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POND SOIL CHARACTERISTICS AND DYNAMICS OF SOIL ORGANIC MATTER AND NUTRIENTS

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Progress Report*

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ABSTRACT

Analyses of soil cores from the bottoms of three freshwater fish ponds in Thailand and three in Peru revealed the typical layering in bulk density, total carbon, total nitrogen, and other selected physical and chemical variables observed in ponds at other CRSP sites and at Auburn University. Thus, we are now confident that the system of dividing soil profiles into S horizon (surface mixed sediment), M horizon (unmixed bulk sediment), T horizon (transition layer), and P horizon (original pond bottom soil) is based on a general feature of pond soil profiles. The soils from Iquitos, Peru, were very highly weathered and low in concentrations of macronutrient cations and micronutrients. There was very weak development of horizons in ponds at Iquitos. Organic matter decomposition in pond soils at Iquitos appears to be nitrogen limited. Ponds at Sae Kaeo, Thailand, had more highly developed horizons than those at Iquitos, Peru. The pond soils at Sae Kaeo also were highly weathered, but higher in cations and micronutrients than the Iquitos pond soils. Respiration per unit carbon ($\text{mg CO}_2 \text{ g}^{-1} \text{ C}$) was significantly different ($P < 0.01$) among layers in ponds from Auburn, Alabama, and Ecuador, and the highest respiration rate was obtained in the uppermost 1.0-cm layer. Higher respiration rate is attributed to a higher ratio of labile to refractive organic matter in the upper layers.

INTRODUCTION

Data on the physical and chemical properties of pond soils and on nutrient dynamics of pond soils are needed to develop a theory of pond soil development, formulate a method of pond soil classification, and improve pond soil management procedures. This report contains data on soils collected from three freshwater ponds at the PD/A CRSP site in Iquitos, Peru, and from three freshwater ponds at the Sae Kaeo Fisheries Station near Sae Kaeo, Thailand. In addition, data on soil respiration in soil cores taken from freshwater ponds at Auburn University are included.

METHODS AND MATERIALS

Peru and Thailand

Three ponds in Peru were sampled on 1 and 2 August 1998 and three ponds at Sae Kaeo, Thailand, were sampled on 21 and 22 February 1999.

Soil cores were taken with a hand-operated, 5-cm diameter core sampler (Wildlife Supply Company, Saginaw, Michigan, USA). Procedures for separating the cores into successive 2-cm-long core segments were described by Munsiri et al. (1995). Core segments were dried at 102°C (moisture content and dry bulk density) or 60°C (other analyses) and transported to Auburn University for analyses.

Samples were analyzed for moisture content (gravimetry), dry bulk density (gravimetry), color (Munsell color chart), wet soil pH (Peru samples only; direct, glass electrode), dry soil pH (1:1 slurry of dry soil and distilled water, glass electrode), exchangeable acidity (Adams-Evans buffer method), total carbon and nitrogen (Leco CHN Analyzer), total phosphorus (Peru samples only; perchloric acid oxidation), total sulfur (Leco Sulfur Analyzer), and acid-extractable phosphorus and metal ions (extraction in a 0.075 N acid solution of 0.05 N hydrochloric acid plus 0.025 N sulfuric acid followed by plasma spectrophotometry). Particle size analyses of samples from Peru were made by the pipette method. All methods followed details provided by Munsiri et al. (1995).

Aerobic and anaerobic incubation methods were used to estimate potentially mineralizable nitrogen and carbon (aerobic incubation only) in soils sampled from 0 to 10 cm and 10 to 20 cm layers of pond bottoms in Peru. Soil samples were refrigerated at 5°C until incubation. Aerobic incubations were done following methods of Wood and Edwards (1992), while anaerobic incubations were done according to methods outlined by Keeney (1982). In aerobic incubations, respired carbon dioxide was trapped in a vial containing 8 ml of 1 M sodium hydroxide (Anderson, 1982).

Soil organic carbon and nitrogen, and inorganic nitrogen [$\text{NO}_3\text{-N}$ plus $\text{NO}_2\text{-N}$ (aerobic incubation only), and $\text{NH}_4\text{-N}$] were measured before incubations were initiated. Soil

inorganic nitrogen and respired $\text{CO}_2\text{-C}$ were measured upon termination of incubation. Soil organic carbon and nitrogen were determined via dry combustion with a LECO CHN-600 analyzer. Inorganic nitrogen was extracted with 2 M potassium chloride and analyzed via the microplate method (Sims et al., 1995). Carbon dioxide in sodium hydroxide traps was determined by titrating excess base with 1 M hydrochloric acid in the presence of barium chloride (Anderson, 1982).

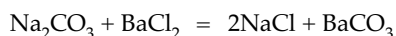
Soil potential nitrogen mineralization was calculated as the difference between final and initial contents of inorganic nitrogen for each incubation. Potential carbon mineralization was calculated as the difference between the incubation base trap and the mean of four blanks.

Additional Soil Respiration Studies

Soil for this study was obtained from six freshwater catfish ponds located on the Auburn University Fisheries Research Unit, Auburn, Alabama, and eight brackishwater shrimp ponds in Ecuador. Samples from the upper 5-cm sediment layer of each pond were collected with a 5-cm-diameter core liner tube. Freshwater and brackishwater sediment cores were then sliced into successive 0.5-cm and 1.0-cm-long segments, respectively, according to methods described in Masuda and Boyd (1994). The cores were obtained from 8 to 15 sites within each pond and combined to provide one sample of each depth layer. All samples were dried in a forced draft oven at 60°C , pulverized with a hammer mill-type soil crusher (Custom Laboratory Equipment Inc., Orange City, Florida, USA) to pass a 20-mesh screen, and stored in plastic bags for further analysis.

Soil moisture was determined by oven drying the samples at 105°C . Total carbon concentrations were measured with a LECO EC12 Induction Furnace Analyzer.

