



PD/A CRSP EIGHTEENTH ANNUAL TECHNICAL REPORT

POND SOIL CHARACTERISTICS AND DYNAMICS OF SOIL ORGANIC MATTER AND NUTRIENTS

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

Claude E. Boyd
Department of Fisheries and Allied Aquacultures
Auburn University, Alabama, USA

C. Wesley Wood
Department of Agronomy and Soils
Auburn University, Alabama, USA

Taworn Thunjai and Martha Rowan
Department of Fisheries and Allied Aquacultures
Auburn University, Alabama, USA

Karen Dube
Central Institute of Fisheries Education
Verosa, Mumbai, India

ABSTRACT

Pond soil cores were obtained from six ponds in Thailand. Cores were segmented into 2-cm-long segments, which were analyzed for texture, bulk density, pH, organic carbon, and major and minor nutrients. The resulting information increases the data base for use in presenting a concept of pond soil development and for preparation of a pond soil classification system. The six ponds in Thailand had profiles with discernible layers (horizons). Bulk density tended to increase with depth in the profile. Concentrations of carbon, nitrogen, and phosphorus decreased with depth, but sulfur concentration increased with depth. Concentrations of mineral nutrients were within the ranges of values found at other sites sampled during this project. There was considerable variation in bottom soil pH estimates made by several methods used in aquaculture. The simplest and most reliable method, direct insertion of a standard pH probe into a 1:1 mixture of dry soil (dried at 40°C and pulverized to pass through a 2.36-mm screen) and distilled water, should be adopted as a standard procedure.

INTRODUCTION

This report contains data on physical and chemical properties of pond soils from freshwater fish ponds at the former PD/A CRSP site at the Thailand Department of Fisheries Ayutthaya Fisheries Station and from shrimp ponds at Banggachi, Thailand. In addition, results of comparisons of different methods of measuring pond soil pH are included. This work was done because we became aware during conduct of this research that many different methods of soil pH measurement were being used in aquaculture. Therefore, our objective was to obtain background data for use in recommending a standard pond soil pH procedure.

During June 2000 we were able to collect additional pond soil cores for physical and chemical analyses from ponds in Brazil and from the PD/A CRSP site in the Philippines. However, it will take several months to complete all of the analyses.

METHODS AND MATERIALS

Three ponds at the Ayutthaya Fisheries Station were sampled on 6 September 1999, and three ponds on a

shrimp farm at Banggachi were sampled on 9 September 1999.

Analyses of Pond Soil Cores from Thailand

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.

Samples were analyzed for moisture content (gravimetry), dry bulk density (gravimetry), color (Munsell color chart), 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 sulfur (Leco Sulfur Analyzer), acid-extractable phosphorus and metal ions (extraction in a 0.075 N acid solution of 0.05 N HCl plus 0.025 N H₂SO₄ followed by plasma spectrophotometry), and distilled-water-extractable phosphorus. Particle size analyses of samples were made by the pipette method. All methods followed details provided by Munsiri et al. (1995) and Boyd and Munsiri (1996).

Soil pH Measurement

Many soil samples used in this study had been retained from earlier research projects on soils from the United States, Honduras, Thailand, Indonesia, Madagascar, and Ecuador. Samples were taken from the upper 5-cm layers of pond bottoms of both brackishwater ponds (saline soils) and freshwater ponds (non-saline soils). All samples had been dried at 60°C in a forced-draft oven and pulverized to pass a screen with 0.85-mm openings. Additional samples for pH measurement were obtained during routine soil sampling at PD/A CRSP sites in Thailand, Honduras, Peru, Kenya, and the United States.

A series of 23 freshwater pond samples and 24 brackishwater pond samples were analyzed for pH (1:1 dry pulverized soil:distilled water) with a combination electrode and with dual electrodes. The pH was measured in two ways with dual electrodes: 1) the dual electrodes were inserted into the mixture and pH measured while stirring, or 2) the reference electrode was held in the supernatant and the glass electrode inserted into the sediment. The pH of these samples was also determined in soil:distilled water ratios of 1:2.5, 1:5, and 1:10; in 1:2 mixtures of soil:0.01 M CaCl₂; and in 1:2.5 mixtures of soil:1.00 M KCl using

Table 1. Concentrations of moisture, dry bulk density, pH, and exchangeable acidity in pond soil profiles from Ayutthaya and Banggachi, Thailand.

Depth (cm)	Moisture (%)	Dry Bulk Density (g cm ⁻³)	pH	Exchangeable Acidity (meq (100 g) ⁻¹)
AYUTTHAYA				
0–2	417.9 ± 187.8	0.34 ± 0.02	6.80 ± 0.09	5.05 ± 0.72
2–4	239.6 ± 67.3	0.44 ± 0.03	6.53 ± 0.07	5.60 ± 0.46
4–6	240.0 ± 84.9	0.45 ± 0.03	6.35 ± 0.10	5.87 ± 0.53
6–8	279.2 ± 140.8	0.50 ± 0.02	6.43 ± 0.14	5.60 ± 0.46
8–10	159.5 ± 32.6	0.52 ± 0.01	6.28 ± 0.13	6.40 ± 0.46
10–12	148.7 ± 27.2	0.52 ± 0.02	6.28 ± 0.12	7.63 ± 0.69
12–14	141.6 ± 19.7	0.53 ± 0.02	6.40 ± 0.15	6.67 ± 0.27
14–16	152.8 ± 30.2	0.47 ± 0.03	6.45 ± 0.16	6.40 ± 0.00
16–18	143.9 ± 17.6	0.52 ± 0.03	6.47 ± 0.16	6.40 ± 0.80
18–20	160.0 ± 40.1	0.54 ± 0.01	6.60 ± 0.23	6.40 ± 0.92
20–22	137.2 ± 29.1	0.57 ± 0.02	6.52 ± 0.22	5.07 ± 0.27
22–24	132.6 ± 20.9	0.56 ± 0.01	6.57 ± 0.26	6.13 ± 0.71
24–26	143.0 ± 29.6	0.56 ± 0.02	6.42 ± 0.31	5.76 ± 0.49
26–28	110.1 ± 5.0	0.54 ± 0.02	6.40 ± 0.25	6.03 ± 0.23
28–30	106.3 ± 5.2	0.58 ± 0.02	6.42 ± 0.37	5.76 ± 0.49
30–32	101.2 ± 6.9	0.63 ± 0.03	6.43 ± 0.32	5.76 ± 0.49
32–34	94.6 ± 7.5	0.66 ± 0.02	6.37 ± 0.35	6.93 ± 0.53
34–36	85.8 ± 3.3	0.76 ± 0.01	6.52 ± 0.31	5.87 ± 0.53
36–38	86.1 ± 2.1	0.74 ± 0.03	6.73 ± 0.10	6.13 ± 0.71
38–40	79.9 ± 5.5	0.64 ± 0.05	6.67 ± 0.08	6.13 ± 0.27
40–42	81.7 ± 12.0	0.73 ± 0.06	6.55 ± 0.05	5.87 ± 0.71
42–44	84.0 ± 2.0	0.71 ± 0.02	6.57 ± 0.12	5.87 ± 0.71
44–46	113.0 ± 43.5	0.71 ± 0.07	6.52 ± 0.07	5.87 ± 0.71
BANGGACHI				
0–2	183.9 ± 26.2	0.44 ± 0.03	6.57 ± 0.20	7.53 ± 0.71
2–4	112.2 ± 13.7	0.59 ± 0.07	6.58 ± 0.19	7.20 ± 1.22
4–6	108.4 ± 15.1	0.63 ± 0.09	6.32 ± 0.24	9.33 ± 2.37
6–8	113.7 ± 10.4	0.60 ± 0.07	6.08 ± 0.28	11.20 ± 2.77
8–10	114.4 ± 16.0	0.60 ± 0.08	5.95 ± 0.22	9.17 ± 2.74
10–12	121.7 ± 5.5	0.54 ± 0.03	5.77 ± 0.35	8.91 ± 2.02
12–14	120.2 ± 0.8	0.54 ± 0.02	5.87 ± 0.39	8.53 ± 2.18
14–16	111.8 ± 3.6	0.60 ± 0.02	6.00 ± 0.43	8.00 ± 3.03

the combination electrode only. In addition, seven replicates of three samples from each series (low, medium, and high pH) were analyzed using the different soil:liquid mixtures and the combination electrode in order to estimate precision of measurements. Stirring was applied intermittently with a glass rod for periods of 10 to 15 s at 4- to 5-min intervals for 30 min before measuring pH. Stirring also was applied during pH measurement except where the soil was allowed to settle so that the reference electrode could be held in the supernatant and the glass electrode held in the sediment.

Fresh, wet samples from ponds at Auburn University and PD/A CRSP sites in Thailand, Honduras, Peru, and Kenya were subjected to direct pH measurement by inserting a combination electrode into the wet soil (upper 5-cm layer) and stirring gently with a glass rod. Samples were then dried at 60°C in a forced-draft oven and pulverized for pH determination in a 1:1 soil:distilled water mixture with a combination electrode.

To determine the influence of time on the pH measurement, triplicates of non-saline and saline soil samples were mixed at a 1:1 ratio with distilled water, and pH was measured with the combination electrode at 2-min intervals.

