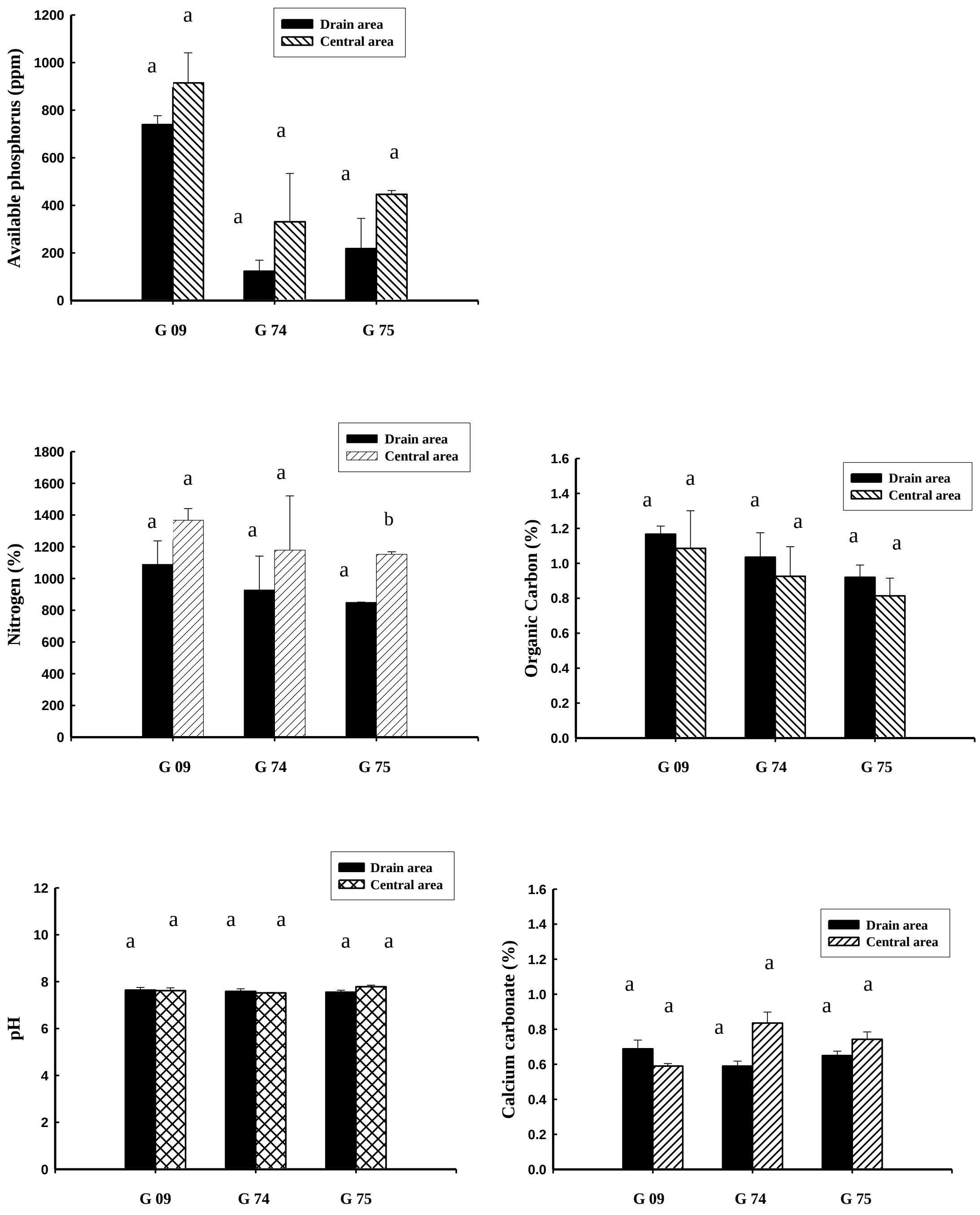


Figure 15. Average and standard deviations for available phosphorus, total nitrogen, organic carbon, pH, and calcium carbonate in pond soil samples from drain areas and central areas of study ponds. Means indicated by the same letter did not differ ($P > 0.05$).