The technique used to measure soil respiration is described by Anderson (1982) and consists of trapping the carbon dioxide evolved during microbial respiration in 1 N sodium hydroxide solution placed inside an airtight chamber. Sodium carbonate resulting from the reaction of carbon dioxide and sodium hydroxide is precipitated with excess barium chloride, and the remaining alkali is then back-titrated with standard 1.00 N hydrochloric acid. The reactions are given in the following equations:



Respiration chambers were prepared in triplicate for each soil layer by adding 15 g of dry soil into 1-quart (946-ml) mason jars. Soils were moistened with bacterial enriched biological oxygen demand (BOD) dilution water. The bacterial inoculum Polyseed[®] was obtained from Polybac Corporation, Bethlehem, Pennsylvania, USA. Preparation of BOD dilution water and seed inoculum followed guidelines recommended by Eaton et al. (1995). PVC tubes (5 cm x 3.18 cm diameter) were inserted vertically into the soil to support 20-ml alkali containers. Support tubes had holes to allow passage of carbon dioxide formed in soil beneath alkali containers. Respiration chambers without soil were carried through the procedure as control blanks. Microcosms were tightly capped with lids. Soils were incubated in the dark for one week in an incubator at 25°C .

Alkali solution containing sodium carbonate was precipitated with 3 N barium chloride in 25-ml centrifuge tubes. Supernatant containing remnant sodium hydroxide was separated from precipitate by centrifugation at 2,500 rpm. The amount of carbon dioxide evolved in soil respiration was estimated by the following equation:

$$\text{CO}_2 \text{ (mg g}^{-1}\text{)} = (\text{B} - \text{V}) \text{N} 22 / \text{W}$$

where

- B = acid used to titrate sodium hydroxide in the blank (ml),
- V = acid used to titrate sodium hydroxide in treatment (ml),
- N = normality of hydrochloric acid (1.00 N),
- 22 = equivalent weight of carbon dioxide,
- W = dry weight of soil confined in respiration chamber (g).

RESULTS AND DISCUSSION

Pond Soils at Iquitos, Peru

The moisture content of the soil in ponds at the Iquitos site decreased rapidly with depth, and dry bulk density increased with depth (Table 1). The S horizon was only 2 cm thick, and the M horizon also was thin, extending from 2 to 6 cm. The T horizon was between 6 and 10 cm depth. The P horizon had quite high dry bulk densities of 1.75 g cm^{-3} and above. Soil color changed very little with depth (Table 2). Ponds at other CRSP sites including newly renovated ponds at Sagana, Kenya (Boyd et al., 1997, 1998), and on the Auburn University Fisheries Research Unit (Munsiri et al., 1995) had much more strongly developed profiles than the ponds at Iquitos.

Wet soil pH was very similar to dry soil pH in ponds at Iquitos (Table 3). At other CRSP sites and at Auburn University, wet soil pH usually has been slightly higher than dry soil pH in acidic soils, and wet soil pH has been slightly lower than dry soil pH in neutral or basic soils (Boyd et al., 1997, 1998). As no definite pattern can be established among wet and dry soil pH and most of the literature on soil pH is based on dry soil pH, we will not measure wet soil pH in future studies. The soil pH

Table 1. Profiles for moisture content and dry bulk density in soil cores from bottoms of aquaculture ponds in Iquitos, Peru. Moisture content averages and standard errors are given as percentages of dry weight. Dry bulk density averages and standard errors are given as gram dry soil per cubic centimeter (g cm^{-3}). Each entry is the average of three ponds.

Depth (cm)	Moisture Content (%)	Dry Bulk Density (g cm^{-3})
0–2	519.1 ± 205.8	0.27 ± 0.14
2–4	327.1 ± 208.4	0.70 ± 0.47
4–6	95.6 ± 54.8	0.97 ± 0.32
6–8	33.9 ± 12.9	1.44 ± 0.22
8–10	26.2 ± 5.2	1.60 ± 0.14
10–12	17.9 ± 0.4	1.78 ± 0.04
12–14	16.2 ± 0.4	1.83 ± 0.05
14–16	16.1 ± 0.2	1.78 ± 0.04
16–18	16.6 ± 0.5	1.81 ± 0.05
18–20	15.3 ± 0.6	1.90 ± 0.10
20–22	15.6 ± 0.7	1.80 ± 0.01
22–24	16.1 ± 0.5	1.75 ± 0.10
24–26	18.0 ± 0.8	1.75 ± 0.04
26–28	17.1 ± 0.8	1.86 ± 0.07
28–30	17.4 ± 0.9	1.92 ± 0.14

was greater in the S and M horizons at Iquitos than in deeper layers because of liming of pond bottoms. Exchangeable acidity of the soils ranged from 9.33 meq (100 g)⁻¹ in surface soils to near 5 meq (100 g)⁻¹ in deeper soils. The surface soils had a greater exchangeable acidity than deeper soils in spite of the higher pH of the surface soils. This phenomenon results because the surface soils were greatly enriched in organic matter (Table 4) and clay (Table 5) compared to deeper layers, and organic matter and clay increase the cation exchange

capacity (CEC) of soil. Soils with a higher CEC will have a greater exchangeable acidity at a given pH than will soils of a lower CEC.

There was a distinct layering of total carbon and total nitrogen in the soil profiles. The S horizon had 3.15% carbon and 0.08% nitrogen, the M horizon averaged about 1% carbon and 0.03% nitrogen, and deeper horizons were very low in carbon and nitrogen content (Table 4). The C/N ratios were 39 in the S horizon, 33 in the M horizon, and 29 to 62 in the T and P horizons. These are much lower C/N ratios than those found in ponds at other CRSP sites and at Auburn University (Boyd et al., 1997, 1998; Munsiri et al., 1995) where C/N ratios ranged between 7 and 20 with most values below 15. The wide C/N ratios in ponds at Iquitos suggest that nitrogen inputs to ponds in feeds and fertilizers have been much lower than at other CRSP sites.

Table 2. Profiles for color in soil cores from bottoms of aquaculture ponds in Iquitos, Peru. Color values are given as standard Munsell Color Chart Units. Each entry is the value of a particular pond.

