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Pond Soil Characteristics and Dynamics of Soil Organic Matter and Nutrients

Eighth Work Plan, Pond Dynamics Research 1 (PDR1)
Progress Report

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Abstract

Soil cores were collected from ponds at the Sagana Fish Culture Farm, Kenya. The pond bottoms had well-developed S horizons of 6 cm depth, but M and T horizons were weakly developed. Recent renovation of ponds with sediment removal explains the weak M and T horizons. The soils were near neutral in pH, with carbon concentrations between 2 and 5%. Carbon:nitrogen ratios were between 10 and 20. Total sulfur concentrations were around 0.5%, and soil phosphorous concentrations were low. The soils had high concentrations of exchangeable bases, and micronutrient concentrations were within normal ranges. Soil incubation studies on pond soils from Thailand, Honduras, and Kenya revealed relatively low microbial respiration rates as compared to typical terrestrial soils, and there was net negative nitrogen mineralization (nitrogen was immobilized). Equilibrium phosphorus concentrations in soil-water mesocosms were: AIT, new ponds, 0.17 mg l^{-1}; AIT, old ponds, 0.12 mg l^{-1}; Honduras, freshwater ponds, 0.22 mg l^{-1}; Honduras, brackishwater ponds, 0.23 mg l^{-1}; Kenya, 0.06 mg l^{-1}. At all sites, pond soils will be sinks for phosphorus added in fertilizer. Pond soils appear to develop distinct profiles within a few years, in contrast to terrestrial soils where soil development takes much longer.

Introduction

This study focuses on collection of data on basic characteristics of pond soil from the Pond Dynamics/Aquaculture CRSP research sites. These data are needed both to provide basic information on the pond ecosystems used in fish and shrimp production at the different CRSP sites and to develop a theory of pond soil development and a systemic method of pond soil classification.

This report contains data on soil characteristics for the CRSP ponds in Kenya, results of ammonia and carbon dioxide dynamics in soils incubated under aerobic conditions, ammonia dynamics in soil incubated under anaerobic conditions, phosphorus equilibrium concentrations in laboratory soil-water mesocosms, and a summary of some of our initial ideas related to the theory of pond soil development.

Methods and Materials

Ponds

The ponds for the Africa CRSP site are located at the Sagana Fish Culture Farm, Kenya. The ponds were renovated between March and July 1997. The renovation included removing soil from parts of the bottoms to ensure that depths and bottom contours were uniform among the ponds (Bowman et al., 1997). The experimental ponds have a surface area of 800 m^2, and the maximum water depth is about 1 m. The ponds had been stocked with tilapia for about two months at time of sampling on 4 and 5 September 1997.

Sampling

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 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.

Physical and Chemical 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).

Soil Incubation Studies

Aerobic and anaerobic incubation methods were used to estimate potentially mineralizable N and C (aerobic incubation only) in soils sampled from 0-to-10-cm and 10-to-20-cm layers of pond bottoms. 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 CO_2 was trapped in a vial containing 8 ml of 1 M NaOH (Anderson, 1982).

Soil organic C and N, and inorganic N (NO_3-N plus NO_2-N [aerobic incubation only], and NH_4-N) were measured before incubations were initiated. Soil inorganic N and respired CO_2-C were measured upon termination of incubation. Soil organic C and N were determined via dry combustion with a LECO CHN-600 analyzer. Inorganic N was extracted with 2 M KCl, and analyzed via the microplate method (Sims et al., 1995). Carbon dioxide in NaOH traps was determined by titrating excess base with 1 M HCl in the presence of $BaCl_2$ (Anderson, 1982).

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

Phosphorus Equilibrium Studies

Water-extractable phosphorus was determined by shaking 1-g samples in 100 ml distilled water for 24 h, filtering the mixture, and measuring phosphorus in filtrates by the ascorbic acid technique (Boyd and Tucker, 1992).

RESULTS AND DISCUSSION

Pond Soils at Sagana, Kenya

The moisture content of the soil in ponds at the Sagana site decreased rapidly with depth, and the dry bulk density increased with depth (Table 1). The soils had a well-developed S horizon that extended to a depth of 6 cm. The M, T, and P horizons were poorly developed in these soils. Also, soil color did not change markedly with depth. Ponds at other CRSP sites and at the Auburn University Fisheries Research Unit (Boyd et al., 1997; Munsiri et al., 1995) had much better profile development than observed at the Sagana site. This suggests that the pond renovation activities greatly altered any profile that had developed in the ponds during previous years.