The influence of drying temperature and particle size on pH was evaluated. Samples of bottom soils from ponds on the Auburn University Fisheries Resource Unit heated to 40°C, 60°C, and 102°C in a forced-draft oven were pulverized to pass screens with the following United States Standard Sieve Series numbers and opening sizes: Number 8, 2.36 mm; Number 20, 0.85 mm; Number 40, 0.425 mm; Number 60, 0.25 mm; Number 100, 0.149 mm; and Number 270, 0.053 mm. The pH measurements were made by a combination electrode in 1:1 soil:distilled water mixtures.

The influence of stirring during the pH measurement was compared to not stirring on a series of soil samples. Also, for selected samples the soil:water mixtures were filtered through fine filter paper (Whatman Number 42), and the pH measured in the mixture was compared to the pH of filtrate.

A new Kelway® Soil Acidity and Moisture Tester, Model HB-2 was obtained. Dry pulverized soils (500 g) from nine brackishwater ponds and eleven freshwater ponds were placed in plastic containers and thoroughly mixed with enough water to provide a 25% moisture content. The soil acidity tester was inserted into the soil, and the soil was pressed around the tester to assure close contact. The pH was measured according to the manufacturer's instructions. Another portion of each soil sample was used for pH determination by a combination electrode in 1:1 soil:distilled water mixtures. In another trial, dry pulverized soil from a freshwater pond at Auburn University was treated by filling the pore space in different aliquots with water of 0, 0.17, 0.34, 0.68, 1.36, 2.72, 5.44, 10.2, 15.0, and 30‰ salinity. Soils were dried and pH was measured by the soil acidity tester and the standard pH meter with the combination electrode as described above.

Statistical analyses included t-tests, Duncan's multiple range test, regression analysis, and tests to determine if slopes and intercepts of regression lines differed from 1.0 and 0.0, respectively. The statistical package SigmaStat was used (SPSS, 1997).

Table 2. Profile for color in soil cores from bottoms of aquaculture ponds from Ayutthaya and Banggachi, Thailand. Color values are given as standard Munsell Color Chart Units. Each entry is the value of a particular pond.

Depth (cm)	Ayutthaya			Banggachi		
	Pond 9	Pond 10	Pond 11	Pond 1	Pond 2	Pond 3
0–2	5Y 4/1	5Y 4/1	5Y 4/1	2.5Y 2.5/1	2.5Y 2.5/1	2.5Y 2.5/1
2–4	5Y 4/1	5Y 2.5/1	5Y 4/1	2.5Y 4/2	2.5Y 4/1	2.5Y 4/1
4–6	5Y 4/1	5Y 2.5/1	5Y 4/1	2.5Y 4/2	2.5Y 5/1	2.5Y 4/1
6–8	5Y 4/1	5Y 4/1	5Y 4/1	2.5Y 2.5/1	2.5Y 5/1	2.5Y 5/1
8–10	5Y 4/1	5Y 4/1	5Y 4/1	2.5Y 3/1	2.5Y 5/1	2.5Y 4/2
10–12	5Y 4/1	5Y 4/1	5Y 4/1	2.5Y 5/1	2.5Y 5/1	2.5Y 4/2
12–14	5Y 4/1	5Y 4/1	5Y 4/1	2.5Y 5/1	2.5Y 5/1	2.5Y 2.5/1
14–16	5Y 4/1	5Y 2.5/1	5Y 4/1	2.5Y 5/1	2.5Y 5/1	2.5Y 4/1
16–18	5Y 4/1	5Y 2.5/1	5Y 4/1			
18–20	5Y 4/1	5Y 2.5/1	5Y 5/1			
20–22	5Y 3/1	5Y 2.5/1	5Y 5/1			
22–24	5Y 3/1	5Y 2.5/1	5Y 5/1			
24–26	5Y 2.5/1	5Y 2.5/1	5Y 5/1			
26–28	5Y 2.5/1	5Y 2.5/1	5Y 5/1			
28–30	5Y 2.5/1	5Y 2.5/1	5Y 5/1			
30–32	5Y 2.5/1	5Y 2.5/1	5Y 5/1			
32–34	5Y 2.5/1	5Y 2.5/1	5Y 5/1			
34–36	5Y 2.5/1	5Y 2.5/1	5Y 5/1			
36–38	5Y 2.5/1	5Y 2.5/1	5Y 4/1			
38–40	5Y 2.5/1	5Y 2.5/1	5Y 4/1			
40–42	5Y 2.5/1	5Y 3/1	5Y 4/1			
42–44	5Y 2.5/1	5Y 3/1	5Y 4/1			
44–46	5Y 4/1	5Y 4/1	5Y 4/1			

Note: 5Y 2.5/1—black; 5Y 3/1—very dark gray; 5Y 4/1—dark gray; 5Y 5/1—gray; 2.5Y 2.5/1—black; 2.5Y 3/1—very dark gray; 2.5Y 4/1—dark gray; 2.5Y 4/2—dark grayish brown; 2.5Y 5/1—gray

RESULTS AND DISCUSSION

Characteristics of Cores

The moisture content of soil was highest in the 0–2 cm layer at Ayutthaya and Banggachi (Table 1). At Ayutthaya, soil moisture content decreased rapidly with depth, but at Banggachi there was little difference in soil moisture between the 2–4 cm layer and deeper layers. Ponds at both sites were in low-lying areas, and the groundwater level was apparently contiguous with the water-saturated bottom soil. Thus, although dry bulk density of soil increased with depth (Table 1), we were unable to core to depths with bulk density of 1.0 g m^{-3} and above as has been the case in ponds at other sites sampled during this research effort (Munsiri et al., 1995; Boyd et al., 1998, 1999, 2000). Soil color did not change appreciably with depth in the cores (Table 2), so the soils apparently were not as highly reduced as most of the other pond soils sampled in this project (Munsiri et al., 1995; Boyd et al., 1998, 1999, 2000).

Because of the variation that occurs by using different measurement techniques for soil pH, we decided against measuring wet soil pH. The dry soil pH appears to be a more reliable method for soil pH (see section on Pond Soil pH Measurement, p. 6), so we only made this measurement. The dry soil pH (Table 1) was highest in the surface 0–2 and 2–4 cm layers and tended to decrease with depth in the cores. However, there was some variation within this pattern. For example, in the cores from ponds at Ayutthaya, the pH was 6.80 in the 0–2 cm layer, 6.28 in the 8–10 cm layer, 6.57 in the 22–24 cm layer, and 6.37 in the 32–34 cm layer. The soils at both sites did not have particularly low pH; most values exceeded 6.

Therefore, it was not surprising that exchangeable acidity was rather low and usually below $7 \text{ meq (100 g)}^{-1}$ and $10 \text{ meq (100 g)}^{-1}$ in samples from Ayutthaya and Banggachi, respectively (Table 1).

Total carbon concentrations were between 0.72 and 1.40% at Ayutthaya and 2.34 and 4.49% at Banggachi (Table 3). The ponds at Banggachi were operated for intensive shrimp production, and they had much higher inputs of nutrients and organic matter than ponds at Ayutthaya. This probably is the reason for the difference in carbon concentration. There was a distinct decrease in carbon concentration with depth in the soil profiles at both sites. Nitrogen concentrations at Ayutthaya were between 0.12 and 0.23% (Table 3), and carbon:nitrogen ratios were approximately 6. At Banggachi, nitrogen concentrations were 0.23 to 0.28% (Table 3), and carbon:nitrogen ratios were approximately 10 to 16. Nitrogen concentrations declined with depth in the soil profile at Ayutthaya but not at Banggachi.

Total sulfur concentration ranged from 0.07% in the 0–2 cm layer to a maximum of 0.32% in the 20–22 cm layer in ponds at Ayutthaya (Table 3). Sulfur concentrations tended to be higher below a depth of 20 cm than in upper layers. Soils in ponds at Ayutthaya had fairly high concentrations of sulfur for a freshwater site, but they were much lower in sulfur concentration than the brackishwater ponds at Banggachi (Table 3). Sulfur concentrations in pond cores at Banggachi exceeded 0.5% at all depths, and the soils below 10 cm depth can be considered potential acid-sulfate soils because they contain more than 0.75% sulfur (Soil Survey Staff, 1994).

Acid-extractable phosphorus concentrations in the samples from Ayutthaya ranged from 18.7 to 28.7 ppm with no clear

indication of increases or decreases with depth (Table 3). At Banggachi, acid-extractable phosphorus concentrations were between 38.3 and 47.0 ppm (Table 3), and no trend in concentration with depth was apparent. Concentrations of water-extractable phosphorus often varied considerably between adjacent layers in soil cores from Ayutthaya (Table 3), but there was a general tendency for concentrations to decline with depth. The 0–2 cm layer contained 0.92 ppm water-extractable phosphorus. This is a high concentration, which probably resulted from recent applications of phosphate fertilizer to ponds. Boyd and Munsiri (1996) demonstrated that fertilizer phosphorus recently adsorbed by pond soil is more readily released than other forms of soil phosphorus. Water-extractable phosphorus concentrations were low at all depths in samples from Banggachi.

