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Chemical and Physical Properties of Shrimp Pond Bottom Soils in Ecuador

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Abstract

Chemical and physical analyses were conducted on bottom soil samples from 74 brackish-water ponds representing 40 shrimp farms in Ecuador. Most ponds had soils with pH > 6 and total carbon concentrations < 2.5%. Carbon was mostly in organic form, for the average concentration of carbonate carbon was 0.06%. The C:N ratio was 8 to 10 in soils with < 2.5% carbon. In ponds built in former mangrove areas, soil carbon was > 2.5% and C:N ratios were 25 to 30. Ponds soils in former mangrove areas also tended to be high in total sulfur and low in pH. Lack of correlation between carbon and sulfur in mangrove soils suggested that most of the sulfur was inorganic and presumably in sulfides. Soils containing above 0.4% free carbonate (as equivalent $CaCO_3$) had pH values > 7. Although carbonate concentration was a major factor controlling soil pH, calcium hardness of pond waters was strongly influenced by salinity (and calcium) in the water supply. Total phosphorus concentrations averaged 898 mg/kg, and dilute acid extractable phosphorus usually accounted for 25–35% of the total. Concentrations of major cations and minor elements varied greatly in soils and exhibited ranges of up to three orders of magnitude. Contrary to opinions of shrimp producers, many pond soils in Ecuador are not acidic and few soils have a high organic matter content. Proper use of soil and water testing could greatly improve the efficiency of liming and other soil management practices.

Shrimp culture in Ecuador has grown steadily since its inception in the 1970s. Ecuador produced 130,000 tons of shrimp in 1997 and over 90% were from aquaculture. Between 1968 and 1995, about 180,000 ha of land was converted to shrimp farms (CLIRSEN 1997). About 15% of the land was former mangrove forests (Boyd and Clay 1998), but most farms were constructed on salitrales (salt flats) and on former agricultural land (Aiken 1990).

Soils are a major factor in pond aquaculture, because ponds are made of soil material, and the condition of pond bottoms influences water quality and production. Banerjea (1967) revealed that the potential for fish production in ponds was influenced by pH and concentrations of organic matter, nitrogen, and phosphorus in soils. Concentrations of nutrients and phytoplankton productivity in pond waters are related to pH and nutrient concentrations in soils (Boyd 1995; Boyd and Munsiri 1996, 1997). Shrimp farms located in former mangrove areas may have soils with high sulfide concentrations. Oxidation of sulfide produces sulfuric acid, and highly acidic conditions can harm shrimp, lessen microbial activity and recycling of nutrients, and decrease the availability of phosphorus by favoring formation of insoluble iron and aluminum phosphates (Boyd 1992). The composition of shrimp pond soils is altered by residues from feeds and fertilizers, settling of dead plankton, and accumulation of sediment and salts (Hopkins et al. 1994; Boyd 1995). Several nutrients and other elements increased in concentration over time in

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shrimp pond soils (Boyd et al. 1994a; Munsiri et al 1996a; Ritvo et al. 1998a). Organic matter accumulation in pond soils from uneaten feed, dead plankton, and shrimp feces increases oxygen demand and favors reducing conditions and release of toxic metabolites such as ammonia, nitrite, hydrogen sulfide, ferrous iron, manganous manganese, and methane (Boyd 1995). Negative correlations between shrimp growth and survival and sulfide concentrations in aquatic soils have been observed (Ritvo et al. 1998c).

Although considerable information of properties of shrimp pond soils were provided by Morales et al. (1991), Boyd et al. (1994a, 1994b), Munsiri et al. (1996b), and Ritvo et al. (1998a), few data have been collected on the characteristics of shrimp pond soils in Ecuador. Ecuadorian shrimp farmers are concerned about effects of pH, organic matter concentrations, and other soil features on shrimp production (Peterson and Daniels 1992). The purpose of this study was to acquire information on the physical and chemical properties of soil from shrimp ponds from different regions in Ecuador.

Materials and Methods

Soil Samples

Soil samples were obtained from 40 shrimp farms between November 1997 and September 1998. Farms were located in the provinces of Guayas (18), El Oro (10), Manabi (7), and Esmeraldas (5). Locations of farms are depicted in Fig. 1. A total of 74 ponds were sampled during this period: Guayas (30), El Oro (19), Manabi, (15) and Esmeraldas (10). Data also were obtained from farm managers as follows: pond size, pond age, stocking and feeding rates, method of feeding, production during previous crop, and pond bottom soil treatments applied.

Soil samples were taken from the upper 5-cm layer of pond bottoms with a 5-cm diameter corer. This layer was selected for sampling because it is more reactive and has a greater influence on water quality than deeper layers (Masuda and Boyd 1994; Munsiri et al. 1995). Cores were obtained from six to eight places within each pond and combined to provide one sample per pond (Boyd 1995). Most samples were taken from ponds during shrimp culture. All samples were dried in a forced draft oven at 60 C, pulverized with a soil crusher (Custom Laboratory Equipment Inc., Orange City, Florida, USA) to pass a 20-mesh screen, and stored in plastic bags.

Soil and Water Analysis

Pore water pH was measured by pushing the glass electrode into freshly collected sediment in the core sampler tube. Soil pH was measured by inserting a glass electrode into a 1:1 mixture of dry, pulverized soil and distilled water. Total carbon concentrations were measured by incinerating soils with a LECO EC12 Induction Furnace Analyzer and measuring the carbon dioxide released. Total sulfur was determined by incinerating samples in a LECO Induction Furnace HP10 and titrating the liberated sulfur with standard KIO_3 using a LECO Sulfur Titrator. Total nitrogen was measured following incineration of soil with a LECO Carbon-Hydrogen-Nitrogen Analyzer CHN 600. Phosphorus and metal ions were extracted from soils with dilute, double-acid solution (0.05N HCl + 0.025N H_2SO_4) and analyzed with a Jarrel-Ash ICAP 9000 Plasma Spectrophotometer (Hue and Evans 1986). The total phosphorus analysis involved digestion of samples in 60% $HClO_4$ followed by measurement of phosphorus in digestates by the ammonium-vanadomolybdate yellow color method (Olson and Sommers 1982). Cation exchange capacity (CEC) was determined by saturating 5-g soil with 30 mL of 1 N $CaCl_2$. Excess salts were removed by washing calcium saturated soils with 95% ethanol until the supernatant had a conductivity ≤ 40 µS/cm. Calcium on exchange sites was then displaced with 30 mL of 1.0 N KCl and measured by

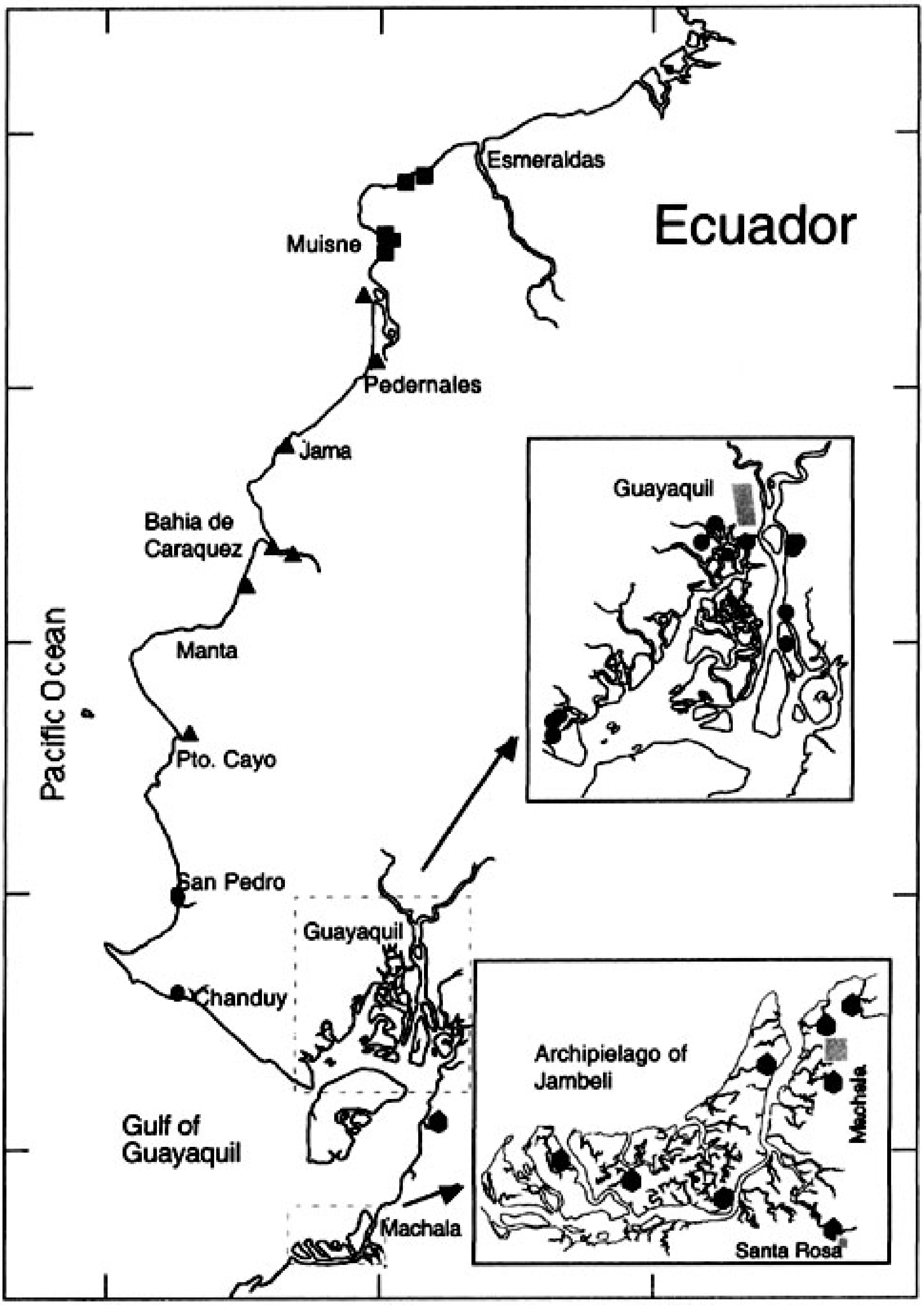

FIGURE 1. *Map of Ecuador showing the locations of shrimp farms where pond soil samples were collected.*