Table 1. Profiles for moisture content, dry bulk density, and color in soil cores from bottoms of freshwater aquaculture ponds in Kenya. 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 ($g\ cm^{-3}$). Color values are given as standard Munsell Color Chart Units (7.5YR 2.5/1—Black; 7.5YR 2.5/2—Very dark brown). Each entry is the average of three ponds.

Depth (cm)	Moisture content (%)	Dry bulk density ($g\ cm^{-3}$)	Color
0 - 2	418.8 ± 30.5	0.20 ± 0.02	7.5YR 2.5/2
2 - 4	255.4 ± 17.5	0.31 ± 0.03	7.5YR 2.5/2
4 - 6	203.8 ± 25.1	0.37 ± 0.04	7.5YR 2.5/2
6 - 8	137.1 ± 21.6	0.59 ± 0.07	7.5YR 2.5/1
8 - 10	91.6 ± 6.5	0.71 ± 0.03	7.5YR 2.5/1
10 - 12	86.0 ± 6.4	0.76 ± 0.04	7.5YR 2.5/1
12 - 14	86.5 ± 28.5	0.80 ± 0.04	7.5YR 2.5/1
14 - 16	84.9 ± 9.9	0.80 ± 0.06	7.5YR 2.5/1
16 - 18	82.3 ± 9.0	0.81 ± 0.06	7.5YR 2.5/1
18 - 20	71.0 ± 3.9	0.87 ± 0.03	7.5YR 2.5/1

Soil pH was near neutral, with dry soil values ranging from 6.97 at the surface to 7.63 at 18 to 20 cm depth (Table 2). The wet soil pH was slightly lower than the dry soil pH, as was observed in earlier work (Boyd et al., 1997). This apparently is a result of the near neutral pH, because in acidic soils, the pH of dry pond soils usually is somewhat higher than that of wet soils (Munsiri et al., 1995). Because soils had a near neutral pH, exchange acidity values were only 3.47 to 4.80 meq/100 g (Table 2). Neither pH nor exchange acidity exhibited clear patterns of change with soil depth.

Table 2. Profiles for wet soil pH, dry soil pH, and exchangeable acidity in soil cores from bottoms of freshwater aquaculture ponds in Kenya. The wet soil pH is directly measured in soil cores and the dry soil pH is measured in 1:1 slurries of dry soil and distilled water. 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	6.73 ± 0.05	6.97 ± 0.10	3.47 ± 0.15
2 - 4	7.17 ± 0.04	6.90 ± 0.03	3.73 ± 0.41
4 - 6	7.13 ± 0.15	6.83 ± 0.17	4.27 ± 0.41
6 - 8	7.07 ± 0.04	6.83 ± 0.20	4.80 ± 0.27
8 - 10	6.73 ± 0.22	6.80 ± 0.24	4.27 ± 0.67
10 - 12	6.73 ± 0.19	6.90 ± 0.27	4.53 ± 0.62
12 - 14	6.73 ± 0.18	7.13 ± 0.28	3.73 ± 0.41
14 - 16	6.67 ± 0.16	7.37 ± 0.17	3.47 ± 0.41
16 - 18	6.67 ± 0.15	7.40 ± 0.12	3.47 ± 0.15
18 - 20	7.13 ± 0.13	7.63 ± 0.08	3.47 ± 0.15

All other pond soil profiles that have been examined by the authors in Alabama, Mississippi, Honduras, Thailand, and Egypt had the highest concentrations of total carbon and total nitrogen at the soil surface, and concentrations of these two elements then declined with depth. Lowest soil carbon concentrations were observed in the original soil (P horizon). However, at the Sagana site, the carbon concentration exceeded 2% at all depths (Table 3), and the highest concentrations were below 10 cm depth. Nitrogen concentrations were greatest in the surface layer at Sagana, but there was no clear pattern of

Table 3. Profiles for total carbon and total nitrogen in soil cores from bottoms of freshwater aquaculture ponds in Kenya. Each entry is the average of three ponds.

Depth (cm)	Total carbon (%)	Total nitrogen (%)
0 - 2	2.60 ± 0.45	0.24 ± 0.06
2 - 4	3.73 ± 0.27	0.17 ± 0.02
4 - 6	3.19 ± 0.29	0.19 ± 0.01
6 - 8	2.95 ± 0.26	0.20 ± 0.04
8 - 10	2.20 ± 0.40	0.15 ± 0.04
10 - 12	4.01 ± 0.69	0.18 ± 0.02
12 - 14	2.04 ± 0.18	0.13 ± 0.03
14 - 16	4.51 ± 0.55	0.16 ± 0.02
16 - 18	2.58 ± 0.04	0.14 ± 0.01
18 - 20	2.15 ± 0.13	0.12 ± 0.01

nitrogen decrease with depth. As with the other CRSP sites, soil carbon concentrations are not high at the Sagana site, with all values being below 5% total carbon. The C/N ratios were usually between 10 and 20. These C/N ratios are generally greater than other CRSP sites where C/N ratios were between 7 and 15 (Boyd et al., 1997), and much higher than the C/N ratios of 5 to 7 found in pond soils at the Auburn University Fisheries Research Unit in Alabama (Munsiri et al., 1995).