Concentrations of calcium and magnesium are provided in Table 4. The high concentrations of calcium and magnesium in soil samples from freshwater ponds at Ayutthaya are surprising. Soil pH is less than 7 at this site, suggesting that free carbonates are not present in the soil, so the source of the calcium and magnesium is not due to naturally occurring calcium and magnesium carbonates. Also, the increase in calcium with depth suggests that applications of calcium to the

water via liming materials or gypsum is not a likely source of the calcium. Magnesium concentrations tended to decline with increasing depth in the soil profile at Ayutthaya. The soil cores from the ponds at Banggachi were higher in calcium and magnesium than those from Ayutthaya (Table 4). Of course, brackishwater ponds typically are higher in calcium and magnesium because these two ions have high concentrations in brackish water.

Potassium and sodium concentrations also were relatively high in soil cores from ponds at Ayutthaya (Table 4) as compared to many freshwater pond soils. For example, most soils from freshwater ponds contain less than 100 ppm each of sodium and potassium (Boyd et al., 1994). Sodium and potassium concentrations tended to be higher in upper layers of soil than in deeper layers at Ayutthaya. Brackish water has high concentrations of sodium and potassium, so it is not surprising that these two elements were more concentrated in soils at Banggachi than in soils at Ayutthaya (Table 4).

Concentrations of iron, manganese, zinc, and copper in pond soils at Ayutthaya and Banggachi (Table 5) were within ranges of minor element concentrations normally found in freshwater and brackishwater pond soils (Boyd et al., 1994, 1998, 1999,

Table 3. Concentrations of total carbon, total nitrogen, total sulfur, acid-extracted phosphorus, and water-soluble phosphorus in pond soil profiles from Ayutthaya and Banggachi, Thailand.

Depth (cm)	Total Carbon (%)	Total Nitrogen (%)	Total Sulfur (%)	Acid-Extracted Phosphorus (ppm)	Water-Soluble Phosphorus (ppm)
AYUTTHAYA					
0–2	1.40 ± 0.19	0.23 ± 0.04	0.07 ± 0.01	28.7 ± 0.7	0.92 ± 0.46
2–4	1.37 ± 0.16	0.20 ± 0.01	0.15 ± 0.04	24.7 ± 3.5	0.05 ± 0.02
4–6	1.27 ± 0.12	0.19 ± 0.02	0.11 ± 0.04	25.0 ± 4.6	0.18 ± 0.15
6–8	1.17 ± 0.05	0.19 ± 0.01	0.12 ± 0.01	29.3 ± 3.0	0.42 ± 0.37
8–10	1.08 ± 0.11	0.18 ± 0.03	0.10 ± 0.01	25.6 ± 5.5	0.85 ± 0.45
10–12	1.06 ± 0.09	0.17 ± 0.02	0.12 ± 0.02	27.3 ± 0.3	0.16 ± 0.12
12–14	1.04 ± 0.08	0.18 ± 0.02	0.09 ± 0.00	27.0 ± 0.6	0.06 ± 0.03
14–16	1.04 ± 0.04	0.17 ± 0.01	0.08 ± 0.02	24.3 ± 3.2	0.15 ± 0.14
16–18	1.04 ± 0.10	0.18 ± 0.04	0.09 ± 0.02	21.0 ± 0.0	0.51 ± 0.48
18–20	1.06 ± 0.11	0.19 ± 0.02	0.09 ± 0.03	19.7 ± 0.3	0.32 ± 0.29
20–22	1.12 ± 0.14	0.19 ± 0.02	0.32 ± 0.20	26.3 ± 1.5	0.08 ± 0.04
22–24	0.95 ± 0.05	0.16 ± 0.00	0.16 ± 0.09	19.7 ± 3.7	0.46 ± 0.42
24–26	0.95 ± 0.12	0.17 ± 0.03	0.16 ± 0.08	20.3 ± 1.9	0.04 ± 0.01
26–28	0.92 ± 0.11	0.16 ± 0.02	0.22 ± 0.06	20.7 ± 0.3	0.05 ± 0.01
28–30	0.95 ± 0.13	0.16 ± 0.02	0.19 ± 0.05	24.7 ± 3.9	0.05 ± 0.01
30–32	0.93 ± 0.09	0.16 ± 0.02	0.19 ± 0.06	25.0 ± 2.1	0.04 ± 0.01
32–34	0.92 ± 0.06	0.17 ± 0.02	0.18 ± 0.04	22.3 ± 3.5	0.04 ± 0.01
34–36	0.93 ± 0.02	0.16 ± 0.01	0.15 ± 0.04	27.7 ± 6.4	0.05 ± 0.01
36–38	0.85 ± 0.05	0.15 ± 0.02	0.16 ± 0.03	26.0 ± 4.7	0.04 ± 0.01
38–40	0.86 ± 0.04	0.15 ± 0.03	0.16 ± 0.03	21.7 ± 5.7	0.12 ± 0.08
40–42	0.95 ± 0.03	0.19 ± 0.00	0.23 ± 0.01	23.0 ± 3.8	0.02 ± 0.00
42–44	0.76 ± 0.16	0.14 ± 0.03	0.15 ± 0.04	26.3 ± 4.7	0.03 ± 0.01
44–46	0.72 ± 0.11	0.12 ± 0.01	0.23 ± 0.01	18.7 ± 4.5	0.03 ± 0.00
BANGGACHI					
0–2	4.49 ± 0.77	0.28 ± 0.03	0.71 ± 0.19	47.0 ± 9.6	0.04 ± 0.01
2–4	4.08 ± 0.84	0.24 ± 0.01	0.64 ± 0.16	43.7 ± 4.3	0.07 ± 0.03
4–6	3.89 ± 0.83	0.26 ± 0.01	0.68 ± 0.21	46.0 ± 4.0	0.07 ± 0.04
6–8	3.62 ± 0.78	0.27 ± 0.02	0.78 ± 0.30	45.3 ± 7.4	0.08 ± 0.05
8–10	3.13 ± 0.47	0.25 ± 0.01	0.53 ± 0.30	46.3 ± 8.0	0.06 ± 0.03
10–12	2.77 ± 0.37	0.23 ± 0.00	0.78 ± 0.27	45.0 ± 10.5	0.07 ± 0.04
12–14	2.74 ± 0.71	0.23 ± 0.02	0.97 ± 0.38	42.0 ± 2.5	0.06 ± 0.03
14–16	2.34 ± 0.58	0.24 ± 0.01	0.92 ± 0.49	38.3 ± 11.4	0.05 ± 0.04

Table 4. Concentrations of calcium, magnesium, sodium, and potassium in pond soil profiles from Ayutthaya and Banggachi, Thailand.

Depth (cm)	Calcium (ppm)	Magnesium (ppm)	Sodium (ppm)	Potassium (ppm)
AYUTTHAYA				
0–2	5,404 ± 736	2,539 ± 190	906 ± 167	354 ± 21
2–4	5,334 ± 614	2,474 ± 259	659 ± 91	357 ± 27
4–6	5,570 ± 914	2,434 ± 217	727 ± 105	348 ± 15
6–8	5,543 ± 640	2,309 ± 205	597 ± 65	336 ± 10
8–10	5,164 ± 1137	1,933 ± 128	565 ± 109	299 ± 33
10–12	5,827 ± 457	2,126 ± 110	547 ± 50	314 ± 3
12–14	5,897 ± 480	2,119 ± 83	667 ± 82	314 ± 13
14–16	6,037 ± 363	2,119 ± 96	562 ± 47	309 ± 16
16–18	6,714 ± 713	2,117 ± 114	531 ± 51	294 ± 13
18–20	6,817 ± 571	2,084 ± 132	689 ± 83	292 ± 11
20–22	7,967 ± 1,106	2,414 ± 390	4,834 ± 4,304	411 ± 115
22–24	7,539 ± 1,000	2,041 ± 144	545 ± 63	279 ± 14
24–26	7,203 ± 1,023	2,064 ± 142	626 ± 10	281 ± 17
26–28	7,396 ± 1,346	2,071 ± 132	528 ± 73	272 ± 25
28–30	7,752 ± 1,473	2,014 ± 120	570 ± 52	262 ± 33
30–32	8,053 ± 1,046	2,009 ± 148	547 ± 138	259 ± 22
32–34	8,114 ± 940	1,990 ± 125	484 ± 75	248 ± 24
34–36	7,988 ± 845	1,994 ± 153	486 ± 88	248 ± 21
36–38	7,804 ± 994	1,934 ± 122	479 ± 80	250 ± 22
38–40	9,029 ± 304	1,916 ± 113	590 ± 132	233 ± 22
40–42	8,490 ± 369	1,980 ± 107	529 ± 100	247 ± 24
42–44	8,105 ± 363	1,863 ± 195	512 ± 132	222 ± 47
44–46	9,528 ± 151	1,885 ± 140	558 ± 157	209 ± 26
BANGGACHI				
0–2	5,521 ± 356	4,519 ± 186	16,004 ± 1,866	1,120 ± 97
2–4	3,808 ± 164	3,958 ± 81	14,637 ± 1,864	1,172 ± 76
4–6	3,484 ± 346	3,868 ± 267	15,779 ± 2,772	1,279 ± 67
6–8	3,804 ± 748	3,984 ± 528	16,750 ± 3,790	1,260 ± 118
8–10	3,712 ± 1,014	3,874 ± 536	17,965 ± 4,214	1,318 ± 113
10–12	4,917 ± 1,990	4,067 ± 640	19,773 ± 5,150	1,349 ± 124
12–14	5,575 ± 2,247	4,132 ± 251	21,566 ± 5,249	1,300 ± 73
14–16	5,751 ± 1,821	3,695 ± 445	15,645 ± 2,543	1,145 ± 279

2000). There are no interesting points to discuss about the minor elements.

