POND SOIL CHARACTERISTICS AND DYNAMICS OF SOIL ORGANIC MATTER AND NUTRIENTS

Ninth Work Plan, Pond Dynamics Research 2 (9PDR2)
Final Report

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ABSTRACT

Soil cores were taken from ponds in Thailand, Honduras, Kenya, Peru, Brazil, and the Philippines. All cores could be delineated into F, S, M, T, and P horizons without difficulty. The major similarities among cores involved an increase in dry bulk density and a decrease in concentrations of total carbon, total nitrogen, and total sulfur with increasing depth into the sediment. There was wide variation in acidity, phosphorus, major cation and micronutrient concentrations, pH, texture, and color in samples from different sites, but differences in these variables with sediment depth did not follow clear trends. The S horizon, the main sediment layer that interacts with pond water quality, varied in thickness from 2 to 10 cm. Pond management should focus on neutralizing acidity and enhancing organic matter decomposition within the S horizon through liming and drying of pond bottoms between crops. Sediment accumulates in deeper parts of ponds over time, and soft sediment should be removed periodically.

Results of sediment analyses were used in formulating a pond soil classification system based on levels of primary and secondary sediment properties. The primary properties are pH, texture, sediment thickness, and organic matter status (mineral or organic in nature). The secondary properties are organic carbon, carbon:nitrogen ratio, acidity (exchangeable acidity and acidity from sulfide oxidation), carbonates, and sodium adsorption ratio. Two optional, tertiary properties, thickness of F horizon and oxidation status of the sediment surface, may be used in the classification system if desired. The classification system is described in this report.

INTRODUCTION

This project on pond dynamics was concerned with the composition of sediment profiles in ponds at PD/A CRSP host country sites and in other selected ponds in the host countries. During the Eighth and Ninth Work Plans, soil cores were obtained from ponds in Thailand, Honduras, Kenya, Peru, Brazil, and the Philippines. Data from all sampling sites other than those in Brazil and the Philippines have been presented and discussed in earlier progress reports (Boyd et al., 1998; 1999; 2000; 2001). Thus, only data from the sites in Brazil and the Philippines will be provided in this report. The data obtained on the composition of pond sediment were used to prepare a simple system for classifying pond soils, and the main objective of this report is to describe this system.

METHODS AND MATERIALS

Pond Soil Cores

The ponds in Brazil were located at the fish culture station of the Brazilian Environmental Institute, Pirassununga, São Paulo State, and on a private fish farm near Chapeco, Santa Catarina State. Ponds in the Philippines were at Central Luzon State University, Muñoz, Philippines. Three ponds were selected at each of the sites. Ponds had surface areas of 300 to 500 m^2, and maximum water depth was about 1 m. Ponds had been stocked for two to four months at the time of sampling, and tilapia was the primary culture species in all ponds. Ponds at Pirassununga, Brazil, and in the Philippines had a history of fertilization and feed application. The ponds at Chapeco, Brazil, were fertilized by manure from pig parlors constructed above them.

Soil cores were taken with a hand-operated, 5-cm-diameter core sampler (Wildlife Supply Company, Saginaw, Michigan, USA, Model No. 242A15). Procedures for separating the cores into successive 2-cm-long 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 (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 (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 HCl plus 0.025 N H_2SO_4) followed by plasma spectrophotometry. Particle size analyses were made by the pipette method. All methods followed details provided by Munsiri et al. (1995) and Thunjai and Boyd (2001).

Pond Soil Classification

The pond soil classification system was developed using data from the literature on pond soils (Boyd, 1995) and the results of the pond soil samples taken during the Eighth and Ninth Work Plans (Boyd et al., 1998; 1999; 2000; 2001). This effort represents the opinions of the investigators, and the system is likely to be revised in the future.

Table 1. Concentrations of moisture, dry bulk density, pH, and exchangeable acidity in soil cores from ponds at Pirassununga and Chapeco, Brazil. Entries are the averages and standard errors of data from three ponds.

Depth (cm)	Moisture (%)	Dry Bulk Density (g cm^{-3})	pH (s.u.)	Exchangeable Acidity (meq (100 g)$^{-1}$)
PIRASSUNUNGA				
0–2	518.85 ± 40.37	0.14 ± 0.02	4.85 ± 0.09	21.33 ± 1.87
2–4	376.52 ± 11.00	0.19 ± 0.01	4.90 ± 0.06	17.33 ± 2.82
4–6	307.26 ± 21.90	0.24 ± 0.04	4.70 ± 0.12	20.27 ± 1.62
6–8	240.65 ± 38.58	0.32 ± 0.08	4.77 ± 0.12	22.40 ± 0.80
8–10	252.14 ± 51.63	0.31 ± 0.09	4.73 ± 0.12	17.87 ± 2.82
10–12	240.08 ± 46.68	0.33 ± 0.09	4.77 ± 0.12	16.27 ± 2.71
12–14	210.96 ± 46.62	0.35 ± 0.10	4.88 ± 0.12	16.00 ± 5.00
14–16	208.29 ± 44.79	0.36 ± 0.09	4.92 ± 0.10	13.07 ± 2.37
16–18	184.33 ± 23.18	0.38 ± 0.06	5.28 ± 0.33	16.00 ± 6.67
18–20	148.90 ± 20.66	0.47 ± 0.12	5.10 ± 0.28	11.73 ± 0.71
20–22	118.47 ± 37.58	0.65 ± 0.37	5.07 ± 0.12	10.93 ± 0.96
22–24	103.55 ± 41.24	0.85 ± 0.67	5.02 ± 0.12	10.40 ± 1.22
24–26	90.56 ± 31.57	0.92 ± 0.63	5.08 ± 0.09	9.87 ± 1.87
26–28	66.29 ± 31.33	1.02 ± 0.45	5.05 ± 0.10	9.87 ± 1.62
28–30	56.82 ± 23.22	1.13 ± 0.40	5.07 ± 0.18	12.53 ± 3.53
30–32	38.99 ± 8.97	1.37 ± 0.36	5.03 ± 0.09	16.00 ± 6.84
32–34	43.02 ± 0.00	1.17 ± 0.00	5.30 ± 0.00	10.40 ± 0.00
34–36	37.33 ± 0.00	1.39 ± 0.00	5.10 ± 0.00	11.20 ± 0.00
CHAPECO				
0–2	339.11 ± 14.82	0.24 ± 0.02	5.88 ± 0.28	12.27 ± 2.81
2–4	248.31 ± 8.37	0.30 ± 0.02	6.03 ± 0.07	13.23 ± 3.79
4–6	199.78 ± 11.52	0.37 ± 0.04	5.92 ± 0.06	11.09 ± 3.21
6–8	176.37 ± 13.69	0.39 ± 0.03	5.87 ± 0.06	10.40 ± 2.12
8–10	137.02 ± 30.23	0.53 ± 0.13	5.90 ± 0.09	10.93 ± 1.85
10–12	123.58 ± 28.39	0.60 ± 0.15	5.85 ± 0.08	11.73 ± 1.22
12–14	128.56 ± 19.75	0.54 ± 0.09	5.82 ± 0.04	12.00 ± 2.88
14–16	118.60 ± 16.36	0.59 ± 0.10	5.90 ± 0.08	10.93 ± 1.22
16–18	101.55 ± 9.53	0.64 ± 0.07	5.85 ± 0.08	11.20 ± 1.39
18–20	92.87 ± 7.09	0.67 ± 0.05	5.75 ± 0.10	10.93 ± 1.85
20–22	86.93 ± 8.94	0.70 ± 0.06	5.75 ± 0.10	13.87 ± 3.23
22–24	85.17 ± 7.02	0.77 ± 0.03	5.70 ± 0.10	13.60 ± 3.67
24–26	83.00 ± 6.75	0.73 ± 0.08	5.63 ± 0.11	14.40 ± 2.77
26–28	85.29 ± 8.26	0.77 ± 0.05	5.58 ± 0.06	13.07 ± 2.01
28–30	82.45 ± 5.49	0.75 ± 0.05	5.68 ± 0.04	13.07 ± 1.22
30–32	80.77 ± 7.02	0.78 ± 0.03	5.60 ± 0.10	13.33 ± 0.44
32–34	79.32 ± 8.67	0.72 ± 0.05	5.77 ± 0.18	12.05 ± 4.17
34–36	78.63 ± 1.64	0.74 ± 0.04	5.60 ± 0.04	13.07 ± 3.23
36–38	76.04 ± 3.01	0.82 ± 0.09	5.53 ± 0.02	14.00 ± 3.96
38–40	64.96 ± 7.46	0.89 ± 0.07	5.58 ± 0.02	12.80 ± 3.39
40–42	58.07 ± 5.83	0.98 ± 0.11	6.00 ± 0.00	8.00 ± 0.00