The total sulfur concentrations tended to decline with depth (Table 4). Values decreased from 0.50 to 0.59% in the upper 0-to-8-cm layer to 0.17% in the 18-to-20-cm layer. Total phosphorus (Table 4) was at higher concentrations in the surface layers (S and M horizons) than in deeper layers. However, the acid-extractable phosphorus concentrations were low and relatively uniform with soil depth. The 0-to-2-cm layer contained 0.07%, or 700 ppm, while the dilute acid-extractable phosphorus was 14.2 ppm. At 18 to 20 cm depth, total phosphorus was 300 ppm (0.03%) and extractable phosphorus was 16.1 ppm. It seems that additions of fertilizers, manures, and feeds to the ponds over the years has caused considerable elevation of total phosphorus. However, this phosphorus has been fixed in a mineral form that is insoluble in dilute acid and therefore quite insoluble in water (Boyd and Munsiri, 1996). These soils will strongly adsorb phosphorus applied to ponds in aquacultural management.

The soils at the Sagana site had high concentrations of calcium, magnesium, sodium, and potassium (Table 5). Magnesium and calcium concentrations did not change with depth. Thus, we assume that liming has not been routinely practiced at the site, and, of course, that the soils are near neutral and liming is not required. Sodium concentrations also were similar at all depths, but potassium declined with depth. The high concentrations of potassium near the surface suggest inputs of this element to ponds in fertilizers and manures.

Concentrations of iron, manganese, zinc, and copper are provided in Table 6. Iron concentrations were greater in S and M horizons than in the P horizon. Iron concentrations are higher than those recorded for ponds at CRSP sites in Honduras, but lower than those recorded for Thailand. Manganese concentrations also were highest in S and M horizons. The surface layer contained 415 ppm as compared to 100 ppm for the deepest layer. Manganese concentrations at the Sagana site are greater than those observed in ponds at the other CRSP sites. Zinc concentrations decreased from 1.73 ppm at the surface to 0.42 ppm at 18 to 20 cm depth. The concentrations of zinc are similar to those of ponds at the brackishwater site in Honduras, but lower than zinc concentrations in soil of the other freshwater CRSP ponds. Copper concentrations did not change appreciably with soil depth at the Sagana site, and concentrations were similar to those found at other CRSP sites (Boyd et al., 1997).

Table 4. Profiles for total phosphorus, dilute acid extractable phosphorus, and total sulfur in soil cores from bottoms of freshwater aquaculture ponds in Kenya. Each entry is the average of three ponds.

Depth (cm)	Total phosphorus (%)	Dilute acid extractable phosphorus (ppm)	Total sulfur (ppm)
0 - 2	0.07 ± 0.01	14.23 ± 0.94	0.50 ± 0.08
2 - 4	0.07 ± 0.01	14.64 ± 1.07	0.55 ± 0.08
4 - 6	0.06 ± 0.01	13.39 ± 1.17	0.54 ± 0.08
6 - 8	0.04 ± 0.00	13.82 ± 1.06	0.59 ± 0.09
8 - 10	0.05 ± 0.00	14.76 ± 1.09	0.41 ± 0.08
10 - 12	0.05 ± 0.01	14.92 ± 0.59	0.36 ± 0.08
12 - 14	0.04 ± 0.01	15.37 ± 0.90	0.32 ± 0.08
14 - 16	0.03 ± 0.00	15.28 ± 0.60	0.30 ± 0.07
16 - 18	0.03 ± 0.00	17.34 ± 0.93	0.23 ± 0.05
18 - 20	0.03 ± 0.01	16.06 ± 0.73	0.17 ± 0.02

The soil texture data for Honduras and Thailand were not provided in the 1997 annual report, so they are included here (Tables 7 and 8) for comparison with the Sagana site data (Table 9). Soils at all CRSP sites contain large percentages of clay. In Thailand and Kenya, clay concentrations tend to increase with depth in the soil profile. In Honduras, clay concentrations tend to increase in the M horizon and then decrease at greater depths. The textures for soil from different depths is named in Table 10. Notice that clay appears in all of the names.