Depth (cm)	Pond 4	Pond 5	Pond 6
0–2	5Y 3/2	2.5Y 3/3	10YR 4/2
2–4	10YR 4/2	2.5Y 4/2	10YR 4/2
4–6	10YR 5/2	2.5Y 4/2	10YR 4/2
6–8	10YR 5/2	7.5Y 4/2	10YR 5/2
8–10	10YR 5/2	7.5Y 4/1	10YR 4/1
10–12	10YR 4/2	7.5Y 4/1	10YR 5/2
12–14	10YR 5/2	7.5Y 4/1	10YR 4/1
14–16	10YR 4/2	7.5Y 4/1	10YR 5/2
16–18	2.5Y 5/2	7.5Y 5/2	10YR 5/2
18–20	10YR 5/2	7.5Y 5/2	10YR 4/2
20–22	10YR 5/3	7.5Y 5/2	10YR 4/1
22–24	10YR 5/2	7.5Y 4/2	10YR 5/2
24–26	10YR 5/2	7.5Y 5/2	10YR 5/2
26–28	10YR 5/2	7.5Y 4/2	10YR 5/2
28–30	10YR 4/2	7.5Y 4/2	10YR 5/2

Note: 2.5Y 3/3—Dark olive brown; 2.5Y 4/2—Dark grayish brown; 2.5Y 5/2—Grayish brown; 5Y 3/2—Dark olive gray; 7.5Y 4/1—Dark gray; 7.5Y 4/2—Brown; 7.5Y 5/2—Brown; 10YR 4/1—Dark gray; 10YR 4/2—Dark grayish brown; 10YR 5/2—Grayish brown; 10YR 5/3—Brown.

Table 3. Profiles for wet soil pH, dry soil pH, and exchangeable acidity in soil cores from bottoms of aquaculture ponds in Iquitos, Peru. The wet soil pH is directly measured in soil core and the dry soil pH is measured in 1:1 slurries of dry soil and distilled water. Averages and standard errors of pH are given as standard pH units. Exchangeable acidity averages and standard errors are given as milliequivalents per 100 grams dry soil (meq (100 g)⁻¹). Each entry is the average of three ponds.

Depth (cm)	Wet Soil pH	Dry Soil pH	Exchangeable Acidity (meq (100 g) ⁻¹)
0–2	6.5 ± 0.1	6.3 ± 0.2	9.33 ± 2.71
2–4	6.5 ± 0.1	6.3 ± 0.3	7.20 ± 3.33
4–6	6.2 ± 0.2	6.2 ± 0.1	5.07 ± 2.18
6–8	5.8 ± 0.5	6.1 ± 0.1	5.33 ± 0.53
8–10	6.3 ± 0.2	5.9 ± 0.3	5.33 ± 1.92
10–12	6.6 ± 0.1	6.0 ± 0.3	6.40 ± 3.33
12–14	6.1 ± 0.4	5.8 ± 0.3	4.80 ± 2.44
14–16	5.6 ± 0.4	5.9 ± 0.3	4.80 ± 2.40
16–18	5.6 ± 0.2	5.8 ± 0.2	5.07 ± 2.54
18–20	5.7 ± 0.4	5.8 ± 0.3	5.33 ± 2.67
20–22	5.9 ± 0.2	5.7 ± 0.3	5.07 ± 2.54
22–24	5.9 ± 0.3	5.7 ± 0.3	5.33 ± 2.67
24–26	5.9 ± 0.0	5.7 ± 0.2	5.47 ± 2.53
26–28	5.5 ± 0.7	5.5 ± 0.3	5.60 ± 2.40
28–30	5.9 ± 0.4	5.5 ± 0.3	5.73 ± 2.68

Total sulfur concentrations (Table 4) were greater in the S and M horizons than in deeper soil, but there was very little sulfur in the soils at Iquitos. In fact, sulfur was undetectable in most samples from the P horizon. Three forms of phosphorus—total, dilute-acid-extractable, and water-extractable—were measured in the samples (Table 6). Total phosphorus concentrations were as high or higher than those measured at other CRSP sites (Boyd et al., 1997, 1998) and at Auburn University (Munsiri et al., 1995), but dilute-acid-extractable phosphorus concentrations were very low, and except in the S and M horizons, water-extractable phosphorus also was low.

The total phosphorus fraction is very difficult to measure because the phosphorus must be liberated from the soil by perchloric acid digestion. The water-extractable phosphorus also is difficult to measure because phosphorus concentrations often are near the lower detection limit. Also, total phosphorus concentrations often have little relationship to the concentrations of extractable phosphorus or water-extractable phosphorus (Boyd and Munsiri, 1996). Thus, for future analyses of pond soil cores, we have decided to measure only dilute-acid-extractable and water-extractable phosphorus.

Table 4. Profiles of total carbon, total nitrogen, and total sulfur in soil cores from bottoms of aquaculture ponds in Iquitos, Peru. Averages and standard errors are given as percentages. Each entry is the average of three ponds.

Depth (cm)	Total Carbon (%)	Total Nitrogen (%)	Total Sulfur (%)
0–2	3.15 ± 0.77	0.08 ± 0.03	0.04 ± 0.02
2–4	1.28 ± 0.55	0.03 ± 0.01	0.02 ± 0.01
4–6	0.77 ± 0.23	0.02 ± 0.01	0.01 ± 0.01
6–8	0.58 ± 0.09	0.01 ± 0.00	0.00
8–10	0.61 ± 0.19	0.01 ± 0.003	0.01 ± 0.01
10–12	0.62 ± 0.23	0.01 ± 0.003	0.01 ± 0.00
12–14	0.44 ± 0.10	0.01 ± 0.003	0.00
14–16	0.39 ± 0.06	0.01 ± 0.00	0.00
16–18	0.37 ± 0.06	0.01 ± 0.00	0.00
18–20	0.49 ± 0.12	0.01 ± 0.003	0.00
20–22	0.36 ± 0.08	0.01 ± 0.003	0.00
22–24	0.29 ± 0.06	0.01 ± 0.003	0.01 ± 0.00
24–26	0.31 ± 0.04	0.01 ± 0.00	0.00
26–28	0.29 ± 0.02	0.01 ± 0.00	0.00
28–30	0.32 ± 0.04	0.01 ± 0.00	0.00

Table 5. Profiles for soil texture and particle size distribution in soil cores from bottoms of aquaculture ponds in Iquitos, Peru. Averages and standard errors for particle size distribution are given as percentages of dry weight. Each entry is the average of three ponds.