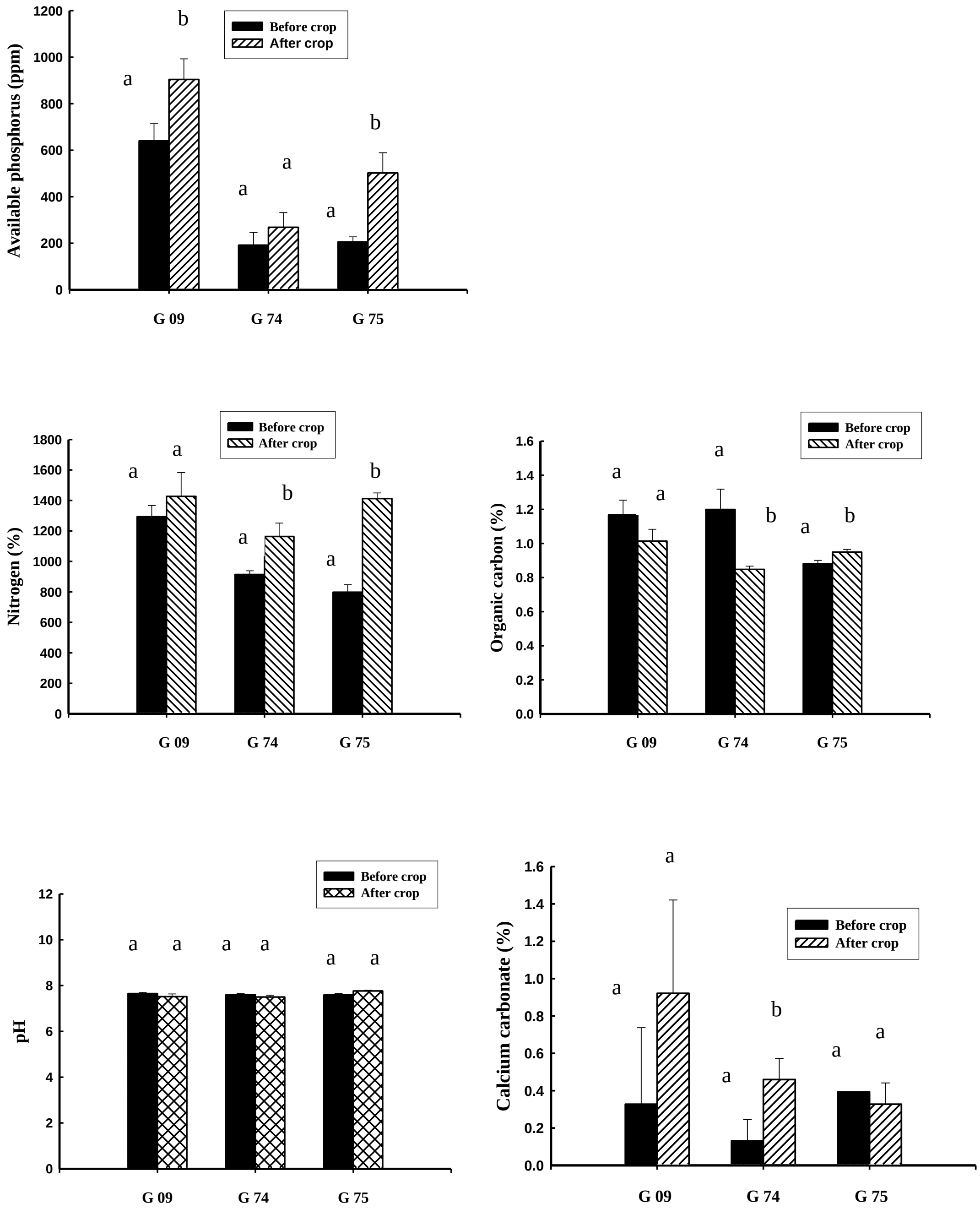


Figure16. Average and standard deviations for available phosphorus, total nitrogen organic carbon, pH, and calcium carbonate in pond soil samples taken over the entire ponds bottom. Means indicated by the same letter did not differ (P > 0.05).