Soil Incubation Studies

Total organic C and N concentrations in 0 to 10 and 10 to 20 cm soil depths beneath aquaculture ponds (Tables 11 and 12) were relatively high in comparison to typical terrestrial soils (Wood and Edwards, 1992), reflecting addition of organic materials and perhaps retarded decomposition beneath ponds. Data in Tables 11 and 12 indicate that C:N ratios were in the 10:1 range, suggesting N net mineralization should occur. However, when these soils were incubated aerobically (Table 13) net N mineral-

Table 5. Profiles for calcium, magnesium, potassium, and sodium in soil cores from bottoms of freshwater aquaculture ponds in Kenya. Each entry is the average of three ponds.

Depth (cm)	Calcium (ppm)	Magnesium (ppm)	Potassium (ppm)	Sodium (ppm)
0 - 2	2,657 ± 72	1,743 ± 60	84 ± 7	145 ± 14
2 - 4	2,680 ± 86	1,739 ± 70	80 ± 9	121 ± 13
4 - 6	2,639 ± 78	1,765 ± 80	70 ± 8	121 ± 15
6 - 8	2,630 ± 65	1,818 ± 85	60 ± 8	116 ± 17
8 - 10	2,541 ± 56	1,873 ± 84	53 ± 6	136 ± 19
10 - 12	2,641 ± 40	1,888 ± 92	37 ± 5	145 ± 21
12 - 14	2,584 ± 45	1,966 ± 100	33 ± 2	142 ± 25
14 - 16	2,575 ± 74	2,062 ± 90	27 ± 3	166 ± 31
16 - 18	2,595 ± 79	2,124 ± 75	28 ± 2	170 ± 33
18 - 20	2,811 ± 103	1,996 ± 88	24 ± 2	179 ± 37

Table 6. Profiles for iron, manganese, zinc, and copper in soil cores from bottoms of freshwater aquaculture ponds in Kenya. Each entry is the average of three ponds.

Depth (cm)	Iron (ppm)	Manganese (ppm)	Zinc (ppm)	Copper (ppm)
0 - 2	37 ± 5	415 ± 24	1.73 ± 0.09	0.31 ± 0.05
2 - 4	50 ± 7	390 ± 14	1.67 ± 0.14	0.33 ± 0.04
4 - 6	33 ± 6	327 ± 14	1.51 ± 0.16	0.21 ± 0.03
6 - 8	36 ± 9	331 ± 22	1.39 ± 0.21	0.33 ± 0.06
8 - 10	31 ± 9	294 ± 36	1.35 ± 0.27	0.35 ± 0.08
10 - 12	38 ± 14	259 ± 45	1.23 ± 0.40	0.26 ± 0.04
12 - 14	37 ± 12	204 ± 45	1.08 ± 0.31	0.48 ± 0.05
14 - 16	45 ± 16	163 ± 35	0.75 ± 0.16	0.33 ± 0.02
16 - 18	27 ± 4	130 ± 37	0.55 ± 0.04	0.48 ± 0.05
18 - 20	19 ± 0	100 ± 26	0.42 ± 0.03	0.33 ± 0.03

ization was negative and microbial respiration (Table 14) was low in comparison to typical terrestrial soils (Wood and Edwards, 1992). Two possibilities exist for explanation of negative net N mineralization in these aerobically incubated soils:

1) Organic N compounds in these soils were recalcitrant and relatively unavailable to heterotrophic microorganisms, which created a N limitation; or
2) N in these soils was denitrified after mineralization resulting in a net loss of inorganic N.

Of these explanations, the former is most likely. This conclusion is supported by data in Table 15 regarding net N mineralization under anaerobic conditions, which in large part indicated net negative N mineralization. Because anaerobic incubations should not result in production of nitrate that could be denitrified and lost, the most likely explanation for net negative N mineralization in these soils is N limitation and subsequent immobilization of N by heterotrophic microbes. These data suggest that these pond soils would not contribute N to the water column, but would likely act as sinks for any available N in overlying waters.

Phosphorus Equilibrium

The surface 0-to-4-cm layer of bottom soil for the five series of three ponds each had the following concentrations and standard deviations of distilled-water-extractable phosphorus

Table 7. Profiles for soil texture in cores from bottoms of aquaculture ponds in Thailand, Honduras, and Kenya. Each entry is the average of three ponds.