Depth (cm)	Soil Texture	Sand (%)	Silt (%)	Clay (%)
0–2	Loam	42.20 ± 16.36	35.27 ± 10.58	22.53 ± 6.38
2–4	Sandy loam	62.84 ± 15.45	24.47 ± 10.66	12.69 ± 4.94
4–6	Sandy loam	68.37 ± 5.85	21.10 ± 3.32	10.53 ± 3.26
6–8	Sandy loam	68.63 ± 2.20	23.26 ± 3.07	8.11 ± 1.33
8–10	Loamy sand	82.70 ± 5.01	11.81 ± 2.93	5.49 ± 2.20
10–12	Loamy sand	78.70 ± 5.86	15.63 ± 3.56	5.67 ± 2.96
12–14	Loamy sand	79.04 ± 5.61	15.83 ± 4.14	5.13 ± 2.34
14–16	Loamy sand	79.00 ± 4.28	16.23 ± 2.85	4.77 ± 2.59
16–18	Loamy sand	81.33 ± 3.37	13.71 ± 1.55	4.96 ± 2.15
18–20	Loamy sand	81.13 ± 4.45	13.99 ± 3.30	4.88 ± 1.95
20–22	Loamy sand	82.20 ± 5.11	13.49 ± 3.78	4.31 ± 2.11
22–24	Loamy sand	82.63 ± 4.94	12.77 ± 3.16	4.60 ± 2.14
24–26	Loamy sand	79.64 ± 3.32	15.03 ± 2.55	5.33 ± 1.69
26–28	Loamy sand	78.54 ± 3.92	16.45 ± 3.31	5.01 ± 1.45
28–30	Loamy sand	81.14 ± 3.38	13.93 ± 2.52	4.93 ± 1.50

Table 6. Profiles for total phosphorus, dilute-acid-extractable phosphorus, and water-extractable phosphorus in soil cores from bottoms of aquaculture ponds in Iquitos, Peru. Averages and standard errors for total phosphorus and dilute-acid-extractable phosphorus are given as parts per million (ppm), and each entry is the average of three ponds. Concentrations for water-extractable phosphorus are given in milligrams per liter for a single pond at each location.

Depth (cm)	Total Phosphorus (ppm)	Dilute-acid-extractable Phosphorus (ppm)	Water-extractable Phosphorus (mg l ⁻¹)
0–2	1,726 ± 288	15.5 ± 2.2	0.238
2–4	1,241 ± 505	14.4 ± 3.2	0.123
4–6	1,020 ± 274	11.0 ± 3.8	0.081
6–8	1,092 ± 74	8.9 ± 3.5	0.074
8–10	618 ± 123	5.0 ± 1.6	0.007
10–12	592 ± 118	3.1 ± 0.5	0.035
12–14	702 ± 162	3.5 ± 0.7	0.006
14–16	732 ± 66	2.7 ± 0.9	0.023
16–18	716 ± 39	2.8 ± 0.9	0.005
18–20	495 ± 88	2.7 ± 0.6	0.020
20–22	561 ± 71	2.4 ± 0.4	0.005
22–24	387 ± 51	2.1 ± 0.6	0.018
24–26	760 ± 199	2.4 ± 0.4	0.004
26–28	656 ± 58	2.8 ± 0.6	0.015
28–30	635 ± 208	2.6 ± 0.7	0.004

The soils at Iquitos were very low in concentrations of calcium, magnesium, sodium, and potassium (Table 7) when compared to soils from ponds at other CRSP sites and Auburn University (Boyd et al., 1997, 1998; Munsiri et al., 1995). Nevertheless, the S and M horizons had greater concentrations of these major ions as compared to the deeper horizons. This phenomenon is the result of additions of major ions to ponds in liming materials and fertilizers used in aquaculture. It is not surprising that the soils at Iquitos are low in concentrations of major ions, because soils in tropical areas with high rainfall and high temperature tend to be highly leached and low in bases.

Table 7. Profiles for calcium, magnesium, potassium, and sodium in soil cores from bottoms of aquaculture ponds in Iquitos, Peru. Averages and standard errors are given as parts per million (ppm). Each entry is the average of three ponds.

Depth (cm)	Calcium (ppm)	Magnesium (ppm)	Potassium (ppm)	Sodium (ppm)
0–2	330 ± 100	14 ± 3	20 ± 4	8.8 ± 0.7
2–4	206 ± 82	6.1 ± 2.4	7.8 ± 2.6	5.9 ± 0.7
4–6	127 ± 46	3.4 ± 1.3	4.4 ± 1.0	4.6 ± 0.7
6–8	121 ± 29	3.1 ± 0.7	4.2 ± 0.4	4.9 ± 0.2
8–10	76 ± 28	2.0 ± 0.7	2.9 ± 0.8	5.1 ± 0.5
10–12	94 ± 51	2.1 ± 0.8	2.8 ± 1.0	4.2 ± 0.4
12–14	59 ± 32	1.7 ± 0.8	2.8 ± 1.0	4.8 ± 0.4
14–16	41 ± 16	1.2 ± 0.4	2.0 ± 0.7	3.7 ± 0.3
16–18	37 ± 16	1.3 ± 0.5	2.1 ± 0.8	4.7 ± 0.5
18–20	33 ± 12	1.3 ± 0.4	2.1 ± 0.5	4.4 ± 0.4
20–22	27 ± 7	1.2 ± 0.3	1.8 ± 0.5	4.3 ± 0.3
22–24	23 ± 6	1.0 ± 0.2	1.9 ± 0.5	4.1 ± 0.2
24–26	31 ± 11	1.8 ± 0.5	1.9 ± 0.6	4.8 ± 0.1
26–28	26 ± 11	1.5 ± 0.5	1.7 ± 0.2	5.1 ± 1.1
28–30	21 ± 7	2.5 ± 1.7	2.2 ± 0.6	3.2 ± 0.8

Concentrations of micronutrients also were quite low in soils at Iquitos (Table 8). Manganese and zinc were higher in concentration in S and M horizons than in deeper layers, but iron and zinc did not exhibit layering.