EDTA titration (Jackson 1958). Exchange acidity was determined with a buffer procedure described by Adams and Evans (1962). Base unsaturation is exchange acidity divided by CEC. Particle size was determined by removing soluble salts with distilled water, oxidizing organic matter with 30% H_2O_2, and dispersing soils in a solution containing 7.94 g Na_2CO_3 and 35.7 g $NaPO_3)_3 \cdot 6H_2O$ per liter. Sand was separated by sieving dispersed soil through a 53-µm screen. Silt and clay in soil suspensions were then determined by the pipet method (Gee and Bauder 1986). Soil textural class was determined by the soil triangle method (Boyd 1995). Free carbonates in soil were decomposed by treatment with 1.00 N HCl, the resulting carbon dioxide was measured, and the $CaCO_3$ equivalence of the carbon dioxide was estimated (Jackson 1958).

Water samples were obtained from the same ponds used for soil sampling. Samples were analyzed for total alkalinity, total hardness, and calcium hardness using a water quality kit (Hach Company, Loveland, Colorado, USA).

Data Analysis

Frequency distribution histograms of all variables were plotted versus concentration to show distribution of data. Regression and other statistical analyses were computed with Sigma Stat software, V.1.O (SPSS® 1997).

Results and Discussion

Most farms were constructed on salt flats or arid agricultural land. Only 10% of ponds sampled were built on former mangrove sites. Taxonomic soil charts produced by the Geographic Militar Institute of Ecuador and the Office de la Recherche Scientific et Technique Outre-Mer (undated) revealed that farms were in areas where soil orders were Vertisols, Inceptisols, Aridisols, and Entisols. Within these orders there were several soil groups as follows: Salorthids, Sulfaquents, Torripsamments, Vertic camborthids, Vertic Paleargids, Vertic Eutropepts, Ustipsamments, Ustropepts, and Ustorthents. Ponds had areas of 1–10 ha, and ranged from 2–12 yr in age. Shrimp ponds were used for semi-extensive or semi-intensive production with feed inputs of 500 to 2,500 kg/ha per yr. Data provided by managers regarding production during the previous crop were incomplete and approximate, but indicated a range of 600 to 1,600 kg/ha. Pond bottom management consisted mainly of dry out and application of agricultural limestone between crops. Liming rates were usually based on manager perception of soil conditions and performance of the previous crop. Fallow periods varied between 4 and 15 d and depended mainly on the availability of larvae for stocking. Chemical amendments such as sodium nitrate or calcium oxide also were used during pond preparation by some managers. Probiotics were applied to some ponds in attempts to enhance microbial decomposition of organic matter. Several farms used feeding trays in an effort to obtain better feed utilization. Suspended solids in inflow were largely removed by sedimentation in the water supply reservoir and canals, and ponds did not have heavy external inputs of sediment. None of the ponds were aerated mechanically.

Preliminary analyses of data revealed no consistent differences in soil variables among regions or soil taxonomic categories. No differences were found in soil variables that could be related to pond size or age. Therefore, soil data were combined as a single set for further consideration.

Soil samples were collected from ponds where shrimp were being cultured or from ponds between culture cycles. However, it was not possible to obtain enough data on shrimp production to allow an analysis among soil characteristics, shrimp growth, shrimp survival, and shrimp yield.

Soil Texture

The average pond bottom soil texture was silty clay with a low sand content and a high proportion of silt and clay (Table 1). Some ponds varied greatly from the average, and soil texture ranged from heavy clays (> 50% clay) to sands (> 75% sand). In highly weathered soils such as those of coastal Ecuador, the clay fraction includes layered silicates and various hydrous oxides of aluminum, iron, and manganese (Lal and Sanchez 1992). Clay minerals are important in determining the CEC and the retention and availability of cations. Weathering of clay minerals may release alkaline earth cations, aluminum, iron, and silicate to the soil solution (Bohn et al. 1985). Smith (1996) estimated that 87% of silica available to diatoms during a shrimp production cycle in ponds was amorphous silica derived from the weathering of clay. Soil tex-

TABLE 1. *Average concentration, standard deviation and range of concentration for different chemical variables in the upper 5-cm sediment layer of 74 brackishwater shrimp ponds of Ecuador. Values are reported on an air dry basis.*

Variable	Mean	SD	Range
pH (pore water)	6.8	0.5	5.4–7.7
pH (1:1)	7.0	0.9	4.8–8.2
Clay (%)	39	16	3–61
Silt (%)	46	14	11–90
Sand (%)	15	20	0–86
Total carbon (%)	2.38	2.56	0.25–14
Total nitrogen (%)	0.16	0.10	0.02–0.52
Total sulfur (%)	0.43	0.37	0.03–2.08
Acid extractable phosphorus (mg/kg)	277	161	64–638
Total phosphorus (mg/kg)	898	243	461–1,549
CEC (meq/100 g)	30.8	10.5	4.5–49.0
Exchangeable acidity (meq/100 g)	3.3	1.8	1.2–10.0
Base unsaturation	0.12	0.06	0.03–0.27
Carbonate (% $CaCO_3$ equivalence)	0.51	0.59	0.03–2.48
Calcium (mg/kg)	3,949	3,087	928–19,864
Potassium (mg/kg)	1,488	487	214–2,594
Magnesium (mg/kg)	3,498	1,624	414–9,531
Sodium (mg/kg)	10,844	7,944	964–43,474
Iron (mg/kg)	661	436	46–2,680
Manganese (mg/kg)	137	145	10–879
Zinc (mg/kg)	9.5	4.3	0.0–24.5
Copper (mg/kg)	6.4	5.0	0.0–36.8
Boron (mg/kg)	20.4	11.5	2.0–67.5
Cobalt (mg/kg)	1.8	1.5	0.0–8.4
Molybdenum (mg/kg)	1.24	0.65	0.00–2.57
Aluminum (mg/kg)	571	274	202–1,184
Barium (mg/kg)	6.0	2.8	0.0–14.0
Lead (mg/kg)	4.1	2.5	0.0–13.3

ture is an important factor in pond construction, and shrimp farmers and other aquaculturists tend to favor sites with a high clay content. However, in Ecuador and other nations, shrimp are successfully cultured on a wide range of soils. A high clay content in soil is associated with a high phosphorus fixation capacity (Boyd and Munsiri 1996), and it often is difficult to initiate plankton blooms in semi-intensive shrimp ponds with heavy clay soils even when heavy phosphate fertilization is used. Better growth and survival of penaeid shrimp has been reported on sandy substrates (Chien et al. 1989; Pruder et al. 1992; Bray and Lawrence 1993). Soils with 5 to 10% clay and a well-graded particle size distribution are preferable to clays for earthwork construction (McCarthy 1998) and more amenable to drying and tilling between crops (Boyd 1995). Thus, selection of high clay content soils for pond culture of shrimp and other species may be less important than once thought.

pH, Acidity, Carbonate and CEC

The pH of pore water (soil pH measured *in situ*) usually was 0.1 to 0.4 pH units lower than soil pH measured in a dry soil:distilled water mixture for the same sample. The greatest frequency for pore water pH was 6.5 to 7.5, but pH of dry soil-distilled water mixtures was most often 7.0 to 8.0 (Fig. 2). The pH usually declines in waterlogged soils as the redox potential declines as a result of microbial activity in the absence of molecular oxygen (Boyd 1995). In aquaculture ponds, a thin layer below the

