BOTTOM SOIL QUALITY IN PONDS FOR CULTURE OF CATFISH, FRESHWATER PRAWN, AND CARP IN THAILAND

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BOTTOM SOIL QUALITY IN PONDS FOR CULTURE OF CATFISH, FRESHWATER PRAWN, AND CARP IN THAILAND

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A Dissertation

Submitted to

the Graduate Faculty of

Auburn University

in Partial Fulfillment of the

Requirements for the

Degree of

Doctor of Philosophy

Auburn, Alabama
May 11, 2006

BOTTOM SOIL QUALITY IN PONDS FOR CULTURE OF CATFISH, FRESHWATER PRAWN, AND CARP IN THAILAND

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Idsariya Wudtisin, daughter of Prawim Wudtisin and Wongduan Wudtisin, was born in Rayong, Thailand, on April 13, 1977. She has two sisters, Wararat and Masalin wudtisin. She earned a bachelor degree in Thailand (B.S. in Environmental Health, from Burapha University in 1998). Then she earned a master's degree in Environmental Science with a distinct award from the graduate school of Kasetsart University in Thailand in 2001 and completed the Ph.D. from Department of Fisheries and Allied Aquacultures, Auburn University in May, 2006.

DISSERTATION ABSTRACT

BOTTOM SOIL QUALITY IN PONDS FOR CULTURE OF CATFISH, FRESHWATER PRAWN, AND CARP IN THAILAND

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Doctor of Philosophy, May 11, 2006
(M.S., Kasetsart University, 2001)
(B.S., Burapha University, 1998)

100 Typed Pages

Directed by Claude E. Boyd

Bottom soil samples were collected from 42 catfish (*Clarias* hybrid) ponds, 40 freshwater prawn (*Macrobrachium rosenbergii*) ponds, and 18 carp (*Puntius* spp.) ponds in Thailand. The ponds ranged from 1 to 30 years in age. Regression analysis revealed that pond age was not a major factor influencing the physical and chemical composition of pond soils. Sediment depth, S horizon thickness, and bulk density of S horizon were greater for carp ponds than for catfish and prawn ponds. This resulted because sediment was removed from catfish and prawn ponds more frequently than from carp ponds. Total carbon, organic carbon, and total nitrogen concentrations were higher in carp ponds than prawn and catfish ponds. However, few ponds had sediment organic carbon concentrations above 3%, and carbon:nitrogen ratios did not differ among the three cultured species.

Total phosphorus and other soil phosphorus fractions increased in the order prawn ponds, carp ponds, and catfish ponds. Soil sulfur concentrations also increased in the same order. There were no differences in major or minor nutrients in bottom soils that would influence aquacultural production. Although there were significant correlations between various soil quality variables, no single variable or group of a few variables would be useful in estimating soil quality.

Best management practices recommended for improving pond bottom quality were drying of bottom between crops, liming, tilling, and periodic sediment removal. Best management practices for preventing high total suspended solids concentrations in pond effluents also were recommended.

ACKNOWLEDGEMENT

The author would like to thank all the people who supported her during her program. She thanks Mr. Prawim Wudtisin, Director General for Department of Marine and Coastal Resources Department, who encouraged her to study in the United States. Thanks to Dr. Claude E. Boyd, who give her an opportunity to do and conduct her research. Dr. John W. Odom, Dr. Chhorn Lim and Dr. Yolanda J. Brady, who assisted her during her study. Besides, the author would like to thanks Mr. Puan Pengseng for his assistance about laboratory works, and thanks to Dr. Tarworn Thunjai for his advice about her dissertation format.

The author also would like to thank the CRSP for financial support under the Pond Dynamics/Aquaculture Collaborative Research Support Program (PD/A CRSP) funded by the United States Agency for International Development. Very special thanks to Miss Wararat Wudtisin, her lovely sister, who always take care of her and give her all supports to living strong overseas.

Style manual or journal used: Journal of the World Aquaculture Society

Computer software used: Microsoft Word 2000, Microsoft Excel 2000, SigmaStat 2.03, and SigmaPlot 8.0.

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INTRODUCTION

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 much attention in marine shrimp culture (Boyd 1995; Limsuwan and Chanratchakool 2004), but much less effort has been devoted to the condition and management of freshwater pond bottoms. 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 stay in the water column.

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). Although no soil management practices had been applied to ponds in those studies, the main problem with pond bottoms was the accumulation of soft sediment in the deeper areas after about 20 years of use.

A recent study of freshwater ponds for tilapia *Oreochromis* spp. in Thailand demonstrated that the composition of bottom soil differed little between ponds less than 5 years old and those over 20 years old (Thunjai et al. 2004). 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 for semi-intensive production of tilapia could be used for at least 25 to 40 years with relatively little bottom soil management intervention.

One objective of the present study was to evaluate pond bottom soil management techniques and pond bottom soil quality in ponds used for production of hybrid catfish *Clarias*, carp *Puntius* spp. and freshwater prawn *Macrobrachium rosenbergii* in Thailand. The other objective was to recommend better practices for pond bottom soil management for use in Thailand.

LITERATURE REVIEW

Aquaculture has developed rapidly in South East Asia. To achieve efficient production of fish, crustaceans, and other aquatic organisms, many natural resources have been used. Feed, lime, manure and fertilizer play an important role to provide greater yields; however, poor management of those materials can have negative effects on water quality and the condition of pond bottom sediment (Munsiri et al. 1995).

A wide variety of organic materials have been used as pond manures. Manures, fertilizers, and feeds applied to ponds to enhance production only can be partially converted to animal biomass (Boyd and Tucker 1998). Large inputs of manure into ponds can result in the accumulation of organic matter in sediment (Munsiri 1995).

The most commonly aquacultural species in Thailand are hybrid catfish (*Clarias macrocephalus x Clarias gariepinus*), Nile tilapia (*Oreochromis niloticus*), freshwater prawn (*Macrobrachium rosenbergii*) and carp (*Pantius spp.*). Areerat (1987) stated that the culture of *Clarias* in Thailand began in the late 1950s, and originally in the Bangkok area. *Clarias* culture gave a higher annual income than other forms of agriculture. The number of *Clarias* farms increased every year and people who lived nearby started to complain about the bad smell of polluted water in catfish ponds. Finally, the municipality forced the farm owners to move away from the Bangkok area (Sidthimunka, 1971). Most of the farms are now found in the central part of Thailand. The polluted water was the result of using large amounts of pig, duck, cow and poultry excreta for maintaining the productivity of natural food of *Clarias* and other species. The use of organic, aquaculture waste products is common in Asian aquaculture.

Hickling (1962) gave the following list of organic materials used in pond fertilization: livestock dung, leaves, grass and weeds; wastes from distilleries, tanneries, dairies, and sugar refineries; cottonseed meal; and dry hay. Many other agricultural wastes and by-products can be similarly useful (Boyd and Tucker 1998).

Zoccarato et al. (1995) conducted a 4-month trail in Northern Italy to evaluate the possibility of recycling pig manure through carp production in ponds. There were three treatments each for common carp and grass carp. The initial mean weights of fish were 450 g and 440 g, respectively. Pond were fertilized with pig manure supplied with feed; or both as a percentage of fish biomass as follow: (A) 3% manure; (B) 1.5% manure and 1.5 % feed; (C) 3% feed. The final mean weight of fish were 570, 1,050 and 1,670 g for common carp and 630, 1,330 and 1,480 g for grass carp in treatments A, B and C, respectively. In Israel, ponds stocked with common carp, tilapia hybrids, silver carp and grass carp received dry chicken manure as the only nutritional input at three different rates. The standard rate was 50 kg dry matter/ha/day, increasing by 25 kg/ha/day every 2 weeks up to 175 kg/ha/day. The other two rates were half, and twice the standard. The total yield and common carp growth rate and yield increased with manuring rate (Milsten et al. 1991). The two studies summarized above clearly illustrate that manures can increase fish production dramatically.

Studies supported by The Pond Dynamic/Aquaculture Collaborative Research Support Program (PD/A CRSP) of the United States Agency for International

Development (USAID) have reported that there is a significantly higher level of fish yield in ponds fertilized with chicken manure than in ponds fertilized with inorganic fertilizer alone (Diana et al. 1990). The ranges of manure application were usually from 50 to 100 kg dry weight/day, but rates as high as 200 kg/day have been used (Boyd 1995).

Organic acids that leak from manures impart color to water. Manure particles suspended in water become mixed with suspended clay particles, and bacterial activity favors flocculation of clay particles (Irwin 1945). The decomposition of organic matter from manure mineralizes nutrients, but large amounts of dissolved oxygen are consumed by aquatic organisms to decompose organic matter. Dissolved oxygen depletion often is a serious water quality problem in heavily manured ponds (Boyd and Tucker 1998).

Boyd and Tucker (1998) provided a list of the problems that can result from using manure as follows: difficulties in handling and storage of the manure, large quantities are necessary to enhance production, high oxygen demand, large residues of sludge in pond bottoms, discoloration of water by humic substances, manures have a high heavy metal content, possibility of antibiotics in certain animal manures, possible off-flavor in fish, potential of disease transfer to humans, and nonacceptance of products from manure-based systems by some consumers.

Bottom soil-water interface

Reactions occurring at the bottom soil-water interface have a major influence on dissolved oxygen concentration. Oxygen diffusion to the pond bottom is slow and often at an insufficient rate to maintain aerobic conditions (Boyd and Tucker 1998). Wind and mechanical aeration produce water currents and mix the water column to oxygenate the bottom soil layers (Ritvo et al. 2004).

Boyd and Tucker (1998) stated that dissolved oxygen concentration in pond waters depend on five major processes: air-water gas transfer, sediment oxygen uptake, animal respiration, plankton respiration, and photosynthesis. The last two factors are considered the major factors affecting the concentration of dissolved oxygen. Photosynthesis is the largest source of oxygen while plankton respiration is the largest sink of oxygen. When oxygen depletion occurs, other terminal electron acceptors are used to mediate the decomposition of organic matter. This process leads to the production of reduced and potentially toxic compounds such as reduced iron and manganese, nitrite, and hydrogen sulfide and reduced organic compounds (Avnimelech and Ritvo 2003). The development of anaerobic conditions clearly has adverse affects on water quality and fish production.

Boyd and Tucker (1998) revealed that in the absence of molecular oxygen, many common heterotrophic bacteria could use nitrate or other oxidized forms of nitrogen instead of oxygen as electron acceptor in respiration. They are the denitrifying bacteria. Nitrate-based fertilizer can be used to supply nitrate for denitrification and sustain an oxidized soil layer. However nitrate fertilizers are expensive and not used by fish farmers in Thailand.

Ritvo et al. (2004) conducted an experiment to measure the effects of common carp bioturbation on fish pond bottom soil. The results showed that bioturbation generated by fish can improve bottom soil quality by increasing oxygen supply to a greater depth in aquaculture pond bottoms, decreasing the concentration of toxic reduced compounds, and sustaining a more efficient food web by recycling nutrients from organic matter.

Pond soil development and Pond soil profiles

Sediment, mud, or soils are materials composing the bottoms of streams, lakes, and ponds. These terms, often used interchangeably, describe the bottom material in ponds (Boyd 1995). The original pond bottom is made of terrestrial soil, and when the pond is filled with water the bottom becomes wet. At this point, the bottom soil is a mixture of solid material and water that is often called mud. Solids settle from the water and cover the pond bottom with loose mineral and organic material known as sediment.

During construction, the surface soil is scraped from the area to be the pond bottom and used as earth fill for embankments. The newly finished pond bottom usually is subsoil low in concentrations of organic matter and nutrients. Pond bottoms are often high in clay content and low in pH in tropical and subtropical areas with highly leached soils.

Once a pond is filled with water, the transformation of the pond bottom into a pond soil begins. Erosion from the watershed brings inorganic matter and suspended soil particles. Wave action, water currents from mechanical aeration, and rainfall erode embankments and shallow edges to suspend soil particles that then settle in deep areas of the pond. Fertilizers, manures, and feeds cause phytoplankton blooms that increase the concentration of suspended organic particles (Boyd et al 2002). The sediment layer may be several to many centimeters thick in older ponds. The four most important features of soil to aquacultural production are texture, organic matter content, pH, and nutrient concentrations (Boyd 1995).

In contrast to terrestrial soil, pond soils develop distinct profiles within a few years, while terrestrial soils take many years to develop a soil profile (Boyd 1995). The major factors influencing pond soil development appear to be sedimentation, organic matter input, and wetting and drying processes between crops (Thunjai 2002).

Pond soils develop profiles with characteristic horizons that can be identified easily in pond bottom cores where waters are deeper than 75 cm and especially in older ponds (Munsiri 1995). The pond soil profiles include the flocculent layer called the F horizon that is recently settled material laying on the bottom above the soil-water interface. Immediately below the F horizon is the soil-water interface and the top of the first sediment layer. The entire first layer is called the S horizon. The uppermost part of the S horizon is called S_o horizon. It is a thin, oxidized (aerobic) surface sublayer has a low bulk density (<0.3 g/cm^3), and it is mixed by water currents and biological agents. The deeper, reduced sublayer beneath the S_o horizon is called the S_r horizon. It is a thicker, anaerobic and not as well mixed as the S_o sublayer. Below the S horizon is the M horizon. This layer is not mixed and denser than the S horizon. The transition from the M horizon to the original pond bottom (P horizon) is named the T horizon. (Munsiri et al. 1995). The original pond bottom beneath the sediment is the P horizon.

Thunjai (2002) reported that total sediment depth in tilapia ponds in Samutprakarn Province,Thailand ranged from 2.7 to 59.3 cm, the S horizon averaged 7.22 cm in depth and ranged between 1.1 to 39.8 cm. Bulk density values were 0.08 to 0.35 g/cm^3. Averaged bulk density was 0.23 g/cm^3.

Soil pH

Soil pH is a measure of the activity of hydrogen in the soil solution. The pH is the negative logarithm of the hydrogen ion activity (H^+) and may be expressed by the following equation:

$$pH = -\log (H^+)$$

Soils are referred to as being acidic, neutral, or alkaline (basic), depending on their pH values on a scale from 0 to 14. A pH of 7 is neutral; less than 7 is acidic; greater than 7 is alkaline (MaCauley et al. 2003).

Before biological activity adds to or removes carbon dioxide from water, the initial pH of pond waters in equilibrium with atmospheric carbon dioxide is a function of the total alkalinity of the water. Low alkalinity waters are acidic, moderate alkalinity water are near neutral, and high alkalinity waters are basic. The activities of plants, animals and bacteria cause the pH to cycle diurnally. High pH (>9) is normally found in the afternoon in aquaculture ponds when conditions favor rapid photosynthesis and removal of carbon dioxide (Boyd and Tucker 1998).

The pH has both direct and indirect effects on other environment variables. For example, the proportion of total ammonia nitrogen ($NH_4^+ + NH_3$) existing in the toxic, un-ionized form (NH_3) increases as the pH increases. In water with low total alkalinity, pH is low resulting in a shortage of inorganic phosphorus and carbon dioxide for plant growth (Boyd and Tucker 1998). However, in water of low alkalinity, rapid photosynthesis sometimes causes a dangerously high pH. Ponds often are treated with liming materials to increase alkalinity.

Thunjai (2002) reported that tilapia ponds in Changrai and Samutprakarn, Thailand had average soil pH of 7.43 and 7.50, respectively. The soil pH were between 6.63 and 9.40 in Changrai and 6.62 and 7.90 in Samutprakarn.

Banerjea (1967) suggested that the best pH range for pond soils is 6.5 to 7.5 while 5.5 to 8.5 is the acceptable pH range. Boyd (1988) also pointed out that optimum pH for good health and high growth rate of freshwater animals is between 6.5-9.0.

Soil Organic Matter

Jimėnez-Montealegre et al. (2002) stated that soil organic matter (SOM) is a heterogeneous mixture. It is composed of products that result from microbial and chemical transformations of organic remains. The increase or decrease of organic matter in the sediments varies between 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 (Jørgensen 1989). Small particles such as clay and finely divided organic matter settle very slowly, while sand and silt settles rapidly.