RESULTS

The data for the analyses of soil cores from ponds in Brazil and the Philippines are summarized in Tables 1 to 14. Each entry in the tables represents the average concentration of a variable in three ponds, and the plus or minus (±) values following means represent standard deviations.

DISCUSSION

Pond Soil Cores

Chemical and physical analyses of soil core segments from Brazil and the Philippines did not reveal features or trends greatly different from those found during the Eighth and Ninth Work Plans for ponds at other sites (Boyd et al., 1998; 1999; 2000; 2001). In general, moisture content decreased and dry bulk density increased with increasing depth in the profile (Tables 1 and 2). The S, M, T, and P horizons could be easily delineated from dry bulk density, as has been the case in all ponds previously sampled. The pH and exchangeable acidity did not differ greatly among depths. The two sites in Brazil had acidic sediment, while sediment at the Philippine site was near neutral in reaction (Tables 1 and 2).

Soil color changed with depth from a lighter color near the surface to a darker color deeper within the profile at the Pirassununga site in Brazil, but soil color changed little with depth at the other two sites (Tables 3 and 4). Color is useful for determining if sediment is oxidized at the surface of the S horizon, but it is of little use in delineating horizons or for other aspects of pond soil classification.

Total carbon, total nitrogen, and total sulfur concentrations decreased with depth (Tables 5 and 6), as was observed in all other ponds of this study (Boyd et al., 1998; 1999; 2000; 2001). Concentrations of carbon in S and M horizons were about 2 to 3% in most samples. Total sulfur values were consistently below 0.1%. Phosphorus concentrations did not differ greatly with sediment depth (Tables 5 and 6).

There were no consistent trends of change in concentrations of major cations with respect to sediment depth (Tables 7 and 8).

Table 2. Concentrations of moisture, dry bulk density, pH, and exchangeable acidity in soil cores from ponds at Muñoz, Philippines. Entries are the averages and standard errors of data from three ponds.

Depth (cm)	Moisture (%)	Dry Bulk Density (g cm^{-3})	pH (s.u.)	Exchangeable Acidity (meq (100 g)$^{-1}$)
0–2	215.38 ± 3.82	0.37 ± 0.01	7.17 ± 0.22	5.60 ± 1.39
2–4	92.06 ± 8.06	0.68 ± 0.03	7.20 ± 0.20	6.67 ± 1.16
4–6	77.26 ± 4.81	0.76 ± 0.03	7.27 ± 0.18	7.20 ± 1.39
6–8	73.17 ± 2.49	0.77 ± 0.01	7.33 ± 0.15	7.20 ± 1.22
8–10	71.12 ± 2.04	0.83 ± 0.03	7.32 ± 0.13	5.60 ± 0.46
10–12	55.74 ± 7.16	0.90 ± 0.05	7.27 ± 0.09	6.40 ± 0.92
12–14	56.78 ± 2.86	0.94 ± 0.04	7.20 ± 0.10	6.93 ± 1.16
14–16	53.27 ± 1.27	0.94 ± 0.03	7.22 ± 0.14	7.47 ± 1.16
16–18	50.70 ± 1.22	0.95 ± 0.04	7.20 ± 0.13	6.67 ± 0.96
18–20	49.45 ± 1.95	0.96 ± 0.05	7.23 ± 0.07	5.87 ± 0.96
20–22	48.74 ± 1.68	1.02 ± 0.03	7.25 ± 0.03	5.87 ± 0.96
22–24	45.33 ± 2.31	1.00 ± 0.05	7.28 ± 0.04	5.33 ± 0.71

Table 3. Profile for color in soil cores from ponds at Pirassununga and Chapeco, Brazil. Color values are given as standard Munsell Color Chart Units.

Depth (cm)	Pirassununga			Chapeco		
	Pond A59	*Pond D20*	*Pond A61*	*Pond 1*	*Pond 2*	*Pond 3*
0–2	10YR 4/3	10YR 4/4	1G 2.5/10Y	10YR 3/6	10YR 3/3	10YR 3/3
2–4	10YR 4/2	1G 4/10GY	1G 2.5/10Y	10YR 3/3	10YR 3/4	10YR 3/3
4–6	10YR 3/2	1G 3/10GY	1G 3/10Y	10YR 3/3	10YR 3/3	10YR 3/2
6–8	10YR 3/2	1G 3/10GY	1G 3/10Y	10YR 2/2	10YR 3/4	10YR 3/2
8–10	10YR 4/1	1G 4/5G	1G 3/10Y	10YR 3/2	10YR 2/2	10YR 3/1
10–12	10YR 4/1	1G 4/5G	1G 3/10Y	10YR 3/2	10YR 3/2	10YR 3/2
12–14	10YR 4/1	1G 4/5G	1G 3/10Y	10YR 2/2	10YR 3/3	10YR 3/2
14–16	10YR 4/1	1G 3/10GY	1G 3/10Y	10YR 3/2	10YR 2/2	10YR 3/2
16–18	10YR 4/1	1G 3/10GY	1G 3/10Y	10YR 3/2	10YR 3/2	10YR 3/2
18–20	10YR 4/1	1G 3/10GY	1G 3/5GY	10YR 3/1	10YR 3/2	10YR 3/3
20–22	7.5YR 5/1	1G 2.5/5GY	1G 3/5GY	10YR 2/2	10YR 3/2	10YR 3/2
22–24	2.5YR 5/1	1G 4/10Y	1G 3/5GY	10YR 2/2	10YR 3/2	10YR 3/2
24–26	2.5Y 5/1	1G 5/10Y	1G 3/5GY	10YR 3/2	10YR 3/1	10YR 3/2
26–28	1G 5/N	7.5YR 4/4	1G 4/5GY	10YR 3/2	10YR 2/2	10YR 3/2
28–30	1G 4/N		1G 4/5GY	10YR 3/2	10YR 3/2	10YR 3/2
30–32	1G 4/5GY		1G 3/5GY	10YR 3/2	10YR 3/2	10YR 2/2
32–34			1G 3/10GY	10YR 3/2	10YR 3/2	10YR 3/2
34–36			1G 4/N		10YR 3/2	10YR 3/2
36–38					10YR 3/2	10YR 3/2
38–40					10YR 3/2	10YR 3/2
40–42					10YR 3/2	10YR 3/2