Except for the surface 0 to 2 cm (S horizon), all other depths were very low in clay content (Table 5). The S horizon was a loam, the M horizon and upper part of T horizon (MT horizon) was a sandy loam, and deeper layers were loamy sand. Ponds at other CRSP sites contained considerably more clay than the Iquitos ponds (Boyd et al., 1997, 1998).

Incubation Studies for Peru Samples

Results of the soil incubations are provided in Table 9. The concentrations of total carbon were 0.99 ± 0.36% and 0.62 ± 0.12% in samples from depths of 0–10 cm and 10–20 cm, respectively. The total nitrogen values were 0.03 ± 0.01% in samples from

Table 8. Profiles for iron, manganese, zinc, and copper in soil cores from bottoms of aquaculture ponds in Iquitos, Peru. Averages and standard errors are given as parts per million (ppm). Each entry is the average of three ponds.

Depth (cm)	Iron (ppm)	Manganese (ppm)	Zinc (ppm)	Copper (ppm)
0–2	33 ± 2	2.1 ± 0.6	8.32 ± 1.19	0.15 ± 0.01
2–4	27 ± 4	1.1 ± 0.5	4.91 ± 2.12	0.14 ± 0.02
4–6	26 ± 4	0.7 ± 0.3	2.44 ± 1.22	0.17 ± 0.01
6–8	32 ± 2	0.6 ± 0.2	1.47 ± 0.69	0.18 ± 0.02
8–10	35 ± 11	0.4 ± 0.1	0.31 ± 0.17	0.15 ± 0.01
10–12	37 ± 15	0.5 ± 0.3	0.29 ± 0.13	0.13 ± 0.03
12–14	30 ± 11	0.4 ± 0.2	0.48 ± 0.34	0.15 ± 0.01
14–16	50 ± 14	0.3 ± 0.1	0.41 ± 0.29	0.10 ± 0.03
16–18	27 ± 11	0.3 ± 0.1	0.31 ± 0.21	0.11 ± 0.03
18–20	53 ± 17	0.3 ± 0.1	0.21 ± 0.11	0.13 ± 0.01
20–22	29 ± 11	0.3 ± 0.1	0.18 ± 0.08	0.11 ± 0.05
22–24	24 ± 9	0.3 ± 0.1	0.13 ± 0.06	0.10 ± 0.03
24–26	24 ± 11	0.4 ± 0.1	0.23 ± 0.09	0.11 ± 0.04
26–28	24 ± 10	0.4 ± 0.1	0.15 ± 0.08	0.10 ± 0.05
28–30	21 ± 10	0.9 ± 0.6	0.18 ± 0.10	0.10 ± 0.04

Table 9. Net aerobic mineralization of nitrogen and carbon dioxide and net anaerobic mineralization of ammonia in soil from two depths from ponds in Iquitos, Peru.

Depth (cm)	Aerobic Incubation		Anaerobic Incubation
	(mg N kg ⁻¹)	(mg CO ₂ kg ⁻¹)	(mg NH ₄ -N kg ⁻¹)
0–10	-20.56 ± 11.58	4.09 ± 1.83	-0.75 ± 1.57
10–20	-24.78 ± 4.05	3.01 ± 1.56	-6.41 ± 3.00

Table 10. Profiles for moisture content and dry bulk density in soil cores from bottoms of aquaculture ponds, Thailand. Moisture content averages and standard errors are given as percentages of dry weight. Dry bulk density averages and standard errors are given as grams dry soil per cubic centimeter (g cm⁻³). Each entry is the average of three ponds.

Depth (cm)	Moisture Content (%)	Dry Bulk Density (g cm ⁻³)
0–2	273.2 ± 75.1	0.33 ± 0.06
2–4	175.0 ± 44.6	0.47 ± 0.07
4–6	139.8 ± 28.0	0.54 ± 0.09
6–8	123.5 ± 19.3	0.59 ± 0.09
8–10	86.0 ± 12.6	0.77 ± 0.09
10–12	78.3 ± 15.0	0.82 ± 0.12
12–14	75.5 ± 16.1	0.85 ± 0.15
14–16	73.5 ± 13.5	0.82 ± 0.11
16–18	65.7 ± 16.1	0.94 ± 0.17
18–20	61.6 ± 16.3	0.97 ± 0.19
20–22	50.9 ± 7.4	1.04 ± 0.11
22–24	36.6 ± 4.9	1.29 ± 0.13
24–26	33.3 ± 4.0	1.29 ± 0.06
26–28	27.2 ± 1.2	1.44 ± 0.04
28–30	26.4 ± 3.4	1.51 ± 0.08

Table 11. Profiles for color in soil cores from bottoms of aquaculture ponds, Thailand. Color values are given as standard Munsell Color Chart Units. Each entry is the value of a particular pond.

Depth (cm)	Pond 1	Pond 2	Pond 3
0–2	5Y 7/4	10YR 5/4	2.5Y 5/3
2–4	5Y 7/4	10YR 5/4	2.5Y 5/3
4–6	5Y 7/4	10YR 4/1	2.5Y 5/3
6–8	5Y 6/3	10YR 4/1	2.5Y 5/3
8–10	5Y 6/3	10YR 4/1	2.5Y 5/3
10–12	5Y 6/3	10YR 4/1	5Y 4/1
12–14	5Y 6/3	10YR 4/1	5Y 4/1
14–16	5Y 6/3	10YR 4/1	5Y 4/1
16–18	5Y 6/3	10YR 4/1	5Y 4/1
18–20	5Y 6/3	10YR 4/1	5Y 5/1
20–22	5Y 6/3	5Y 5/2	5Y 5/1
22–24	5Y 6/2	5Y 5/2	5Y 5/1
24–26	5Y 6/2	5Y 5/2	5Y 5/1
26–28	5Y 6/2	5Y 5/2	5Y 5/1
28–30	5Y 6/2	5Y 5/2	5Y 5/1

Note: 2.5Y 5/3—Light yellowish brown; 5Y 4/1—Dark gray; 5Y 5/1—Gray; 5Y 5/2—Olive gray; 5Y 6/2—Light olive gray; 5Y 6/3—Pale olive; 5Y 7/4—Pale yellow; 10YR 4/1—Dark gray; 10YR 5/4—Yellowish brown.