Depth (cm)	Thailand		Honduras		Kenya
	New ponds	*Old ponds*	*Freshwater ponds*	*Brackishwater ponds*	*Freshwater ponds*
0 - 2	Silty clay	Silty clay	Silty clay	Silty clay	Silty clay
2 - 4	Silty clay	Clay	Silty clay	Silty clay	Silty clay
4 - 6	Silty clay	Silty clay	Silty clay	Silty clay	Clay
6 - 8	Silty clay	Clay	Silty clay	Silty clay	Clay
8 - 10	Clay	Clay	Silty clay	Silty clay	Clay
10 - 12	Clay	Clay	Silty clay	Silty clay	Clay
12 - 14	Clay	Clay	Silty clay	Silty clay	Clay
14 - 16	Clay	Clay	Silty clay	Silty clay	Clay
16 - 18	Clay	Clay	Silty clay	Silty clay	Clay
18 - 20	Clay	Clay	Silty clay	Clay	Clay
20 - 22		Clay	Silty clay	Clay	
22 - 24		Clay	Silty clay loam	Clay	
24 - 26		Clay	Silty clay loam	Clay loam	
26 - 28		Clay		Clay loam	
28 - 30		Clay			
30 - 32		Clay			
32 - 34		Clay			
34 - 36		Clay			

Table 8. Profiles for particle size distribution in soil cores from bottoms of aquaculture ponds in Thailand. Averages and standard errors are given as percentages of dry weight. Each entry is the average of three ponds.

Depth (cm)	New ponds			Old ponds		
	Sand	*Silt*	*Clay*	*Sand*	*Silt*	*Clay*
0 - 2	5.82 ± 0.48	44.67 ± 2.99	49.52 ± 1.75	2.74 ± 0.36	48.13 ± 2.80	49.13 ± 3.13
2 - 4	3.85 ± 0.73	40.83 ± 1.31	55.32 ± 1.75	1.87 ± 0.12	35.60 ± 1.87	62.53 ± 1.91
4 - 6	3.21 ± 0.64	40.30 ± 1.03	56.49 ± 1.56	2.47 ± 0.41	39.59 ± 1.06	57.95 ± 1.47
6 - 8	3.80 ± 0.36	40.21 ± 0.67	55.99 ± 1.04	1.80 ± 0.29	33.68 ± 1.54	64.52 ± 1.50
8 - 10	4.26 ± 0.51	38.84 ± 0.84	56.91 ± 0.07	1.73 ± 0.17	35.99 ± 0.63	62.28 ± 0.73
10 - 12	4.88 ± 0.53	36.86 ± 1.25	58.25 ± 0.48	2.02 ± 0.57	36.54 ± 0.28	61.44 ± 0.45
12 - 14	3.96 ± 0.25	36.34 ± 1.37	59.69 ± 0.61	1.85 ± 0.39	40.74 ± 0.93	57.41 ± 0.57
14 - 16	3.70 ± 0.32	35.29 ± 1.10	61.01 ± 0.81	1.59 ± 0.28	39.27 ± 1.09	59.13 ± 0.81
16 - 18	3.95 ± 0.51	35.10 ± 1.04	60.95 ± 0.61	1.91 ± 0.32	38.69 ± 1.00	59.40 ± 0.71
18 - 20	3.72 ± 0.64	35.41 ± 1.27	60.87 ± 0.78	2.27 ± 1.02	37.86 ± 1.01	59.87 ± 0.70
20 - 22				2.90 ± 0.34	37.57 ± 1.68	59.53 ± 1.35
22 - 24				3.09 ± 0.38	37.06 ± 1.81	59.85 ± 1.53
24 - 26				3.56 ± 0.36	35.00 ± 0.92	61.44 ± 0.59
26 - 28				3.60 ± 0.07	34.49 ± 0.33	61.91 ± 0.26
28 - 30				4.21 ± 0.49	34.56 ± 0.61	61.23 ± 0.26
30 - 32				5.50 ± 0.87	34.64 ± 0.27	59.87 ± 0.76
32 - 34				5.42 ± 1.12	34.86 ± 0.19	59.72 ± 1.04
34 - 36				4.39 ± 0.67	35.82 ± 0.38	59.79 ± 0.31

(equilibrium phosphorus): AIT, new ponds, 0.167 ± 0.099 mg l^{-1}; AIT old ponds, 0.123 ± 0.094 mg l^{-1}; Honduras, freshwater site, 0.221 ± 0.09 mg l^{-1}; Honduras, brackishwater site, 0.278 ± 0.075 mg l^{-1}; Kenya, 0.058 ± 0.023 mg l^{-1}. A series of 20 soil samples from potential aquaculture sites in Thailand which represented 10 soil suborders and a wide range in soil properties had water-extractable phosphorus concentrations of 0.0 to 0.16 mg l^{-1} (Boyd and Munsiri, 1996). None of these soils had been fertilized. Thus, with the exception of the Kenya site, the phosphorus equilibrium concentrations in surface layers of pond soil were higher than native phosphorus equilibrium concentrations found in the series of samples from Thailand.