10YR 4/3—brown; 10YR 4/2—dark grayish brown; 10YR 4/1—dark gray; 7.5YR 5/1—gray; 2.5YR— reddish gray; 2.5Y 5/1—gray; 1G 5/N—gray; 1G 4/N—dark gray; 1G 4/5GY—dark greenish gray; 10YR 4/4—dark yellowish brown; 1G 4/10GY—dark greenish gray; 1G 3/10GY—dark greenish gray; 1G 4/5G—dark greenish gray; 1G 3/10GR—; 1G 2.5/5GY—greenish black; 1G 4/10Y—dark greenish gray; 1G 5/10Y—greenish gray; 7.5YR 4/4—brown; 1G 2.5/10Y—greenish black; 1G 3/10Y—dark greenish gray; 1G 3/5GY—dark greenish gray; 1G 4/5GY—dark greenish gray; 1G 3/10GY—dark greenish gray; 10YR 3/6— dark yellowish brown; 10YR 3/3—dark brown; 10YR 2/2—very dark brown; 10YR 3/2—very dark grayish brown; 10YR 3/1—very dark gray; 10YR 3/4—dark yellowish brown

However, concentrations of major cations were higher in samples from the Philippines site than in those from the two sites in Brazil. Concentrations of minor nutrients did not have consistent patterns of change with sediment depth (Tables 9 and 10), but concentrations were within the ranges of those found in other ponds sampled during this study (Boyd et al., 1998; 1999; 2000; 2001).

Soil particle size analysis revealed a high percentage of clay in sediment from all sites (Tables 11 and 12). All samples had clay or silty clay as texture names (Tables 13 and 14).

Pond Bottom Soil Classification

A systematic procedure for classifying terrestrial soil, known as soil taxonomy, is widely used by soil scientists (Soil Survey Staff, 1994). Soil taxonomy uses data on soil physical and chemical properties, but it also relies heavily on the appearance of the soil profile. Terrestrial soil profiles develop over many centuries and consist of several well-defined layers known as horizons. The presence or absence of specific horizons, the thickness of individual horizons, and the appearance and characteristics of soil in different horizons are major factors in soil taxonomy.

When aquaculture ponds are constructed, one or more of the upper horizons of the terrestrial soil is usually removed, and subsoil is exposed to water when ponds are filled. The main requirement is that soil for ponds consist of a mixture of particle sizes and contain enough fine, clay-size particles to resist seepage. Some references suggest that the soil should contain at least 20 to 30% clay, but soils with only 5 to 10% clay content can be used to construct ponds. However, as soon as a pond is constructed, the characteristics of the pond bottom begin to change. These changes result from erosion, sorting, and sedimentation of particles from within or from outside the pond and from the accumulation of organic matter. Pond soil classification should be based primarily on the sediment that accumulates in pond bottoms and is in direct contact with the pond water rather than upon the original soil from which the pond was constructed.

Table 4. Profile for color in soil cores from ponds at Muñoz, Philippines. Color values are given as standard Munsell Color Chart Units.

Depth (cm)	Pond 6B	Pond 6G	Pond 5F
0–2	2.5Y 4/2	2.5Y 4/2	2.5Y 4/1
2–4	2.5Y 4/2	2.5Y 4/2	2.5Y 4/1
4–6	2.5Y 5/3	2.5Y 4/2	2.5Y 4/1
6–8	2.5Y 5/3	2.5Y 4/2	2.5Y 4/1
8–10	2.5Y 5/3	2.5Y 4/2	2.5Y 4/1
10–12	2.5Y 5/3	2.5Y 4/2	2.5Y 4/1
12–14	2.5Y 5/3	2.5Y 4/2	2.5Y 4/1
14–16	2.5Y 5/3	2.5Y 4/2	2.5Y 4/1
16–18	2.5Y 5/3	2.5Y 4/2	2.5Y 4/1
18–20	2.5Y 5/3	2.5Y 4/2	2.5Y 4/1
20–22	2.5Y 5/3	2.5Y 4/2	2.5Y 4/1
22–24	2.5Y 5/3	2.5Y 4/2	2.5Y 4/1

2.5Y 4/2—dark grayish brown; 2.5Y 5/3—light olive brown; 2.5Y 4/1—dark gray

Initial efforts at describing sediment cores revealed that several layers (horizons) were easily defined in ponds at Auburn

Table 5. Concentrations of total carbon, total nitrogen, total sulfur, acid-extractable phosphorus, and water-soluble phosphorus in soil cores from ponds at Pirassununga and Chapeco, Brazil. Entries are the averages and standard errors of data from three ponds.