0–10 cm and 0.02 ± 0.00% in the 10–20 cm depth samples. Thus, C/N ratios were 33 in 0–10 cm samples and 31 in 10–20 cm samples. It is not surprising that nitrogen mineralization was negative (nitrogen was not mineralized but actually removed from the soil by microorganisms) under both aerobic and anaerobic conditions. However, similar results have been obtained in soils from other CRSP sites with lower C/N ratios. Thus, organic matter decomposition in pond soils must be either nitrogen-limited, which does not seem likely at other sites with a narrow C/N ratio, or nitrogen is denitrified after mineralization. The latter is probably the general situation, but ponds at Iquitos are likely also nitrogen-limited. We do not feel that the soil incubations are providing much useful information about nutrient dynamics in ponds, and we plan to stop conducting them in future work.

Pond Soils at Sae Kaeo, Thailand

The moisture content and dry bulk density values (Table 10) for ponds at Sae Kaeo showed the typical layering found in ponds at other sites (Munsiri et al., 1995; Boyd et al., 1997, 1998). The S horizon was about 4 cm thick, the M horizon extended from 4 to 20 cm, and the T horizon occurred between 20 and 26 cm. The bulk density of the P horizon (original soil) was around 1.5 g cm⁻³. Soil color was darker in the S horizon and in the upper part of the M horizon than in deeper layers (Table 11).

The soil pH was higher (5.9 to 6.2) in the S horizon than in deeper layers (Table 12). This was the result of limestone applications to ponds in the past. The original soil had a pH of 5.3. Soil acidity did not change with depth and was usually around 5 meq (100 g)⁻¹ (Table 12).

The typical decrease in total carbon and total nitrogen concentrations with depth was observed in the ponds (Table 13). The S horizon and upper part of the M horizon had carbon concentrations slightly above 2%, and concentration decreased

with depth to about 0.5% in the P horizon. Nitrogen concentrations declined from about 0.2% near the surface to 0.03% in the deepest layer. The C/N ratio was about 10 to 11 in the S horizon and upper part of the M horizon. This ratio then increased to 16.7 in the deepest layer. Total sulfur tended to be slightly higher (0.03 to 0.04%) in the upper 6-cm layer than in deeper layers (0.01 to 0.02%). Nevertheless, total sulfur concentrations were very low.

Dilute-acid-extractable phosphorus concentrations were different from other ponds that have been sampled.

Table 12. Profiles for dry soil pH and exchangeable acidity in soil cores from bottoms of aquaculture ponds, Thailand. The wet soil pH was directly measured in soil core and the dry soil pH was measured in 1:1 slurries of dry soil and distilled water. Averages and standard errors of pH are given as standard pH units. Exchangeable acidity averages and standard errors are given as milliequivalents per 100 grams dry soil ($\text{meq } (100 \text{ g})^{-1}$). Each entry is the average of three ponds.

Depth (cm)	Dry Soil pH	Exchangeable Acidity ($\text{meq } (100 \text{ g})^{-1}$)
0–2	6.2 ± 0.2	5.07 ± 0.71
2–4	5.9 ± 0.2	5.33 ± 0.96
4–6	5.7 ± 0.2	5.87 ± 0.71
6–8	5.8 ± 0.4	6.13 ± 1.33
8–10	5.6 ± 0.3	5.60 ± 0.80
10–12	5.6 ± 0.2	5.33 ± 0.53
12–14	5.7 ± 0.3	5.07 ± 0.27
14–16	5.6 ± 0.3	4.53 ± 0.53
16–18	5.5 ± 0.3	4.80 ± 0.46
18–20	5.5 ± 0.4	4.80 ± 0.46
20–22	5.5 ± 0.4	4.27 ± 0.53
22–24	5.5 ± 0.4	4.80 ± 0.46
24–26	5.3 ± 0.5	4.80 ± 0.46
26–28	5.3 ± 0.5	5.33 ± 0.71
28–30	5.3 ± 0.5	5.60 ± 0.80

Table 13. Profiles of total carbon, total nitrogen, and total sulfur in soil cores from bottoms of aquaculture ponds, Thailand. Averages and standard errors are given as percentages. Each entry is the average of three ponds.

Depth (cm)	Total Carbon (%)	Total Nitrogen (%)	Total Sulfur (%)
0–2	2.32 ± 0.51	0.22 ± 0.05	0.03 ± 0.01
2–4	2.14 ± 0.47	0.20 ± 0.06	0.04 ± 0.01
4–6	2.15 ± 0.61	0.20 ± 0.07	0.03 ± 0.01
6–8	2.11 ± 0.57	0.19 ± 0.07	0.02 ± 0.01
8–10	1.74 ± 0.51	0.13 ± 0.06	0.03 ± 0.00
10–12	1.55 ± 0.51	0.12 ± 0.06	0.02 ± 0.01
12–14	1.49 ± 0.52	0.11 ± 0.05	0.03 ± 0.01
14–16	1.54 ± 0.65	0.16 ± 0.08	0.02 ± 0.01
16–18	1.32 ± 0.61	0.10 ± 0.05	0.02 ± 0.00
18–20	1.24 ± 0.58	0.09 ± 0.05	0.02 ± 0.01
20–22	0.98 ± 0.39	0.08 ± 0.05	0.02 ± 0.02
22–24	0.91 ± 0.44	0.09 ± 0.05	0.03 ± 0.00
24–26	0.73 ± 0.37	0.06 ± 0.03	0.01 ± 0.01
26–28	0.67 ± 0.29	0.06 ± 0.02	0.01 ± 0.00
28–30	0.50 ± 0.16	0.03 ± 0.01	0.01 ± 0.01

Concentrations were between 15 and 20 ppm in the surface 10-cm layer, from 22 to 33 ppm between 10 and 26 cm, and less than 20 ppm in the 26-to-30-cm layer (Table 14). No explanation is available, but we suspect that greater phosphorus inputs were made to the ponds in the past than at present. This would explain the greater phosphorus concentrations in the lower part of the M horizon. Water-extractable phosphorus concentrations were not closely related to dilute-acid-extractable phosphorus concentrations.