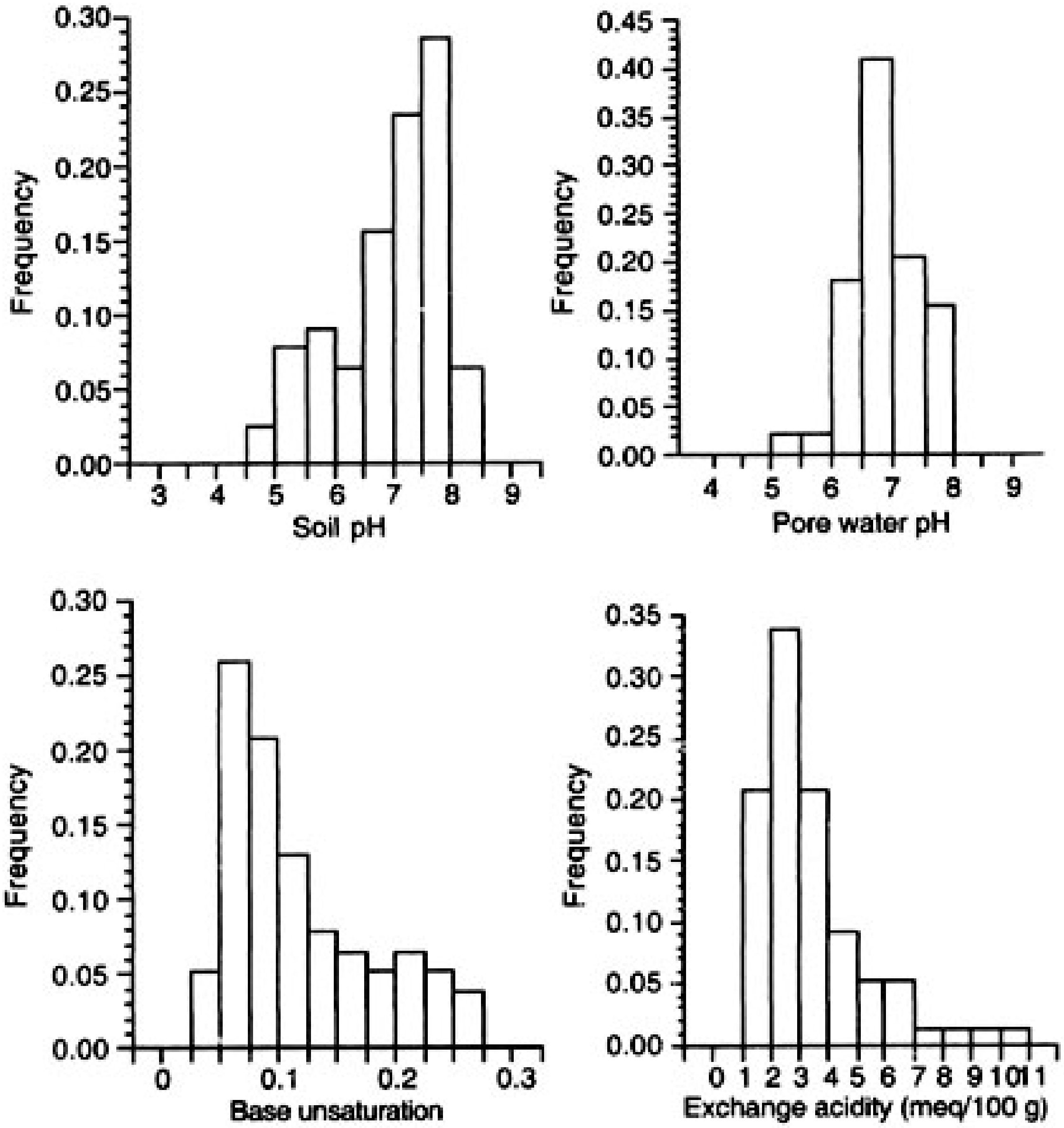

FIGURE 2. *Frequency distribution of soil pH, pore water pH, base unsaturation, and exchange acidity in the upper 5-cm sediment layer of shrimp ponds in Ecuador.*

soil-water interface normally is aerobic. Thus, pH measured in an aerobic mixture of dry soil and distilled water should be superior to the pore water pH as an indicator of the pH at the soil-water interface. Under aerobic conditions, soil pH is influenced by the degree of base unsaturation of cation exchange sites, the presence or absence of carbonates, and acidity resulting from oxidation of sulfide minerals in some soils (Boyd 1995).

Soil pH varied greatly among samples (Table 1; Fig. 2), but slightly more than half were neutral or alkaline in reaction. Major factors that influenced soil pH, base unsaturation, exchange acidity, carbonates, and sulfur (Figs. 2, 3, 4), also varied considerably among samples. Distributions of the pH-controlling factors were skewed to the left. This suggests that most soils tended to be on the low side of the range for base unsaturation, exchange acidity, and sulfur, and this should favor higher pH. Skewness toward low concentrations of carbonates should favor lower pH. There was a strong correlation between increasing exchange acidity and decreasing pH (Fig. 5). All samples with pH < 7.0 had exchangeable acidity > 5 meq/100 g. Base unsaturation also was negatively correlated with soil pH (Fig. 5), and samples with pH < 7 usually had base unsaturation > 0.1. There was no correlation between soil sulfur content and soil pH, but most samples with pH < 6 had sulfur concentrations $> 0.3\%$. The correlation between carbonate concentration soil pH was not significant, but no samples with more than 0.36% carbonate (as equivalent $CaCO_3$) had pH < 7.0 (Fig. 6).

Base unsaturation and exchange acidity should be very low in soils containing carbonates. Carbonate also will obscure the usual relationship of low pH when sulfide concentration is high, because carbonate

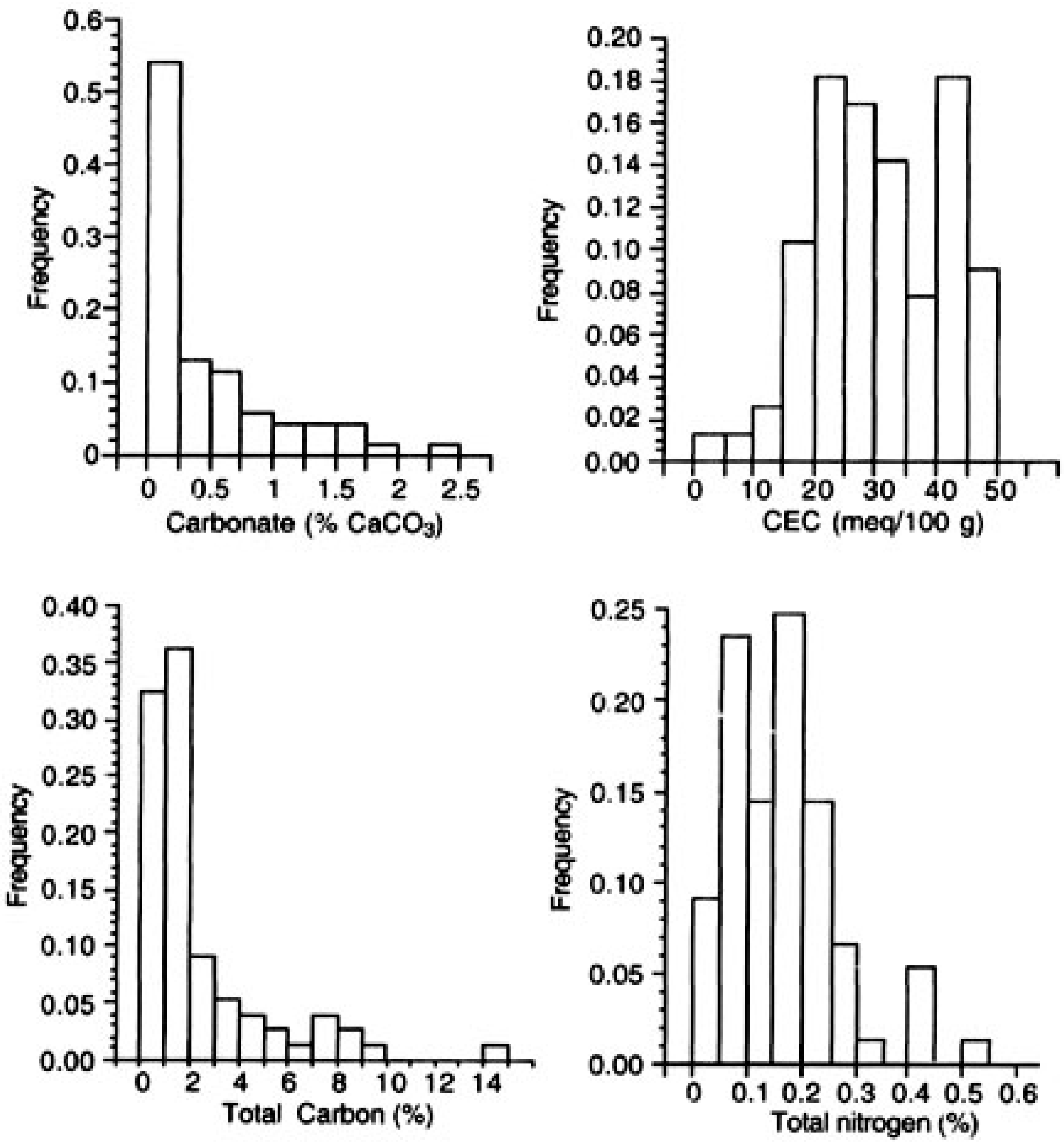

FIGURE 3. *Frequency distribution of carbonate, cation exchange capacity (CEC), total carbon, and total nitrogen in the upper 5-cm sediment layer of shrimp ponds in Ecuador.*

will neutralize acidity resulting from sulfide oxidation and cause a higher pH than expected.

Carbonate in Ecuadorian shrimp pond soil may have originated from natural deposition of calcium and magnesium carbonates or from pond liming. Pond bottoms often are treated between crops with 1,000 to 2,000 kg/ha of agricultural limestone. Pond soils have a bulk density of about 1.4 tons/m^3 (Munsiri et al. 1995). If lime reacts to a depth of 0.1 m, 1,000 kg/ha calcium carbonate will provide a concentration of about 0.071% calcium carbonate. Of course, some of the limestone will be used for neutralizing acidity, but over time, a considerable accumulation of carbonate could result from routine liming of non-acidic soils. Unnecessary liming increases shrimp production costs, and free calcium carbonate in pond bottoms will decrease availability of soil phosphorus (Boyd 1995).