The phosphorus equilibrium concentrations for profiles from a single pond from each site (Table 16) revealed that phosphorus concentrations generally declined with increasing soil profile depth at the two Thailand (AIT) sites and the site in Kenya. Thus, at these sites, aquacultural inputs apparently caused the increase in phosphorus. The phosphorus equilibrium

Table 9. Profiles for particle size distribution in soil cores from bottoms of aquaculture ponds in Honduras. Averages and standard errors are given as percentages of dry weight. Each entry is the average of three ponds.

Depth (cm)	**Brackishwater ponds**			**Freshwater ponds**		
	Sand	*Silt*	*Clay*	*Sand*	*Silt*	*Clay*
0 - 2	5.60 ± 0.77	50.62 ± 1.53	43.77 ± 1.42	2.30 ± 0.13	45.22 ± 1.16	52.48 ± 1.26
2 - 4	4.55 ± 1.94	46.58 ± 2.00	48.87 ± 0.18	1.92 ± 0.21	42.65 ± 0.39	55.43 ± 0.42
4 - 6	2.21 ± 0.87	50.87 ± 0.64	46.92 ± 0.39	2.39 ± 0.21	42.64 ± 0.73	54.97 ± 0.80
6 - 8	1.83 ± 0.59	50.95 ± 1.82	47.21 ± 1.40	2.07 ± 0.10	41.14 ± 23.14	56.80 ± 0.81
8 - 10	1.07 ± 0.21	51.71 ± 0.53	47.23 ± 0.61	2.44 ± 0.25	48.32 ± 4.50	49.24 ± 4.74
10 - 12	2.26 ± 0.45	50.48 ± 1.46	47.27 ± 1.10	2.65 ± 0.19	42.14 ± 0.82	55.21 ± 1.00
12 - 14	2.59 ± 0.87	49.55 ± 1.87	47.87 ± 1.38	2.59 ± 0.32	42.13 ± 0.93	55.28 ± 1.18
14 - 16	3.60 ± 1.22	47.27 ± 1.90	49.13 ± 0.92	3.93 ± 0.52	41.23 ± 0.35	54.84 ± 0.75
16 - 18	6.79 ± 1.96	42.05 ± 2.25	51.16 ± 0.83	6.31 ± 0.75	44.84 ± 0.43	48.85 ± 1.07
18 - 20	11.90 ± 1.61	36.36 ± 0.2	51.73 ± 1.82	8.55 ± 1.20	46.47 ± 1.46	44.99 ± 1.97
20 - 22	17.06 ± 3.60	35.57 ± 1.80	47.37 ± 1.81	8.58 ± 1.05	50.72 ± 2.58	40.71 ± 2.34
22 - 24	26.84 ± 8.29	32.42 ± 3.36	40.73 ± 4.93	10.73 ± 1.63	52.04 ± 3.89	37.24 ± 3.88
24 - 26	28.85 ± 10.24	32.19 ± 4.43	38.96 ± 5.81			
26 - 28	28.66 ± 11.28	32.76 ± 4.95	38.59 ± 6.38			

Table 10. Profiles for particle size distribution in soil cores from bottoms of freshwater aquaculture ponds in Kenya. Averages and standard errors are given as percentages of dry weight. Each entry is the average of three ponds.

Depth (cm)	**Sand**	**Silt**	**Clay**
0 - 2	5.9 ± 0.8	45.86 ± 3.93	48.24 ± 4.75
2 - 4	4.6 ± 0.4	41.33 ± 2.30	54.07 ± 2.10
4 - 6	5.2 ± 0.7	35.34 ± 3.94	59.43 ± 4.13
6 - 8	6.2 ± 0.8	32.21 ± 3.99	61.63 ± 3.87
8 - 10	6.9 ± 0.7	31.21 ± 4.75	61.92 ± 4.36
10 - 12	7.8 ± 0.7	26.50 ± 4.66	65.67 ± 4.52
12 - 14	14.6 ± 2.8	17.30 ± 0.24	68.13 ± 2.63
14 - 16	12.6 ± 2.3	17.59 ± 0.14	69.64 ± 2.27
16 - 18	9.5 ± 1.4	21.05 ± 1.65	69.45 ± 0.42
18 - 20	11.2 ± 1.5	18.15 ± 0.68	70.68 ± 1.05

Table 11. Profiles for total carbon in wet soils from bottoms of aquaculture ponds. Each entry is the average of three ponds.