Boyd et al. (2002) stated that soil organic matter is about 45 to 50% carbon, so a rough approximation of organic matter may be obtained by multiplying soil organic carbon by two. Soil organic carbon concentrations rapidly increased to 2 or 3% in the S and M horizons, but they remain low in soil from greater depth in pond bottoms (Munsiri et al. 1995).

The concentrations of organic matter in aquaculture pond soils range 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 loading of ponds is discontinued, the nutrients dissolved in the water columns decline quickly and limit the growth of phytoplankton (Diana et al. 1990).

According to Thunjai (2002), for 17 tilapia ponds in Changrai,Thailand, organic carbon averaged 2.22 %. The organic carbon was between 1.08 and 3.08 %. Boyd et al. (1994) reported the average organic carbon concentrations in 358 freshwater ponds from Honduras, Rwanda, Bhutan, and the United States and 346 brackish water ponds from Thailand, Ecuador, Philippines, and Venezuela. The averages were remarkably similar, 1.78% and 1.79%, respectively. However, some samples from freshwater ponds contained up to 8% organic carbon, and some samples from intensive brackish water shrimp ponds contained more than 10% organic carbon.

Banerjea (1967) concluded that the acceptable range of organic carbon for aquaculture ponds is 0.5 to 2.5 %. The best range is 1.5 to 2.5 %. 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.

Nitrogen in Aquaculture Ponds.

Hargreaves (1998) stated that fertilizer and formulated feed are an important source of nitrogen to ponds. An excess of nitrogenous inputs can lead to the deterioration of water quality. Nitrogenous compounds such as nitrite and ammonia are potentially harmful to aquatic species. Fish excreta and sediment flux from mineralization of organic matter and diffusion of reduced sediment are usually important sources of ammonia in the ponds. Phytoplankton uptake and nitrification are considered the principle sinks of ammonia. Boyd and Tucker (1998) stated that application of nitrogen to fertilize ponds usually is in the form of urea, which rapidly hydrolyzes to ammonia, salts of ammonium and nitrate, or organic nitrogen in manure. Ammonia (NH_3) and ammonium (NH_4^+) normally exist in the water in a temperature and pH dependent equilibrium.

$$NH_4^+ + OH^- = NH_3\uparrow + H_2O$$

As the pH increases, the proportion of NH_3 increases (Boyd and Tucker 1998).

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

Phosphorus in Aquaculture Ponds

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

Boyd and Tucker (1998) stated that plants assimilate phosphorus as orthophosphate ions, which may be considered as ionization products of orthophosphoric acid. (H_3PO_4):

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

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

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

Boyd and Tucker (1998) also revealed that at a normal environmental pH range in aquaculture ponds of 7 to 9, most of the orthophosphate exists as a mixture of $H_2PO_4^-$ and HPO_4^{2-}, that can be considered equally available to plankton. Phytoplankton cells and the particulate matter or detritus of algal origin are the largest phosphorus fraction in aquaculture pond waters.

Pond soil can be considered a source or a sink for phosphorus, and aerobic soils are particularly important as a phosphorus sink (Boyd and Musig 1981). Phosphorus normally reacts with aluminum and calcium in sediments to form complexes with relatively low solubilities under aerobic conditions. The vital key that affects the solubilities of calcium 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 adsorbed to calcite and precipitated as hydroxyapatile. When pH is decreasing, calcium phosphates increase in solubility (Golterman 1995).

The solubility of gibbsite (aluminum hydroxide) is regulated by pH. It is a common aluminum compound in soil (Adams 1971) and dissolves as follows:

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

Thus, 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 reacts with phosphorus to form insoluble aluminum phosphate:

$$Al^{3+} + H_2PO^-_4 = AlPO_4 + 2H^+$$

Boyd and Tucker (1998) summarized literature showing that mud removed phosphorus from water in the form of iron, aluminum, and calcium phosphate compounds with limited solubilities. 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 mud. Under aerobic conditions, much of the phosphorus is basically combined with amorphous ferric (Fe^{3+}) oxyhydroxide gels or as phosphorus coprecipitated in coating of ferric oxide surrounding silt or clay particle. Under anaerobic conditions, ferric iron is normally reduced to soluble ferrous (Fe^{2+}) iron and the associated phosphorus is soluble.

Bohn et al. (2001) revealed that 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 $Ca(HPO_4)_2$.

Shrestha and Lin (1996) pointed out that the amount of phosphorus loss to sediment is usually different among aquatic culture systems. Boyd (1985) demonstrated that 55 % 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).

Dobbins and Boyd (1967) suggested that the application of phosphorus in fertilized ponds should be based on phosphorus concentration in bottom soil and other bottom soil characteristics. According to Masuda and Boyd (1994), total phosphorus concentrations in clayey bottom soils of ponds at Auburn, Alabama, were greater in deep water than shallow water areas. The highest phosphorus concentration was in the 5 to 10 cm soil layer. However, phosphorus accumulated above its original concentration to depths between 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).

Thunjai (2002) reported high phosphorus concentrations in bottom soil of tilapia ponds at Samutprakarn, Thailand. The 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. The average was 9 ppm. He concluded the high concentrations resulted from applying phosphorus fertilizer to ponds over several years.

Best management practices (BMPs)

BMPs are the most economically feasible and technically practical methods of reducing environment impacts. For example, BMPs provide means to prevent overfeeding of fish to avoid excessive nutrient loading in ponds, and to minimizing the environment impact from effluent released from ponds to receiving water (Boyd et al. 2003).

Thunjai (2002) pointed out that high soil organic matter, loss of the oxidized layer and accumulation of soft sediment, are the major concerns for bottom soil management in aquaculture.

Aquaculture pond bottom soils receive large amounts of nutrients and organic matter from erosion, uneaten feed and fertilizer. It is generally thought that nutrients and organic matter tend to accumulate in the bottom soils as pond age increases (Boyd 1992). High nutrient concentrations are not undesirable in pond soil, but large amounts of organic matter can have adverse effects (Boyd 1995). Thus, BMPs are needed for preventing excessive accumulation of organic matter in pond soils.

According to pond studies by Boyd and Teichert-Coddington (1994), when the ponds were completely dried, the decomposition rate of organic matter in pond soil 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 of organic matter and chemical oxidation of reduced substances.

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.

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 or total alkalinity of water in old ponds.

Pond draining and the discharge of effluents through ditches to streams can cause erosion and suspension of soil particles (Schwartz and Boyd 1994). Thus, ponds should be drained slowly to lessen 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.

MATERIALS AND METHODS

The ponds for this study were selected in Supanburi Province in central Thailand (Fig. 1) with the assistance of the Thailand Department of Fisheries. There were 42 ponds for culture of hybrid catfish *Clarias macrocephalus* × *C. gariepinus*, 40 ponds for culture of freshwater prawn, and 18 ponds for culture of carp. The fish and prawn farms were visited in February 2002, and information on pond features, culture methodology and production data, and bottom soil management were obtained by interviewing the owners. Water and soil samples also were collected. Additional information on production practices were requested from biologists in the Department of Fisheries or obtained from publications on practical aquaculture in Thailand (Brohmanonda and Sahavacharin 1985; Areerat 1987).

Soil and water samples

Bottom soil samples were taken with 5-cm diameter, clear plastic, core liner tubes (Wildlife Supply Company, Buffalo, New York, USA). Workers waded into ponds and inserted the tubes into the bottoms by hand at five places in the deep end of each pond where water was 1 to 1.5 m in depth. Tubes were hammered with a wooden mallet to force them into the original pond bottom soil or P horizon (Munsiri et al. 1995). Tubes were beneath the water, and a plastic cap was put on the upper end so that they could be withdrawn from the bottom with soil cores intact and undisturbed by water movement. Caps were placed on the bottom ends of tubes before they were lifted from the water to prevent soil cores from slipping out. Tubes were maintained in a vertical position to avoid disturbing the surface of the core.

Water was siphoned from the tubes by aid of flexible, 0.75-cm diameter latex tubing leaving only 1 to 2 cm of water above the core surfaces. The thickness of the S horizon and total sediment thickness (S and M horizons) was measured with a ruler (Munsiri et al. 1995).

Soil cores were pressed upward in the core liner tubes using a core removal tool (Wildlife Supply Company). A core segment ring made from a piece of core liner tube (Munsiri et al. 1995) was placed on top of the core liner tube containing the soil core. The part of the soil core comprising the S horizon was pressed into the core segment ring. The S horizon was separated by inserting a thin, 10-cm wide spatula between the bottom of the core segment ring containing the S horizon and the core liner tube containing the rest of the core. The S horizon from one core in each pond was placed in a tared soil moisture canister. The S horizons from the other four cores from each pond were combined in a single plastic container to make a composite sample from each pond. The samples were held in an insulated ice chest for 6 to 12 h until they were transferred to drying ovens.

Water samples were dipped from the surface of each pond. These samples were stored in tightly-sealed, 1,000-mL plastic bottles.

Soil analyses

Soil samples in tared canisters were dried to constant weight at 102°C, and the dry bulk density was calculated (Blake and Hartge 1986) in grams per cubic centimeter. Composite soil samples were dried at 60°C for 72 h in a mechanical convection oven. The dry soil samples and water samples were shipped to Auburn University for further analyses.

Dry samples were pulverized with a mechanical soil crusher (Custom Laboratory Equipment, Inc., Orange City, Florida, USA) to pass a 40-mesh (0.425-mm) sieve and stored in plastic containers.

Soil pH was measured with a glass electrode inserted into a 1:1 mixture of dry, pulverized soil and distilled water (Thunjai et al. 2001). The concentration of total carbon was measured with a Leco Model EC 12 induction furnace carbon analyzer (Leco, St. Joseph, Michigan, USA). Organic carbon was measured by the Walkley-Black sulfuric acid (H_2SO_4)-potassium dichromate ($K_2Cr_2O_7$) oxidation procedure (Nelson and Sommers 1982). Total nitrogen concentrations were determined with a Leco Carbon-Hydrogen-Nitrogen Analyzer CHN 600 by the Auburn University Soil Testing Laboratory.

Total phosphorus was measured by the dry ash method (Tavares and Boyd 2003). In this procedure, 1.00 g of dry soil was placed in a 10-mL high-form crucible, covered with a pyrex watch glass, and ashed at 450°C for 4 h or until the ash was a grayish-white color. After cooling, the ash was treated with 10 mL of 1 N nitric acid (HNO_3). The crucible was placed on a hotplate and heated until the nitric acid evaporated. Next, 10 mL of 1 N hydrochloric acid (HCl) was added to the ash, and the temperature was increased until the hydrochloric acid boiled. The acid and residue were transferred to a 100-mL volumetric flask and made to volume with distilled water. The sample was filtered through an acid-washed, Number 40 Whatman filter paper. The filtrate was analyzed for phosphorus by the vanadomolybdate method (Olsen and Sommers 1982). Water-soluble phosphorus was measured by shaking 2-g soil samples with 100 mL of distilled water for 24 h, removing the soil by filtration through a Whatman Number 40 filter paper, and measuring phosphorus concentrations in the extracts by the ascorbic acid method (Boyd and Tucker 1992). Dilute-acid soluble phosphorus was extracted from 1.0-g soil samples with a solution of 0.05 N hydrochloric acid and 0.025 N sulfuric acid. Extracts were filtered through Whatman Number 40 filter paper, and dilute-acid extractable phosphorus was measured with a Jarrel-Ash ICAP 9000 Plasma Spectrophotometer by the Auburn University Soil Testing Laboratory. Phosphorus also was extracted from soil samples by the Lancaster (Mississippi) method for calcareous soils (Hue and Evans 1986). The extractant was made by adding 90 mL glacial acetic acid (CH_3COOH), 6.5 g of malonic acid [$CH_2(CO_2H)_2$], 120 g of malic acid [$CH_2CHOH(CO_2H_2)_2$], and 1.38 g of ammonium fluoride (NH_4F) to 750 mL of deionized water. The solution was mixed well to dissolve reagents, and 3.0 g of aluminum chloride ($AlCl_3$) were added and the solution mixed again. The pH was adjusted to 4.0 with ammonium hydroxide (NH_4OH), and the solution was diluted to 1,000 mL with deionized water. Extraction consisted of placing 5-g soil in 20 mL of extracting solution and shaking at 180 oscillations/min for 5 min. The extracts were passed through a Whatman Number 40 filter paper. Phosphorus in filtrates was measured by the vanadomolybdate method (Olsen and Sommers 1982).

Soil sulfur was measured by the method of Bardsley and Lancaster (1960). A 2.5-g soil sample was mixed with 0.5 g of sodium bicarbonate ($NaHCO_3$) in a crucible, and 0.5 g of sodium bicarbonate was spread over the surface of the sample. The crucible and its contents were placed in a muffle furnace for 3 h. After cooling, the contents of the crucible were transferred to a 50-mL Erlenmeyer flask. A 25-mL volume of extracting solution containing 4.6 g of monosodium phosphate ($NaH_2PO_4 \cdot H_2O$) dissolved in 2 N acetic acid was added, and the flask was agitated for 30 min at 150 oscillations/min. Following filtration through a Whatman Number 40 filter paper, the solution was analyzed for sulfate-sulfur by the barium chloride method. The sulfur concentration in the soil was calculated.

Major cations and minor elements were extracted from soil samples with a solution of 0.05 N hydrochloric acid and 0.025 N sulfuric acid (Hue and Evans 1986). Ionic concentrations in extracts were measured with a Jarrel-Ash ICAP 9000 Plasma Spectrophotometer by the Auburn University Soil Testing Laboratory.

The cation exchange capacity (CEC) was determined by saturating exchange sites with potassium by shaking soil samples in a 1 N potassium chloride (KCl) solution. After washing the soils free of excess potassium chloride solution, the potassium was exchanged with ammonium by shaking samples in a neutral, 1 N ammonium chloride (NH_4Cl) solution. Potassium displaced by ammonium was measured in the ammonium chloride solution using an Atomic absorption Spectrophotometer. The amount of potassium displaced in milliequivalents per 100 g of soil was equal to the cation exchange capacity (CEC) of the soil sample.

Major cations, calcium, magnesium, sodium and potassium, and minor elements, aluminum, iron, manganese, zinc, copper, boron, cadmium, chromium, and lead, were extracted from soil samples with dilute, double acid solution (0.05 N hydrochloric acid + 0.025 N sulfuric acid as described by Hue and Evans 1986). Concentrations of elements in extracts were determined by ICAP.

Exchangeable acidity was measured from the pH change in a solution containing 20 g soil and 40 mL buffer. The buffer was made by dissolving 10 g *p*-nitrophenol, 7.5 g boric acid (H_3BO_4), 37 g potassium chloride (KCl), and 5.25 g potassium hydroxide (KOH) in distilled water, adjusting the pH to 8.00 ± 0.01, and diluting to 1,000 mL (Hue and Evans 1986). A pH change of 0.10 units in 40 mL of this buffer equals 0.08 mEq of exchangeable acidity.

Particle-size analysis was conducted by a simplified hydrometer method described by Weber (1977). The sample was suspended in a 0.5% solution of hexametaphosphate [$(NaPO_3)_6$] in a 1-L sedimentation cylinder and hydrometer readings were made after 40 sec to allow estimation of percentage clay plus silt and after 2 hr to permit estimation of percentage clay. Silt was estimated as clay plus silt minus clay and sand was calculated as 100% minus percentage clay and silt.

Water analyses

Water samples were analyzed for total alkalinity (acidimetry), total hardness (titration with ethylenediaminetetraacetic acid), chloride (mercuric nitrate-diphenylcarbazone method), sulfate (barium chloride turbidimetry), and major cations (ICAP) following protocol described by Clesceri et al. (1998).

RESULTS

Study area

The study area was situated within the Central Plain of Thailand. The terrain was mostly flat, and the land form resulted from low alluvial terraces of both old and recent alluvium (Khaewreenrom 1990). Soils can be classified as inseptsols, and they can vary from very sandy to heavy clays. The soils also can vary greatly in pH with some areas having extremely acidic soils and others with neutral to slightly alkaline soils. Annual rainfall is about 1,400 mm. There is a distinct wet season from June to September with relatively little rainfall during the rest of the year. Average annual air temperature within the Central Plain is 28 to 30°C. The hottest weather corresponds to the later part of the dry season and the rainy season.