Many farmers apply liming materials to pond waters during crops. Agricultural limestone and other liming materials will not dissolve appreciably in water with total alkalinity and total hardness concentrations > 60–70 mg/L (Boyd and Tucker 1998). Water samples collected from shrimp ponds in Ecuador ranged from 8 to 141 mg/L total alkalinity ($\bar{x} \pm SE = 88 \pm 8$ mg/L) and from 815 to 5,015 mg/L total hardness ($\bar{x} \pm SE = 2{,}017 \pm 284$ mg/L). About 25% of the hardness resulted from calcium, and the rest was primarily from magnesium. Obviously, most shrimp ponds in Ecuador will not benefit from liming the water during crops. Some farmers apply dolomitic agricultural limestone to ponds to increase magnesium concentration in the water. The large difference between total hardness and

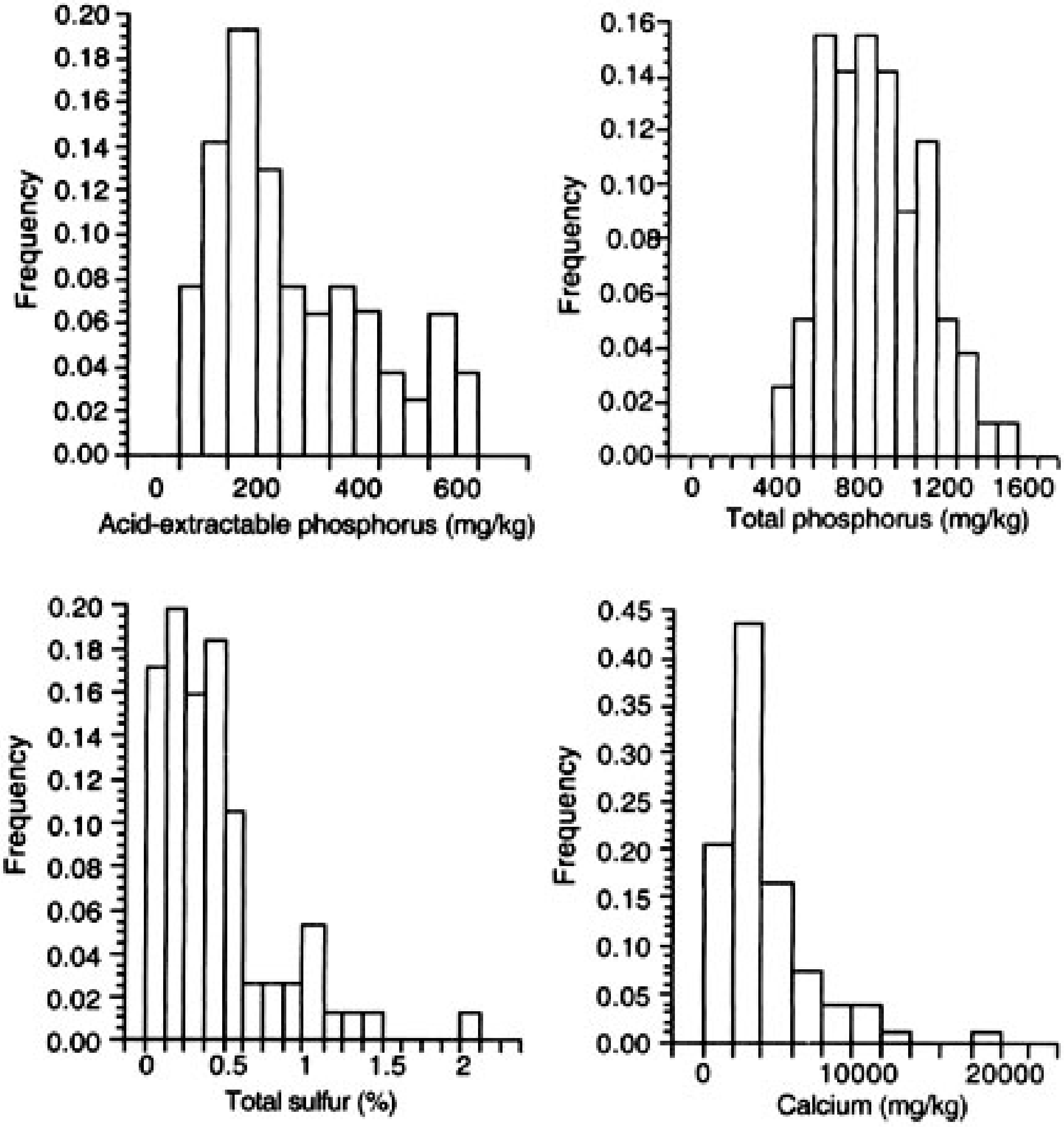

FIGURE 4. *Frequency distribution of acid-extractable phosphorus, total phosphorus, total sulfur and calcium in the upper 5-cm sediment layer of shrimp ponds in Ecuador.*

calcium hardness reveals that waters have high concentrations of magnesium already.

Boyd (1974) developed a lime requirement method for freshwater pond soils based on the degree of base unsaturation and the exchangeable acidity. In this study, it was found that liming soils to decrease base unsaturation to 0.2 would provide a soil pH above 6 and a total alkalinity in water above 20 mg/L. This method is not applicable to shrimp pond soils, for a higher total alkalinity is needed. A modification of this procedure (Pillai and Boyd 1985) determines the amount of liming material needed to achieve 0% base unsaturation and total alkalinity of about 60 mg/L. This procedure should be used to determine the lime requirement of shrimp pond soils with pH < 7. Where pond soils have appreciable amounts of sulfide, oxidation of sulfide in the aerobic layer will create sulfuric acid and neutralize alkalinity. In addition to liming soils based on the lime requirement test of Pillai and Boyd (1985), the total alkalinity of pond waters should be checked where soils contain appreciable sulfide (acid-sulfate soils). If total alkalinity falls below 60 mg/L, agricultural limestone should be applied over surfaces at 500 kg/ha. Results of the present investigation suggest that many shrimp ponds in Ecuador do not need to be limed, and use of these simple tests could result in more efficient liming procedures, and in many cases, prevent unnecessary expenditures for liming material and labor.

The CEC is a measure of soil cation adsorption capacity (Foth and Ellis 1988). Soil with a high CEC requires more liming material than soil of the same pH but of lower CEC. At the same degree of base unsaturation, a soil with a higher CEC will provide greater concentrations of cations

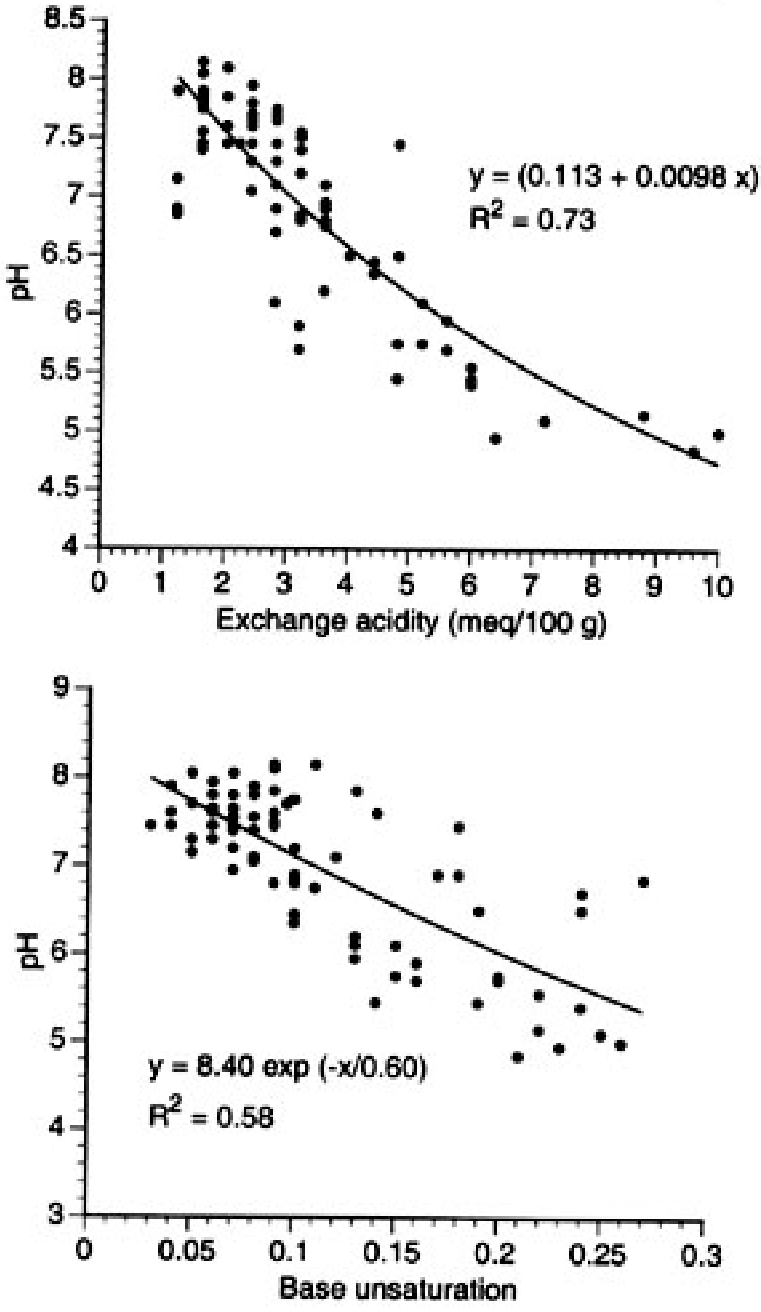

FIGURE 5. *(Upper) Relationship between pH and exchange acidity. (Lower) Relationship between pH and base unsaturation.*

such as Ca^{2+}, Mg^{2+}, Na^+, and K^+ in soil solution than a soil of lower CEC. The CEC of shrimp pond soils in Ecuador averaged 31 meq/100 g (Table 1) and few soils had CEC $<$ 20 meq/100 g (Fig. 3). Nevertheless, brackishwater has high concentrations of cations, and aside from influencing the amount of liming material needed to neutralize acidic soils, the CEC probably is not an important factor in shrimp ponds.