Concentrations of macronutrient cations (Table 15) and micronutrients (Table 16) are within the ranges of concentrations found in pond soils from other sites (Munsiri et al., 1995; Boyd et al., 1997, 1998). Calcium, magnesium, and potassium concentrations tended to be greater in the S horizon and the

Table 14. Profiles for dilute-acid-extractable phosphorus and water-extractable phosphorus in soil cores from bottoms of aquaculture ponds, Thailand. Averages and standard errors are given as parts per million (ppm) and each entry is the average of three ponds.

Depth (cm)	Dilute-acid-extractable Phosphorus (ppm)	Water-extractable Phosphorus (mg l^{-1})
0–2	20.26 ± 6.98	0.049 ± 0.023
2–4	20.80 ± 7.52	0.061 ± 0.035
4–6	18.31 ± 5.06	0.058 ± 0.035
6–8	15.63 ± 2.24	0.045 ± 0.013
8–10	20.53 ± 6.67	0.084 ± 0.050
10–12	24.40 ± 7.74	0.101 ± 0.053
12–14	27.33 ± 9.30	0.094 ± 0.048
14–16	25.72 ± 8.07	0.058 ± 0.023
16–18	31.47 ± 13.33	0.091 ± 0.055
18–20	33.92 ± 14.70	0.106 ± 0.054
20–22	33.28 ± 16.30	0.125 ± 0.076
22–24	29.51 ± 17.02	0.161 ± 0.118
24–26	22.70 ± 11.85	0.109 ± 0.078
26–28	18.92 ± 9.45	0.106 ± 0.072
28–30	11.78 ± 3.62	0.066 ± 0.042

Table 15. Profiles for calcium, magnesium, potassium, and sodium in soil cores from bottoms of aquaculture ponds, Thailand. Averages and standard errors are given as parts per million (ppm). Each entry is the average of three ponds.

Depth (cm)	Calcium (ppm)	Magnesium (ppm)	Potassium (ppm)	Sodium (ppm)
0–2	1,077 ± 173	187 ± 42	90 ± 16	37.3 ± 7.1
2–4	886 ± 154	165 ± 57	74 ± 14	35.8 ± 1.0
4–6	105 ± 105	178 ± 50	73 ± 3	34.4 ± 2.4
6–8	1,375 ± 518	167 ± 49	68 ± 1	36.6 ± 4.2
8–10	846 ± 236	143 ± 53	52 ± 10	32.8 ± 1.9
10–12	821 ± 254	135 ± 50	46 ± 10	32.1 ± 2.0
12–14	832 ± 305	138 ± 52	43 ± 11	30.7 ± 4.4
14–16	911 ± 463	127 ± 46	40 ± 11	33.8 ± 3.9
16–18	748 ± 329	131 ± 48	40 ± 10	30.3 ± 2.8
18–20	612 ± 236	119 ± 44	35 ± 8	24.5 ± 1.6
20–22	494 ± 157	108 ± 42	32 ± 6	28.0 ± 1.1
22–24	502 ± 201	125 ± 50	37 ± 10	28.3 ± 2.8
24–26	389 ± 163	102 ± 38	32 ± 8	23.2 ± 1.3
26–28	403 ± 175	110 ± 40	35 ± 7	25.1 ± 3.4
28–30	366 ± 163	111 ± 45	35 ± 10	33.2 ± 3.5

upper part of the M horizon than in deeper layers. This no doubt reflects the inputs of calcium and magnesium in liming material and potassium in fertilizer. Sodium concentrations showed no appreciable change with depth. Iron and manganese concentrations tended to be greater in the middle part of the M horizon than at greater depths. We do not have an explanation for this phenomenon. Zinc appears to have accumulated slightly in the S and M horizons, but copper concentrations showed no apparent trends of layering.

Soil Respiration Studies

Freshwater samples were collected and analyzed for respiration before brackishwater samples. Differences between adjacent successive 0.5-cm soil layers of freshwater samples were not statistically different ($P < 0.05$). Therefore, brackishwater soil samples that were sampled a few months later were sampled at 1-cm intervals to reduce the number of samples to the lowest amount necessary.

Table 16. Profiles for iron, manganese, zinc, and copper in soil cores from bottoms of aquaculture ponds, Thailand. Averages and standard errors are given as parts per million (ppm). Each entry is the average of three ponds.

Depth (cm)	Iron (ppm)	Manganese (ppm)	Zinc (ppm)	Copper (ppm)
0–2	487 ± 45	38.7 ± 4.2	5.28 ± 1.95	1.75 ± 0.09
2–4	509 ± 94	40.0 ± 10.7	4.44 ± 1.15	1.69 ± 0.29
4–6	622 ± 79	47.6 ± 6.6	6.01 ± 1.88	1.89 ± 0.04
6–8	691 ± 231	55.0 ± 14.4	10.14 ± 4.50	1.83 ± 0.08
8–10	679 ± 176	46.1 ± 9.0	6.42 ± 2.21	1.54 ± 0.21
10–12	823 ± 268	52.5 ± 15.2	7.97 ± 3.24	1.61 ± 0.19
12–14	891 ± 242	55.9 ± 15.7	7.62 ± 2.78	1.61 ± 0.26
14–16	811 ± 284	47.6 ± 12.8	6.58 ± 2.50	1.46 ± 0.17
16–18	895 ± 209	42.7 ± 7.1	6.82 ± 2.81	1.50 ± 0.21
18–20	842 ± 237	36.3 ± 7.4	5.62 ± 2.25	1.34 ± 0.14
20–22	753 ± 185	27.4 ± 4.3	4.95 ± 1.52	1.20 ± 0.15
22–24	638 ± 40	22.5 ± 3.3	4.40 ± 2.28	1.33 ± 0.26
24–26	582 ± 126	15.1 ± 3.1	3.24 ± 1.64	1.21 ± 0.14
26–28	579 ± 120	13.1 ± 3.0	2.87 ± 1.62	1.41 ± 0.15
28–30	471 ± 13	10.0 ± 2.9	1.68 ± 0.75	1.43 ± 0.21

Table 17. Average concentrations and standard errors of carbon, respiration rate, and respiration rate per unit carbon in successive 0.5-cm layers of six freshwater pond soils incubated in the dark at 25°C for one week. Soil moisture in all soils and layers was 33 ± 2%.