The Central Plain is primarily an agricultural region with rice production being the major crop. There are many canals that serve as a source of irrigation water. These canals also are the water source for aquaculture ponds in the Central Plain.

Ponds

The ponds were made by constructing earthen embankments around the area in which water was impounded. Carp and freshwater prawn ponds tended to have larger water surface areas than catfish ponds, but catfish ponds tended to be deeper than other ponds (Table 1). The inside slopes of embankments of some catfish ponds were lined with stone to minimize erosion. Water for filling ponds was either pumped from canals into ponds using “long-tailed” pumps (Yoo and Boyd 1993) or gates with dam boards (monks) were installed to allow water from canals to enter ponds. Ponds were emptied using pumps or gates.

Ponds varied in age from 1 year to 30 years (Table 2), but few ponds were more than 15 years old. Over 60% of ponds were 10 years or less in age.

Production methods

The description of production methodology will be given separately for each of the three species. The description will begin at the end of harvest, and pond preparation for the next crop will be the first activity described.

Catfish

Following draining and harvest, most farmers treat the wet pond bottom with lime (burned limestone) at about 600 to 800 kg/ha. This treatment apparently is intended mainly to temporarily raise the soil pH and effect disinfection. However, it also has a more lasting effect by neutralizing soil acidity and increasing the total alkalinity and total hardness of pond waters (Boyd and Tucker 1998). Bottoms usually are allowed to dry from 10 to 14 days, and at about 2-year intervals, sediment is removed manually by aid of shovels from the deep ends of ponds. This sediment usually is placed on the embankments. After dry-out, burned lime was spread over bottoms at 800 to 1,600 kg/ha. The pond was then filled to a depth of 50 to 80 cm with water and fish were stocked. The water level gradually was increased to the full-pond depth of 1.5 to 2.5 m as fish grew.

Stocking rates ranged from 30 /m^2 with large fingerlings to about 300 /m^2 with small fingerlings. Fertilizer was not used in ponds, but chicken slaughterhouse wastes were minced and applied to ponds daily at roughly 10% of estimated fish body weight. However, feeding with slaughterhouse waste was based largely on each farmer's judgment, and records of typical annual inputs to ponds were not available. Some farmers also applied pelleted feed twice daily. The feed contained 35% crude protein, and daily feed inputs for fingerlings, juvenile, and adult fish probably were about 8 to 10%, 4 to 6%, and 1 to 2%, respectively. Again, farmers did not keep good records, and estimates of typical annual inputs could not be made.

Water quality deteriorates rapidly in catfish ponds because of the large inputs of waste and feed. Waters had visibly high concentrations of suspended organic matter and often were black in color. Mechanical aeration was not used to increase dissolved oxygen concentrations, but these catfish are air-breathers and can tolerate low dissolved oxygen concentrations quite well. Water exchange was used to improve water quality. Typically, farmers added about 20% of pond volume every 3 days to flush low quality water from ponds.

Catfish were harvested after 4 to 6 months when they have reached 150 to 300 g in size. The ponds were drained, and the fish captured by scoop nets. Typical production was 60,000 to 80,000 kg/ha/year.

Freshwater prawn

After draining for final harvest, accumulated sediment was removed from the deeper areas of the pond by aid of a tractor. The bottoms were dried for about 2 weeks. This procedure kills disease organisms, wild fish, and other organisms that can persist in ponds between crops. Where pond bottoms could not be dried, rotenone was applied to bottoms to kill wild fish and other organisms. Pond soils were limed at 60 to 625 kg /ha.

Following refilling with water, ponds were stocked with prawns at 25 to 75 /m^2. Fertilizers were not used, and prawns were provided a commercial, pelleted feed containing 40 to 45% crude protein. Daily feed inputs declined from about 8 to 10% of body weight for recently stocked prawn to about 2% of body weight for adult prawn. Daily feed input reached 50 to 70 kg /ha.

Water quality is a critical factor in freshwater prawn culture. When dense blooms of phytoplankton develop in ponds, dissolved oxygen concentration often declines. Farmers exchanged water to flush out excess nutrients and plankton, but mechanical aeration was not used to enhance dissolved oxygen concentrations. The normal water exchange program was given as follows:

- During the first 2 months of culture, water exchange was not necessary, but water was applied weekly to gradually fill ponds completely.

- During the remainder of the grow-out period, water was exchanged 2 to 4 times per month by removing one-third of the pond water and replacing it with water from the supply canal.

- Emergency water exchange was applied anytime that deteriorating water quality was considered harmful to prawns.

Water exchange also was thought to improve prawn growth by aiding the molting process.

Most prawn farmers applied microbial inocula to ponds. This treatment was thought to improve microbial degradation of waste from feed. In addition, farmers dragged a chain over the pond bottom two or three times during the period when water was discharged for water exchange. This procedure was considered useful in suspending organic particles so that they could be flushed from ponds. However, farmers indicated that the chain dragging procedure was not appropriate where large amounts of waste had accumulated on the bottom. In these cases, a small hand-operated suction device (dredge) was used to remove accumulated wastes and soft sediment.

Prawns grow at variable rates, but after 6 months of culture marketable-sized prawn usually can be found in ponds. Seines with 4- to 5-cm mesh openings were used to partially harvest prawns at intervals. The seine was stretched across the width of the pond and pulled the entire length of the pond. Most small prawns passed through the mesh openings, but any small prawns caught in the seine were returned to the pond. After 11 to 12 months of culture, ponds were drained completely to complete the harvest of prawns. Normal production usually was 1,800 to 3,000 kg/ha/year (crop).

Carp

There were two systems of carp culture. One system involved production of carp in relatively small ponds. These ponds were drained each year for harvest. Sediment was removed when considered necessary and usually at 3- to 5-year intervals. Bottoms were dried for 2 or 3 weeks and ponds refilled. Data on stocking rate could not be obtained. Chicken house wastes were applied to these ponds, but the farmers could not provide an estimate of the amount used. Pelleted feed containing 25% crude protein also was applied to ponds at 1 to 2% of body weight one time per day. Mechanical aeration was not applied, and farmers only used water exchange when water quality deteriorated to dangerous levels in ponds. Fish were harvested by draining ponds. Production usually was about 3,000 to 4,000 kg/ha/year.

The other carp production system was integrated with chicken farming. The chicken houses were constructed over relatively large (2 to 5 ha) carp ponds, and waste feed and feces from chicken cages fell into the pond. Other inputs of fertilizers and feeds were not made to ponds. Mechanical aeration was not applied, and water exchange was only applied in water quality emergencies. Fish were harvested by seining, and 4,000 to 6,000 kg/ha typically were removed per year. After 3 to 5 years, ponds may be completely drained to permit sediment removal.

Bottom soils

The means, standard deviations, and ranges for soil variables were presented by culture species for sediment physical characteristics, pH, carbon fractions, nitrogen, phosphorus fractions, sulfur, and cation exchange capacity and exchangeable acidity

(Tables 3, 4, and 5). Tables 6, 7, and 8 contain information on major cations, calcium, magnesium, potassium, and sodium, and minor elements, aluminum, iron, manganese, zinc, copper, and boron concentrations. The variables were compared among culture species, including tilapia ponds in Thailand (Thunjai et al. 2004), in Fig. 2.

Sediment physical characteristics

Sediment depth was highly variable among ponds for all three culture species (Tables 3, 4, and 5). Much of this variation likely was related to the length of time that had passed since sediment was removed from individual ponds. Mean sediment depth ranged from 11.9 cm in freshwater prawn ponds to 33.4 cm in carp ponds. Sediment depth was significantly greater ($P < 0.05$) in carp ponds than in ponds for prawn and catfish (Fig. 2). This difference was related to less frequent removal of sediment from carp ponds. Total sediment thickness in tilapia ponds was 16 cm (Fig. 2), and more similar to catfish and prawn ponds than carp ponds.

The thickness of the S horizon also varied greatly among ponds for all species (Tables 3, 4, and 5). Mean S horizon thickness was greater in carp ponds than in catfish and prawn ponds ($P < 0.05$). Tilapia ponds had an average S horizon thickness of 7 cm (Fig. 2) – similar to catfish and prawn ponds.

Dry bulk density was greater ($P < 0.05$) in sediment of carp ponds than in that of catfish and prawn ponds. Tilapia ponds had an average dry bulk density of 0.23 g /cm^3 (Fig. 2). Thus, average bulk density of the S horizon ranged from 0.17 to 0.28 g /cm^3 in ponds for the culture of four, freshwater species in Thailand. Munsiri et al. (1995)

defined the S horizon as the upper, well-mixed layer of sediment with a dry bulk density of 0.3 g /cm^3 or less. Results of this study and the findings for tilapia ponds in Thailand support the bulk density limit in the definition of the S horizon suggested by Munsiri et al. (1995). The S horizon is the layer that is most active in exchange of substances between sediment and water, and it is thought to have a large influence on pond water quality (Boyd 1995).

The particle size distribution in bottom soils differed greatly among ponds (Tables 3, 4, and 5). Sand concentrations were low averaging between 0.21 and 13.72%. Catfish and carp ponds were similar in sand concentration and had more sand ($P < 0.05$) than prawn ponds. Average silt concentrations were between 53.2% and 63.6%, and prawn ponds had a greater percentage of silt than catfish or carp ponds. Average clay concentrations were from 33.1 to 38.3%, and catfish ponds had a greater percentage of clay than carp ponds. In general, pond soils contained more than 30% clay and 50% silt. The differences in percentages of sand, silt, and clay probably were related to original characteristics of pond bottom soil rather than the influence of aquaculture. In spite of the differences among ponds in percentages of sand, silt, and clay, soil texture based on average particle size was silty clay loam for the three groups of ponds, and most ponds actually had soils of this texture. However, a few ponds used for catfish culture had sandy loam soils and several ponds for all species had silt loam soils. The texture classes found in the ponds are suitable for pond aquaculture (Boyd 1995). Thunjai et al. (2004) did not determine the particle-size distribution of tilapia pond soils in Thailand.

pH

Soil pH ranged from 3.81 in a carp pond to 7.82 in a catfish pond (Tables 3, 4, and 5). However, average pH did not differ ($P > 0.05$) among the three types of ponds (Fig. 2). Moderate amounts of liming materials had been applied annually to the ponds, but most ponds still had slightly acidic soils with pH values between 6 and 6.8. In tilapia culture, liming rates usually were 3 or 4 times greater than those used in the ponds for this study. Soil pH in tilapia ponds averaged 7.5 and only one pond out of 35 ponds in the study by Thunjai et al. (2004) had a pH below 7.

The optimum pH range for aquaculture pond soils is 7.5 to 8.0, for microbial activity is most rapid in this pH range (Boyd and Pipoppinyo 1994). Microbial decomposition of organic matter recycles nutrients and prevents accumulation of large amounts of organic matter in pond bottoms.

Carbon

Concentrations of total carbon ranged from 0.38 to 7.08% (Tables 3, 4, and 5). The average total carbon concentration of 3.02% in carp ponds was more than two-fold greater ($P < 0.05$) than those of catfish and prawn ponds – 1.46 and 1.38%, respectively. Tilapia ponds were similar to carp ponds with respect to total carbon concentration (Fig. 2).

Organic carbon concentration ranged from 0.26 to 5.07%, but few samples had more than 3%. Carp ponds had a higher average organic carbon concentration ($P < 0.05$) than catfish or prawn ponds (Fig. 2). Tilapia ponds had an average organic carbon concentration of 1.90% - similar to carp ponds. Results of organic carbon analyses for many ponds in Thailand confirm the statement by Boyd (1995) that aquaculture pond soils seldom contain more then 3% organic carbon.

The optimum range of organic carbon in pond soils is 1 to 3% (Banerjea 1967). Lower concentrations are unfavorable for growth of benthic organisms that are important food for young of many species, and higher concentrations favor anaerobic conditions at the soil water interface.

The organic carbon method by sulfuric-acid-potassium dichromate oxidation does not oxidize all of the organic matter in a soil sample (Nelson and Sommers 1982). The induction furnace method used for total carbon oxidizes essentially all organic carbon, and it decomposes soil carbonate to release and measure inorganic carbon. Soils in this study were usually slightly acidic or neutral in reaction and not thought to contain appreciable carbonate. Thus, the difference between total carbon and organic carbon likely consisted primarily of organic matter resistant to oxidation by acidic, potassium dichromate solution and heat. Total carbon analysis requires an expensive, complex instrument while organic carbon can be measured with relatively simple laboratory apparatus or with a portable kit (Queiroz and Boyd 1998). Soil organic carbon also is of more concern to aquaculturists because it is the more labile form that decomposes rather quickly and can lead to low redox potential in the pond bottom (Boyd 1995). Soil organic matter contains about 50 to 58% carbon, and factors of 1.724 to 2.0 have been used to convert organic carbon concentrations to organic matter concentrations (Nelson and Sommers 1982).

There was a strong relationship between organic carbon and total carbon for soils from ponds for all three species. The coefficients of determination (R^2) for regressions were 0.935 for catfish, 0.748 for carp, and 0.744 for prawn. The regression line for data from all samples (Fig. 3) has $R^2 = 0.851$.

Nitrogen, phosphorus, and sulfur

Total nitrogen concentration ranged from less than 0.05 to more than 0.5% (Tables 3, 4, and 5). Carp pond soils had an average total nitrogen concentration of 0.28% that was greater ($P < 0.05$) than averages for catfish ponds (0.18%) and prawn ponds (0.l4%). Carbon:nitrogen ratio did not differ ($P > 0.05$) for the three groups of ponds and the average for all ponds combined was 9.3. Assuming that pond soil organic matter is about 52% carbon, it would contain roughly 5% nitrogen. Terrestrial soil organic matter also contains about 5% nitrogen (Brady 1990). The carbon: nitrogen ratio, however, was quite variable among samples (Fig. 4), but the R^2 value for the regression was 0.757 and verifies that there is a close relationship between soil carbon and soil nitrogen in aquaculture pond soils. Of coarse, this relationship has long been recognized in terrestrial soils (Brady 1990).Tilapia ponds in Thailand had an average total nitrogen concentration of 0.19% and a carbon:nitrogen ratio of 11 (Thunjai et al. 2004). The ideal carbon:nitrogen ratio for aquaculture ponds is thought to be 8 to 12 (Boyd 1995).

Total phosphorus concentration averaged 1,567, 1,085, and 334 ppm in catfish, carp, and prawn pond soils, respectively (Tables 3, 4, and 5), and each type of pond differed from the others (Fig. 2). The input of feed and animal by-products to ponds to promote fish production increased in the same order as did total phosphorus concentrations. Averages for dilute-acid extractable and water-soluble phosphorus did not differ between carp and prawn ponds, but catfish ponds had much higher concentration than the other two classes of ponds. The Lancaster extraction method extracted an average of about 200 ppm phosphorus from soils of catfish and carp ponds. This concentration was greater ($P < 0.05$) than that of 76 ppm extracted by this solution from prawn pond soils. There was a positive relationship between total phosphorus concentration and phosphorus extracted by the three solutions as follows: water-extractable phosphorus, $R^2 = 0.201$; dilute-acid extractable phosphorus, $R^2 = 0.417$; Lancaster solution-extractable, $R^2 = 0.436$. However, total phosphorus would not be a good predictor of any of the three fractions because of the relatively low R^2 values. Thunjai et al. (2004) did not measure total phosphorus or determine the amount of phosphorus extracted by the Lancaster method for tilapia pond soils. However, concentrations of water and dilute-acid extractable phosphorus averaged 9 and 217 ppm, respectively, for tilapia pond soils. According to Banerjea (1967), increasing phosphorus concentrations in pond soils favor a greater potential for fish production. Nevertheless, if pond soils become saturated with phosphorus, they will no longer remove phosphorus from pond water. High concentration of phosphorus in water form dense phytoplankton blooms and low dissolved oxygen concentrations will occur frequently (Banerjea 1967; Boyd 1995).