Depth (cm)	**Total Carbon** (%)	**Total Nitrogen** (%)	**Total Sulfur** (%)	**Acid–extractable Phosphorus** (ppm)	**Water–soluble Phosphorus** (ppm)
PIRASSUNUNGA					
0–2	3.51 ± 0.04	0.08 ± 0.01	0.04 ± 0.01	13.47 ± 0.58	0.05 ± 0.01
2–4	3.33 ± 0.05	0.08 ± 0.01	0.04 ± 0.02	14.27 ± 0.35	0.07 ± 0.01
4–6	3.13 ± 0.04	0.07 ± 0.01	0.05 ± 0.01	15.20 ± 0.46	0.06 ± 0.02
6–8	3.02 ± 0.05	0.06 ± 0.01	0.04 ± 0.01	14.80 ± 1.51	0.07 ± 0.03
8–10	2.89 ± 0.05	0.06 ± 0.01	0.04 ± 0.01	14.93 ± 0.96	0.07 ± 0.01
10–12	2.73 ± 0.06	0.06 ± 0.01	0.02 ± 0.02	15.87 ± 0.87	0.07 ± 0.01
12–14	2.28 ± 0.08	0.05 ± 0.01	0.02 ± 0.02	16.67 ± 1.09	0.08 ± 0.01
14–16	2.49 ± 0.08	0.05 ± 0.01	0.03 ± 0.02	17.07 ± 1.96	0.10 ± 0.02
16–18	2.15 ± 0.06	0.04 ± 0.01	0.02 ± 0.02	13.87 ± 1.96	0.09 ± 0.02
18–20	1.51 ± 0.04	0.03 ± 0.01	0.02 ± 0.02	17.60 ± 3.21	0.09 ± 0.04
20–22	1.35 ± 0.06	0.03 ± 0.01	0.01 ± 0.01	14.27 ± 2.87	0.09 ± 0.04
22–24	1.31 ± 0.06	0.03 ± 0.01	0.02 ± 0.02	16.93 ± 4.35	0.09 ± 0.04
24–26	1.34 ± 0.07	0.03 ± 0.01	0.01 ± 0.01	14.53 ± 2.47	0.06 ± 0.03
26–28	1.12 ± 0.06	0.03 ± 0.01	0.03 ± 0.02	13.20 ± 4.55	0.07 ± 0.04
28–30	1.21 ± 0.04	0.03 ± 0.01	0.03 ± 0.01	13.07 ± 2.77	0.05 ± 0.02
30–32	1.19 ± 0.03	0.03 ± 0.01	0.03 ± 0.01	12.67 ± 2.08	0.06 ± 0.02
32–34	1.38 ± 0.00	0.03 ± 0.00	0.00 ± 0.00	12.80 ± 0.00	0.09 ± 0.00
34–36	1.11 ± 0.00	0.02 ± 0.00	0.07 ± 0.00	12.40 ± 0.00	0.10 ± 0.00
CHAPECO					
0–2	3.71 ± 0.32	0.09 ± 0.02	0.05 ± 0.02	14.93 ± 0.58	0.32 ± 0.04
2–4	3.46 ± 0.20	0.08 ± 0.01	0.06 ± 0.02	15.60 ± 0.83	0.32 ± 0.05
4–6	3.22 ± 0.15	0.07 ± 0.01	0.09 ± 0.01	13.87 ± 0.48	0.32 ± 0.05
6–8	3.07 ± 0.09	0.07 ± 0.01	0.06 ± 0.01	12.40 ± 2.84	0.27 ± 0.02
8–10	2.74 ± 0.30	0.06 ± 0.01	0.07 ± 0.01	15.60 ± 0.83	0.37 ± 0.05
10–12	2.73 ± 0.37	0.06 ± 0.01	0.07 ± 0.01	15.07 ± 1.50	0.33 ± 0.07
12–14	2.68 ± 0.30	0.06 ± 0.01	0.05 ± 0.01	15.33 ± 2.31	0.29 ± 0.04
14–16	2.42 ± 0.28	0.05 ± 0.01	0.05 ± 0.02	15.07 ± 0.87	0.30 ± 0.05
16–18	3.11 ± 0.67	0.06 ± 0.02	0.04 ± 0.01	15.60 ± 1.85	0.24 ± 0.04
18–20	3.00 ± 0.63	0.07 ± 0.01	0.05 ± 0.01	15.33 ± 0.35	0.30 ± 0.14
20–22	2.81 ± 0.66	0.06 ± 0.02	0.04 ± 0.01	14.13 ± 0.35	0.21 ± 0.03
22–24	2.90 ± 0.71	0.06 ± 0.02	0.03 ± 0.02	15.47 ± 1.27	0.23 ± 0.04
24–26	2.74 ± 0.60	0.06 ± 0.01	0.05 ± 0.01	17.60 ± 1.67	0.21 ± 0.02
26–28	2.79 ± 0.60	0.06 ± 0.01	0.04 ± 0.01	15.20 ± 1.40	0.21 ± 0.02
28–30	2.77 ± 0.64	0.06 ± 0.01	0.03 ± 0.01	14.00 ± 1.40	0.19 ± 0.02
30–32	2.69 ± 0.59	0.06 ± 0.02	0.03 ± 0.01	14.93 ± 0.35	0.17 ± 0.03
32–34	2.65 ± 0.64	0.05 ± 0.01	0.03 ± 0.02	15.60 ± 0.61	0.14 ± 0.01
34–36	2.74 ± 0.66	0.05 ± 0.01	0.04 ± 0.01	14.80 ± 1.74	0.14 ± 0.02
36–38	2.33 ± 0.59	0.04 ± 0.01	0.01 ± 0.00	14.60 ± 1.14	0.12 ± 0.01
38–40	2.26 ± 0.25	0.05 ± 0.01	0.04 ± 0.02	12.80 ± 0.33	0.14 ± 0.01
40–42	2.19 ± 0.30	0.05 ± 0.01	0.04 ± 0.02	18.40 ± 0.00	0.12 ± 0.01

Table 6. Concentrations of total carbon, total nitrogen, total sulfur, acid-extractable phosphorus, and water-soluble phosphorus in soil cores from ponds at Muñoz, Philippines. Entries are the averages and standard errors of data from three ponds.

Depth (cm)	**Total Carbon** (%)	**Total Nitrogen** (%)	**Total Sulfur** (%)	**Acid–extractable Phosphorus** (ppm)	**Water–soluble Phosphorus** (ppm)
0–2	2.84 ± 0.36	0.09 ± 0.02	0.09 ± 0.01	15.20 ± 0.40	0.29 ± 0.20
2–4	2.27 ± 0.25	0.07 ± 0.01	0.07 ± 0.00	13.73 ± 2.22	0.24 ± 0.11
4–6	1.90 ± 0.11	0.06 ± 0.01	0.06 ± 0.01	13.07 ± 1.79	0.24 ± 0.07
6–8	1.66 ± 0.10	0.05 ± 0.00	0.04 ± 0.02	16.27 ± 3.53	0.27 ± 0.08
8–10	1.60 ± 0.05	0.05 ± 0.00	0.04 ± 0.01	15.20 ± 4.33	0.29 ± 0.09
10–12	1.31 ± 0.10	0.04 ± 0.00	0.03 ± 0.01	14.53 ± 2.28	0.22 ± 0.06
12–14	1.20 ± 0.11	0.04 ± 0.01	0.04 ± 0.02	14.13 ± 1.62	0.19 ± 0.03
14–16	1.24 ± 0.09	0.04 ± 0.00	0.05 ± 0.01	13.87 ± 1.92	0.21 ± 0.03
16–18	1.20 ± 0.12	0.05 ± 0.01	0.02 ± 0.02	14.13 ± 1.50	0.16 ± 0.03
18–20	1.12 ± 0.09	0.04 ± 0.00	0.04 ± 0.01	15.87 ± 1.33	0.15 ± 0.05
20–22	1.06 ± 0.06	0.03 ± 0.00	0.03 ± 0.01	17.33 ± 0.27	0.18 ± 0.05
22–24	0.94 ± 0.08	0.03 ± 0.00	0.02 ± 0.01	22.27 ± 6.67	0.18 ± 0.09

Table 7. Concentrations of calcium, magnesium, sodium, and potassium in soil cores from ponds at Pirassununga and Chapeco, Brazil. Entries are the averages and standard errors of data from three ponds.