Soils at both sites were categorized as clays or silty clays (Table 6). At Ayutthaya, clay concentrations were generally between 50 and 60% at all depths, and there was no distinct layering of clay concentrations (Table 7). Most of the remaining particles were silt-sized. At Banggachi, clay content was 40 to 45% in the upper 12-cm layer of the profile and about 30% in the deeper layer (Table 7). Silt content tended to increase as clay content decreased. Sand comprised 8 to 12% of particles in soils at Banggachi.

This project on pond soils has yielded a large amount of information on the characteristics of pond soil cores. Samples have been collected as follows: Thailand, four sites (15 ponds); Philippines, one site (3 ponds); Honduras, two sites (6 ponds); Kenya, one site (3 ponds); Brazil, two sites (6 ponds); Peru, two sites (6 ponds); and the United States, five sites (18 ponds). We have completed all analyses except those on samples from Brazil and the Philippines. These analyses should be completed by October or November 2000.

Pond Soil Profile Development

We have obtained cores from ponds that range from 2 to 52 years in age. Even the youngest ponds developed profiles

with distinct layers (horizons). The thicknesses of the S and M horizons (Munsiri et al., 1995) tend to increase with pond age. Concentrations of organic matter are usually low in new ponds and quickly increase to 2 to 4% in the S horizon and 1 to 3% in the M horizon. Afterwards, there seems to be little change in organic matter concentration with increasing pond age, but the thicknesses of the S and M horizons tend to increase over time. Aquaculture activities also influence bottom soil profiles, as upper layers of soil tend to have greater concentrations of phosphorus as a result of fertilization and higher pH and calcium and magnesium concentrations as a result of liming. The dominant processes in pond soil development appear to be external inputs of mineral sediment (soil particles), internal input of organic sediment (dead plankton), internal resuspension and resedimentation, and changes in soil properties resulting from nutrient and lime inputs. Soil profile development appears to be much faster than in terrestrial soils, because the soil was already developed before ponds were constructed. Thus, the parent material for pond bottom soil development is the soil in the pond bottom and soil particles entering as suspended solids from the water supply. The particle size distribution, the nature of the clay minerals, and the acidity of this material influences the characteristics of pond soil profiles and horizons, but the major factor leading to formation of profiles and horizons in pond soils is sedimentation.

Examination of the data suggests that the factors around which to develop a pond soil classification system are:

- Thicknesses of S and M horizons;
- Bulk density of S horizon;
- pH and acidity of S horizon;
- Organic carbon and C/N ratio;
- Total sulfur concentration;
- Cation exchange capacity; and
- Texture (particle size distribution).

As soon as all of the chemical analyses have been completed, we will begin preparation of the pond soil classification system.

Pond Soil pH Measurement

Values for pH obtained from samples by both dual electrodes and combination electrodes with electrodes inserted into the soil-water mixture were highly correlated for both non-saline and saline soil (Figure 1). The slopes and intercepts of the regression lines did not differ from 1.0 and 0.0 ($P > 0.05$). Means of pH measured for replicate samples by the two methods did not differ for the six samples (Table 8). There were no differences in the precision of the two methods based on F-tests of variances ($P > 0.05$). Thus, a combination electrode and dual electrodes should provide comparable pH readings

Table 5. Concentrations of iron, manganese, zinc, and copper in pond soil profiles from Ayutthaya and Banggachi, Thailand.

Depth (cm)	Iron (ppm)	Manganese (ppm)	Zinc (ppm)	Copper (ppm)
AYUTTHAYA				
0-2	388 ± 83	688 ± 29	13.67 ± 0.88	7.00 ± 0.58
2-4	464 ± 73	657 ± 21	14.67 ± 2.19	7.67 ± 0.33
4-6	511 ± 97	666 ± 29	14.00 ± 1.53	7.33 ± 0.33
6-8	523 ± 99	687 ± 49	14.33 ± 0.67	7.67 ± 0.33
8-10	507 ± 146	588 ± 103	13.33 ± 1.20	7.33 ± 0.33
10-12	565 ± 67	635 ± 64	16.33 ± 0.67	8.33 ± 0.33
12-14	652 ± 91	614 ± 66	17.67 ± 1.20	8.33 ± 0.33
14-16	688 ± 92	631 ± 67	19.00 ± 0.58	8.67 ± 0.67
16-18	667 ± 90	636 ± 71	19.33 ± 0.88	8.33 ± 0.88
18-20	660 ± 119	614 ± 75	18.67 ± 0.88	8.33 ± 0.88
20-22	540 ± 105	574 ± 81	16.33 ± 3.18	5.33 ± 2.67
22-24	557 ± 194	585 ± 69	16.33 ± 1.45	6.00 ± 2.08
24-26	709 ± 128	573 ± 84	17.00 ± 1.53	6.67 ± 1.86
26-28	703 ± 244	589 ± 79	16.33 ± 1.76	6.00 ± 3.06
28-30	661 ± 274	546 ± 55	15.67 ± 3.84	6.00 ± 3.06
30-32	669 ± 129	544 ± 25	16.00 ± 1.73	6.33 ± 1.67
32-34	469 ± 212	544 ± 29	15.33 ± 2.33	5.00 ± 2.00
34-36	516 ± 121	532 ± 19	14.67 ± 2.19	5.67 ± 2.19
36-38	647 ± 161	547 ± 34	15.67 ± 1.67	6.33 ± 2.03
38-40	504 ± 92	529 ± 45	13.67 ± 1.76	3.00 ± 1.73
40-42	600 ± 94	538 ± 28	16.67 ± 2.67	6.33 ± 1.67
42-44	869 ± 127	801 ± 168	15.33 ± 5.78	5.67 ± 2.96
44-46	511 ± 87	566 ± 48	13.00 ± 3.21	3.00 ± 1.53
BANGGACHI				
0-2	345 ± 66	167 ± 63	12.33 ± 2.19	0.00 ± 0.00
2-4	590 ± 113	103 ± 35	11.33 ± 1.86	0.33 ± 0.33
4-6	760 ± 194	91 ± 27	17.00 ± 5.51	0.67 ± 0.67
6-8	796 ± 146	98 ± 35	18.67 ± 7.45	1.33 ± 0.67
8-10	794 ± 149	106 ± 47	12.67 ± 5.78	1.33 ± 0.67
10-12	713 ± 71	132 ± 58	12.33 ± 5.04	1.00 ± 0.58
12-14	534 ± 208	142 ± 49	14.00 ± 10.54	0.67 ± 0.67
14-16	747 ± 154	236 ± 95	18.67 ± 9.68	1.67 ± 0.33

when inserted into a mixture of soil and distilled water. The small differences of 0.05 to 0.1 pH units sometimes observed in this study between the dual electrodes and the combination electrode were attributed to experimental error.

There was a strong correlation between soil pH determined with the dual electrodes and the combination electrode when the dual electrodes were arranged with the indicating electrode in the sediment and the reference electrode in the supernatant (Figure 2). However, at $P = 0.05$ the slope of the regression line did not equal 1.0 and the intercept did not equal 0.0 for non-saline soil, and while the intercept was 0.0 for saline soil, the slope did not equal 1.0. The difference in pH measured by the combination electrode and that measured by dual electrodes with the indicating electrode in the sediment and the reference electrode in the supernatant ranged from -0.25 to 0.35 (average = 0.23) for non-saline soil and from -0.80 to 0.39 (average = 0.17) for saline soil. By use of regression equations, it was found that the difference in pH by the two methods decreased from -0.38 pH units at pH 4 to -0.28 pH units at pH 8 for non-saline soils and from 0.22 pH units at pH 4 to -0.06 pH units at pH 8 for saline soils.

Although the method of inserting the indicating electrode in the sediment and the reference electrode in the supernatant theoretically minimizes liquid junction and suspension effects on soil pH measurements, the differences in pH values obtained by the two methods do not appear large enough to justify the greater difficulty in positioning the two electrodes at different positions in the soil:distilled water medium. The high correlation between the two procedures also justifies the use of the easier method of inserting either a combination electrode or the dual electrodes directly into the sediment and measuring pH while stirring.

Table 6. Profile for soil texture in soil cores from bottoms of aquaculture ponds from Ayutthaya and Banggachi, Thailand. Each entry is the average of three ponds.

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

Table 7. Profile for particle sizes in soil cores from bottoms of aquaculture ponds from Ayutthaya and Banggachi, Thailand. Averages and standard errors are given as percentages. Each entry is the average of three ponds.