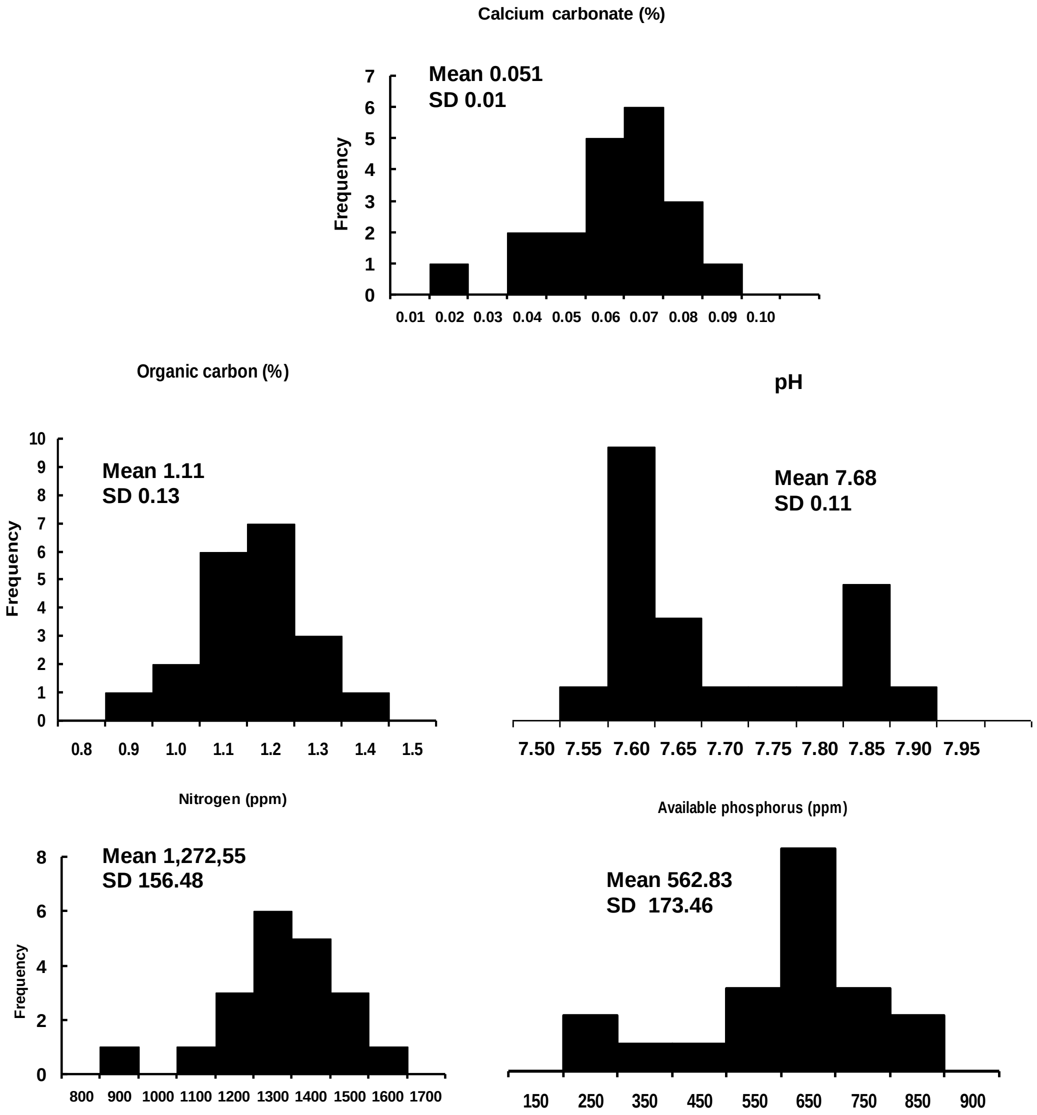


Figure 17. Frequency distribution histograms for organic carbon (%), pH, nitrogen (ppm), phosphorus (ppm), and calcium carbonate (%) in pond soil samples from twenty ponds.

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