	Total carbon (%)	
	0 - 10 cm depth	*10 - 20 cm depth*
Thailand - New ponds	2.20 ± 0.09	1.47 ± 0.18
Honduras - Freshwater ponds	2.01 ± 0.10	1.21 ± 0.14
Honduras - Brackishwater ponds	1.41 ± 0.07	0.96 ± 0.14
Kenya - Freshwater ponds	2.90 ± 0.23	2.28 ± 0.26

Table 12. Profiles for total nitrogen in wet soils from bottoms of aquaculture ponds. Each entry is the average of three ponds.

	Total nitrogen (%)	
	0 - 10 cm depth	*10 - 20 cm depth*
Thailand - New ponds	0.25 ± 4.55	0.11 ± 0.02
Honduras - Freshwater ponds	0.26 ± 0.01	0.13 ± 0.02
Honduras - Brackishwater ponds	0.20 ± 0.01	0.14 ± 0.02
Kenya - Freshwater ponds	0.25 ± 0.02	0.04 ± 0.02

Table 13. Profiles for net aerobic nitrogen mineralization (30 days incubation) of soil cores from bottoms of aquaculture ponds. Each entry is the average of three ponds.

	Net aerobic nitrogen mineralization (mg NH_4-N kg^{-1}soil)	
	0 - 10 cm depth	*10 - 20 cm depth*
Thailand - New ponds	-119.70 ± 45.15	-67.35 ± 85.50
Honduras - Freshwater ponds	-67.27 ± 56.10	-11.93 ± 11.68
Honduras - Brackishwater ponds	-33.05 ± 22.24	-12.46 ± 17.49
Kenya - Freshwater ponds	-134.61 ± 5.00	-30.52 ± 39.42

concentrations tended to increase with greater soil profile depth in Honduras. This suggests that the native soils in Honduras are extremely high in soluble phosphorus, and aquacultural activities have probably resulted in dissolution and loss of soluble phosphorus from surface layers. In Kenya, removal of surface soil in pond renovation was probably the reason for the relatively low phosphorus concentrations in the upper part of the profile.

Table 14. Profiles for CO_2 respiration for 7 days aerobic incubation of soil cores from bottoms of aquaculture ponds. Each entry is the average of three ponds.

	CO_2 respiration ($mg\ CO_2\ kg^{-1}$ soil)	
	0 - 10 cm depth	*10 - 20 cm depth*
Thailand - New ponds	42.46 ± 13.28	20.27 ± 8.57
Honduras - Freshwater ponds	27.16 ± 3.97	8.68 ± 4.79
Honduras - Brackishwater ponds	33.66 ± 12.88	20.36 ± 17.38
Kenya - Freshwater ponds	14.63 ± 3.55	10.17 ± 0.51

Table 15. Profiles for NH_4-N anaerobic incubation for 7 days of soil cores from bottoms of aquaculture ponds. Averages and standard errors are given as milligrams NH_4-N per kilogram of soil ($mg\ kg^{-1}$). Each entry is the average of three ponds.

	NH_4-N anaerobic incubation ($mg\ NH_4\text{-}N\ kg^{-1}$ soil)	
	0 - 10 cm depth	*10 - 20 cm depth*
Thailand - New ponds	-16.60 ± 25.15	-21.97 ± 4.12
Honduras - Freshwater ponds	-18.65 ± 12.29	-6.73 ± 1.72
Honduras - Brackishwater ponds	10.47 ± 1.85	-2.67 ± 4.84
Kenya - Freshwater ponds	-44.33 ± 17.92	-20.50 ± 6.07

Soil Development

The factors influencing pond soil development are illustrated in Figure 1. This depiction of soil development is modified from the theory of terrestrial soil development which holds that soil development is a function of parent material, climate, activity of organisms, topography, and time. The same factors influence pond soil formation, but in the case of pond soils, ponds are built on existing soils and the parent material for pond soils is the pond bottom provided by the construction process. Usually, the O and A horizons are removed in the construction process, and the initial pond bottom consists of the B horizon. (These horizons are per terrestrial soil classification.) Of course, in some cases, additional soil material enters the pond as suspended particles in the water supply which settle onto the original pond bottom. If sediment input from outside is large, it may influence soil formation to a great extent. The internal ("within pond") processes of pond soil formation can be classified as additions, removals, transfers, and transformations.