Depth (cm)	Ayutthaya			Banggachi		
	Sand (%)	Silt (%)	Clay (%)	Sand (%)	Silt (%)	Clay (%)
0-2	1.47 ± 0.53	43.49 ± 1.53	55.04 ± 2.05	9.88 ± 3.62	47.96 ± 1.79	42.16 ± 4.09
2-4	0.81 ± 0.34	39.35 ± 2.35	59.84 ± 2.36	10.85 ± 4.75	44.60 ± 1.33	44.55 ± 4.16
4-6	0.71 ± 0.06	39.87 ± 2.12	59.43 ± 2.13	8.09 ± 3.41	47.34 ± 1.30	44.57 ± 2.54
6-8	1.34 ± 0.33	43.09 ± 1.42	55.57 ± 1.41	9.27 ± 4.23	48.62 ± 0.79	42.11 ± 4.19
8-10	1.18 ± 0.54	39.38 ± 0.63	59.44 ± 0.73	10.10 ± 1.79	45.09 ± 1.42	44.81 ± 3.03
10-12	1.08 ± 0.30	39.83 ± 1.28	59.09 ± 1.16	10.42 ± 3.96	48.95 ± 2.23	40.64 ± 6.16
12-14	1.04 ± 0.31	42.15 ± 3.17	56.81 ± 2.95	11.62 ± 5.10	56.05 ± 6.91	32.33 ± 9.50
14-16	0.78 ± 0.07	40.88 ± 1.81	58.33 ± 1.73	11.98 ± 5.07	56.72 ± 4.48	31.30 ± 8.57
16-18	0.70 ± 0.05	40.86 ± 3.80	58.44 ± 3.83			
18-20	0.92 ± 0.17	42.70 ± 4.58	56.37 ± 4.70			
20-22	0.86 ± 0.47	43.01 ± 5.72	56.13 ± 6.19			
22-24	0.73 ± 0.17	44.11 ± 2.79	55.16 ± 2.95			
24-26	0.97 ± 0.39	41.82 ± 3.84	57.21 ± 3.91			
26-28	0.80 ± 0.20	41.91 ± 3.81	57.29 ± 4.01			
28-30	0.48 ± 0.06	44.29 ± 2.92	55.23 ± 2.91			
30-32	0.76 ± 0.10	43.86 ± 2.60	55.37 ± 2.68			
32-34	0.80 ± 0.23	41.73 ± 1.15	57.47 ± 1.35			
34-36	0.85 ± 0.14	35.35 ± 6.54	63.80 ± 6.44			
36-38	1.19 ± 0.11	48.19 ± 5.29	50.61 ± 5.23			
38-40	1.21 ± 0.31	37.60 ± 5.91	61.19 ± 6.14			
40-42	1.34 ± 0.45	42.24 ± 1.32	56.43 ± 1.37			
42-44	0.95 ± 0.10	44.10 ± 1.52	54.95 ± 1.61			
44-46	1.97 ± 0.41	44.35 ± 1.64	53.68 ± 1.38			

Table 8. Means ± SD for the pH of seven replicates of three saline and three non-saline soil samples. The pH values were measured with a combination electrode and dual electrodes with electrodes inserted into 1:1 mixtures of soil and distilled water.

Electrode Type	Low ¹	Medium ¹	High ¹
NON-SALINE			
Dual	5.31 ± 0.04 ^a	7.24 ± 0.04 ^a	7.84 ± 0.02 ^a
Combination	5.31 ± 0.02 ^a	7.19 ± 0.02 ^a	7.81 ± 0.02 ^a
SALINE			
Dual	4.08 ± 0.03 ^a	7.35 ± 0.04 ^a	8.67 ± 0.03
Combination	4.10 ± 0.03 ^a	7.34 ± 0.04 ^a	8.47 ± 0.05 ^a

¹ Means indicated by the same letter do not differ at $P = 0.05$; vertical comparisons within either non-saline or saline blocks only.

Table 9. Means ± SD for the pH of seven replicates of three non-saline bottom soil samples. The pH values were measured by the combination electrode in different dilutions of distilled water and in 0.01 M CaCl₂ and 1.00 M KCl.

Method	Low ¹	Medium ¹	High ¹
1:1 (water)	5.17 ± 0.02 ^a	7.16 ± 0.06 ^a	8.01 ± 0.02 ^a
1:2.5 (water)	5.44 ± 0.07 ^b	7.41 ± 0.02 ^b	8.16 ± 0.02 ^b
1:5 (water)	5.51 ± 0.06 ^b	7.59 ± 0.08 ^{bc}	8.26 ± 0.03 ^b
1:10 (water)	5.58 ± 0.02 ^b	7.62 ± 0.06 ^c	8.40 ± 0.03 ^c
1:1 (0.01 M CaCl ₂)	3.98 ± 0.02 ^c	6.44 ± 0.02 ^d	7.40 ± 0.02 ^d
1:1 (1.00 M KCl)	3.57 ± 0.02 ^c	7.16 ± 0.02 ^a	7.58 ± 0.04 ^e

¹ Means indicated by the same letter do not differ at $P = 0.05$, vertical comparisons only.

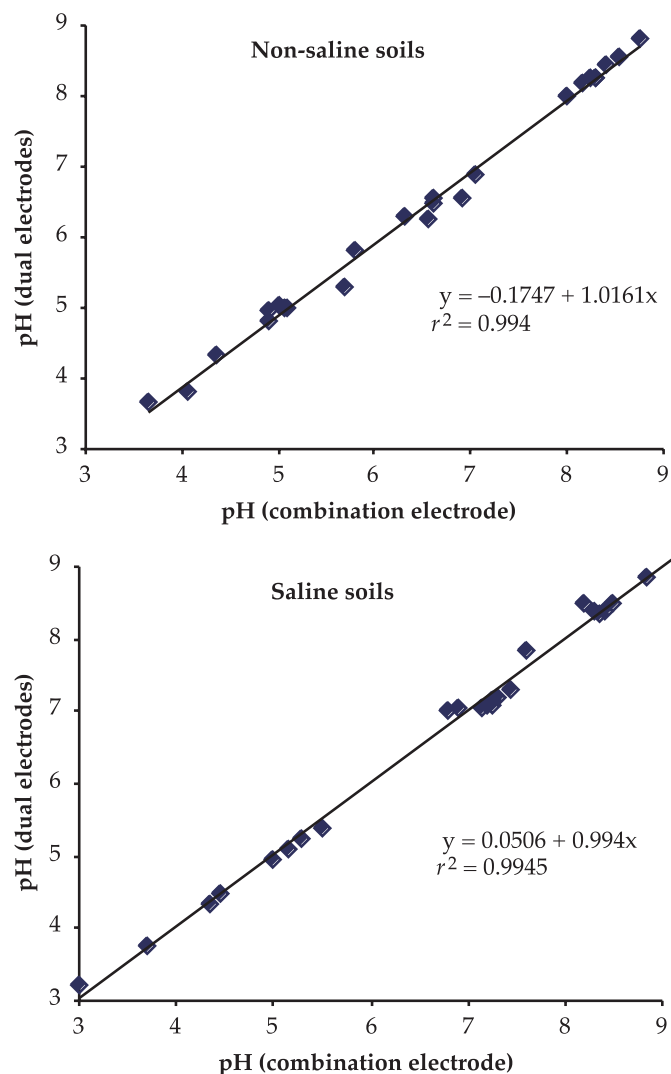


Figure 1. Relationship between pH values obtained with a combination electrode and with dual electrodes in saline and non-saline soil samples. The electrodes were inserted into 1:1 mixtures of distilled water and soil.

Values for pH measured at 1:1 soil:distilled water ratios were lower than those obtained at smaller soil:distilled water ratios (Figure 3; Tables 9 and 10) over the entire pH range considered. Average decreases in pH between the 1:1 soil:water ratios and the 1:2.5, 1:5, and 1:10 ratios were 0.16, 0.32, and 0.47 pH units, respectively, for non-saline soils. For saline soils, these decreases were 0.22, 0.41, and 0.58, respectively. Based on regression equations, differences in pH did not change appreciably with pH over the pH range of the samples. However, at $P = 0.05$ the slopes usually did not equal 1.0 and the intercepts did not equal 0.0 for the regression lines of pH in 1:1 soil:water ratios versus the other ratios. Variation in repeated measurements was usually less ($P < 0.05$) at the 1:1 soil:distilled water ratio than at other soil:distilled water ratios (Tables 9 and 10).

It seems prudent to use 1:1 soil:distilled water ratios in pond soil pH measurement because most of the recommendations regarding pond soil pH have been developed for 1:1 soil:water ratios; the higher soil:water ratios tended to give higher pH, and no improvement in precision resulted from greater dilutions. For some heavy clay soils, the 1:1 soil:distilled water ratio gives a stiff paste in which stirring during pH measurement is difficult. In such cases, enough distilled water may be added to provide a more fluid mixture. This usually can be accomplished at a 1:1.5 soil:distilled water ratio, but in some clays a 1:2 ratio may be necessary. In order to minimize the increase in pH reading, as little extra water as possible should be added. In practice, a 1:1 mixture can be made initially and then water added from a squeeze bottle as necessary.

Soil pH measured in 0.01 M CaCl₂ and 1.00 M KCl for non-saline soil samples was considerably lower than pH measured in a 1:1 dilution with distilled water (Tables 9 and 10; Figure 4). The pH values determined in distilled water and in electrolyte solution were highly correlated (Figure 4), but intercepts did not equal 0.0 and slopes did not equal 1.0 at $P = 0.05$. Soil pH values measured in 0.01 M CaCl₂ averaged 0.79 pH units lower than those for distilled water, while in 1.00 M KCl, values averaged 0.39 pH units lower than in distilled water.