Ponds of the three types of aquaculture differed in average sulfur concentration. Individual values for all ponds ranged from 73 to 7,197 ppm, and averages were 837, 1,590, and 2,874 ppm for prawn, carp, and catfish pond soils, respectively (Tables 3, 4, and 5). The increase in sulfur concentration is in order of increasing input of organic matter in feed and other organic material to the ponds for the three species. Thus, the soil sulfur probably was primarily in organic form. The study of tilapia pond soils was conducted in Samutprakarn area where soils often contain deposits of iron pyrite (FeS_2) (Thunjai et al. 2004). Sulfur concentrations reached 3.03%, and the average was 1.18%. Sulfur concentrations above 0.75% are indicative of acid-sulfate soils (Soil Survey Staff 1994). Such soils tend to be highly acidic (Dent 1986), and heavy applications of liming materials are necessary to counteract acidity from pyrite oxidation.

Cation exchange capacity and exchangeable acidity

The CEC of the soils did not differ among the three types of pond culture (Fig. 2). The averages for CEC were near 30 mEq/100 g. The lowest CEC was 11.92 mEq/100 g and the greatest value was 43.8 mEq/100 g (Tables 3, 4, and 5). These CEC values are similar to those for tilapia ponds in Thailand (mean = 35 and range = 12.1 to 42.6 mEq/100 g) (Thunjai et al. 2004). These are rather high CEC values, and a moderate to high CEC is desirable in pond soils. It is associated with adequate concentrations of major cations to assure that pond waters contain enough cations to promote good osmoregulatory function in the culture species (Boyd 1995).

The exchangeable acidity was low (0 to 6.0 mEq/100 g) as expected from the near neutral pH of the samples. This was the result of frequent applications of liming materials to the pond bottoms. Exchangeable acidity usually was less than 1 mEq/100 g in soils from tilapia ponds (Thunjai et al. 2004).

Major cations

Individual calcium concentrations ranged from 1,216 to 7,832 ppm. The averages were nearly 5,000 ppm for catfish and carp ponds and about 4,000 ppm for prawn ponds (Tables 6, 7, and 8). Catfish ponds had greater concentrations of soil calcium than prawn ponds, but they did not differ in calcium concentration from carp ponds (Fig. 2). Magnesium concentrations were roughly one-tenth of calcium concentrations and ranged from 94 to 938 ppm. The averages for the three bottom soil groups ranged from 438 to 498 ppm, but did not differ ($P > 0.05$). There was no correlation ($P > 0.05$) between soil calcium and soil magnesium for the samples. Potassium concentrations were between 27 and 479 ppm for individual samples with averages between 144 and 205 ppm. Carp ponds had greater soil potassium concentrations than the other ponds. This likely resulted from potassium entering ponds from the chicken houses or from chicken manure applied to ponds. Sodium concentrations averaged between 28 and 700 ppm for the three classes of fish culture. Averages were between 136 and 183 ppm, and they did not differ among the types of pond culture.

Means for all samples were as follows: calcium, 4,866 ppm; magnesium, 465 ppm; potassium, 169 ppm; sodium, 161 ppm. These values correspond to the following concentrations in milliequivalents per 100 g soil: calcium, 24.28; magnesium, 3.83; potassium, 0.43; sodium, 0.7. The total concentration of major ions is equal to 29.24 mEq/100g. The average CEC for all samples was 30.39 mEq /100 g. Thus, the measured CEC agreed quite closely with the concentration of exchangeable cations in the soil.

The exchangeable cations were extracted with dilute acid. Thus, if soils had contained appreciable calcium carbonate, the acid would have dissolved the calcium carbonate and the concentration of major ions would have exceeded the CEC. Thus, the difference in total carbon concentration and the organic carbon concentration found in this study does not represent inorganic carbon in carbonate. The difference, as mentioned above, resulted from a lower percentage recovery of organic carbon by the Walkley-Black method as compared to the induction furnace method.

Thunjai et al. (2004) did not report concentrations of major cations for samples of bottom soils from tilapia ponds in Thailand. Boyd et al. (1994) developed concentration categories for major cations in pond soils based on data from 358 ponds mostly in the United States. When ranked according to these concentration categories, the averages (all ponds) for samples in this study were high for calcium, very high for magnesium, potassium, and sodium. However, no guidelines for optimum concentrations of major cations in soils of fish and prawn ponds could be found in the literature.

Minor elements

Aluminum concentrations ranged from 0.6 to 226 ppm (Tables 6, 7, and 8), but averages (83 to 104 ppm) for the three kinds of pond culture did not differ ($P > 0.05$) (Fig. 2). Iron and manganese concentrations were as variable as those of aluminum (Tables 6, 7, and 8). Average iron concentrations of 91 and 96 ppm in prawn and catfish pond soil, respectively, were lower ($P < 0.05$) than the average of 202 ppm for carp pond soil. The average manganese concentration of 55 ppm in catfish pond soil was lower ($P < 0.05$) than average values of 86 and 90 ppm in prawn and carp pond soils, respectively. Zinc and copper concentrations were much lower than those for aluminum, iron, and manganese as usually is the case in soil samples (Brady 1990). The greatest zinc concentration was 32 ppm while the highest copper value was 6.9 ppm. The average zinc was higher ($P < 0.05$) in soils of carp ponds than in those of the other two types of aquaculture. Copper concentrations also were greater in carp pond soils. Boron concentrations ranged between 1.0 and 6.8 ppm. Average concentrations of boron did not differ among ponds for different species ($P > 0.05$). Nickel was measurable in pond soils and ranged from 0.5 to 4.1 ppm and average nickel concentrations did not differ ($P > 0.05$) among the three kinds of aquaculture. The ICAP procedure also analyzed samples for cobalt, cadmium, chromium, and lead. However, all samples contained less than detectable concentrations (< 0.1 ppm) of these four elements.

Thunjai et al. (2004) did not provide data on minor element concentrations in soils from tilapia ponds in Thailand. Boyd et al. (1994) reported concentration categories for soil chemical variables based on analyses of 358 samples from freshwater aquaculture ponds mostly in the United States. By comparison with these categories the averages for minor elements in pond soils from Thailand were medium in aluminum, medium (prawn and catfish ponds) or high (carp ponds) in iron, high in manganese, very high in zinc, medium or high in copper, and very high in boron. In general, minor elements tended to be higher in the carp pond soils than in soils from catfish and prawn ponds. The reason for this tendency is not known. However, animal manures are typically high in concentrations of minor elements (Boyd and Tucker 1998). Thus, the application of chicken house wastes to carp ponds was possibly the reason for the tendency for higher concentrations of minor elements in soils of carp ponds than in other ponds. As with major cations, optimum soil concentrations of minor elements are not known (Boyd et al. 1994).

Correlation among soil variables

A correlation matrix for soil physical and chemical variables is provided (Table 9). Because of the large sample size (n = 100), a number of the correlation coefficients were significant. However, most did not account for a large proportion of the variation between two variables. The largest correlation coefficients were as follows: total sediment depth versus S horizon depth (r = 0.785); silt versus sand (r = 0.932); pH versus exchangeable acidity (r = 0.840); organic carbon versus total carbon (r = 0.955); total carbon versus total nitrogen (r = 0.870); organic carbon versus total nitrogen (r = 0.811). None of the correlations listed above are surprising; however, it was interesting that so many of the variables were not correlated. This suggests that there is no single soil quality variable or a few soil quality variables that can be measured and used to estimate overall soil quality.

Soil pH and organic carbon are the two most commonly measured soil quality variables in commercial aquaculture. The two variables are thought to be important indicators of the potential of ponds to produce fish or shrimp (Banerjea 1967; Boyd 1995). However, neither of these two variables were useful as general predictors of soil chemical and physical characteristics.

Influence of pond age

Regression analyses between pond age (X) and all individual soil quality variables (Y) were conducted to ascertain if pond soil variables changed in relation to pond age. There were few significant correlations between pond age and any of the variables (Table 10). Earlier studies (Tucker 1985; Thunjai et al. 2004) found that pond age and total and organic carbon in pond soils were correlated, but the relationship did not account for much of the variation in organic carbon concentration. Munsiri et al. (1995) and Tepe and Boyd (2002) found that several soil quality variables increased in pond soils over time. A study of shrimp farm bottom soils in Madagascar also revealed that total phosphorus concentrations increased as ponds aged (Boyd et al. 2006).

Studies showing an increase in pond soil quality variables over time were conducted in ponds where sediment was not routinely removed or never removed. Sediment was removed at intervals from ponds in the present study. Thus, the lack of correlation between pond age and sediment quality in freshwater aquaculture ponds in Thailand probably is related to the practice of sediment removal.

Water quality

Water quality analyses (Tables 11, 12, and 13; Fig. 5) were restricted to pH that could be measured on site, and major ions, total alkalinity, and total hardness that do not change appreciably during sample storage in sealed bottles (Boyd and Tucker 1998).

The pH was seldom below 7, but one catfish pond had a pH of 5.45. Average pH for the three groups of ponds ranged from 7.60 to 7.86, but there were no differences among the groups. A pH of 7 to 8.5 is considered excellent for pond fish culture (Boyd and Tucker 1998). Thus, most ponds had acceptable pH.

Total alkalinity and total hardness concentrations exhibited wide ranges of 0.48 to 235.7 mg/L and 47.0 to 805.8 mg/L, respectively. However, concentrations for most ponds were above 50 mg/L and below 300 mg/L. The lowest concentration of average total alkalinity (79.0 mg/L) in freshwater prawn ponds differed ($P < 0.05$) from those of catfish (117.1 mg/L) and carp (104.4 mg/L) ponds. Total hardness did not differ among the different classes of ponds, and total hardness and total alkalinity were not correlated. Nevertheless, total hardness was consistently greater in concentration than total alkalinity. This is a common phenomenon in aquaculture ponds. When liming materials, burnt lime, hydrated lime, or agricultural limestone, are added to water they react with carbon dioxide to increase the bicarbonate concentration (alkalinity) and calcium and magnesium concentration (hardness). However, native acidity from bottom soils and hydrogen ions from decomposition and nitrification react with alkalinity and lessen its concentration, but the calcium and magnesium ions remain to increase total hardness (Boyd and Tucker 1998).

Ponds for food fish production should have total alkalinity concentrations of 50 to 200 mg/L (Boyd and Tucker 1998). Most ponds in this study had acceptable concentrations of alkalinity. Total hardness concentrations also should exceed 50 mg/L, but concentrations above 200 mg/L are acceptable (Boyd and Tucker 1998).

Concentrations of major anions and cations varied widely among individual ponds. Chloride concentrations were as low about 2 mg/L and as high as 400 mg/L, but averages for the three kinds of aquaculture were between 22.8 and 54.6 mg/L, and they did not differ ($P > 0.05$). Sulfate concentrations ranged from about 3 mg/L to over 200 mg/L, but averages were 53.6 to 65.9 mg/L and did not differ.

Calcium concentrations were mostly above 20 mg/L, and averages exceeded 30 mg/L, while magnesium concentrations normally were above 5 mg/L with averages of 11.6 to 15.0 mg/L. Catfish ponds had a higher average calcium concentration than carp or prawn ponds. Magnesium concentration did not differ among the three ponds of aquaculture. The ratio of calcium to magnesium averaged 3.42:1. There was a significant relationship between calcium and magnesium concentrations (Fig. 6) in the pond waters.

Potassium and sodium concentrations also varied greatly among ponds. Averages were between 5.5 and 9.6 mg /L for potassium and 33.2 and 63.0 mg/L for sodium. Potassium concentrations were greatest in carp ponds ($P < 0.05$), but sodium concentrations did not differ ($P > 0.05$) among the three culture types. The average sodium and potassium concentrations for all ponds was 55.5 mg/L and 6.9 mg/L, respectively, for a sodium:potassium ratio of 8.04:1.

Soil pH was not correlated ($P > 0.05$) with any of the measured water quality variables. In unlimed ponds, there is a positive correlation between soil pH and total hardness, total alkalinity, calcium, and magnesium in pond water (Boyd 1974). However, ponds in this study had been routinely treated with liming materials. Liming increased soil pH and the concentration of alkalinity, hardness, calcium, and magnesium in the water obscuring the natural relationships among these variables.

Soil calcium and magnesium were not correlated with water calcium and magnesium. Again, liming would have obscured a relationship if it had existed in the original pond soils. There was a correlation between soil potassium and water potassium

($R^2 = 0.228$), but the correlation was likely partially obscured by additions of potassium in feeds and agricultural wastes. The relationship between soil sodium and water sodium had an $R^2 = 0.648$.

It was not possible to measure variables such as nitrogen and phosphorus fractions, dissolved organic matter, dissolved oxygen, and soil redox potential to regress them against soil quality variables. It is likely that some of these variables would have been correlated with soil quality.

DISCUSSION

The results reported above suggest that pond age is not an important factor determining the quality of catfish, freshwater prawn, and carp pond bottom soils in Thailand. This finding is in agreement with that of an earlier study of tilapia pond bottom soils in Thailand (Thunjai et al. 2004).

There were some differences in pond bottom soil quality among ponds for the culture of the three species of this study and tilapia. Carp ponds had a greater total sediment depth and thickness of the S horizon than ponds for other species. This probably was related to the longer period between sediment removal from carp ponds than other ponds.

Carp, catfish, and prawn ponds had lower soil pH than tilapia ponds because tilapia ponds were treated with greater amounts of liming material.

Carp ponds and tilapia ponds had greater concentrations of total and organic carbon than catfish and prawn ponds. Catfish ponds receive the largest inputs of organic matter and prawn ponds the lowest inputs. However, sediment removal is done more frequently in these two types of aquaculture than in the other two kinds. Nitrogen concentration tended to increase in response to increasing carbon concentrations, and carbon to nitrogen ratios were similar among ponds for the different culture species.

Total phosphorus and the different soil phosphorus fractions increased in the order prawn ponds, carp ponds, and catfish ponds. Phosphorus inputs to the ponds increased in the same order, and phosphorus is rapidly removed from pond water and bound in sediment (Boyd 1995). Sediment removal did not obscure this relationship even though large amounts of phosphorus were likely removed in sediment. The practice of removing sediment is likely beneficial in preventing saturation of sediment near the sediment-water interface with phosphorus.

Sulfur concentrations increased in the same order as total phosphorus concentrations. The soils of the Central Plain usually do not contain pyritic sulfur (Khaewreenrom 1990), and the sulfur in soils of this study probably was primarily organic sulfur. Tilapia ponds are much higher in sulfur concentration and contained pyritic sulfur.

The ponds of this study and tilapia ponds had moderately high and similar CEC. This is a native characteristic of the soils and not related to pond aquaculture.

The differences in major cations and minor elements are not thought to be significant in aquaculture. However, some of the differences, and especially differences in minor elements, may be related to aquaculture inputs.

The pond soils generally had favorable quality for use in aquaculture. However, ponds had been subjected to soil management to include liming, dry-out between crops, and sediment removal.

There is considerable concern about the possible negative environmental impacts of pond aquaculture (Goldburg and Triplett 1997; Clay 1997, 2004). With respect to pond soils, erosion of earthwork, draining for harvest, and sediment removal can increase inputs of suspended soils to nearby streams or other water bodies.

Best management practices for pond soils

Based on evaluation of pond features, production practices, and physical and chemical characteristics of bottom soil, a list of best management practices for possible use in freshwater pond aquaculture in Thailand have been developed. These practices should maintain pond bottom soil quality within a suitable range for aquaculture and avoid negative, off-site environmental impacts.

Practice 1. After ponds are drained for harvest, bottoms should be dried for 2 to 3 weeks before refilling with water.

Accumulation of fresh, labile organic matter in pond bottoms can lead to high rates of microbial respiration. Sediment usually is anaerobic below a depth of a few centimeters in ponds for extensive production. In intensive ponds, only the upper few millimeters of sediment are aerobic (Munsiri et al. 1995), and if organic matter inputs are especially great, microbial respiration can result in dissolved oxygen depletion at the sediment-water interface. This phenomenon is undesirable because potentially toxic compounds from anaerobic metabolism of bacteria, e.g., nitrite, ferrous iron, hydrogen sulfide, and organic fermentation products, can enter the water.