Depth (cm)	Calcium (ppm)	Magnesium (ppm)	Sodium (ppm)	Potassium (ppm)
PIRASSUNUNGA				
0–2	1,117 ± 262	253 ± 72	20 ± 3	64 ± 6
2–4	1,028 ± 208	251 ± 73	17 ± 3	58 ± 9
4–6	836 ± 152	182 ± 49	15 ± 2	45 ± 5
6–8	891 ± 138	211 ± 43	13 ± 2	49 ± 3
8–10	913 ± 191	217 ± 55	12 ± 1	49 ± 7
10–12	953 ± 202	227 ± 57	13 ± 1	45 ± 7
12–14	927 ± 261	217 ± 72	10 ± 1	41 ± 9
14–16	1,026 ± 293	236 ± 85	10 ± 2	42 ± 11
16–18	1,966 ± 731	303 ± 165	11 ± 1	37 ± 10
18–20	1,476 ± 335	251 ± 111	10 ± 2	33 ± 9
20–22	1,100 ± 321	229 ± 104	8 ± 1	33 ± 10
22–24	1,010 ± 255	219 ± 78	7 ± 1	32 ± 9
24–26	1,013 ± 362	272 ± 80	8 ± 2	32 ± 10
26–28	973 ± 377	226 ± 100	8 ± 1	28 ± 8
28–30	827 ± 241	320 ± 86	10 ± 1	28 ± 12
30–32	799 ± 232	253 ± 47	8 ± 1	27 ± 11
32–34	828 ± 0	441 ± 0	6 ± 0	14 ± 0
34–36	544 ± 0	204 ± 0	7 ± 0	21 ± 0
CHAPECO				
0–2	2,561 ± 198	802 ± 103	17 ± 1	127 ± 12
2–4	2,465 ± 184	808 ± 104	15 ± 2	109 ± 10
4–6	2,328 ± 289	769 ± 142	16 ± 2	98 ± 8
6–8	1,643 ± 539	519 ± 182	10 ± 2	68 ± 12
8–10	1,948 ± 204	599 ± 99	14 ± 2	90 ± 7
10–12	1,894 ± 232	586 ± 114	14 ± 1	95 ± 7
12–14	1,706 ± 126	523 ± 65	14 ± 1	93 ± 8
14–16	1,574 ± 23	494 ± 4	13 ± 2	93 ± 10
16–18	1,559 ± 89	509 ± 22	12 ± 1	93 ± 5
18–20	1,457 ± 46	486 ± 33	12 ± 1	95 ± 7
20–22	1,275 ± 22	413 ± 24	12 ± 1	96 ± 7
22–24	1,087 ± 55	346 ± 14	12 ± 2	97 ± 8
24–26	1,038 ± 96	326 ± 19	11 ± 1	98 ± 5
26–28	993 ± 78	298 ± 14	11 ± 1	99 ± 6
28–30	945 ± 41	269 ± 12	10 ± 1	95 ± 5
30–32	905 ± 34	254 ± 20	13 ± 1	91 ± 6
32–34	864 ± 43	225 ± 16	11 ± 1	86 ± 8
34–36	1,541 ± 740	424 ± 230	14 ± 3	109 ± 33
36–38	813 ± 101	204 ± 6	11 ± 2	80 ± 10
38–40	767 ± 116	190 ± 17	11 ± 4	77 ± 11
40–42	621 ± 0	158 ± 0	11 ± 0	58 ± 0

University. These layers were defined by Munsiri et al. (1995) as follows: F horizon, layer of flocculent material on the pond bottom consisting of recent sediment; S horizon, well-mixed sediment with high moisture content and low bulk density (< 0.3 g cm^{-3}); M horizon, mature, stable, un-mixed sediment with dry bulk density of 0.3 to 0.7 g cm^{-3}; T horizon, transition layer; and P horizon, original pond bottom with bulk density less than 1 g cm^{-3}. Chemical analyses revealed that a major characteristic of the soil profile, at least in ponds constructed on mineral soils, was a decrease in organic carbon with depth. Also, there tended to be greater accumulation of nitrogen and phosphorus in S and M horizons than in T and P horizons.

Data collected during the Eighth and Ninth Work Plans showed that a sediment layer develops in ponds within a period of only two or three years. Suspended solids settling in

Table 8. Concentrations of calcium, magnesium, sodium, and potassium in soil cores from ponds at Muñoz, Philippines. Entries are the averages and standard errors of data from three ponds.

Depth (cm)	Calcium (ppm)	Magnesium (ppm)	Sodium (ppm)	Potassium (ppm)
0–2	4,435 ± 316	843 ± 69	174 ± 20	88 ± 8
2–4	4,140 ± 343	812 ± 67	158 ± 17	68 ± 5
4–6	4,060 ± 290	817 ± 68	156 ± 13	66 ± 1
6–8	4,173 ± 286	810 ± 71	162 ± 11	64 ± 3
8–10	4,052 ± 233	794 ± 81	164 ± 13	66 ± 3
10–12	4,052 ± 182	800 ± 87	164 ± 15	67 ± 6
12–14	3,886 ± 228	819 ± 88	166 ± 11	68 ± 7
14–16	3,955 ± 280	820 ± 94	159 ± 11	67 ± 6
16–18	3,822 ± 299	822 ± 98	158 ± 10	68 ± 7
18–20	3,850 ± 369	837 ± 103	155 ± 9	66 ± 7
20–22	3,654 ± 334	858 ± 118	155 ± 13	71 ± 6
22–24	3,691 ± 441	874 ± 131	153 ± 11	64 ± 8

ponds were derived from erosion on pond watersheds; erosion of pond bottoms and sides by wave action and water currents; and organic matter from uneaten fish feed, organic fertilizer, and dead plankton. The sediment contained layers (horizons), but horizons were not always as well-defined as those described for ponds at Auburn University (Munsiri et al., 1995). The F, S, M, T, and P horizons could be discerned visually, and dry bulk density tended to differ among ponds. Pond sediment tended to be a non-structured, fluid mixture of particles that increased in bulk density and decreased in organic matter with increasing depth. Although the horizons described by Munsiri et al. (1995) could be easily identified, the appearance of these horizons was similar among ponds, and the main visual difference in sediment among ponds was sediment thickness.

Soil taxonomy relies on both visual differences and measurable differences in chemical and physical characteristics among soil profiles. Unfortunately, visual differences among pond soil profiles were limited. Analyses of pond soils by Boyd et al. (1994) and pond soil cores from ponds at PD/A CRSP sites during the present study revealed large differences in chemical and physical characteristics among ponds. However, aquaculture was observed to be successful over a wide range of soil characteristics. Only a few soil properties are known to influence aquacultural production (Banerjea and Ghosh, 1967; Boyd, 1995), and pond soil classification should be based on these properties. Thus, we abandoned our initial plan to apply a modified system of soil taxonomy to aquaculture pond soil classification in favor of a simpler classification system.

We prepared a classification system based on the following soil properties: texture; sediment thickness; organic matter content; carbon:nitrogen (C/N) ratio; pH and acidity; amount of sulfur; amount of carbonate; and sodium content. The properties will be considered as either primary or secondary ones. The primary properties will be texture, sediment thickness, organic matter, and pH, and the other variables will be secondary properties. The condition of the flocculent layer (F horizon) and the surface of the sediment also can be included in the classification system as tertiary properties if desired.

Texture

Aquaculture ponds usually are located in mineral soils that contain less than 5% organic carbon. A few aquaculture ponds

Table 9. Concentrations of iron, manganese, zinc, and copper in soil cores from ponds at Pirassununga and Chapeco, Brazil. Entries are the averages and standard errors of data from three ponds.