Additions of organic materials include uneaten feed, feces, dead algae, manure, etc. Mineral materials also are added to deeper areas of ponds via sedimentation of mineral particles eroded from pond embankments and shallow areas by wave action and water currents generated by mechanical aeration. The organic material becomes mixed with the mineral particles and melanization (darkening of light-colored mineral matter by organic matter) occurs. Organic matter also settles onto the surface of the sediment resulting in a flocculent layer that is similar to the organic litter on the surface of terrestrial soils.

Removal of material from surface layers of pond soils occurs when ponds are drained. The outflowing water currents suspend the surface organic layer and mineral soil, and it is removed from the ponds in effluents. Ponds do not have high rates of infiltration (seepage), so leaching of materials from the soil profile is not as significant a factor as in terrestrial soils.

Transfers of material in pond bottoms result from a number of factors, such as bioturbation, erosion and resedimentation, leucinization, and salinization. Bioturbation is restricted to

Table 16. Water-extractable phosphorus concentrations in $mg\ l^{-1}$ at 2-cm depth intervals in single ponds.

Depth in profile (cm)	**Thailand**		**Honduras**		**Kenya**
	New Pond	*Old Pond*	*Freshwater*	*Brackishwater*	
0–2	0.305	0.099	Lost	0.255	0.041
2–4	0.112	0.055	0.063	0.188	0.034
4–6	0.052	0.062	0.080	0.239	0.022
6–8	0.024	0.050	0.062	0.209	0.012
8–10	0.016	0.065	0.099	0.433	0.010
10–12	0.008	0.109	0.127	0.665	0.006
12–14	0.006	0.105	0.144	0.672	0.006
14–16	0.005	0.114	0.278	0.799	0.005
16–18	0.005	0.085	0.607	0.831	0.008
18–20	0.010	0.054	0.708	0.811	0.005
20–22		0.036	0.561	0.847	
22–24		0.022	0.515	0.617	
24–26		0.014		0.552	
26–28		0.006		0.563	
28–30		0.008			
30-32		0.003			
32-34		0.003			
34-36		0.003			

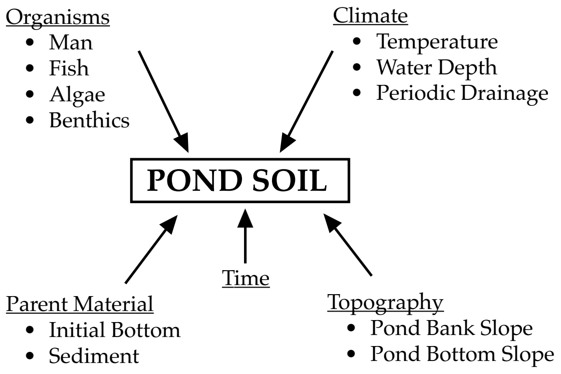

Figure 1. External factors of pond soil development.

activity of fish, benthic animals, and other organisms that suspend sediment, but for a discussion of pond soil formation, it is better to speak of pedoturbation to include physical processes such as erosion and resedimentation and wetting and drying between crops. Thus, pedoturbation includes all factors that result in gross redistribution of soil particles in the pond bottom. Two other processes that can be considered transfers of material are leucinization (the paling of pond soil by disappearance of dark organic material through drainage and respiration) and salinization. Salinization is probably only important in brackishwater ponds.

Transformations include aerobic and anaerobic decomposition, formation of organic matter through photosynthesis, humification (conversion of raw organic matter to humus), ripening (chemical, physical, and biological changes that occur when sediment is exposed to air when ponds are drained between crops), and gleization (darkening of soils when iron and manganese are reduced under anaerobic conditions).

Pond soils appear to develop distinct profiles within a few years in contrast to terrestrial soil, where soil development takes much longer. The major factors influencing pond soil development appear to be sedimentation, organic matter input, and wetting and drying processes between crops.

ANTICIPATED BENEFITS

This research will be useful in explaining various water quality phenomena observed during normal PD/A CRSP investigations which utilize these ponds. The data further confirm that the system of delineating soil horizons suggested by Munsiri, Boyd, and Hajek of Auburn University are applicable to ponds in general. Adoption of this system or some other system of delineating pond soil profiles is essential to developing a pond bottom soil taxonomy. The study suggests that pond soil organic matter decomposes rather slowly, and this will be useful in attempts to explain why pond soils tend to contain more organic matter than terrestrial soils. These findings also will be useful in developing a theory of pond soil development and explaining why pond bottoms quickly form distinct profiles.

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