The concentration of labile organic matter increases during an aquaculture crop usually reaching a maximum near harvest time. When ponds are drained, some of the labile organic matter is suspended by outflowing water and removed from ponds (Ayub, et al. 1993), but much remains. Drying of the pond bottom allows air to enter into pore spaces and cracks to accelerate aerobic microbial activity and oxidize reduced compounds (Wurtz 1960; Boyd 1995). This is beneficial in reducing the amount of labile organic matter that will be present at the beginning of the next crop. It also oxidizes inorganic compounds so that they can be used again as sources of oxygen by anaerobic bacteria with the anaerobic zone of sediment. The labile organic fraction and reduced inorganic compounds can be mostly oxidized within 2 or 3 weeks. The refractory organic matter usually does not decompose fast enough to cause anaerobic conditions at the sediment-water interface (Boyd 1995).

Freshwater fish and prawn farmers in Thailand practiced bottom dry-out between crops when ponds were drained for harvest. The reported dry-out period of 2 to 3 weeks is probably adequate in ponds without deep sediment. Drying for longer periods usually is not beneficial because soils become so dry that bacterial activity is retarded for lack of moisture (Boyd and Teichert-Coddington 1994). Deep sediment will take several months to dry.

Practice 2. The bottoms of empty ponds should be tilled to a depth of 10 to 15 cm with a disk harrow to improve soil aeration.

Tilling greatly increases the exposure of pond soil to the air to accelerate drying and oxidation. Tilling is especially important in soils with a clay content over 20 or 30%. Although such soils often crack into columnar blocks upon drying (Pettry and Switzer 1993), air cannot enter into the blocks (Boyd 1995). Tilling pulverizes these blocks of soil to allow the wet soil from inside the blocks to dry and oxidize. Farmers interviewed in this study did not till pond bottoms between crops. Many of the ponds had a clay content above 20%, and tilling of pond bottoms would likely be beneficial in freshwater aquaculture in Thailand.

Practice 3. Pond bottom soils should be treated with liming materials to increase soil pH to between 7.5 and 8.

Acidic bottom soils are associated with low total alkalinity in pond waters (Boyd and Tucker 1998). Aquaculture ponds with low alkalinity waters do not have a large reserve of carbon dioxide but they have high concentrations of nitrogen and phosphorus. Phytoplankton blooms that develop in ponds with low alkalinity water cause an excessively high pH by depleting the free carbon dioxide supply. Moreover, acidic conditions in bottom soils limit the growth of benthic organisms important as natural food for culture species. Bacteria also are limited by low pH, and organic matter may accumulate in pond bottoms and nutrient recycling will be slow.

Pillai and Boyd (1985) presented a lime requirement method for determining the liming rate for aquaculture ponds. However, if this method cannot be used, the lime requirement could be based on soil pH. Ponds with soil pH of 7.5 or above would not need lime. A liming rate of 500 kg /ha would likely be adequate for pH values between 7.0 and 7.4, and the liming rate could be increased incrementally as soil pH declines (Table 14). Where producers do not have a means of measuring soil pH, an initial liming rate of 2,000 kg /ha could be used, and afterwards, 500 kg /ha could be applied annually.

Ponds for catfish, freshwater prawns, and carp would benefit from greater applications of liming materials for soil pH was below 7 in many of them. However, tilapia ponds in Thailand are heavily limed, and in some cases, applications could be reduced (Thunjai et al. 2004).

Practice 4. Sediment should be removed from ponds before it becomes deep enough to interfere with pond management procedures.

Part of the sediment in ponds has its origin in suspended solids in incoming water that settle to the pond bottom. Erosion of pond embankments and shallow areas by waves and water currents suspends soil particles that tend to settle in deep areas. Organic matter from plankton, uneaten fish feed, and feces also become sediment (Boyd 1995). Sediment is comprised mainly of mineral soil particles, but organic matter deposits onto the sediment as a flocculent layer and is gradually mixed into the sediment mass (Munsiri et al. 1995).

Deep sediment has several undesirable effects in ponds (Boyd 1995; Steeby et al. 2001). Feed pellets may sink into it and not be eaten by the culture animals. Feed pellets decompose rapidly and may cause localized zones of especially low redox potential. Soft sediment fills nets and seines during harvest making it difficult to pull them. A large volume of mud in nets or seines can injure aquatic animals and also make them difficult to remove. When ponds are dried between crops, areas with deep sediment will not dry out.

Sediment removal is practiced by fish and freshwater prawn farmers in Thailand. Nevertheless, some ponds, and especially carp ponds, had deep sediment. More attention to sediment removal would be beneficial in some ponds.

Some farmers interviewed in this study dragged chains over pond bottoms or used suction devices to remove soft sediment during crops. Previous studies showed little benefit of such practices (Beveridge et al. 1994; Gomes 2003), and disturbance of anaerobic sediment might release harmful amounts of metabolites into the water. Microbial products also are applied to ponds to improve the quality of soft sediment. A recent review (Boyd and Silapajarn 2005) did not find documentation of soil and water quality benefits following applications of microbial products. Therefore, sediment removal appears to be the most effective way of dealing with soft sediment in aquaculture ponds.

Practice 5. Use sedimentation basins to remove suspended soil particles from incoming water.

In some cases, the water supply for ponds was highly turbid with suspended soil particles from erosion on watersheds. Because these particles will settle in ponds, it is beneficial to install a sedimentation basin to remove coarse suspended particles before they enter ponds. A settling time of 1 or 2 h can be beneficial, but for best results, a settling time of 4 h or more should be provided (Boyd 1995).

Practice 6. Install vegetation, stone, or other cover on pond embankments to reduce the potential for erosion.

Erosion of pond embankments can be a major source of settleable solids in ponds. Soil particles may be suspended by waves and currents in ponds and by rain falling on bare soil of embankments. Installation of cover to avoid erosion reduces the sediment load to ponds and protects the embankments.

Practice 7. Use proper side slopes and compaction when constructing new ponds or renovating old ones.

This practice will reduce the tendency of earthwork to erode and reduce the internal sediment load in ponds. It also reduces maintenance costs for repairing embankments.

Recommended side slopes for embankments made of clay, clayey sand, clayey gravel, sandy clay, silty sand, or silty gravel are 3:1 (horizontal:vertical) on the wet side and 2:1 on the dry side. Slopes of 3:1 should be provided on both sides of an embankment made of silty clay or clayey silt. Where well-graded soil has been compacted properly, the side slopes may be 1:1 or 2:1 on both sides (Yoo and Boyd 1993). Even with proper side slopes, vegetative cover or rock must be provided to avoid erosion.

Practice 8. In ponds with mechanical aeration, install aerators to prevent water currents from eroding insides of embankments. Install rip-rap (stone) on bottom in front of aerators to prevent scouring of the pond bottom. If bottoms of heavily aerated ponds are tilled between crops, compact bottoms with heavy roller before refilling.

Mechanical aerators induced strong water currents in ponds. If the aerators are placed too close to embankments, currents flowing parallel to embankments may cause erosion. However, if water currents are directed at embankments even greater erosion may occur. There also is a tendency for increased erosion of the pond bottom in front of aerators. Tilling of pond bottoms loosens the soil making it more susceptible to erosion by water currents generated by aerators.

Mechanical aerators were not used by farmers interviewed in this study. However, mechanical aeration is a very effective practice that improves water quality and allows greater production. In the future, freshwater aquaculturists in Thailand will probably use aeration. It is commonly used by marine shrimp farmers in Thailand.

Practice 9. Do not leave ponds empty longer than necessary during rainy weather to prevent erosion of soil from shallow area with deposition of soil in deeper areas.

Practice 10. Do not allow livestock to walk on pond embankments or wade in shallow water edges.

Livestock can make paths by walking along the same route each day. These paths often are sites of erosion that can develop into small gullies.

Practice 11. Avoid operating equipment that will cause ruts and other inundations in pond bottoms.

Ruts or other depressions in pond bottoms often fill with soft sediment. They also create areas that cannot be drained and dried completely.

Best management practices for preventing off-site impacts

Aquaculture in ponds can cause negative, off-site environmental effects. For example, effluents contain suspended solids, nutrients, and organic matter and they can cause turbidity, sedimentation, and eutrophication in receiving water bodies (Goldburg and Triplett 1997). Sediment removed from ponds may be discarded in piles on vacant land (Boyd et al. 1994). This practice can result in destruction of vegetation and other terrestrial ecological nuisances. Moreover, erosion of sediment piles can cause turbidity and sedimentation in nearby water bodies. Best management practices also can be used to avoid off-site environmental impacts. Some soil-related practices that would be useful in Thailand are listed below:

Practice 12. Design and construct discharge canals to minimize bottom scouring and erosion of side slopes. This should include installation of grass cover and stone reinforcement of erosion prone areas in canals.

Rather complex engineering practices are necessary to minimize erosion in earthen canals (Yoo and Boyd 1993). However, the basic principle is to make the channel cross section large enough to prevent excessive water velocity and make the channel side slopes gentle enough to prevent erosion.

Practice 13. Do not use water jets to wash pond bottoms by hydraulic pressure as is sometimes done by marine shrimp farmers in Thailand.

The practice of washing pond bottoms is a method of sediment removal. However, the material suspended by water pressure is discharged into canals. The effluent from pond cleaning can cause turbidity, excessive oxygen demand and sedimentation in canals. This will lessen the quality of water for other water users.

Practice 14. Pass pond effluents through a settling basin to remove coarse suspended solids before final discharge into natural waters.

Settling basins have already been discussed above.

Practice 15. Dispose of sediment removed from pond bottoms or settling basins in a responsible manner.

Preferably, the sediment should be placed back over the areas on pond bottoms and embankments from which it originated. Pond sediment has a high nutrient content, so it could be spread over and incorporated into agricultural soil. Pond sediment also can be used as earthfill. If it is spread over the land, grass cover should be established to prevent erosion.

The quality of bottom soils in ponds for the three types of aquaculture was generally good. However, it could be improved and external environmental impacts prevented through the use of BMPs. This would help improve the sustainability of catfish, freshwater prawn, and carp farming in Thailand.

Table 1. Number, areas, and depths of catfish, carp, and freshwater prawn culture pond used in this study.

	Catfish	Prawn	Carp
Number of ponds	42	40	18
Pond area (m^2)	400-6,400	2,400-40,000	600-48,000
Average area (m^2)	1,904	8,480	16,096
Pond depth (m)	1.5-2.0	1.0-1.5	1.0-2.0
Average depth (m)	1.65	1.37	1.44

Table 2. Distribution of ponds by age.

Pond age (yr)	Catfish (n=42)	Prawn (n=40)	Carp (n=18)
1-5	24	12	4
6-10	6	6	10
11-15	4	12	2
16-20	4	7	2
>20	4	3	0

Table 3. Physical characteristics, carbon, nitrogen, phosphorus, sulfur, and exchangeable cation data for bottom soil samples from 42 catfish ponds in Thailand.

Variables	Mean ± SD [1/]	Minimum	Maximum
Sediment depth (cm)	19.9 ± 18.5	0	60.9
S-horizon thickness (cm)	8.9 ± 8.7	1	32
Dry bulk density (g/cm^3)	0.17 ± 0.10	0.02	0.42
Particle size distribution:			
Clay (%)	38.3 ± 4.3	25.7	47.7
Silt (%)	53.7 ± 17.6	0	74.6
Sand (%)	9.02 ± 17.47	0	72.51
pH (standard units)	6.63 ± 0.75	4.64	7.82
Total carbon (%)	1.46 ± 0.8	0.38	3.46
Organic carbon (%)	1.20 ± 0.66	0.26	2.85
Total nitrogen (%)	0.18 ± 0.11	0.03	0.54
Sulfur (ppm)	1591 ± 1433	125	7197
Total carbon/total nitrogen	8.1 ± 3.2	3.54	17.65
Exchange acidity (mEq/ 100 g)	1.7 ±0.8	0	4.1
Cation exchange capacity (mEq/ 100 g)	29.3 ± 6.5	11.9	36.5
Dilute acid - extractable phousphorus (ppm)	190 ± 320	0.98	1769
Water - extractable phousphorus (ppm)	22.4 ± 24.3	0.13	131
Lancaster -extraction phosphorus (ppm)	200 ± 172	6.93	709
Total phosphorus (ppm)	1566 ± 1197	28.6	5948

SD [1/] = Standard deviation

Table 4. Physical characteristics, carbon, nitrogen, phosphorus, sulfur, and exchangeable cation data for bottom soil samples from 40 freshwater prawn ponds in Thailand.

Variables	Mean ± SD [1]	Minimum	Maximum
Sediment depth (cm)	11.9 ± 9.7	0	47
S-horizon thickness (cm)	4.2 ± 2.8	1	10.4
Dry bulk density (g/ cm^3)	0.18 ± 0.06	0.06	0.32
Particle size distribution (%)			
Clay	36.2 ± 5.4	10.8	42.9
Silt (%)	63.6 ± 5.4	57.1	89.2
Sand (%)	0.2 ± 1.3	0	7.5
pH (standard units)	6.71 ± 0.81	4.33	7.51
Total carbon (%)	1.38± 0.43	0.64	2.55
Organic carbon(%)	1.07± 0.36	0.45	1.81
Total nitrogen (%)	0.14 ± 0.04	0.06	0.22
Sulfur (ppm)	837 ± 951	73.1	5194
Total carbon/total nitrogen	9.9 ± 1.8	6.22	16.09
Exchange acidity (mEq/ 100 g)	1.7 ± 0.8	0.3	3.4
Cation exchange capacity (mEq/ 100 g)	31.4 ± 4.8	20.8	43.8
Dilute acid - extractable phousphorus (ppm)	5 ± 4	0.5	15.9
Water - extractable phousphorus (ppm)	5.7± 6.9	0.1	32.3
Lancaster -extraction phosphorus (ppm)	75.6± 52.3	18.7	316.8
Total phosphorus (ppm)	344 ± 179	43.3	769

SD [1] = Standard deviation

Table 5. Physical characteristics, carbon, nitrogen, phosphorus, sulfur, and exchangeable cation data for bottom soil samples from 18 carp ponds in Thailand.

Variables	Mean ± SD [1/]	Minimum	Maximum
Sediment depth (cm)	33.4 ± 16.6	0	63.6
S-horizon thickness (cm)	17.1 ± 11.0	0	42
Dry bulk density (g/ cm^3)	0.28 ± 0.07	0.12	0.4
Particle size distribution :			
Clay (%)	33.1 ± 7.8	21	41.7
Silt (%)	53.2 ± 20.1	1.7	69.2
Sand (%)	13.7 ± 18.4	0	56.6
pH (standard units)	6.48 ± 0.87	3.81	7.25
Total carbon (%)	3.02 ± 1.5	1.14	7.08
Organic carbon(%)	2.08 ± 1.06	1.02	5.07
Total nitrogen (%)	0.28 ± 0.12	0.11	0.62
Sulfur (ppm)	2873.7 ± 1801.46	342.6	6199.8
Total carbon/total nitrogen	10.8 ± 2.0	5.46	15.22
Exchange acidity (mEq/ 100 g)	2 ± 1.3	0.6	6
Cation exchange capacity (mEq/ 100 g)	31.1 ± 6.9	17.7	41.3
Dilute acid - extractable phousphorus (ppm)	34.5 ± 86	1	369.5
Water - extractable phousphorus (ppm)	9.1 ± 7.5	0.1	23.1
Lancaster -extraction phosphorus (ppm)	206.8 ± 155.9	29.3	557.8
Total phosphorus (ppm)	1085. ± 624	159	2683

SD [1/] = Standard deviation

Table 6. Major cations and minor elements in bottom soil samples from 42 catfish ponds in Thailand.