Differences between pH measured in distilled water and in an electrolyte solution were less for saline soil than for non-saline soil (Tables 9 and 10; Figure 4) because the saline soil samples contained soluble salts that dissolved in the distilled water to provide electrolytes. The pH averaged 0.04 pH units higher in 0.01 M CaCl₂ than in distilled water, while pH averaged 0.32 pH units lower in 1.00 M KCl than in distilled water. There was a strong correlation between pH measured in electrolyte

Table 10. Means \pm SD for the pH of seven replicates of three saline bottom soil samples. The pH values were measured by the combination electrode in different dilutions of distilled water and in 0.01 M CaCl₂ and 1.00 M KCl.

Method	Low ¹	Medium ¹	High ¹
1:1 (water)	3.99 \pm 0.03 ^a	7.01 \pm 0.01 ^a	7.93 \pm 0.02 ^a
1:2.5 (water)	4.23 \pm 0.04 ^b	7.31 \pm 0.02 ^b	8.13 \pm 0.03 ^b
1:5 (water)	4.42 \pm 0.05 ^b	7.51 \pm 0.09 ^{bc}	8.28 \pm 0.04 ^c
1:10 (water)	4.62 \pm 0.03 ^c	7.65 \pm 0.03 ^c	8.41 \pm 0.06 ^c
1:1 (0.01 M CaCl ₂)	4.21 \pm 0.06 ^b	6.92 \pm 0.04 ^a	7.95 \pm 0.02 ^a
1:1 (1.0 M KCl)	3.94 \pm 0.07 ^a	6.36 \pm 0.01 ^d	8.13 \pm 0.02 ^b

¹ Means indicated by the same letter do not differ at $P = 0.05$; vertical comparisons only.

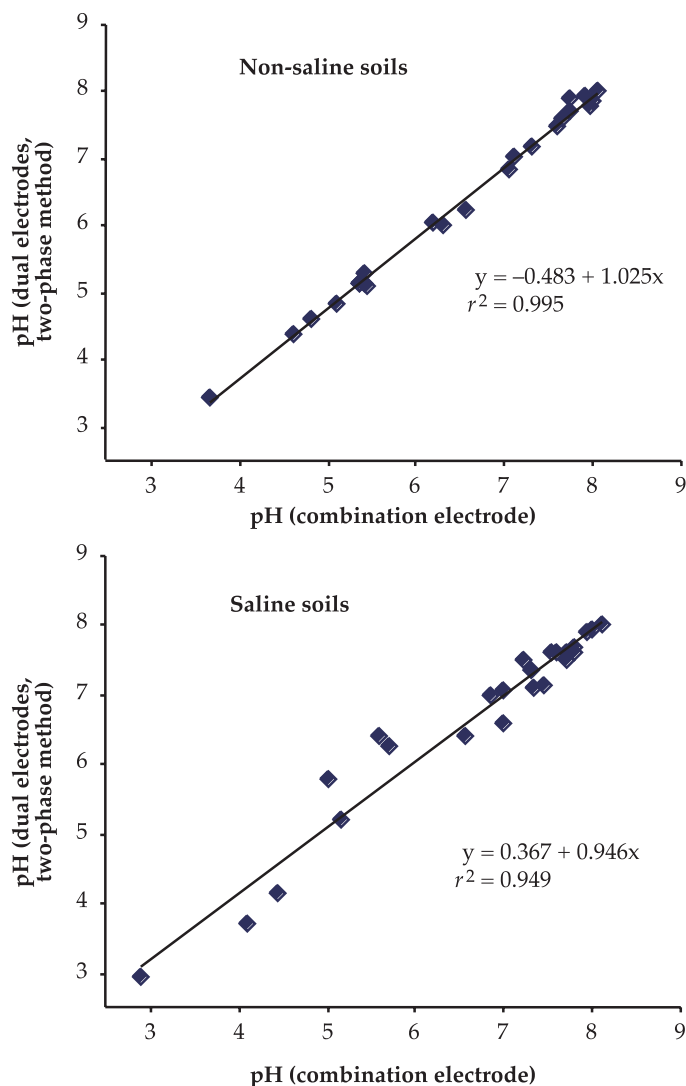


Figure 2. Relationship between pH values obtained with a combination electrode and with dual electrodes in saline and non-saline soil samples. The combination electrode was inserted directly into the 1:1 mixtures of distilled water and soil; with the dual electrodes, the glass (indicating) electrode was inserted into the sediment phase and the reference electrode was held in the supernatant phase (two-phase method).

solutions and in distilled water for saline soils (Figure 4) but slopes did not equal 0.0 and intercepts did not equal 1.0 at $P = 0.05$.

Electrolyte solutions and distilled water provided considerably different values for soil pH. Precision is not better using electrolyte solutions, and interpretations of results obtained with electrolyte solutions are difficult because most recommendations about pond soil pH are based on measurements made in 1:1 soil:distilled water mixtures. Thus, there does not appear to be any advantage to using electrolyte solutions.

Trends of difference in pH measured between or among methods were similar for saline and non-saline soil samples. Thus, the influence of stirring the soil:water mixtures versus not stirring during pH measurement in 1:1 dry soil:distilled water ratios and the difference in pH measured in filtrates versus mixtures were only evaluated for a series of non-saline soil samples. Even though there was a strong correlation between pH measured

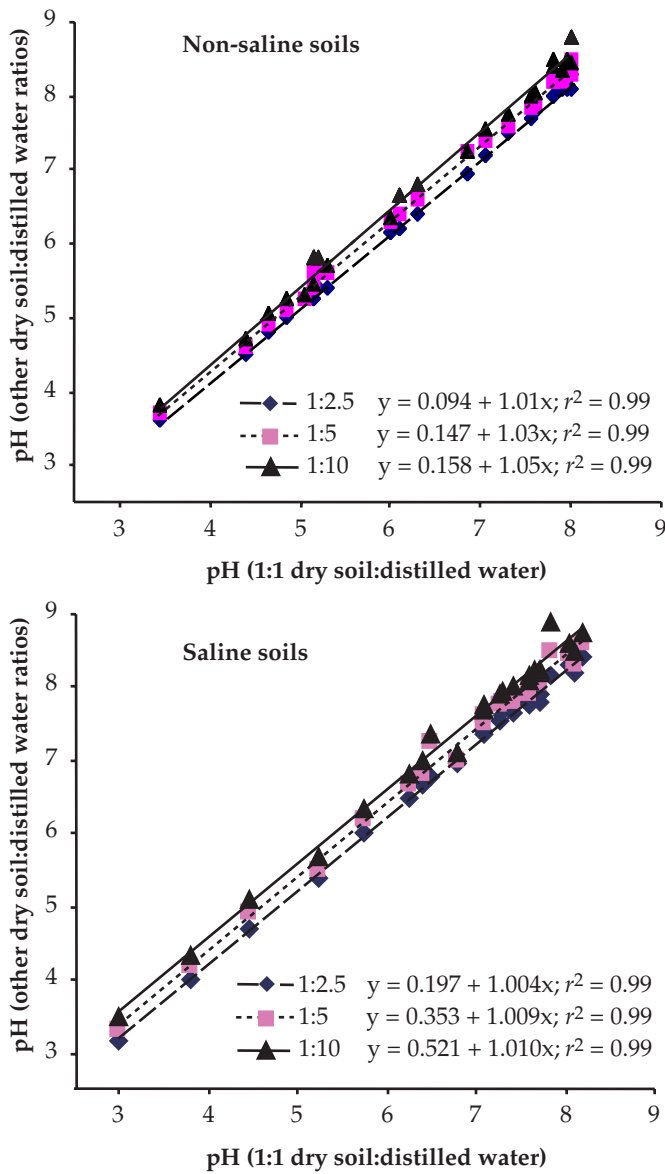


Figure 3. Relationship between pH measured in saline and non-saline soils with the combination electrode inserted into the 1:1 dry soil:distilled water mixture and pH measured with the combination electrode inserted into the other dry soil:distilled water ratio mixtures.

with stirring and pH measured without stirring when the combination electrode was inserted into the soil:distilled water mixture (Figure 5), the non-stirring method always gave higher results than the stirring method. The differences ranged from 0.60 to 1.50 pH units (mean \pm SD = 0.92 ± 0.27). In addition, the pH meter drifted badly without stirring, resulting in a longer time and greater difficulty in obtaining a reading. Thus, stirring is necessary to obtain accurate and precise pH measurements in a short period.