Depth (cm)	Iron (ppm)	Manganese (ppm)	Zinc (ppm)	Copper (ppm)
PIRASSUNUNGA				
0–2	795 ± 11	253 ± 66	15 ± 1	18 ± 7
2–4	743 ± 71	251 ± 39	19 ± 2	19 ± 7
4–6	981 ± 69	182 ± 46	16 ± 1	20 ± 10
6–8	933 ± 58	211 ± 41	16 ± 1	23 ± 9
8–10	941 ± 28	217 ± 39	16 ± 1	26 ± 11
10–12	933 ± 31	227 ± 41	16 ± 1	24 ± 11
12–14	959 ± 41	217 ± 44	13 ± 2	22 ± 11
14–16	935 ± 54	236 ± 47	14 ± 3	23 ± 12
16–18	689 ± 193	303 ± 36	12 ± 2	21 ± 9
18–20	845 ± 138	251 ± 32	11 ± 2	18 ± 8
20–22	868 ± 138	229 ± 29	9 ± 3	18 ± 6
22–24	855 ± 115	219 ± 26	8 ± 3	16 ± 5
24–26	781 ± 143	272 ± 26	7 ± 3	14 ± 4
26–28	799 ± 202	226 ± 29	7 ± 3	12 ± 3
28–30	819 ± 61	320 ± 39	8 ± 3	20 ± 12
30–32	850 ± 69	253 ± 39	7 ± 2	18 ± 10
32–34	817 ± 0	441 ± 0	6 ± 0	7 ± 0
34–36	1,022 ± 0	204 ± 0	5 ± 0	11 ± 0
CHAPECO				
0–2	109 ± 49	802 ± 28	41 ± 3	12 ± 4
2–4	99 ± 31	808 ± 51	44 ± 4	13 ± 3
4–6	173 ± 86	769 ± 67	46 ± 2	17 ± 7
6–8	184 ± 29	519 ± 100	35 ± 11	16 ± 3
8–10	307 ± 56	599 ± 44	44 ± 5	26 ± 3
10–12	377 ± 102	586 ± 42	45 ± 6	27 ± 5
12–14	410 ± 95	523 ± 39	42 ± 5	30 ± 3
14–16	454 ± 36	494 ± 28	37 ± 4	31 ± 1
16–18	467 ± 85	509 ± 31	34 ± 1	29 ± 1
18–20	442 ± 15	486 ± 44	31 ± 2	32 ± 2
20–22	556 ± 71	413 ± 64	27 ± 3	36 ± 1
22–24	537 ± 49	346 ± 42	28 ± 6	38 ± 1
24–26	614 ± 52	326 ± 27	27 ± 4	39 ± 2
26–28	562 ± 72	298 ± 42	24 ± 2	40 ± 1
28–30	611 ± 20	269 ± 50	21 ± 5	40 ± 2
30–32	755 ± 81	254 ± 55	21 ± 6	40 ± 2
32–34	709 ± 54	225 ± 78	14 ± 3	39 ± 3
34–36	580 ± 277	424 ± 52	21 ± 10	29 ± 11
36–38	812 ± 23	204 ± 57	10 ± 1	40 ± 1
38–40	817 ± 72	190 ± 30	9 ± 1	37 ± 1
40–42	784 ± 0	158 ± 0	6 ± 0	44 ± 0

are built in organic soils, but such soils are not well suited for aquaculture. In mineral soils, texture is important because light texture (sandy or loamy) facilitates the exchange of dissolved oxygen and other substances between water and sediment. Also, when ponds are drained and their bottoms dried between crops, light-textured soils dry quicker and aerate better than heavier-textured soils. The system for assigning texture of terrestrial soils using a soil triangle provides 12 soil texture classes. Most of the soil texture classes given for terrestrial soils are suitable for pond aquaculture, so such a complex system is not needed. The following five soil texture classes should be enough for aquaculture pond sediment classification:

Clay	> 60% clay
Clayey	30 to 60% clay
Loamy	< 30% clay; < 60% sand
Sandy	< 10% clay; > 60% sand
Sand	> 90% sand

Table 10. Concentrations of iron, manganese, zinc, and copper in soil cores from ponds at Muñoz, Philippines. Entries are the averages and standard errors of data from three ponds.

Depth (cm)	Iron (ppm)	Manganese (ppm)	Zinc (ppm)	Copper (ppm)
0–2	44 ± 12	286 ± 103	3.5 ± 1.6	1.6 ± 0.5
2–4	46 ± 12	353 ± 100	4.3 ± 1.8	1.9 ± 0.9
4–6	39 ± 10	335 ± 77	4.5 ± 1.1	2.4 ± 0.9
6–8	36 ± 8	319 ± 62	5.2 ± 1.2	1.9 ± 0.5
8–10	34 ± 8	292 ± 45	5.3 ± 0.9	2.0 ± 0.4
10–12	35 ± 9	312 ± 34	5.3 ± 0.6	2.7 ± 0.1
12–14	41 ± 11	399 ± 67	5.6 ± 0.6	3.7 ± 0.5
14–16	40 ± 7	379 ± 56	5.7 ± 0.6	3.3 ± 0.9
16–18	63 ± 14	513 ± 169	5.6 ± 0.8	4.0 ± 0.7
18–20	106 ± 45	588 ± 219	5.2 ± 1.1	2.8 ± 0.0
20–22	126 ± 84	526 ± 156	5.3 ± 0.9	4.4 ± 0.4
22–24	213 ± 157	585 ± 113	5.1 ± 1.0	3.6 ± 0.4

Sediment Thickness

Sediment thickness is a critical variable in pond management because accumulation of soft sediment makes ponds shallow, encourages anaerobic conditions at the sediment-water interface, lengthens the fallow period for bottom dry-out, traps sinking feed pellets, and interferes with harvest (Boyd, 1995). Suggested categories for sediment thickness are as follows:

Thin	< 5 cm
Moderately thick	5 to 10 cm
Thick	11 to 25 cm
Very thick	> 25 cm

Pond bottoms quickly become covered with sediment, so the term sediment will be used instead of soil in the classification system.

Organic Matter

Organic matter is a minor component of mineral soils, but it is a major component of organic soils. Pond soils containing more than 15% organic carbon will be considered organic soils. Organic soils will be separated into three groups relative to organic carbon content as follows:

Low	15 to 25% organic carbon
Medium	26 to 40% organic carbon
High	> 40% organic carbon

Most aquaculture ponds are constructed in mineral soil of low organic matter content, but as ponds age, organic matter accumulates. Pond sediments can have too little organic matter for optimum growth of benthic organisms, or they may contain so much organic matter that anaerobic conditions frequently develop in the pond bottom (Boyd, 1995). Pond sediment usually contains between 0.5 and 5% organic carbon, and the optimum concentration is considered to be 1 to 3%. Thus, the following categories are suggested for organic carbon in sediment of ponds constructed on mineral soil:

Low	< 1% organic carbon
Moderate	1 to 3% organic carbon
High	> 3% organic carbon

Table 11. Profile for particle sizes in soil cores from ponds at Pirassununga and Chapeco, Brazil. Entries are the averages and standard errors of data from three ponds.