Variables	Mean ± SD [1/]	Minimum	Maximum
Calcium (ppm)	5189 ± 1682	1649	7833
Potassium (ppm)	143 ± 68	27	373
Magnesium (ppm)	438 ±211	95	939
Sodium (ppm)	183 ±146	28	701
Aluminium (ppm)	83 ± 69	1	226
Iron (ppm)	97 ± 137	<0.5	686
Manganese (ppm)	55 ± 49	8	253
Zinc (ppm)	7.29 ± 6.63	<0.5	32.12
Copper (ppm)	1.51 ± 1.05	<0.5	3.79
Boron (ppm)	1.87 ± 0.93	1.19	6.83
Nickel (ppm)	1.75 ± 1.07	<0.5	4.05

SD [1/] = Standard deviation

Table 7. Major cations and minor elements in bottom soil samples from 40 freshwater prawn ponds in Thailand.

Variables	Mean ± SD [1/]	Minimum	Maximum
Calcium (ppm)	4081 ± 1320	1216	6361
Potassium (ppm)	148 ± 40	53	226
Magnesium (ppm)	457 ± 158	211	853
Sodium (ppm)	168 ± 127	52	619
Aluminium (ppm)	104 ± 49	1	191
Iron (ppm)	91 ± 84	>0.5	320
Manganese (ppm)	86 ± 56	12	225
Zinc (ppm)	6.6 ± 3.38	0.55	12.56
Copper (ppm)	1.87 ± 1.44	>0.5	5.53
Boron (ppm)	1.79 ± 1.01	1.05	6.74
Nickel (ppm)	2.06 ± 0.84	>0.5	4.03

SD [1/] = Standard deviation

Table 8. Major cations and minor elements in bottom soil samples from 18 carp ponds in Thailand.

Variables	Mean ± SD [1]	Minimum	Maximum
Calcium (ppm)	4881 ± 1389	2348	7434
Potassium (ppm)	204 ± 90	80	479
Magnesium (ppm)	498 ± 195.16	104	734
Sodium (ppm)	136 ± 76	4	252
Aluminium (ppm)	102 ± 65	1	198
Iron (ppm)	203 ± 203	<0.5	766
Manganese (ppm)	90 ± 68	14.1	260
Zinc (ppm)	11.1 ±5.9	1.4	24
Copper (ppm)	2.57 ± 2.06	0.53	6.88
Boron (ppm)	1.85 ± 0.42	1.3	3.22
Nickel (ppm)	2 ± 1	<0.5	4.1

SD [1] = Standard deviation

Table 9. Correlation coefficient (r) matrix for bottom soil variables from 100 ponds used for culture of catfish, freshwater prawn, and carp in Thailand.

	TSD	SHD	BD	Clay	Silt	Sand	pH	TC	OC	TN	C/N	TP	WEP	DEP	LEP	CEC	EA	Ca	Mg	K	Na	Al	Fe	Mn	Z	Cu	B	Ni
TSD	-																											
SHD	0.785	-																										
BD	0.439	0.515	-																									
Clay	0.021	0.015	0.238	-																								
Silt	0.230	0.274	0.047	0.501	-																							
Sand	0.232	0.288	0.002	0.191	0.932	-																						
pH	0.108	0.064	0.130	0.121	0.031	0.011	-																					
TC	0.304	0.284	0.391	0.074	0.000	0.014	0.112	-																				
OC	0.274	0.260	0.426	0.090	0.052	0.053	0.165	0.955	-																			
TN	0.269	0.256	0.283	0.080	0.106	0.157	0.039	0.870	0.811	-																		
C/N	0.133	0.118	0.019	0.093	0.225	0.301	0.070	0.266	0.087	0.275	-																	
TP	0.188	0.197	0.058	0.202	0.331	0.321	0.120	0.186	0.191	0.382	0.047	-																
WEP	0.018	0.003	0.151	0.231	0.226	0.165	0.040	0.065	0.035	0.011	0.075	0.449	-															
DEP	0.028	0.039	0.279	0.292	0.481	0.537	0.004	0.021	0.022	0.257	0.295	0.646	0.444	-														
LEP	0.305	0.284	0.122	0.002	0.278	0.354	0.015	0.353	0.373	0.489	0.084	0.661	0.285	0.517	-													
CEC	0.063	0.072	0.385	0.034	0.511	0.625	0.234	0.292	0.326	0.218	0.048	0.086	0.094	0.310	0.045	-												
EA	0.071	0.023	0.054	0.151	0.155	0.238	0.840	0.458	0.376	0.195	0.129	0.026	0.010	0.052	0.025	0.078	-											
Ca	0.280	0.223	0.067	0.006	0.009	0.019	0.513	0.154	0.176	0.289	0.032	0.518	0.220	0.354	0.422	0.226	0.341	-										
Mg	0.039	0.050	0.355	0.012	0.331	0.397	0.151	0.242	0.252	0.167	0.007	0.119	0.169	0.220	0.037	0.571	0.066	0.141	-									
K	0.100	0.114	0.363	0.231	0.280	0.251	0.095	0.357	0.400	0.306	0.063	0.179	0.165	0.249	0.033	0.313	0.039	0.026	0.479	-								
Na	0.045	0.054	0.102	0.008	0.166	0.204	0.228	0.087	0.120	0.228	0.046	0.064	0.139	0.015	0.008	0.399	0.033	0.240	0.530	0.341	-							
Al	0.137	0.073	0.054	0.052	0.007	0.005	0.432	0.047	0.009	0.118	0.075	0.347	0.092	0.151	0.159	0.147	0.407	0.656	0.021	0.120	0.233	-						
Fe	0.012	0.077	0.090	0.089	0.314	0.368	0.410	0.164	0.086	0.043	0.140	0.138	0.066	0.091	0.077	0.335	0.363	0.555	0.186	0.094	0.231	0.559	-					
Mn	0.043	0.016	0.246	0.028	0.122	0.136	0.154	0.148	0.120	0.037	0.139	0.212	0.184	0.118	0.138	0.234	0.089	0.110	0.539	0.149	0.095	0.031	0.083	-				
Zn	0.162	0.196	0.417	0.242	0.033	0.139	0.101	0.318	0.358	0.207	0.032	0.055	0.055	0.050	0.225	0.020	0.068	0.115	0.177	0.274	0.119	0.449	0.429	0.350	-			
Cu	0.081	0.058	0.178	0.119	0.065	0.108	0.184	0.056	0.007	0.072	0.124	0.214	0.125	0.168	0.081	0.201	0.124	0.515	0.037	0.089	0.371	0.569	0.598	0.223	0.519	-		
B	0.083	0.063	0.159	0.063	0.001	0.036	0.210	0.012	0.021	0.075	0.108	0.019	0.057	0.119	0.104	0.139	0.115	0.122	0.261	0.073	0.168	0.090	0.015	0.246	0.001	0.062	-	
Ni	0.042	0.097	0.099	0.016	0.021	0.054	0.198	0.243	0.230	0.092	0.073	0.286	0.147	0.168	0.098	0.127	0.249	0.365	0.209	0.234	0.020	0.642	0.376	0.280	0.508	0.252	0.030	-

Correlation coefficients (r) greater than 0.198 and 0.257 are significant at probability levels of 5% and 1%, respectively.
TSD = total sediment depth; SHD = S horizon thickness; BD = dry bulk density; TC = total carbon; OC = organic carbon; TN = total nitrogen; c/n =carbon/nitrogen; TP = total phosphorus; WEP = water extractable phosphorus; DEP = dilute acid extractable phosphorus; LEP = Lancaster solution extractable P; CEC = cation exchange capacity, EA = exchangeable acidity

Table 10. Correlation on coefficients (r) for relationships between pond age (X) and bottom soil quality variables (Y) in 42 catfish ponds, 40 freshwater prawn ponds, 18 carp ponds in Thailand.

Variables	Catfish [1/]	Prawn [2/]	Carp [3/]
Sediment depth (cm)	0.338	0.032	0.298
S-horizon thickness (cm)	0.349	0.105	0.167
Dry bulk density (g/cm^3)	0.474	0.071	0.173
pH (standard units)	0.114	0.513	0.265
Total carbon (%)	0.173	0.0774	0.100
Organic carbon (%)	0.205	0.0547	0.032
Total nitrogen (%)	0.164	0.134	0.232
Sulfur (ppm)	0.300	0.035	0.071
Total carbon/total nitrogen	0.315	0.122	0.322
Particle size distribution:			
Clay (%)	0.122	0.077	0.212
Silt (%)	0.297	0.055	0.603
Sand (%)	0.286	0.335	0.579
Total phosphorus (ppm)	0.063	0.205	0.158
Lancaster extractable Phosphorus (ppm)	0.170	0.045	0.100
Water - extractable phosphorus (ppm)	0.276	0.032	0.277
Dilute acid - extractable phosphorus (ppm)	0.285	0.084	0.032
Exchange acidity (mEq/ 100 g)	0.032	0.465	0.063
Cation exchange capacity (mEq/ 100 g)	0.454	0.118	0.089
Calcium (ppm)	0.158	0.187	0.063
Potassium (ppm)	0.438	0.158	0.184

Table 10 Continued.

Variables	Catfish [1]	Prawn [2]	Carp [3]
Magnesium (ppm)	0.438	0.239	0.148
Sodium (ppm)	0.251	0.148	0.055
Aluminium (ppm)	0.158	0.063	0.243
Iron (ppm)	0.032	0.063	0.032
Manganese (ppm)	0.032	0.468	0.152
Zinc (ppm)	0.055	0.182	0.014
Copper (ppm)	0.118	0.205	0.277
Boron (ppm)	0.202	0.077	0.326
Nickel (ppm)	0.126	0.307	0.214

[1] Correlation on coefficients (r) greater than or equal to 0.304 and 0.393 are significant levels of 5% and 1%, respectively.

[2] Correlation on coefficients (r) greater than or equal to 0.312 and 0.466 are significant levels of 5% and 1%, respectively.

[3] Correlation on coefficients (r) greater than or equal to 0.468 and 0.590 are significant levels of 5% and 1%, respectively.

Table 11. Concentrations of water quality variables in 42 catfish ponds in Thailand.

Variables	Mean ± SD [1/]	Minimum	Maximum
pH	7.6 ± 0.62	5.45	8.45
Total alkalinity (mg/L as $CaCO_3$)	117 ± 58	0.5	236
Total hardness (mg/L as $CaCO_3$)	184 ± 123	71	806
Chloride (mg/L)	43 ± 72	3	403
Sulfate (mg/L)	65.9 ± 62.6	3.4	236
Calcium (mg/L)	55 ± 45	17	279
Potassium (mg/L)	7.1 ± 7.8	2.3	40.7
Magnesium (mg/L)	15.0 ±13.7	4.0	82.8
Sodium (mg/L)	63 ± 72	7	328

SD [1/] = Standard deviation

Table 12. Concentrations of water quality variables in 40 freshwater prawn ponds in Thailand.

Variables	Mean ± SD [1]	Minimum	Maximum
pH	7.86 ± 0.41	6.9	8.3
Total alkalinity (mg/L as $CaCO_3$)	79 ± 23	28	162
Total hardness (mg/L as $CaCO_3$)	137 ± 54	62	266
Chloride (mg/L)	58 ± 86	2	364
Sulfate (mg/L)	55 ± 41	4.9	172
Calcium (mg/L)	39 ± 16	6.6	79
Potassium (mg/L)	5.5 ± 2.3	2.6	13.3
Magnesium (mg/L)	11.6 ± 8.2	2.2	41.4
Sodium (mg/L)	57.7 ± 56.1	3.8	265.8

SD [1] = Standard deviation

Table 13. Concentrations of water quality variables in 18 carp ponds in Thailand.

Variables	Mean ± SD[1/]	Minimum	Maximum
pH	7.76± 0.47	7	8.4
Total alkalinity (mg/L as $CaCO_3$)	104 ± 40	43	185
Total hardness (mg/L as $CaCO_3$)	159 ± 89	47	450
Chloride (mg/L)	23 ± 42	2	193
Sulfate (mg/L)	53.6 ± 40.5	10.3	170.6
Calcium (mg/L)	34.5 ± 16.1	8.3	72.6
Potassium (mg/L)	9.6 ± 4.9	2.3	19.3
Magnesium (mg/L)	12.2 ± 5	5.3	22.8
Sodium (mg/L)	33.2 ± 10.1	14.6	50.6

SD[1/] = Standard deviation

Table 14. Lime requirement for aquaculture pond bottom soil based on soil pH.

Soil pH	Lime requirement (kg/ha)
7.5 or above	0
7.4 to 7.0	500
6.9 to 6.5	1,000
6.4 to 6.0	1,500
5.9 to 5.5	2,000
5.5 or less	3,000

[1] Based on agricultural limestone with neutralizing value of 100%.

Sample areas

Source : http://www.thailand-community.de/th-map.htm Nov 1, 2005

Figure 1. Map of Thailand showing location of sampling areas.

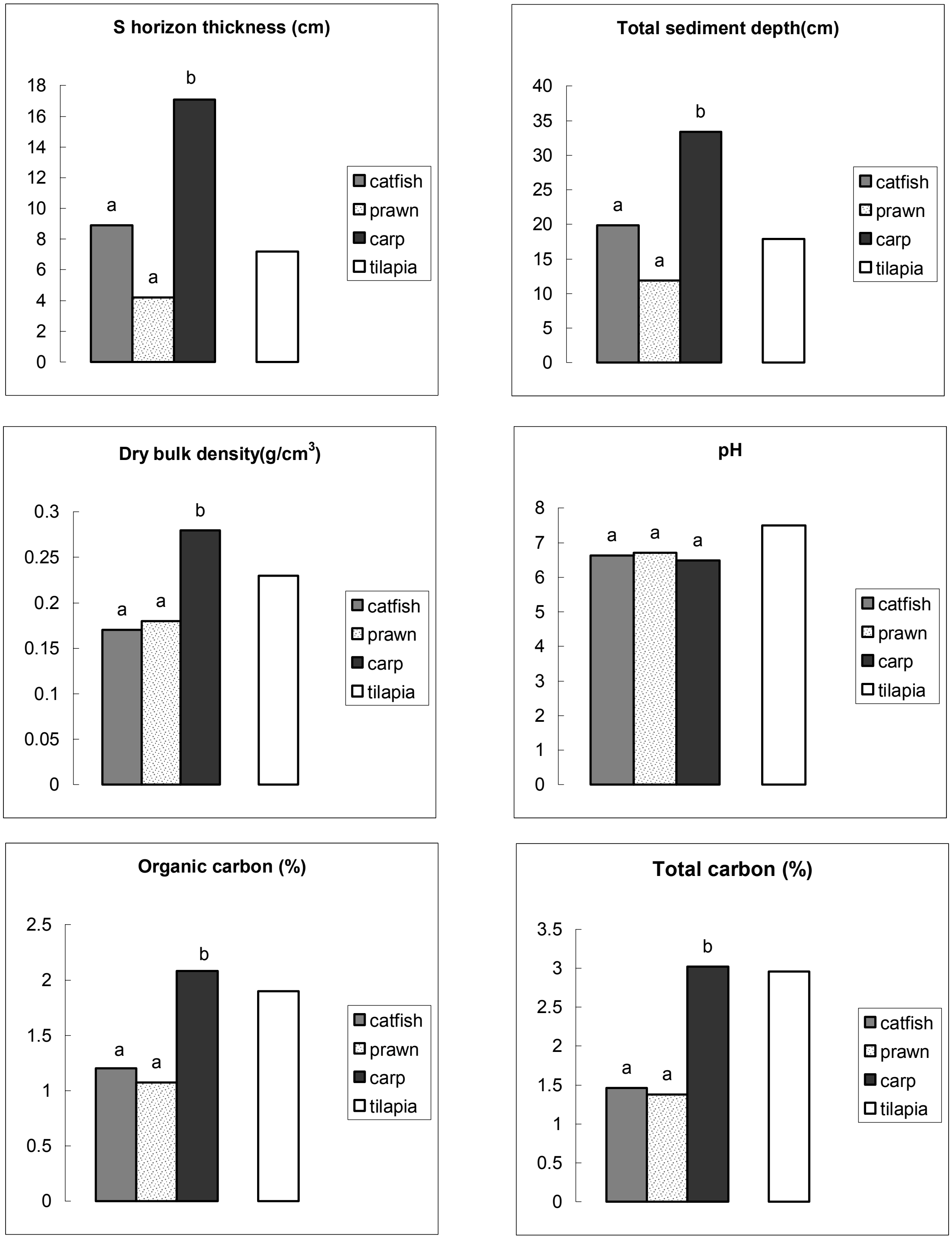


Figure 2. Histograms showing average concentrations of soil quality variables measure in bottom soils from catfish, freshwater prawn, and carp ponds in Thailand. Bars in each histogram represented by the same letter are not different ($P > 0.05$). Data on concentrations of some variables in Tilapia pond soil in Thailand (Thanjai, 2002) are provided for visual but not statistic.