Carbon

The analyzer used in this study measured both organic and inorganic carbon. The major source of inorganic carbon in pond bottoms is carbonate. The contribution of carbon from carbonate to total carbon was relatively small because the average concentration in terms of calcium carbonate was

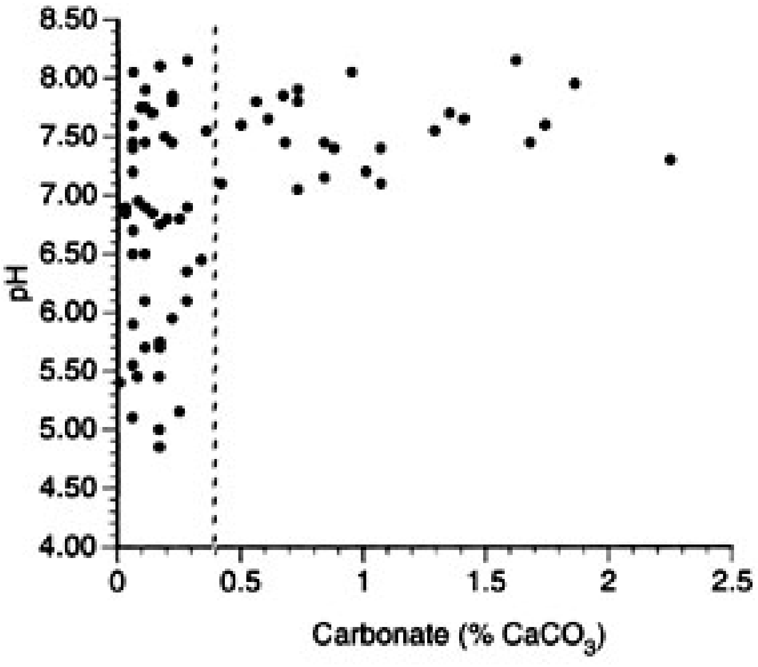

FIGURE 6. *Relationship between pH and calcium carbonate in brackishwater shrimp pond soils of Ecuador.*

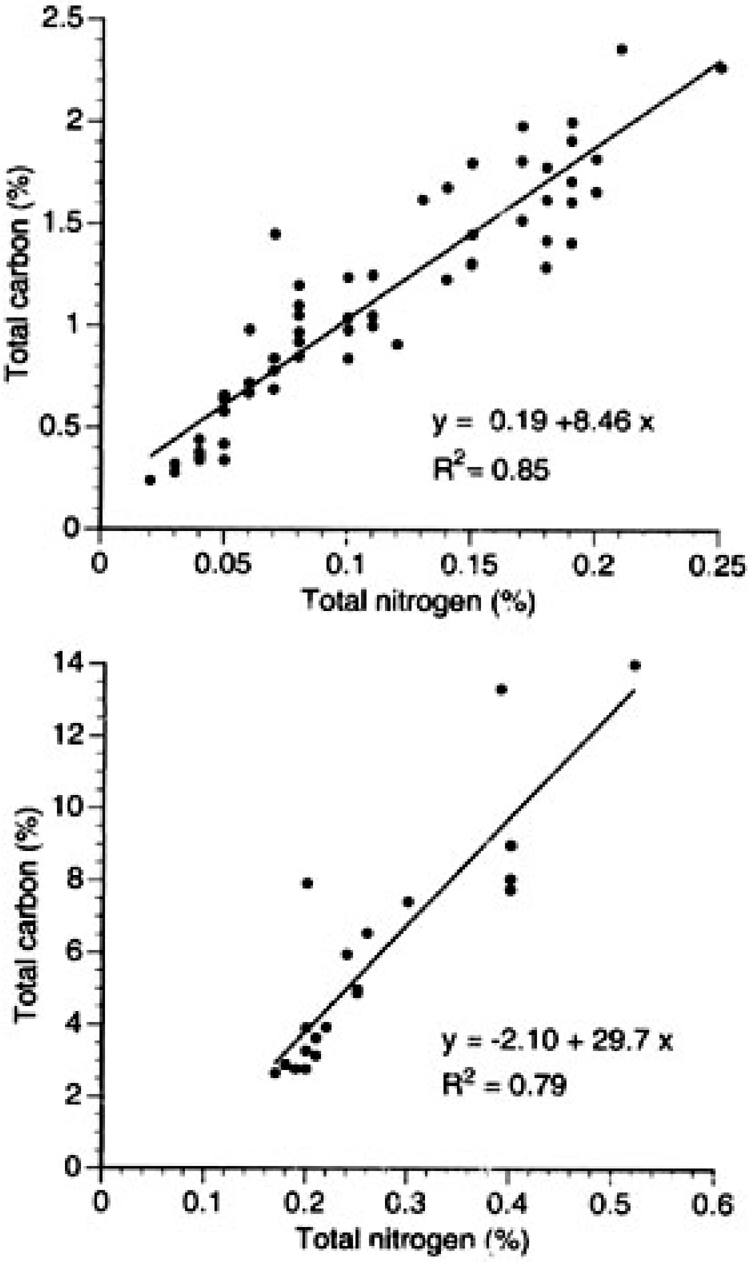

FIGURE 7. *(Upper) Relationship between total carbon and total nitrogen for soils containing < 2.5% total carbon. (Lower) Relationship between total carbon and nitrogen for soils containing > 2.5% total carbon.*

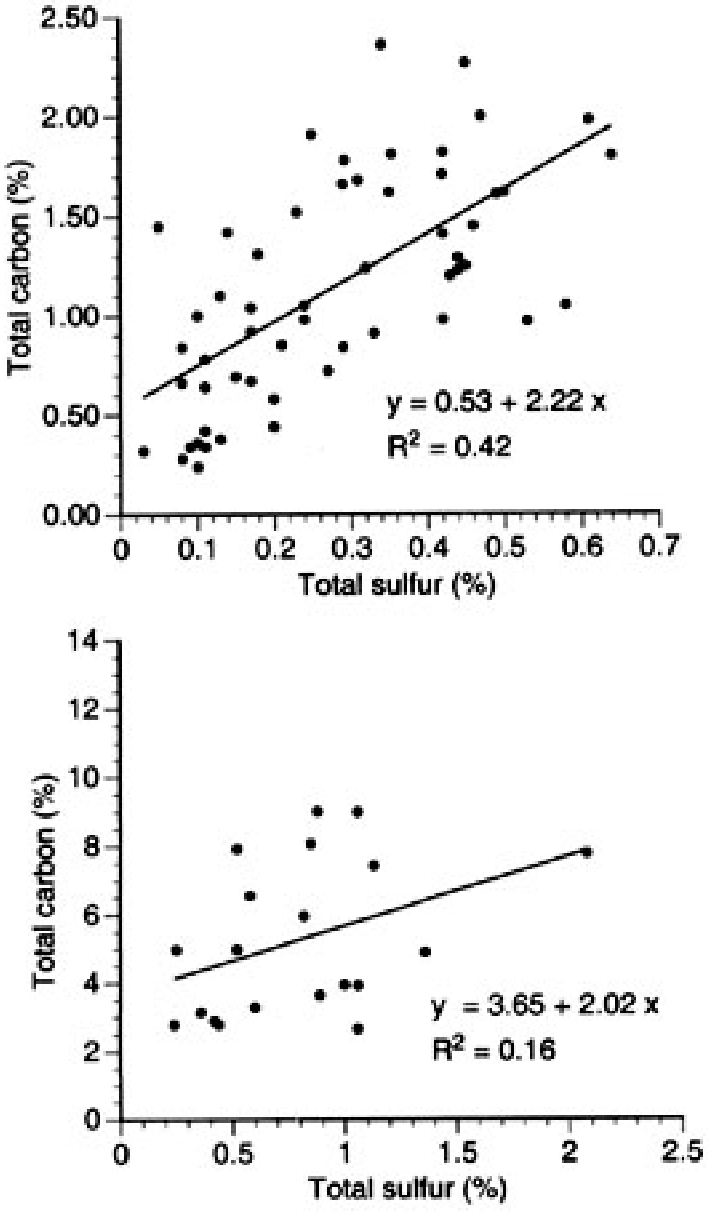

FIGURE 8. *(Upper) Relationship between total carbon and total sulfur for soils containing < 2.5% total carbon. (Lower) Relationship between total carbon and sulfur for soils containing > 2.5% total carbon.*

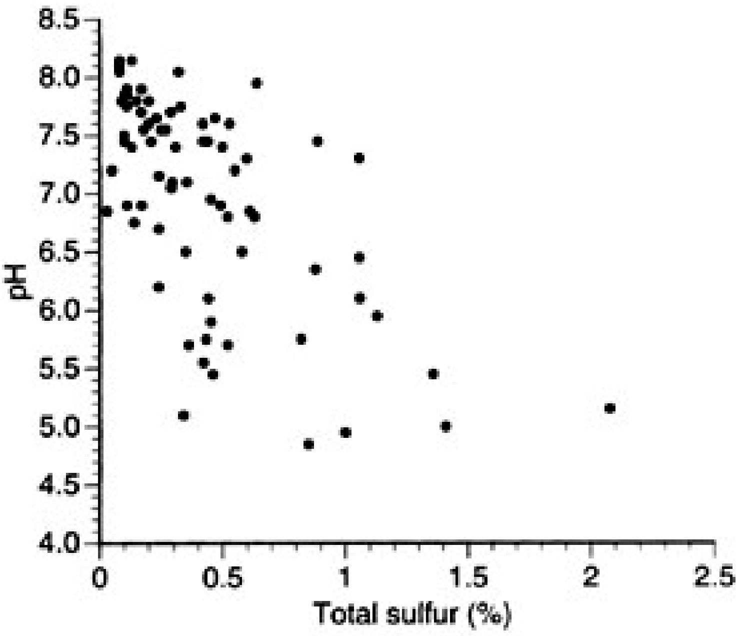

FIGURE 9. *Relationship between pH and sulfur in the upper 5-cm sediment layer of shrimp ponds in Ecuador.*

0.51% (equivalent to 0.06% C) and the maximum concentration was only 2.48% (equivalent to 0.29% C). There is a high correlation between carbon concentrations measured with the analyzer and by the $K_2Cr_2O_7$-H_2SO_4 oxidation commonly used by laboratories in Ecuador (Ayub and Boyd 1994).