There was also a good correlation between pH measured by the combination electrode inserted into 1:1 dry soil:distilled water mixtures and that measured in the filtrate from these mixtures (Figure 6). However, the pH measured in the filtrate was always higher than the pH measured in the mixture. The values measured in the filtrate were 0.1 to 1.15 pH units higher than those in the mixture (mean \pm SD = 0.46 ± 0.26). We do not

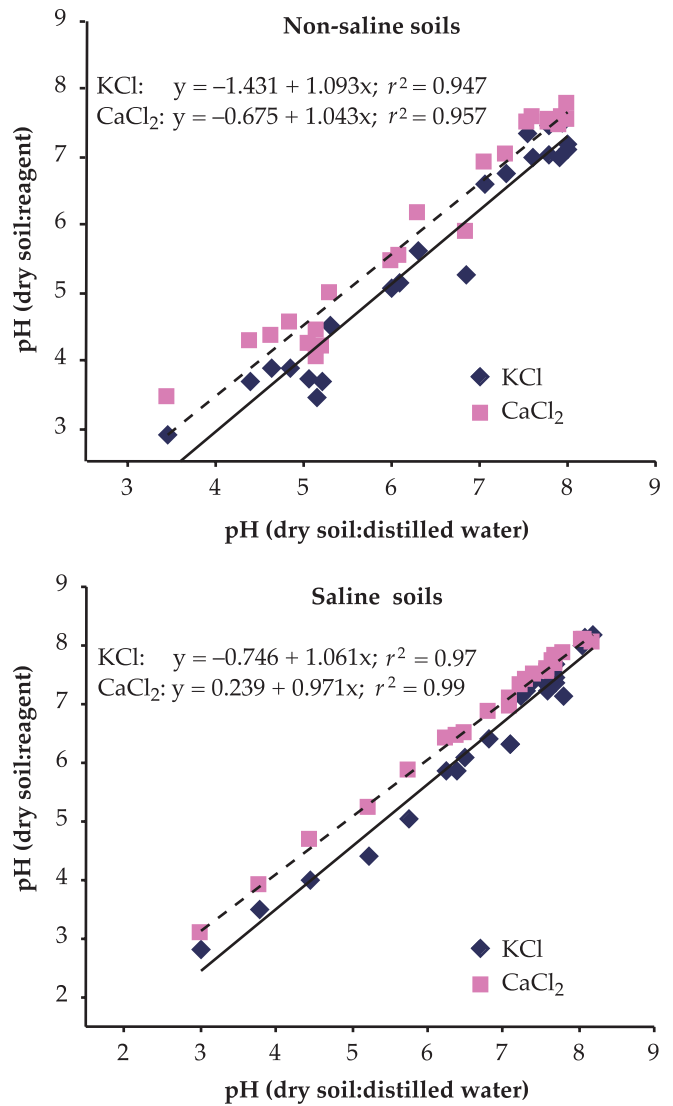


Figure 4. Relationship between pH measured in saline and non-saline soil with the combination electrode inserted into 1:1 dry soil:distilled water mixtures and pH measured with the combination electrode inserted into mixtures of dry soil and 0.01 M CaCl₂ or 1.00 M KCl.

understand why this difference occurred, but separation of the soil and aqueous phases does not seem appropriate because of the discrepancy. Also, filtration is time-consuming.

The particle size of samples did not have a significant effect at $P = 0.05$ on the pH measured in three samples dried at different temperatures. However, there were several differences in pH related to different drying temperatures (Table 11). The most striking difference was the lower pH ($P < 0.05$) of sample 3 when dried at 105°C as compared to 60°C or 40°C; other differences also occurred in the data. We cannot offer a good explanation as to why drying caused pH to change. However, in ponds, bottom soils seldom are exposed to temperatures above 40°C. It seems logical that samples dried at 40°C would be altered less in physical and chemical properties, including pH, than samples dried at higher temperatures. Drying at 40°C is slower than at higher temperatures, so a forced-draft oven should be used to accelerate drying and minimize biological changes during drying.

The effect of stirring time (intermittent stirring during the interval) for two samples is provided in Figure 7. The pH of one sample increased initially and then decreased to a constant value after 20 min. The pH of the other sample increased to a stable value after 20 min. This suggests that the usual intermittent stirring for 30 min should be adequate to reach a constant pH value.

The pH measured by inserting the combination pH electrode directly into fresh samples of waterlogged pond soil was lower than pH measured in 1:1 dry soil:distilled water mixtures of samples from the PD/A CRSP sites in Thailand, Honduras, Peru, and Kenya (Table 12). Wet soil pH and pH of dry soil in

distilled water for samples from 22 ponds at the US site (Auburn University Fisheries Research Unit) were highly correlated (Figure 8). The slope of the regression line did not equal 1.0, and the intercept did not equal 0.0 at $P = 0.05$. The wet soil pH was greater than the dry soil pH for all samples and averaged 0.49 pH units higher. However, wet soil pH is not always greater than dry soil pH. For example, in three brackishwater shrimp ponds in Peru, pH averaged 7.20 ± 0.29 in wet soil and 7.60 ± 0.17 in 1:1 dry soil:distilled water mixtures.

The difference between pH measured in wet and dry soil is not consistent. Data in Table 5 revealed differences of 0.23 to 2.13 pH

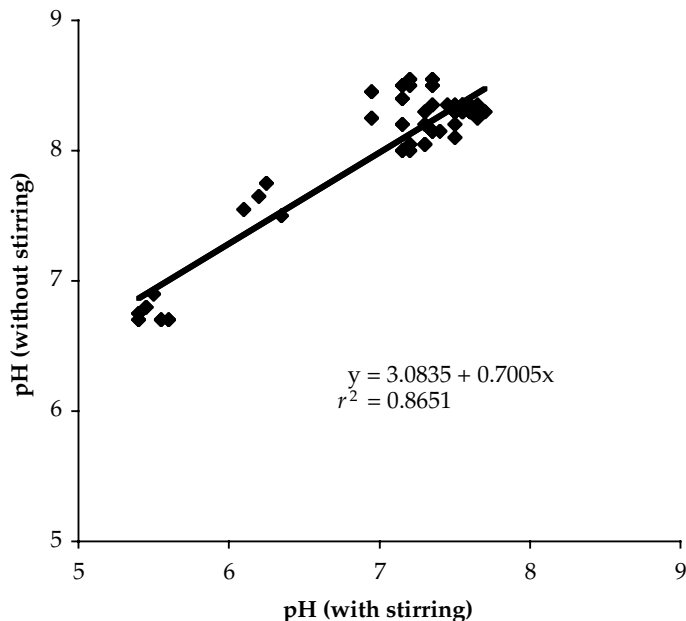


Figure 5. Relationship between pH measurements made by inserting a combination electrode into 1:1 dry soil:distilled water mixtures and either stirring or not stirring while taking the measurement.

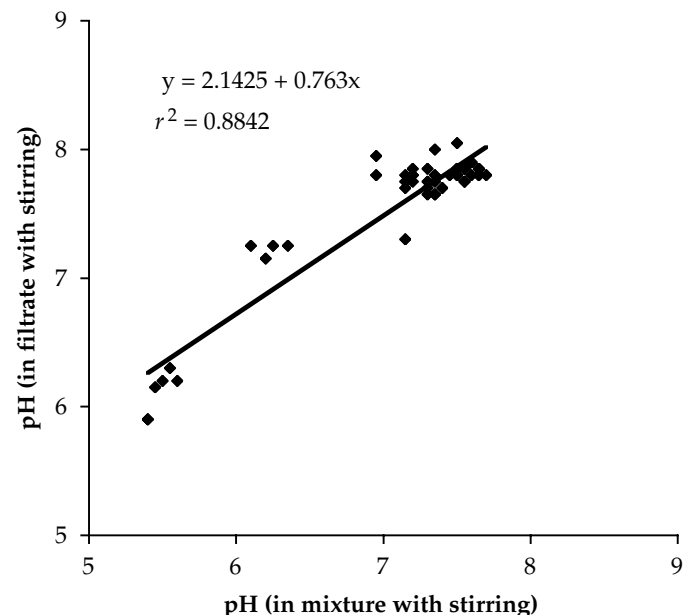


Figure 6. Relationship between pH measurements made by inserting a combination electrode into 1:1 dry soil:distilled water mixtures and by measuring the pH in filtrates of the mixtures.

Table 11. The pH \pm SD of 1:1 mixtures of dry soil and distilled water in which soil samples had been dried at three temperatures and passed through sieves of different mesh sizes.

Temperature (°C)	Sieve Mesh Size (mm)					
	2.36	0.85	0.425	0.25	0.149	0.053
PH (SAMPLE 1) ¹						
40	7.98 \pm 0.03 ^a	8.00 \pm 0.00 ^a	7.73 \pm 0.03 ^a	7.70 \pm 0.00 ^a	7.68 \pm 0.03 ^a	7.93 \pm 0.08 ^a
60	7.90 \pm 0.00 ^a	7.95 \pm 0.09 ^a	7.98 \pm 0.05 ^b	8.03 \pm 0.03 ^b	8.02 \pm 0.03 ^b	7.68 \pm 0.03 ^b
105	7.91 \pm 0.01 ^a	8.00 \pm 0.00 ^a	7.95 \pm 0.00 ^b	8.00 \pm 0.00 ^b	7.97 \pm 0.06 ^b	7.90 \pm 0.00 ^a
PH (SAMPLE 2) ¹						
40	7.77 \pm 0.03 ^a	7.70 \pm 0.00 ^a	7.60 \pm 0.00 ^a	7.55 \pm 0.00 ^a	7.50 \pm 0.00 ^a	7.58 \pm 0.03 ^a
60	7.74 \pm 0.08 ^a	7.42 \pm 0.08 ^b	7.23 \pm 0.06 ^b	7.20 \pm 0.00 ^b	7.25 \pm 0.00 ^b	7.22 \pm 0.03 ^b
105	7.43 \pm 0.41 ^b	7.12 \pm 0.08 ^c	7.12 \pm 0.03 ^b	7.03 \pm 0.06 ^b	7.12 \pm 0.06 ^c	7.07 \pm 0.08 ^c
PH (SAMPLE 3) ¹						
40	6.72 \pm 0.08 ^a	7.05 \pm 0.05 ^a	7.30 \pm 0.17 ^a	7.43 \pm 0.20 ^a	7.10 \pm 0.00 ^a	7.32 \pm 0.03 ^a
60	6.87 \pm 0.06 ^a	6.85 \pm 0.06 ^a	5.93 \pm 0.03 ^b	6.02 \pm 0.03 ^b	6.20 \pm 0.10 ^b	6.93 \pm 0.03 ^b
105	5.48 \pm 0.53 ^b	5.18 \pm 0.03 ^b	5.13 \pm 0.06 ^c	5.10 \pm 0.00 ^c	5.18 \pm 0.03 ^c	5.23 \pm 0.08 ^c