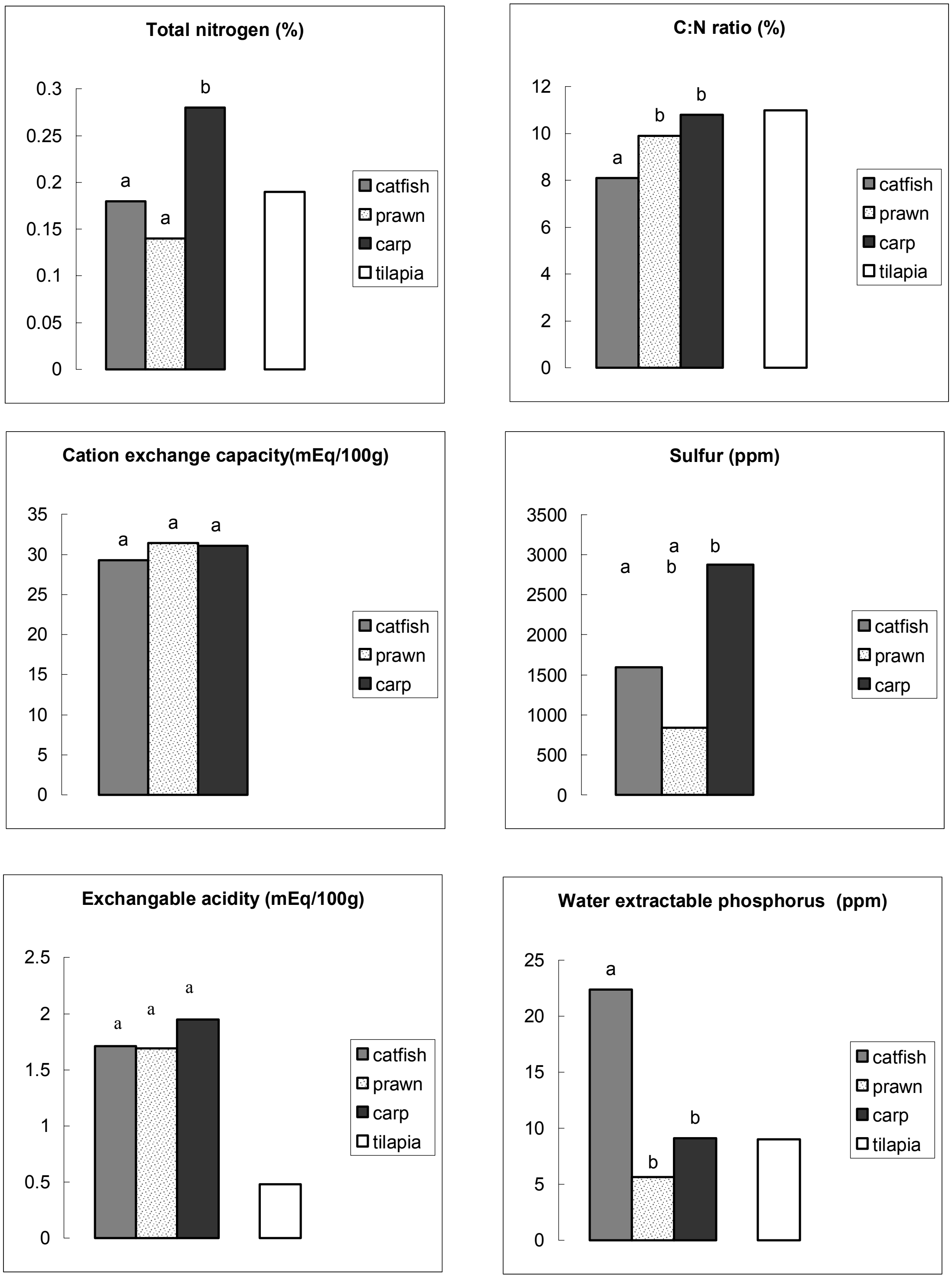


Figure 2. Continued.

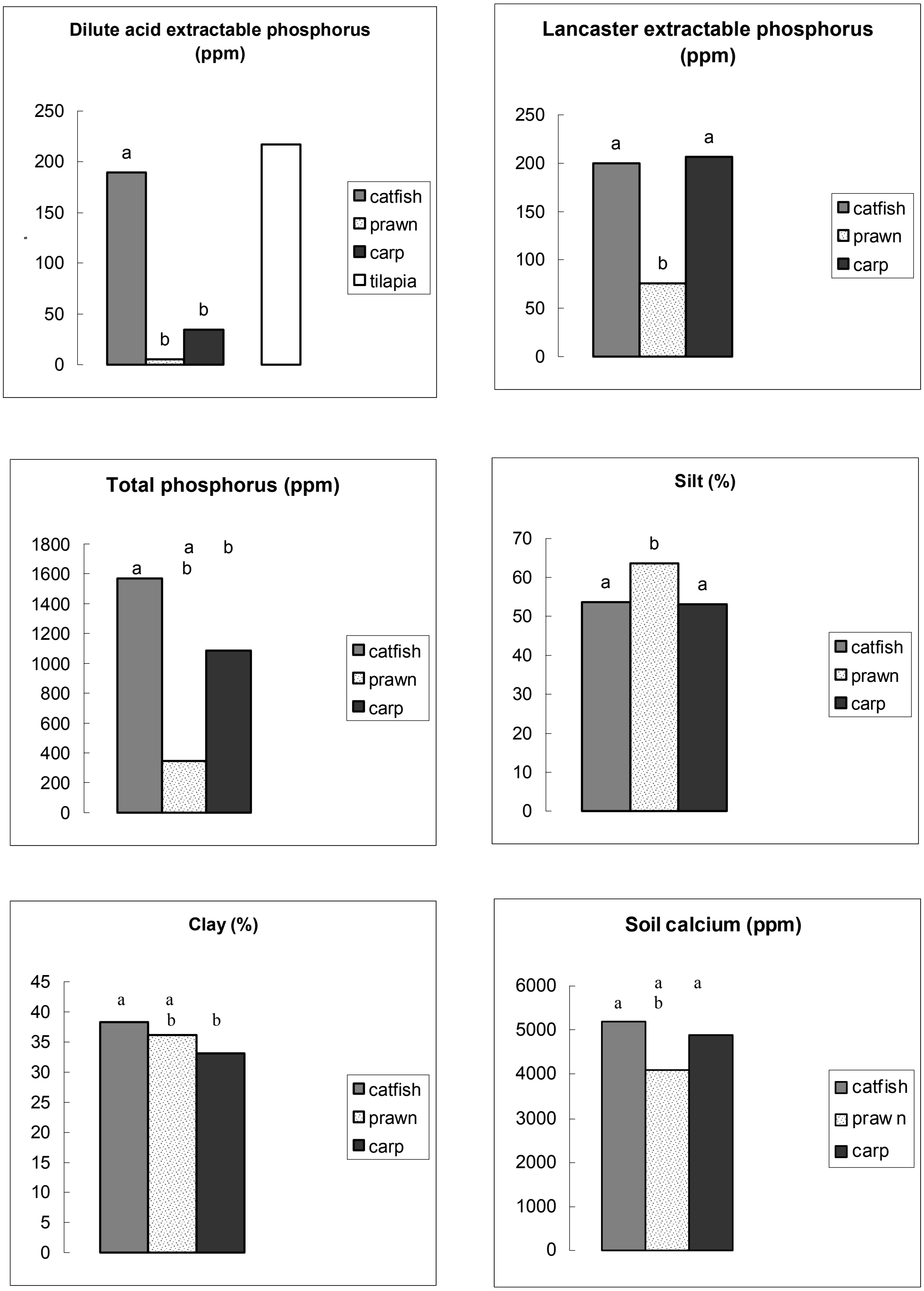


Figure 2. Continued.

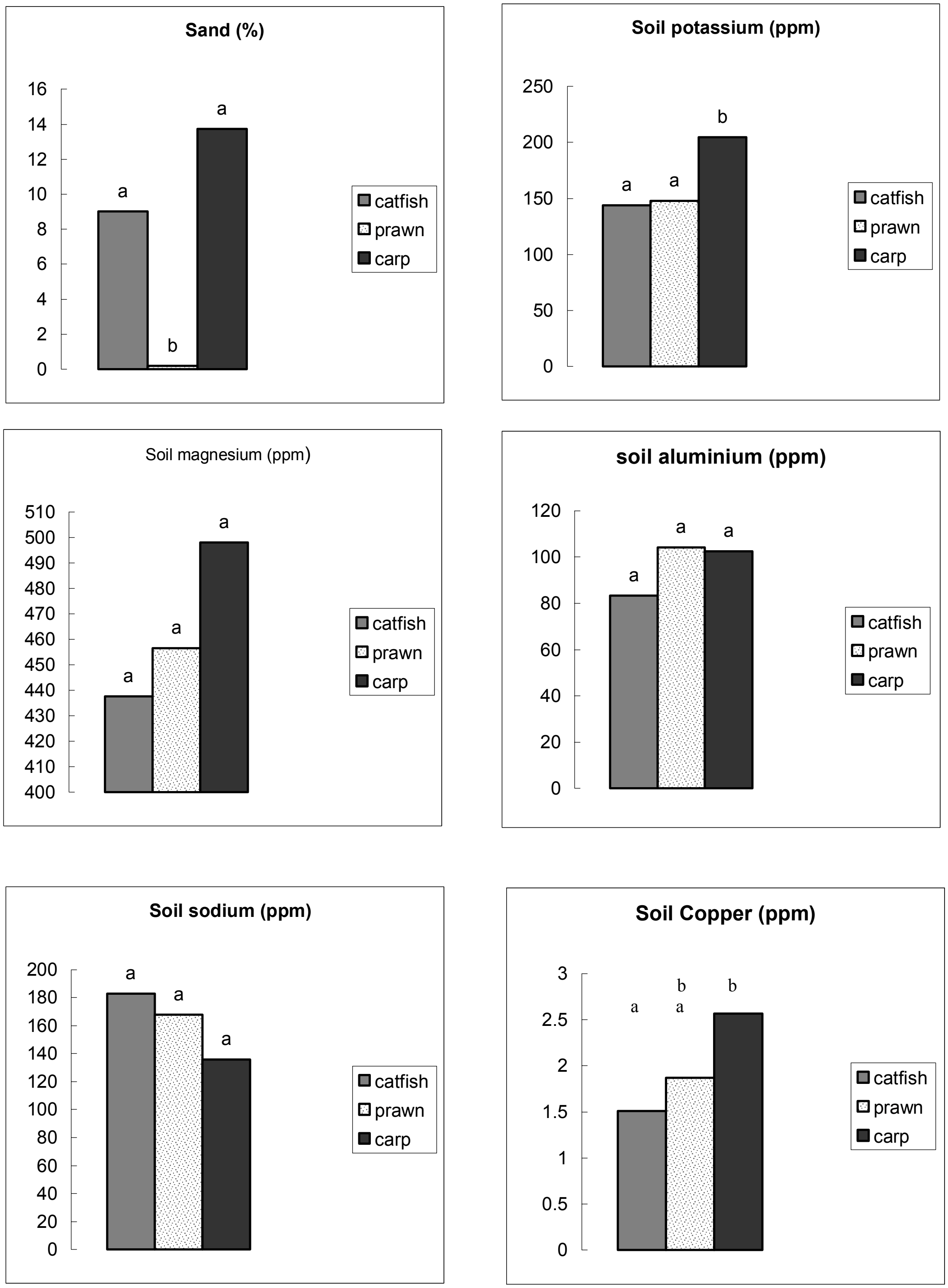
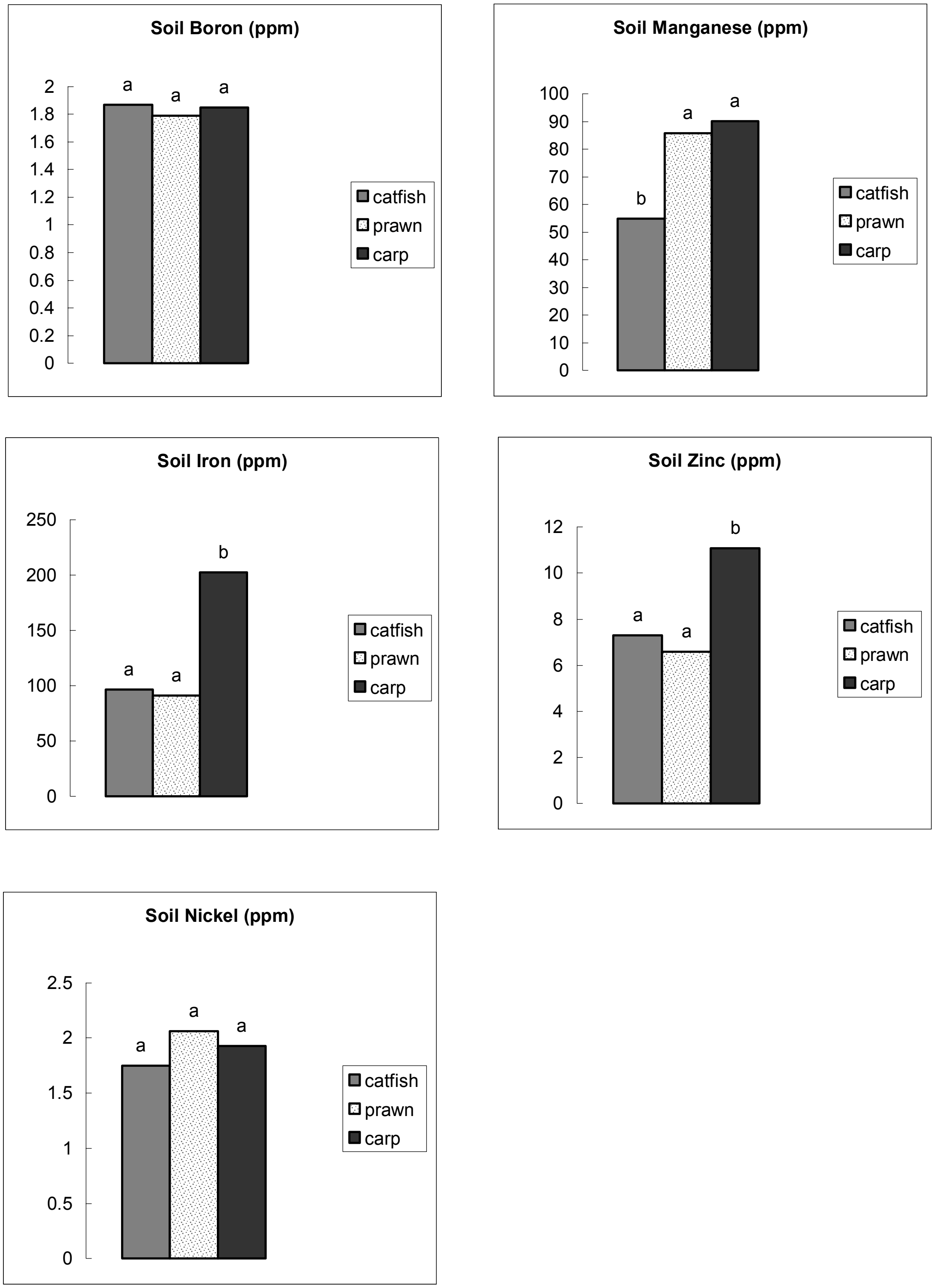


Fig. 2 Continued.