Average concentration of carbon in all ponds was 2.38% and the median was 1.41%. About 70% of the samples had carbon concentrations < 2%, and only 15% had carbon concentrations > 5% (Fig. 3). Average soil carbon concentration in ponds not built on former mangrove land was 1.4%. This value is within the range of concentrations measured in other pond soils by Boyd et al. (1994b), Smith (1996), and Munsiri et al. (1996a, 1996b). In this study, carbon concentrations as high as 14% were found in soils of ponds built in former mangrove areas.

Discussions with many shrimp farmers in many nations by one author (CEB) reveal that they think that pond soils accumulate organic carbon at a high rate. The major sources of organic carbon in aquaculture ponds are settled, uneaten feed, feces, and dead plankton that tend to have low concentrations of structural carbohydrates. Such substances are considered labile organic matter because they can be readily decomposed by bacteria when environmental conditions are favorable (Boyd 1995). Studies of organic carbon concentrations in shrimp ponds (Munsiri et al. 1996b) and freshwater fish ponds (Munsiri et al. 1995) revealed that carbon concentrations do not accumulate at high rates. Organic carbon is steadily decomposed during the culture period, and if pond bottoms are dried between crops, decomposition rates increase (Ayub et al. 1993; Boyd and Teichert-Coddington 1994). The present study reveals that shrimp pond soils in Ecuador do not generally have high concentrations of organic carbon unless they were constructed in former mangrove areas. Of course, problems with excessive organic matter deposition may occur in localized areas, especially in draining channels and other deeper parts of the pond where smaller particles tend to set-

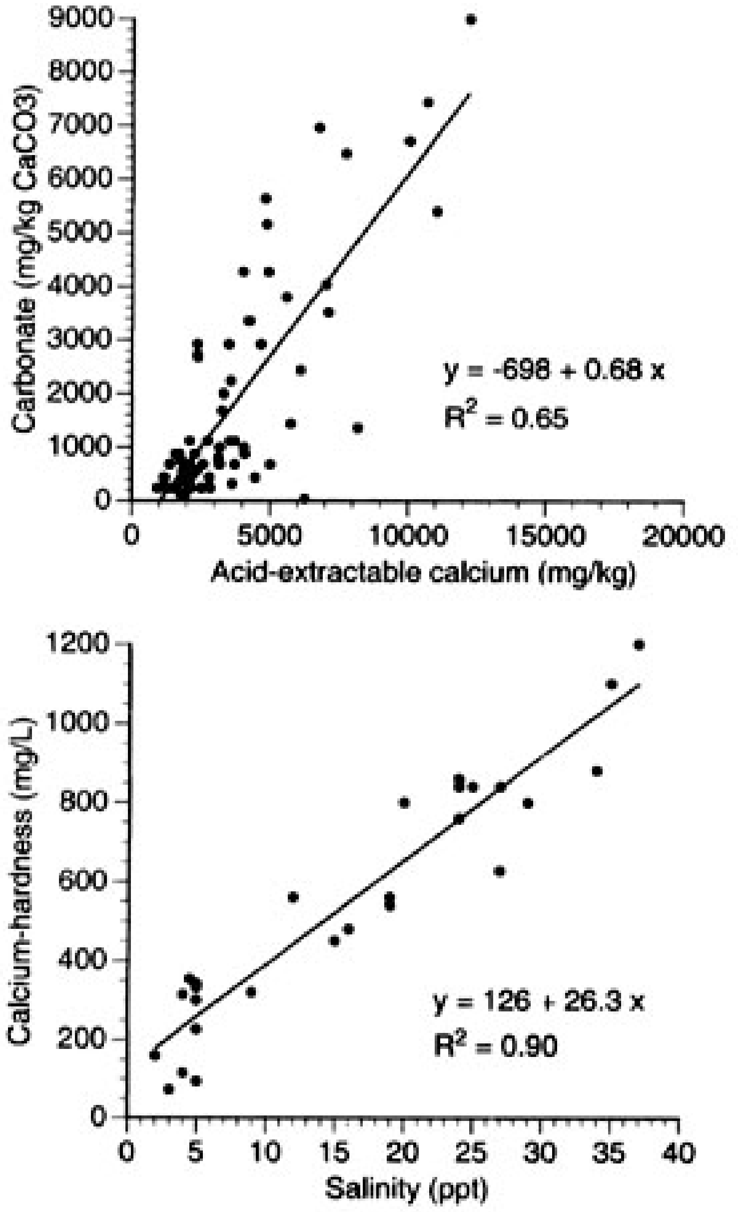

FIGURE 10. *(Upper) Relationship between carbonate and acid extractable calcium in the upper 5-cm sediment layer of shrimp ponds of Ecuador. (Lower) Relationship between calcium hardness and salinity in brackishwater shrimp ponds of Ecuador.*

tle (Boyd 1977) and in corners of ponds where scums of plankton and other organic matter accumulate as a result of wind-driven water currents.

Nitrogen

The nitrogen analyzer measured total nitrogen and did not distinguish between inorganic and organic forms. Most of the nitrogen in soils usually is associated with organic matter, and Smith (1996) reported that 86% of the nitrogen in shrimp pond soils was organic nitrogen. The average nitrogen concentration in shrimp pond soils from Ecuador was 0.16% (Table 1), and 90% of the samples contained < 0.25% N (Fig. 3). There was a high correlation between carbon and nitrogen (Fig. 7). Samples containing < 2.5% carbon had C:N ratios of 6 to 10 (average = 8.5). Earlier studies also found C:N ratios in soils of brackishwater and freshwater aquaculture pond soils to be between 6 and 12 (Boyd et al. 1994b; Munsiri et al. 1996a, 1996b; Smith 1996). However, in this study, shrimp pond soils with > 2.5% carbon had C:N ratios of 25 to 30. These samples came from ponds that had been constructed in former mangrove areas, and the majority of the organic matter was fibrous, low-nitrogen content remains of mangrove plants. Such residues are known as refractory organic matter because they decompose very slowly compared to the less fibrous organic residues of higher nitrogen content from uneaten feed, shrimp feces, and dead plankton (Boyd 1995).

Application of nitrogen fertilizer at 50 to 100 kg N/ha to bottom soils with high concentrations of organic matter and a wide C:N ratio would help decompose this residual material (Boyd 1995). It probably would require repeated treatments with nitrogen fertilizer for several years to cause significant decreases in soil carbon and C:N ratio. Of course, this treatment would probably not be beneficial in ponds where soils contain > 15 or 20% carbon. The finding that former mangrove soils have a wide C:N ratio could be useful in identifying areas where mangroves have been replaced by shrimp farms or other development. This information might be useful in responding to allegations by environmentalists that shrimp farming has been a major cause of mangrove loss (Boyd 1997).

Phosphorus

Total phosphorus concentrations were usually 3 to 4 times greater than concentrations of dilute-acid extractable phosphorus, and both estimates of soil phosphorus exhibited much variation among samples (Table 1; Fig. 4). Phosphorus is strongly bound in soils, and pond soils tend to be a sink for added phosphorus. In acidic soils, phosphorus precipitates as iron and aluminum phosphates, and it may be adsorbed onto iron

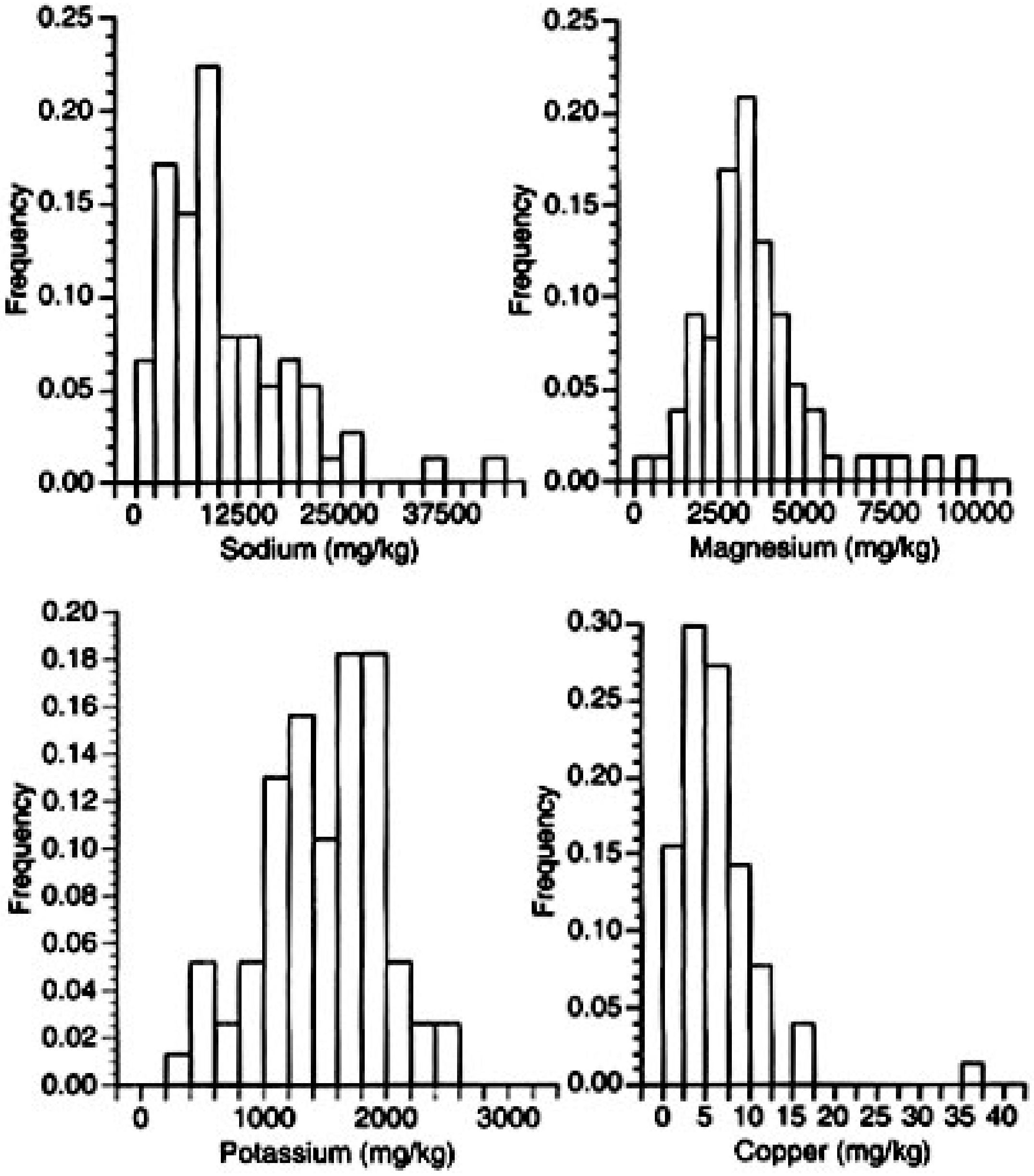

FIGURE 11. *Frequency distribution of sodium, magnesium, potassium, and copper in the upper 5-cm sediment layer of shrimp ponds in Ecuador.*