Depth (cm)	Pirassununga			Chapeco		
	Sand	*Silt*	*Clay*	*Sand*	*Silt*	*Clay*
0–2	11.25 ± 3.70	38.27 ± 3.99	50.48 ± 1.56	16.93 ± 4.02	42.49 ± 5.82	40.58 ± 2.01
2–4	14.94 ± 4.42	35.43 ± 5.88	49.63 ± 1.76	14.07 ± 3.47	44.56 ± 0.80	41.36 ± 3.09
4–6	20.82 ± 0.52	33.65 ± 6.58	45.53 ± 6.54	16.46 ± 3.73	45.52 ± 1.17	38.03 ± 2.56
6–8	20.71 ± 0.46	33.60 ± 5.55	45.69 ± 5.70	16.98 ± 2.74	41.63 ± 1.53	41.39 ± 2.10
8–10	19.74 ± 3.53	37.57 ± 8.02	42.69 ± 5.70	18.97 ± 4.59	35.84 ± 4.40	45.19 ± 2.93
10–12	18.22 ± 1.97	36.61 ± 6.74	45.17 ± 5.66	15.31 ± 4.33	42.42 ± 2.03	42.27 ± 2.33
12–14	21.56 ± 3.60	36.13 ± 3.65	42.31 ± 6.93	11.50 ± 3.53	45.58 ± 2.20	42.92 ± 1.96
14–16	22.79 ± 2.90	32.87 ± 5.79	44.34 ± 4.83	10.16 ± 2.60	46.48 ± 3.12	43.36 ± 0.78
16–18	23.47 ± 6.68	36.07 ± 9.09	40.45 ± 8.00	9.96 ± 3.64	44.48 ± 1.85	45.56 ± 1.84
18–20	27.95 ± 6.73	30.91 ± 8.10	41.14 ± 1.86	9.19 ± 2.39	44.07 ± 2.67	46.73 ± 0.43
20–22	37.70 ± 15.01	25.88 ± 11.05	36.41 ± 6.22	8.62 ± 1.84	45.32 ± 2.97	46.05 ± 1.17
22–24	39.10 ± 14.21	24.65 ± 10.73	36.25 ± 4.72	4.79 ± 1.19	46.91 ± 2.18	48.31 ± 2.25
24–26	41.87 ± 12.31	22.01 ± 8.53	36.12 ± 5.79	3.87 ± 0.92	45.55 ± 0.63	50.57 ± 1.22
26–28	46.75 ± 8.28	18.35 ± 5.40	34.89 ± 4.19	3.78 ± 0.79	47.50 ± 2.42	48.72 ± 3.00
28–30	41.15 ± 11.23	21.64 ± 8.02	37.21 ± 3.68	5.96 ± 2.45	47.86 ± 1.86	46.19 ± 4.25
30–32	47.99 ± 12.19	19.04 ± 7.53	32.97 ± 4.68	5.71 ± 1.11	45.30 ± 2.41	48.99 ± 1.30
32–34	59.79 ± 0.00	11.06 ± 0.00	29.16 ± 0.00	6.90 ± 1.48	42.96 ± 1.48	50.15 ± 1.12
34–36	41.31 ± 0.00	20.29 ± 0.00	38.40 ± 0.00	7.48 ± 3.71	42.25 ± 3.22	50.28 ± 0.49
36–38				7.86 ± 2.24	45.14 ± 3.65	47.00 ± 1.40
38–40				11.07 ± 1.34	45.11 ± 2.21	43.82 ± 0.87
40–42				12.55 ± 0.44	44.51 ± 1.05	42.94 ± 1.49

Table 12. Profile for particle sizes in soil cores from ponds at Muñoz, Philippines. Entries are the averages and standard errors of data from three ponds.

Depth (cm)	Sand	Silt	Clay
0–2	13.20 ± 3.86	41.48 ± 1.39	45.32 ± 4.14
2–4	11.46 ± 3.75	42.50 ± 2.85	46.04 ± 2.66
4–6	10.59 ± 3.59	41.67 ± 3.14	47.73 ± 3.80
6–8	8.89 ± 3.27	46.99 ± 2.17	44.12 ± 4.22
8–10	9.43 ± 2.97	42.49 ± 2.36	48.08 ± 3.10
10–12	9.13 ± 2.88	42.48 ± 2.33	48.39 ± 2.69
12–14	9.95 ± 2.46	41.59 ± 1.96	48.45 ± 2.52
14–16	9.42 ± 2.25	42.08 ± 1.79	48.51 ± 2.69
16–18	9.01 ± 1.94	41.11 ± 1.85	49.88 ± 2.87
18–20	11.41 ± 2.32	41.83 ± 3.24	46.76 ± 4.87
20–22	13.44 ± 4.69	37.82 ± 0.28	48.75 ± 4.42
22–24	16.33 ± 7.42	36.74 ± 0.38	46.93 ± 7.10

C/N Ratio

The C/N ratio can vary greatly in aquaculture pond soils, but in most ponds the values will fall between 8 and 15. Ponds with low C/N ratios tend to have highly decomposable organic matter, and anaerobic conditions at the sediment-water interface may be a common problem. At high C/N ratios, organic matter will decompose very slowly because of nitrogen deficiency. Three categories are suggested for C/N ratio:

Low	< 8
Medium	8 to 15
High	> 15

Usually, C/N ratios above 20 are found only in organic soils.

Acidity and pH

Acidity in sediment is derived from two major sources: 1) oxidation of sulfides and 2) exchangeable aluminum. Soils with a high sulfide content are called acid-sulfate soils, for when exposed to air, sulfide oxidizes to sulfuric acid. Soils with high sulfide content normally are found in coastal wetlands such as mangrove forests or in former coastal wetlands. Some sulfidic soils also may be organic soils. Aluminum hydroxides and oxides occur in many soils, and aluminum ions occur on the cation exchange sites of these soils. Exchangeable aluminum is

Table 13. Profile for soil texture in soil cores from ponds at Pirassununga and Chapeco, Brazil.

Depth (cm)	Pirassununga	Chapeco
0–2	Clay	Silty Clay
2–4	Clay	Silty Clay
4–6	Clay	Silty Clay
6–8	Clay	Silty Clay
8–10	Clay	Clay
10–12	Clay	Silty Clay
12–14	Clay	Silty Clay
14–16	Clay	Silty Clay
16–18	Clay	Silty Clay
18–20	Clay	Silty Clay
20–22	Clay	Silty Clay
22–24	Clay	Silty Clay
24–26	Clay	Silty Clay
26–28	Clay	Silty Clay
28–30	Clay	Silty Clay
30–32	Clay	Silty Clay
32–34	Clay	Silty Clay
34–36	Clay	Silty Clay
36–38		Silty Clay
38–40		Silty Clay
40–42		Silty Clay
42–44		Silty Clay
44–46		Silty Clay

Table 14. Profile for soil texture in soil cores from ponds at Muñoz, Philippines.

Depth (cm)	Soil Texture
0–2	Silty Clay
2–4	Silty Clay
4–6	Silty Clay
6–8	Silty Clay
8–10	Silty Clay
10–12	Silty Clay
12–14	Silty Clay
14–16	Silty Clay
16–18	Silty Clay
18–20	Silty Clay
20–22	Clay
22–24	Clay

in equilibrium with aluminum ions in the pore water, and hydrolysis of aluminum ions releases hydrogen ions in the pore water. The greater the proportion of aluminum ions to basic ions (calcium, magnesium, sodium, and potassium) on cation exchange sites in sediment, the lower the pH. Although the pH is related to the ratio of acidic to basic ions, the acidity of soil is related to the total amount of exchangeable aluminum in soil. Two soils may have the same pH because they have equal ratios of aluminum ions to basic ions. However, if the cation exchange capacity (CEC) of these two soils differs, the soil with the highest CEC will have the greatest exchangeable acidity. The need for lime in a soil is indicated by pH, but the amount of liming material that must be applied to raise pH to the desired level is a function of exchangeable acidity. Exchangeable acidity is the most common type of acidity in soils, and even acid-sulfate soils have exchangeable acidity. The suggested categorization of soil based on pH contains seven classes:

Strongly acidic	< 4.0
Acidic	4.1 to 5.0
Moderately acidic	5.1 to 6.8
Neutral	6.9 to 7.1
Moderately basic	7.2 to 7.9
Basic	8.0 to 8.9
Strongly basic	> 9.0

However, three classes should be adequate for exchangeable acidity:

Low	< 10 meq $(100\ g)^{-1}$
Medium	10 to 30 meq $(100\ g)^{-1}$
High	> 30 meq $(100\ g)^{-1}$

It is recommended that pond sediments be classified as sulfidic if they contain more than 0.5% total sulfur. Sulfidic sediment should be ranked according to sulfur content as follows:

Low	0.5 to 1.0% total sulfur
Medium	1.1 to 2.0% total sulfur
High	> 2.0% total sulfur

Carbonate and Sodium

A pH of 8 or above usually is found only in sediments containing free carbonates or high concentrations of sodium and potassium (alkali soils). Pond sediment can be categorized based on the presence or absence of free carbonates. Three levels of carbonate content should be recognized as follows:

Low	< 1% $CaCO_3$ equivalent
Medium	1 to 10% $CaCO_3$ equivalent
High	> 10% $CaCO_3$ equivalent

The pH of non-alkali soils containing carbonate usually will not exceed 8.