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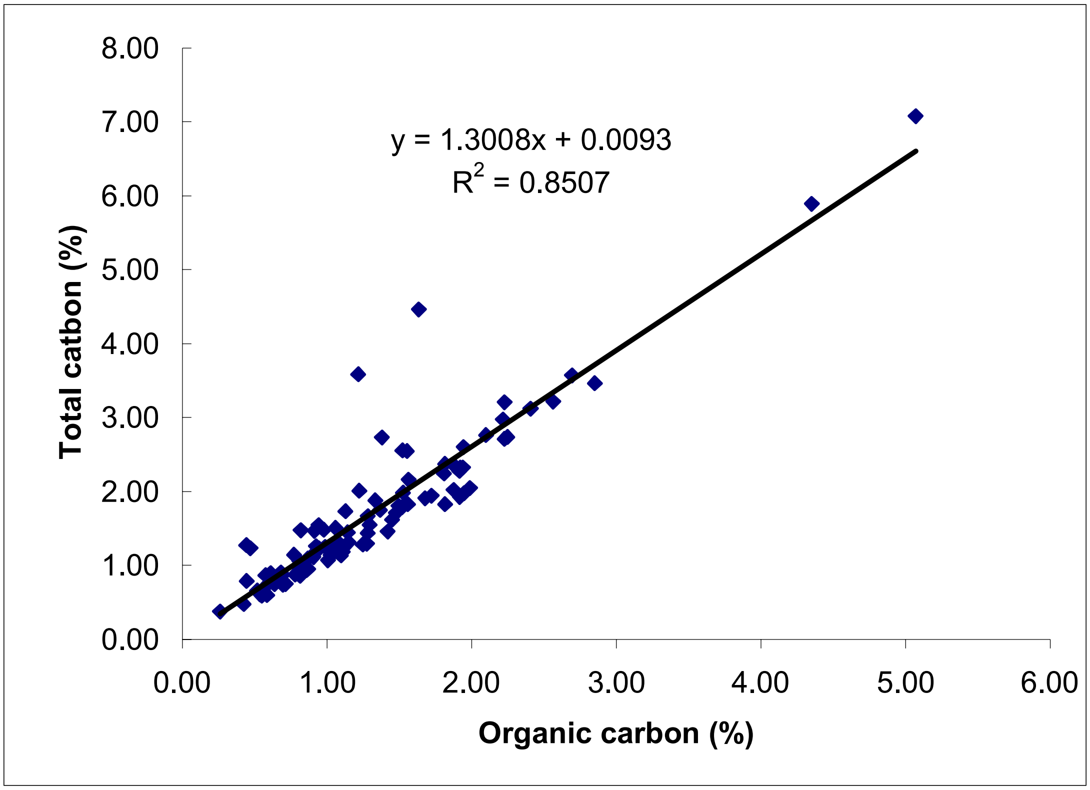

Figure 3. Relationship between soil organic carbon concentration and soil total carbon concentration in samples from ponds for production of catfish, freshwater prawn, and carp in Thailand

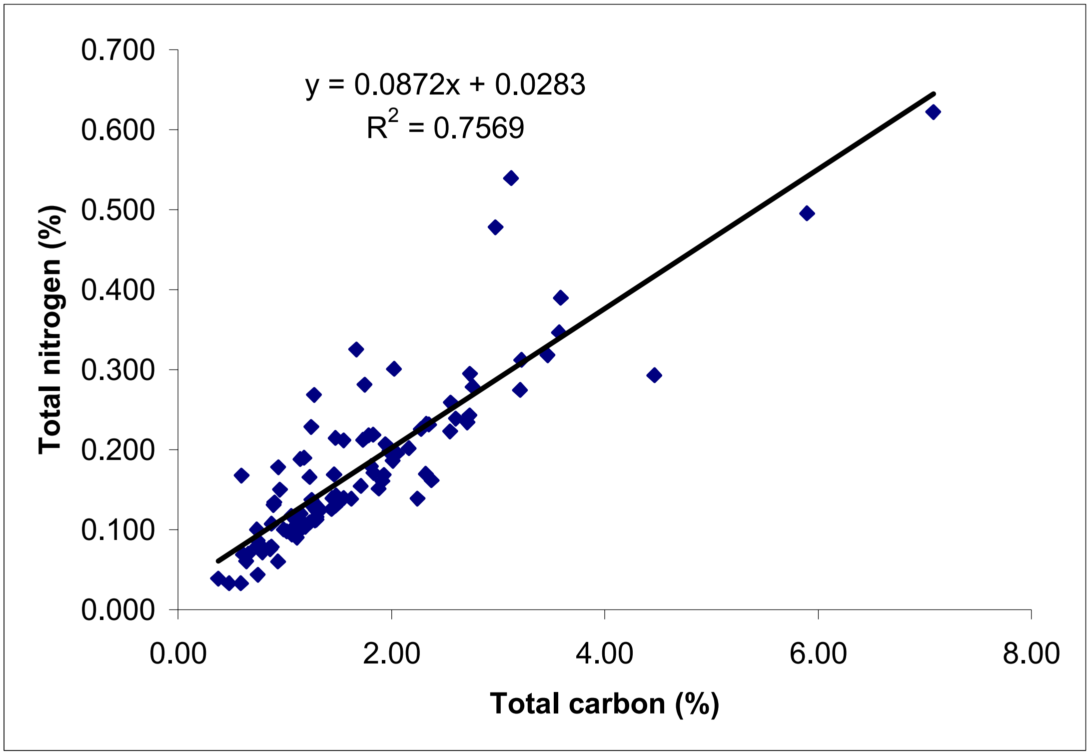

Figure 4. Relationship between soil total carbon concentration and soil total nitrogen concentration in samples from ponds for production of catfish, freshwater prawn, and carp in Thailand.

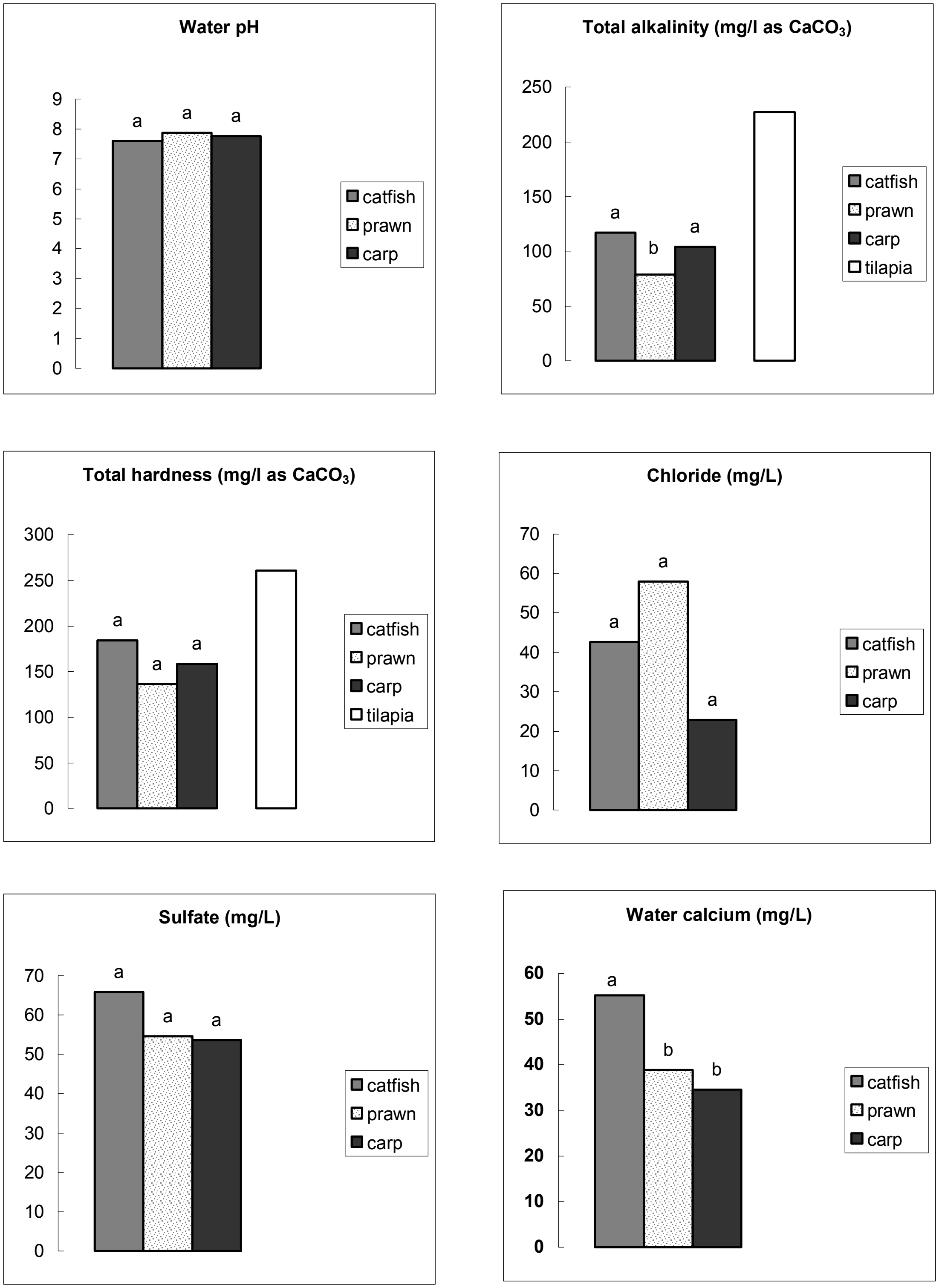

Figure 5. Histogram showing average concentrations of water quality variables in ponds for culture of catfish, freshwater prawn, and carp in Thailand. Bars in each histogram indicated by the same letter did not differ ($P > 0.05$).

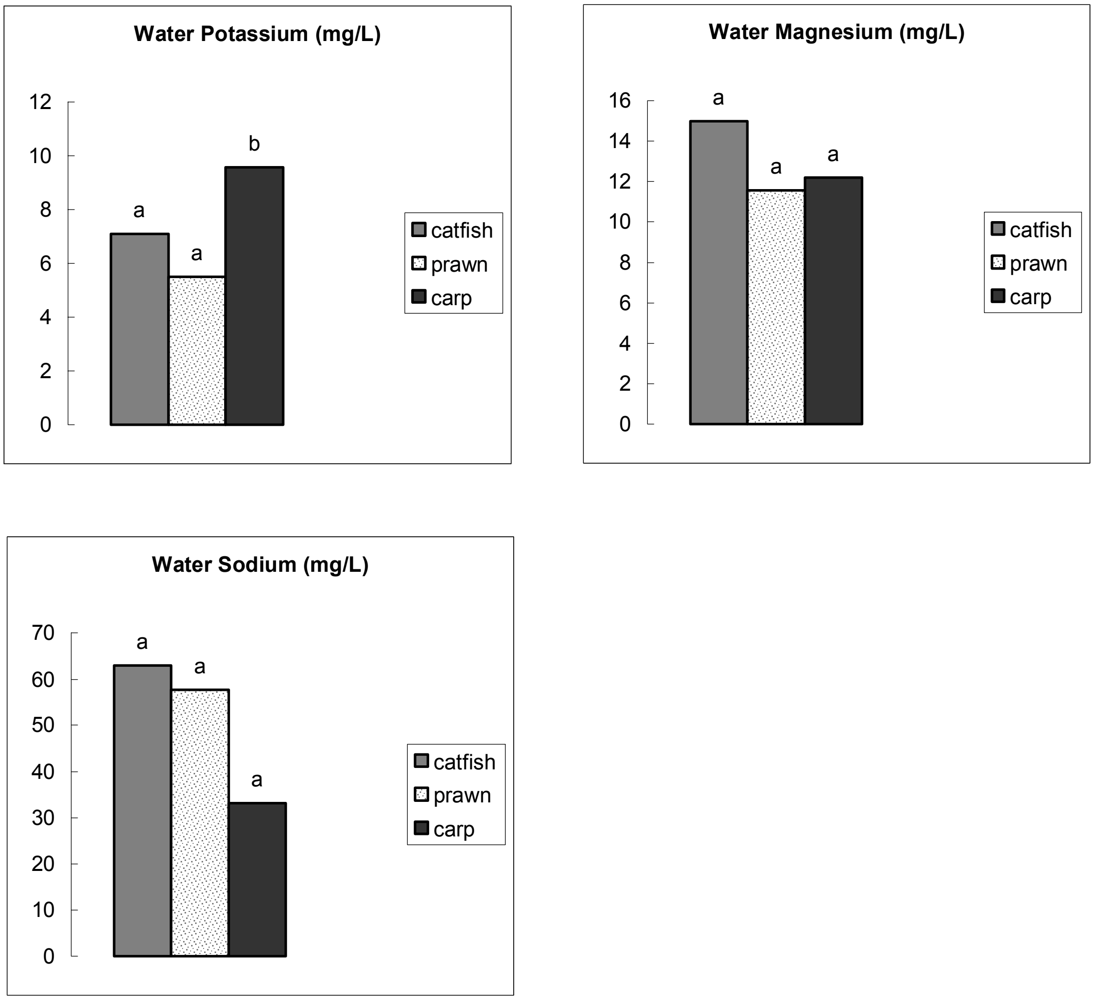

Figure 5. Continued.

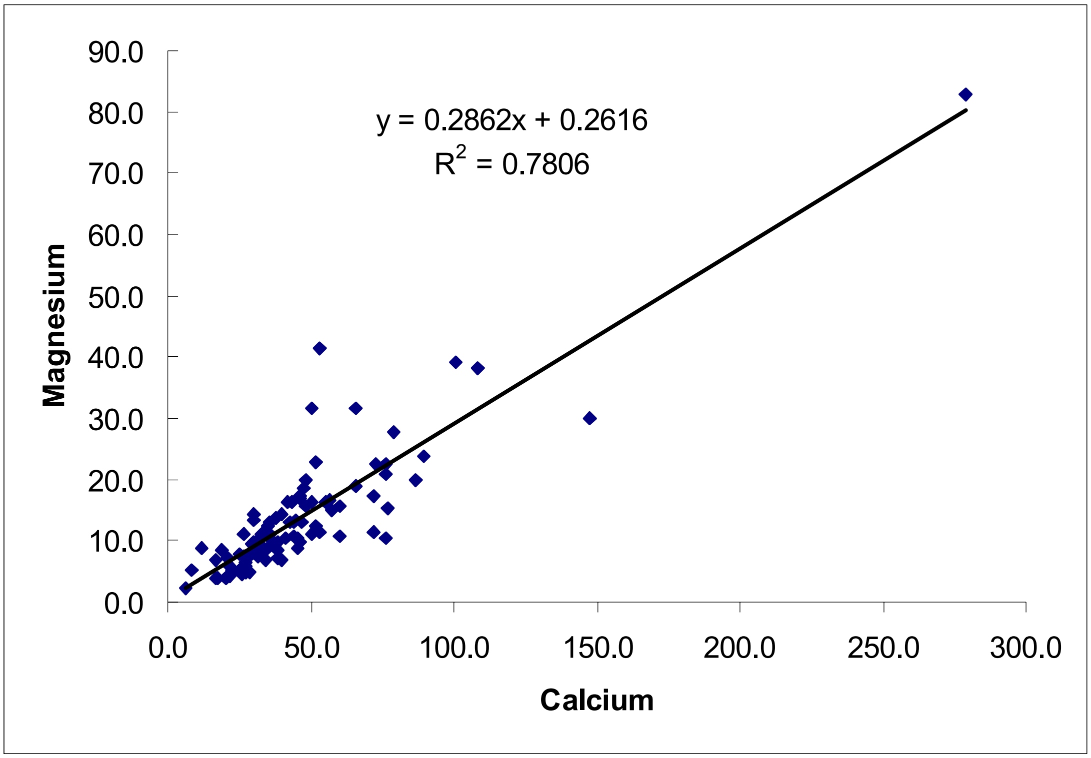

Figure 6. Relationship between magnesium concentration and calcium concentration in water samples from ponds for catfish, freshwater prawn, and carp production in Thailand.

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