and aluminum oxides (Boyd 1995). In neutral and alkaline soils, phosphorus tends to precipitate as calcium phosphates. Under aerobic conditions, dissolved phosphate concentrations in soil-water systems usually are quite low at equilibrium. The solubility of soil phosphorus in water tends to increase as a function of increasing concentrations of dilute-acid extractable phosphorus (Boyd and Munsiri 1996) in soils containing iron and aluminum phosphates. Acid is particularly efficient in dissolving calcium phosphates, so the ratio of dilute-acid extractable phosphorus to total phosphorus is less in acidic soils than in neutral to basic ones. Boyd et al. (1994b) suggested that brackishwater pond soils contained more calcium phosphate than those of freshwater ponds because the higher concentrations of calcium in brackishwater as opposed to freshwater favors precipitation of calcium phosphate.

Sulfur

The sulfur analyzer measured the combined amount of organic, sulfate, and sulfide sulfur in soils. Sulfur concentrations > 0.75% indicated potential acid-sulfate soils in which oxidation of sulfides to sulfuric acid causes low pH (Soil Taxonomy Staff 1994). The average concentration of total sulfur was 0.43% (Table 1), and about 75% of samples were < 0.50% sulfur. Eleven samples, all of which came from former mangrove areas, had > 0.75% sulfur. In soils with < 2.5% carbon (non-mangrove soils), there was a good correlation between carbon and sulfur concentrations (Fig. 8). This suggests that much of the soil sulfur was in organic matter. Non-organic sulfur

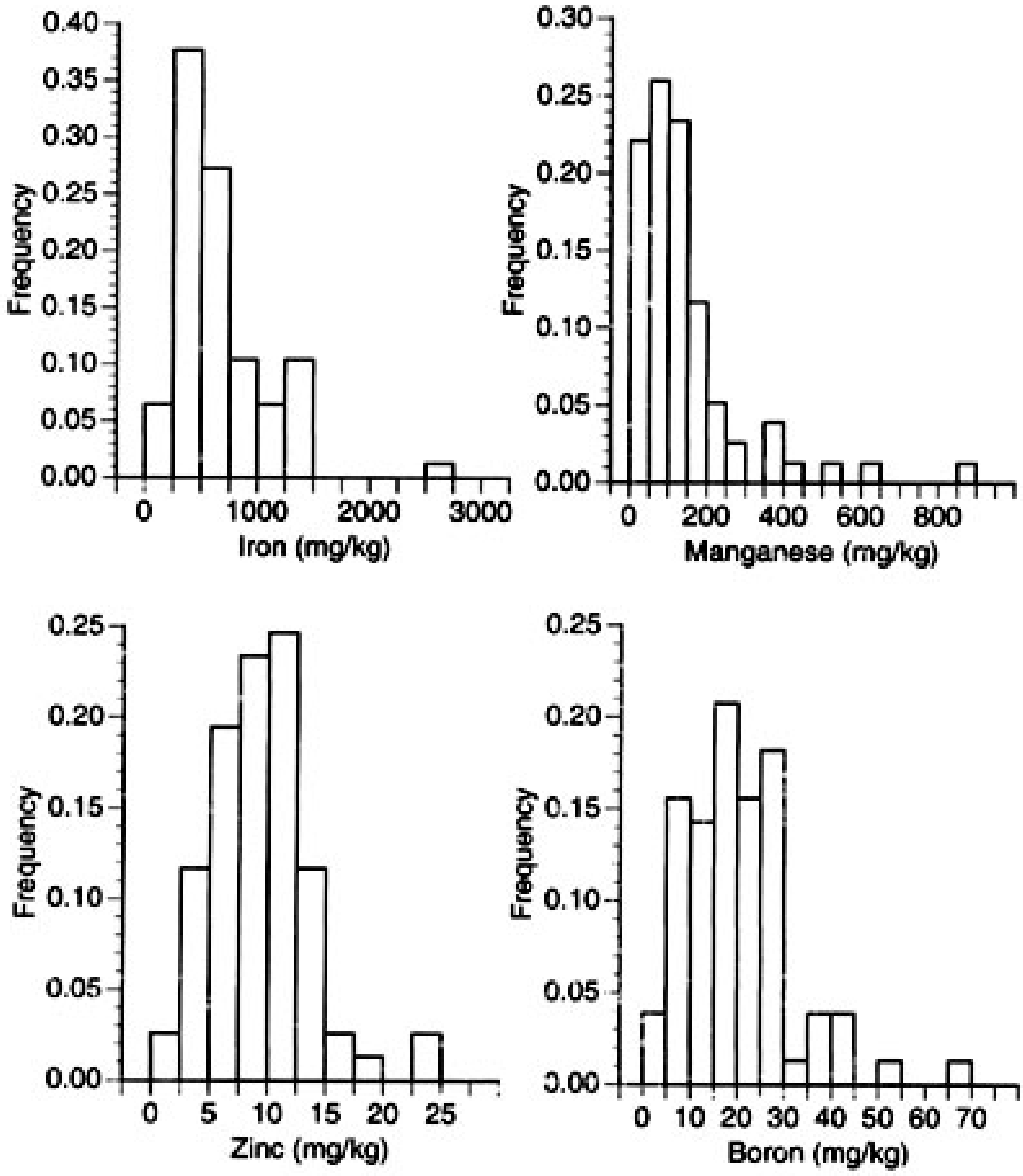

FIGURE 12. *Frequency distribution of iron, manganese, zinc, and boron in the upper 5-cm sediment layer of shrimp ponds in Ecuador.*

is present in sulfates and sulfides. The weak correlation between sulfur and carbon in soils containing > 2.5% carbon (Fig. 8) suggests that much of the sulfur was in sulfides, and the trend of low pH in soils of high sulfur content supports this contention (Fig. 9).

Sulfur inputs to shrimp ponds are feed and sulfate in the water. Under anaerobic conditions, sulfate bacteria oxidize organic matter. Sulfate is the oxygen source (terminal electron acceptor), and it is reduced to sulfide (Paul and Clark 1996). Sulfate-reducing bacteria may be responsible for much of the organic matter decomposition in many estuarine environments (Wellsbury et al. 1996). Hydrogen sulfide often occurs in anaerobic sediment, and iron and other metal sulfides may form (Munsiri et al. 1996b; Ritvo et al. 1998b). Iron sulfide (iron pyrite) commonly is found in mangrove soils. Pyrite formation is a slow process (Connell and Patrick 1969), but accumulation rates equal to 0.02% of soil mass per year have been measured (Andriesse et al. 1973). Hydrogen sulfide is extremely toxic to aquatic animals (Chien 1992; Bagarinao and Vetter 1992), and oxidation of sulfides can exert a large oxygen demand in sediment. Suplee and Cotner (1996) reported that sulfide oxidation accounted for 84% of the oxygen demand in shrimp pond soil near the end of the growing season.

Drying of bottom soils containing 1% sulfur caused oxidation of sulfide and a decline in total sulfur concentration (Masters and Smith 1995). Ritvo et al. (1998b) reported higher shrimp yields in ponds with higher concentrations of soil iron. They recommended treatment of pond soils with iron to enhance sulfide formation and lessen the possibility for elevated concentrations