The sodium content of soil affects soil texture and pH. Soils with high concentrations of sodium relative to calcium and magnesium concentrations tend to be dispersed and to have a high pH. The sodium status of soil often is expressed as the sodium adsorption ratio (SAR):

$$SAR = \frac{Na}{[\frac{1}{2}(Ca - Mg)]^{0.5}}$$

where Na, Ca, and Mg are cation concentrations in meq kg^{-1}. The SAR can be used to divide soils into different classes with respect to sodium status. When SAR exceeds 12, soil pH usually will be above 8. Freshwater pond sediments usually will have an SAR below 10, while brackishwater pond sediments will have a higher SAR. There should be three levels of SAR:

Low	SAR < 10
Medium	SAR 10 to 30
High	SAR > 30

Flocculent Layer and Sediment Surface

The F horizon is more pronounced over some pond sediments than others. The surface of the S horizon may be either reduced or oxidized, and the thickness of the oxidized layer varies. The depth of the F horizon and the degree of oxidation of the upper part of the S horizon will change with time during the aquaculture crop, so these properties change more rapidly and more often than the other properties used in the classification system. Nevertheless, for some purpose it will be useful to include the thickness of the F horizon and the degree of oxidation of the S horizon in pond sediment classification. The following categories are suggested:

Thickness of F horizon - thin (< 1 cm); normal (1 to 3 cm); thick (> 3 cm)

Degree of oxidation of S horizon - thin (< 2 mm); normal (2 to 10 mm); thick (> 10 mm)

Depth of Samples for Classification

Pond sediment composition changes with depth, and in many sediment the levels of variables will change between horizons. This should not present a problem in pond soil classification because the classification system will be based on the characteristics of the S horizon. The reason for selecting the S horizon for classifying pond soils is that this layer is the first layer below the soil-water interface and is the only layer in direct contact with pond water. Exchanges of substances between pond water and bottom soil occur in this layer. There usually is no direct contact of pond water with the M, T, and P horizons below the S horizon.

A transparent core tube can be used to secure samples, and the S horizon can be identified and removed for analysis. The total sediment depth, thickness of the F horizon, and oxidation status of the sediment surface also can be obtained from inspection of the core before the S horizon is removed.

Use of Classification System

The proposed system allows a pond sediment to be classified using four primary and five secondary properties. There also is the option to use two tertiary properties if desired. Adoption of a standardized way to indicate the levels of these properties for a sample is essential, and for convenience, the indication of levels should result in a sediment name. A name consisting of words denoting levels of up to 11 properties would be very long. The name can be shortened if words are used only for the levels of the primary properties pH, organic matter, sediment thickness, and organic status (organic or mineral). A pond sediment could be described in words as an acidic, loamy, thin sediment. As most pond sediments are mineral in nature, it is not necessary to use the word mineral in the description. The word organic must be included in the designation of a sediment that contains more than 15% organic carbon, e.g., a moderately acidic, sandy, thick, organic sediment. The sediment name can be completed by providing, in parentheses and after the primary descriptor words, abbreviations denoting levels of secondary properties. The additional information should be abbreviated as follows: OC = organic carbon; CN = C/N ratio; EA = exchangeable acidity; CS = calcareous sediment; SS = sulfidic sediment; SR = sodium adsorption ratio. The degree of intensity—high, medium, or low—should be indicated with the subscript h, m, or l, respectively. Using the suggestions above, an example of a sediment name could be an acidic, loamy, thin sediment (EA_h; OC_l; CN_m; SR_l). Because the word organic is missing, this name implies that the sediment is of mineral nature even though the word mineral does not appear as a descriptor. Also, the absence of the abbreviations CS and SS reveals that the sediment is neither calcareous nor sulfidic.

Where it is desired to use the tertiary properties, we suggest the following abbreviations: F and S for F horizon and S horizon; subscripts o and r indicate oxidized and reduced conditions, respectively, at the surface of the S horizon; subscripts l, m, and h indicate thin, medium, and thick. These abbreviations should follow the parentheses containing the secondary property descriptors as follows: acidic, loamy, thin sediment (EA_h; OC_l; CN_m; SR_l) F_l S_r or acidic, loamy, thin sediment (EA_h; OC_l; CN_m; SR_l) F_l $S_{o,m}$. In the first case, F_l indicates a thin flocculent layer and S_r denotes that the sediment surface is reduced. In the second case, $S_{o,m}$ indicates that the sediment surface is oxidized to a normal depth.

An example of the use of soil chemical and physical data to classify and name a pond sediment is provided here. A sediment has the following composition: clay, 45%; pH, 6.2; sediment thickness, 24 cm; organic carbon, 2.1%; C/N ratio, 10; total sulfur, 0.11%; exchangeable acidity, 5 meq (100 g)$^{-1}$; free carbonate, 0%; SAR, 5.5; F horizon = 5 cm; S horizon reduced at surface. The name follows:

moderately acidic, clayey, thick sediment (EA_l; OC_m; CN_m; SR_l) F_h, S_r.

Note, CS (calcareous sediment) and SS (sulfidic sediment) do not appear as secondary properties because no free carbonate was present and sulfur was below 0.5%.

Consider another example for a sediment with the following composition: clay, 32%; pH, 3.5; sediment thickness, 8 cm; organic carbon, 17%; C/N ratio, 32; total sulfur, 2.1%; exchangeable acidity, 14 meq (100 g)$^{-1}$; free carbonate, 0%; SAR, 7; F horizon = 1 mm; sediment surface oxidized to 5 mm depth. The name follows:

strongly acidic, clayey, moderately thick, organic sediment (EA_m; OC_l; CN_h; SS_h; SR_l) F_l, $S_{o,m}$.

Note, CS does not appear because there was no free carbonate in the sediment.

We plan to present this pond classification system in a scientific journal. We hope the procedure described above, or a slight modification of it, will be adopted as a standard procedure in pond aquaculture.

ANTICIPATED BENEFITS

This research has demonstrated three important points about pond sediments:

1) Reactions between pond soil and pond water occur primarily in the upper 2 to 10 cm layer.
2) Low pH, high acidity, and elevated organic matter concentration in surface sediment appear to be the most common chemical problem with pond soils.
3) Accumulation of soft sediment in ponds is the most common physical problem with pond soils.

These observations suggest that soil management in ponds should focus on liming—to reduce acidity and increase pH—and drying of bottoms between crops. These two procedures can enhance the degradation of organic matter and improve soil quality. Also, soft sediment should periodically be removed from the deep areas of ponds. It is anticipated that these findings will greatly improve pond soil management procedures.

The research also provides a method of pond sediment classification. It is anticipated that this method, or a refinement of it, will become the standard procedure for describing aquaculture pond sediment. A uniform method of describing pond soils will be beneficial in describing soils from different areas. The information provided by the sediment name also will serve to indicate the type of bottom soil management needed.

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