Layer (cm)	Carbon (%)	Respiration (mg CO ₂ g ⁻¹)	Respiration per g of C (mg CO ₂ g ⁻¹)
0.0–0.5	2.49 ± 0.10	4.85 ± 0.25	195.0 ± 7.0
0.5–1.0	2.36 ± 0.11	4.45 ± 0.35	189.2 ± 11.5
1.0–1.5	2.35 ± 0.13	4.11 ± 0.41	169.6 ± 11.8
1.5–2.0	2.26 ± 0.13	3.73 ± 0.38	164.7 ± 16.7
2.0–2.5	2.14 ± 0.12	3.33 ± 0.36	155.2 ± 17.0
2.5–3.0	1.98 ± 0.09	2.87 ± 0.33	143.7 ± 15.1
3.0–3.5	2.01 ± 0.07	2.69 ± 0.31	132.6 ± 14.4
3.5–4.0	1.97 ± 0.08	2.59 ± 0.37	130.3 ± 16.3
4.0–4.5	1.90 ± 0.09	2.28 ± 0.29	120.0 ± 15.3
4.5–5.0	1.82 ± 0.10	2.04 ± 0.25	110.1 ± 10.8

Carbon concentrations in both freshwater and brackishwater ponds were higher in the first layer and decreased with increasing soil depth (Tables 17 and 18). Within the 5-cm layer samples, average carbon reduction between the upper and lower layers was 0.67% and 0.49% for freshwater and brackishwater ponds, respectively. That is, there was approximately 1.4 and 1.3 times more carbon in the uppermost layer compared to the bottom layer. Respiration was also higher in upper layers compared to lower layers in both freshwater and brackishwater ponds as would be expected from the higher carbon concentration. Microbial respiration in the 0.0-to-0.5-cm layer of freshwater ponds was 2.4 times higher compared to the 4.5-to-5.0-cm layer. This proportional difference between amounts of carbon and microbial respiration among layers can be attributed to difference in organic matter composition. The amount of reactive carbon was greater in the first layers. To account for this difference in respiration between layers caused by different concentrations of carbon, the respiration rate was normalized by dividing the respiration rate in each layer by its respective carbon concentration. Highly significant statistical differences ($P < 0.01$) in soil respiration (mg CO₂ g⁻¹ C) were found among layers in freshwater pond soils. Hsu's MCB test revealed that all layers below 2.5-cm depth differed from the first 0.0-to-0.5-cm layer. Respiration per unit carbon was also higher in the first 0-to-1-cm layer of brackishwater soil, although no statistically significant differences were found among layers. Variability of soil organic matter composition within layers of different shrimp ponds was greater than the variation among layers. All freshwater soil samples came from different ponds of Auburn University Fisheries Research Unit, while brackishwater soils were obtained from shrimp farms at different locations, which probably explains the higher variability.

The amount of carbon lost in the uppermost layer of freshwater pond bottom soil during the one-week incubation period was estimated as 0.13% (4.85 mg CO₂ g⁻¹ × 12 ÷ 44 × 100 g × 1 g ÷ 1000 mg). Similarly, the percentage of carbon lost in the uppermost layer of brackishwater soil was 0.05%. Average soil respiration per unit carbon was higher in freshwater soils compared to brackishwater soils. These results reflect differences in organic matter composition and factors intrinsically related to experimental conditions such as pH, moisture, texture, and salt content in soils (Boyd and Pippopinyo, 1994). Freshwater samples were collected during the northern winter at water temperatures of 12 to 14°C, while soils from Ecuador were collected when temperatures were 24 to 28°C. Organic

Table 18. Average concentrations and standard errors of carbon, respiration rate, and respiration rate per unit carbon in successive 1.0-cm layers of eight brackishwater pond soils incubated in the dark at 25°C for one week. Soil moisture in all soils was 30 ± 4%.

Layer (cm)	Carbon (%)	Respiration (mg CO ₂ g ⁻¹)	Respiration per g of C (mg CO ₂ g ⁻¹)
0.0–1.0	2.00 ± 0.25	1.90 ± 0.27	132.3 ± 32.2
1.0–2.0	1.69 ± 0.25	1.44 ± 0.15	116.4 ± 25.3
2.0–3.0	1.65 ± 0.28	1.20 ± 0.14	92.2 ± 15.7
3.0–4.0	1.53 ± 0.25	1.07 ± 0.14	81.3 ± 12.5
4.0–5.0	1.51 ± 0.27	1.42 ± 0.15	83.0 ± 15.4

matter deposited in freshwater ponds had probably been decomposing at lower rates, therefore the ratio of labile to more refractive organic matter was higher in these ponds when the samples were taken.

A meaningful interpretation of the influence of soil organic carbon on the overlying water quality such as oxygen demand and transfer and absorption of nutrients and metabolites requires knowledge not only of its concentration but also of its composition. Labile organic matter is more reactive and will exert a higher oxygen demand. This study demonstrated that concentration of labile organic carbon decreased with increasing soil depth. This method should be considered only an index of decomposability, because the experiments were performed under aerobic conditions. Under waterlogged conditions, decomposition of organic matter below the first mm of the water-soil phase is anaerobically driven. However, it is suggested that for studies directed at correlating water quality with soil organic matter characteristics, the first 1 to 2 cm of soil should be sampled.

ANTICIPATED BENEFITS

The results of soil analyses from the PD/A CRSP site at Iquitos, Peru, will be useful in explaining soil and water quality phenomena observed during investigations conducted in these ponds and other ponds at the site. The data from the ponds in Peru and Thailand add to the database that is needed for delineating soil profiles and using the characteristics of soil profiles in developing a system of pond bottom soil taxonomy. The soil respiration data confirm earlier observations based on chemical and physical properties that the surface few centimeters, probably not more than the upper 5-cm layer, is the most important part of the pond soil profile with respect to influence on pond water quality.

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