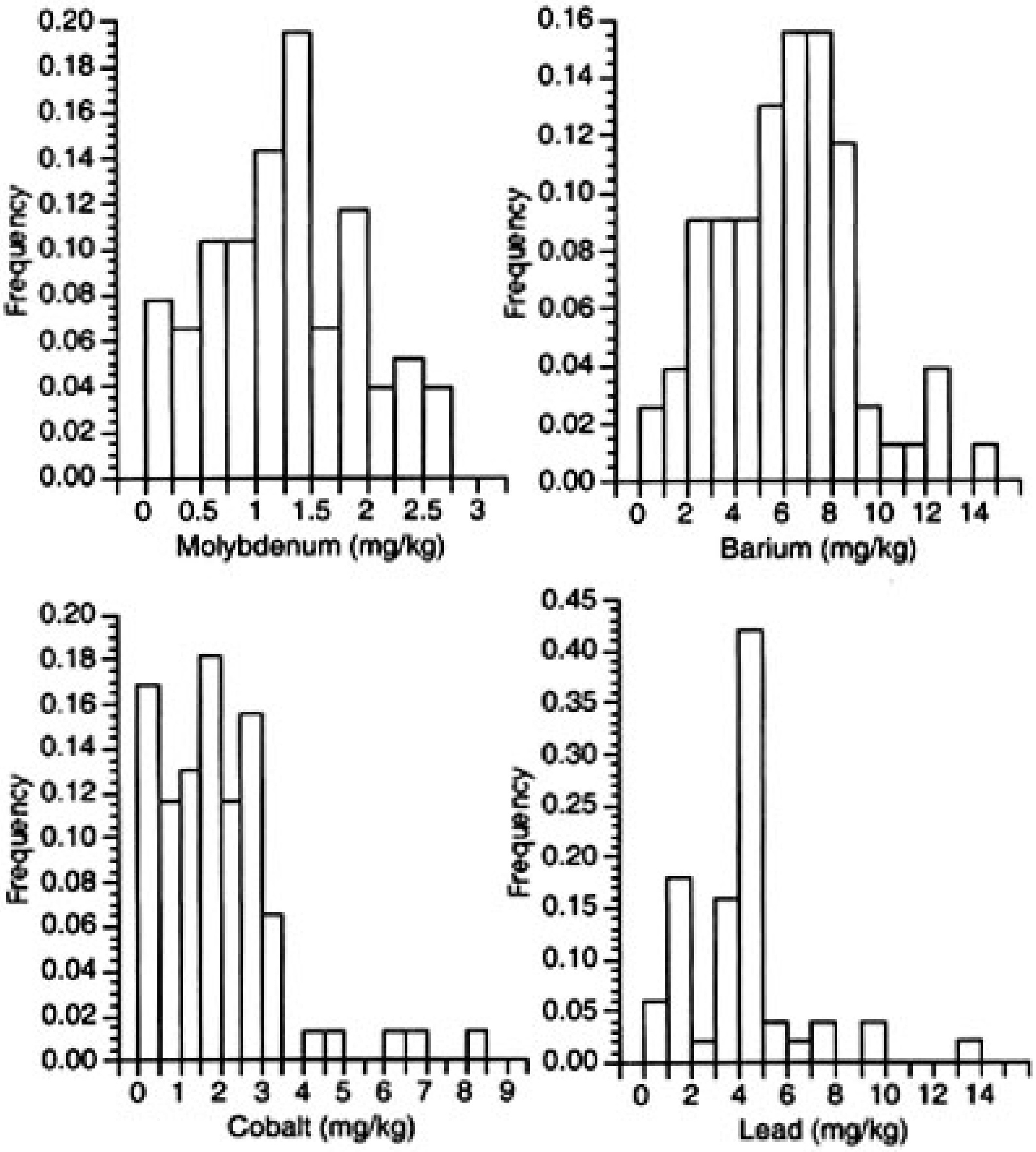

FIGURE 13. *Frequency distribution of molybdenum, barium, cobalt, and lead in the upper 5-cm sediment layer of shrimp ponds in Ecuador.*

of hydrogen sulfide. Precipitation of insoluble metal sulfides appeared to be a major factor controlling the bioavailability of trace metals in anoxic sediment (Di Toro et al. 1990; Casas and Crecelius 1994).

Macronutrient Cations

Concentrations of soil calcium averaged 3,949 mg/kg (Table 1), and most samples contained less than 6,000 mg/kg (Fig. 4). There was a high, positive correlation between acid-extractable calcium and carbonate concentrations in soils (Fig. 10). Thus, in soils with high calcium concentrations, much of the calcium is combined with carbonate. The other calcium fractions in pond soils are calcium on exchange sites, dissolved calcium, other calcium minerals, and minor amounts of calcium in organic matter.

The major sources of calcium in brackishwater ponds are inflowing water and liming materials. The average concentration of calcium hardness (calcium expressed in terms of equivalent $CaCO_3$) in the shrimp ponds was 532 mg/L. This is lower than the average calcium hardness of 1,000 mg/L in seawater (Boyd 1990). Nevertheless, the average calcium hardness in the shrimp ponds is equal to an amount that would result from complete dissolution of 5,320 kg of agricultural limestone (100% $CaCO_3$) in a 1-ha pond of 1 m depth. Shrimp and other crustaceans absorb calcium ion from water during molting (Fieber and Lutz 1982), and a calcium hardness of at least 50 mg/L is necessary to satisfy calcium requirements for molting (Boyd and Tucker 1998). Average calcium hardness concentrations were ten-fold greater than the minimum requirement. Calcium hardness concentrations were highly and positively correlated with increasing salinity (Fig. 10), and if salinity is adequate for shrimp, calcium hardness also will be sufficient.

Ritvo et al. (1999) obtained data from 81 ponds at two shrimp farms in Texas suggesting that shrimp production and soil calcium concentrations were negatively correlated. High calcium concentrations should decrease phosphate availability and reduce primary productivity in ponds (Boyd 1995). However, the ponds studied by Ritvo et al. (1999) received feed applications, and decreased primary productivity should not influence shrimp production. Thus, the negative influence of calcium should be investigated further, for if the observation is correct, excessive liming should be avoided because it could be counterproductive.

Average concentrations of potassium, magnesium, and sodium in pond soils were 1,488, 3,498 and 10,844 mg/kg, respectively (Table 1). Seawater contains 380, 1,290 and 10,700 mg/L of potassium, magnesium, and sodium, respectively (Brown et al. 1989). Soils with a high CEC can adsorb greater amounts of major cations than soils with a low CEC, and calcium and magnesium carbonates occurred in the samples. However, the major factor causing variation in concentrations of major cations (Fig. 11) probably was differences in concentrations of major cations in source water for ponds. Major cations are adsorbed on cation exchange sites and accumulate in pond sediments during drying when pore water evaporates from the soil. Ritvo et al. (1998a) reported an increase of major cations in pond soils of Texas shrimp farms in consecutive production cycles, and Munsiri et al. (1996b) showed that 11-yr-old shrimp ponds in Honduras had greater concentrations of major cations than 3-yr-old shrimp ponds. More research is needed to understand if major cation concentrations in pond soils influence microbial activity, mineral recycling, benthic productivity, water quality, and shrimp production.

Micronutrients and Other Elements

Data on concentrations of iron, aluminum, manganese, zinc, copper, boron, cobalt, molybdenum, barium, and lead in pond soils are presented in Table 1 and Figs. 11–14. Most elements showed a wide range in concentration, occasionally as high as 3 orders of magnitude. Differences in concentrations are most likely related to the properties of the different pond bottom soils and possibly to inputs in feeds, fertilizer, and other products.

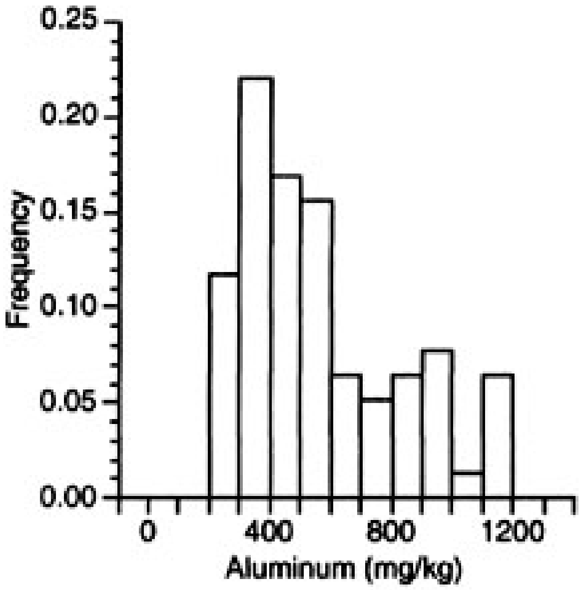

FIGURE 14. *Frequency distribution of aluminum in the upper 5-cm sediment layer of shrimp ponds in Ecuador.*

Several procedures have been used to extract minor elements from soils (Pickering 1981). Mild extractants such as salt solutions and weak acids tend to extract soluble salts and exchangeable forms of minor elements (McLean and Bledsoe 1992). Luoma and Bryan (1982) found that metal concentrations determined by weak acid extraction correlated better with metal concentrations in the bivalve *Scorbicula plana* than concentrations determined with stronger extraction methods. The dilute acid extractant was selected for use in this study because previous studies on micronutrients in shrimp pond soils had employed it (Boyd et al. 1994b; Munsiri et al. 1996b). However, the bioavailability of the micronutrient fraction extracted in dilute acid in this study is unknown.

Application

Most farms in this study conduct chemical analyses of wet soil samples and send samples to laboratories for organic matter analyses. Other soil analyses are made less frequently. Fresh samples of wet soils are anaerobic and their pH does not reflect the pH of aerobic soil at the soil-water interface. Soil pH should be measured in 1:1 mixtures of dry, pulverized soil and distilled water. Soil organic carbon concentrations of up to 2.5% seem normal in shrimp ponds, but the practice of drying ponds between crops to enhance organic matter decomposition is useful in lessening the possibility for excessive organic matter accumulation. Ponds do not need to be limed unless soil pH is < 7 or total alkalinity of pond water is < 60 mg/L. The lime requirement test of Pillai and Boyd (1985) can be used to measure lime requirements of pond soils, and total alkalinity of water can be measured with water quality test kits. Soil samples for pH and organic matter analyses should be taken from several different places in a pond and combined to provide a composite sample for analysis, because areal variation in pond soil characteristic is great (Ritvo et al. 1998d).

Application of nitrogen fertilizers to pond bottoms between crops might enhance the decomposition of organic matter in soils with a wide C : N ratio. Because shrimp can be successfully cultured over a very wide range of concentrations of major cations and minor elements in soils, it is doubtful that the concentrations of these elements have much influence on shrimp culture. Concentrations of major and minor elements in the water supply are more likely to influence shrimp production.

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