¹Means indicated by the same letter do not differ at $P = 0.05$, vertical comparisons only.

units. The samples from Thailand that differed in wet and dry pH by 2.13 pH units were known to contain iron pyrite. Pyrite oxidizes when dried to release sulfuric acid (Dent, 1986). Standard pH probes are so large that they cannot be positioned to contact only soil in the thin surface aerobic layer (Munsiri et al., 1995), and they indicate the pH in the pore water in the anaerobic soil near the soil-water interface. The lime requirement and other pond soil assessments requiring information on pH are based on the pH of aerobic soil. The pH of aerobic pond soils are controlled by the same factors controlling pH in dry soil-distilled water mixtures. Therefore, aquaculturists should not rely upon pH measurements made by inserting standard pH electrodes into samples of freshly collected soil. Soil samples from the upper 5-cm layer should be dried and pulverized and the pH determined in 1:1 mixtures of dry, pulverized soil and distilled water.

The portable soil acidity tester often is used to measure pH directly in bottoms of ponds that have been drained for harvest. Results of comparisons between the portable soil acidity tester and a standard pH meter with combination electrode are provided in Figure 9. The absolute differences between the two methods averaged 1.22 pH units for non-saline soils and 1.42 pH units for saline ones. The soil acidity tester gave lower pH values than the pH meter for all saline pond soil samples, but both lower and higher values were obtained for non-saline pond soils.

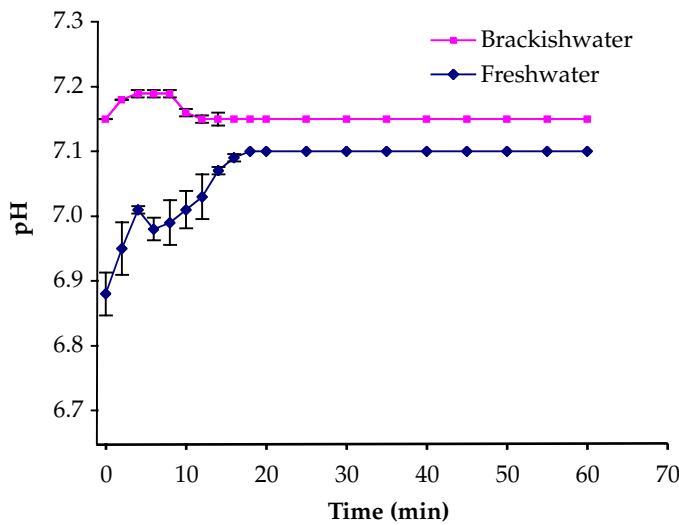


Figure 7. Influence of intermittent stirring time on the pH in a 1:1 mixture of dry soil and distilled water.

Table 12. Means ± SD for bottom soil pH from three ponds measured directly in freshly collected wet, non-saline soil and in 1:1 mixtures of dry soil and distilled water with the combination electrode.

Sample Description	Wet ¹	Dry ¹
Thailand	7.65 ± 0.19 ^a	6.37 ± 0.04 ^b
	7.28 ± 0.03 ^a	6.32 ± 0.05 ^b
	5.51 ± 0.29 ^a	3.38 ± 0.05 ^b
Honduras	7.48 ± 0.06 ^a	7.07 ± 0.03 ^b
Peru	6.53 ± 0.15 ^a	6.30 ± 0.26 ^a
Kenya	7.17 ± 0.04 ^a	6.90 ± 0.03 ^b

¹Means indicated by the same letter do not differ at P = 0.05, horizontal comparisons only.

There were positive, though weak, correlations between the two methods for both types of soil samples, but the correlation coefficients were too low to be of much predictive value. Results reported in Figure 10 reveal that the presence of salt in the soil did not greatly affect the pH as measured with the combination electrode. The soil pH in the control soil (0‰ salinity) was 6.15, the pH at 0.68 and 1.36‰ salinity was 5.85, and the pH at 30‰ salinity was 6.05. The soil acidity tester measured a lower pH at 0‰ salinity than did the standard pH meter; values were 5.5 and 6.15, respectively. The pH difference between the two methods of measurement was much greater at salinities of 0.68‰ and more

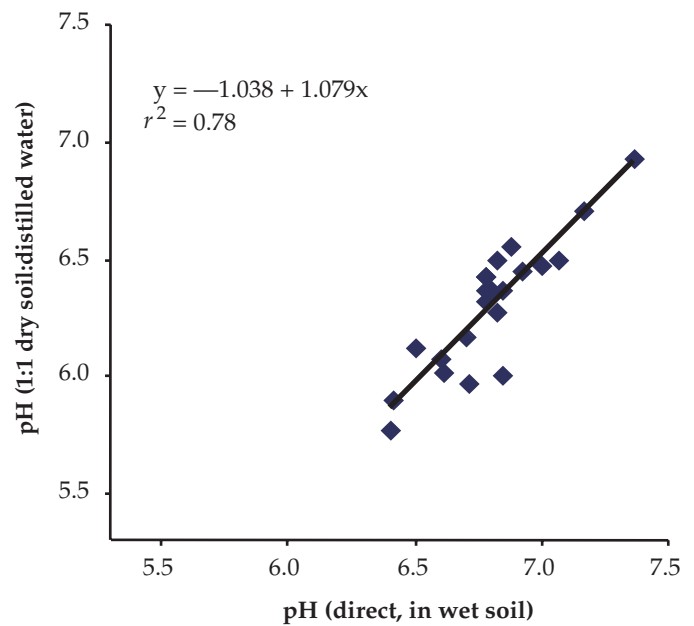


Figure 8. The pH of pond soil measured by insertion of the combination electrode directly into freshly collected, wet soil and in 1:1 dry soil:distilled water mixtures. Soil samples were taken from ponds on the Auburn University Fisheries Research Unit, Auburn, Alabama.

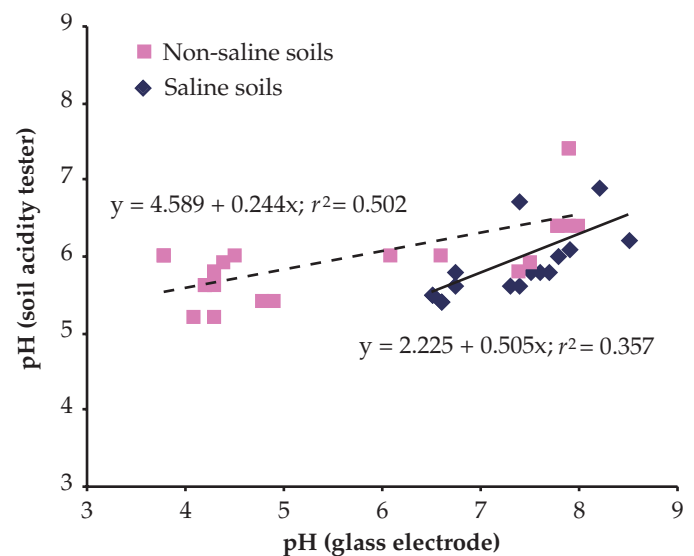


Figure 9. Relationship between pH measured in saline and non-saline bottom soils using either a portable acidity tester or a glass electrode inserted into a 1:1 mixture of dry soil and distilled water.

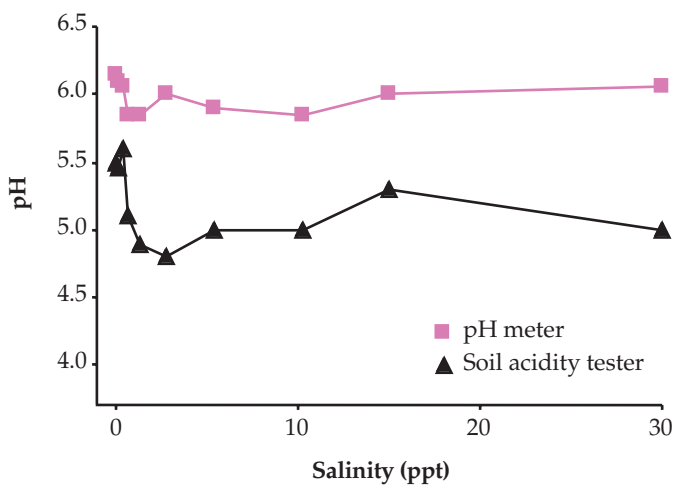


Figure 10. Influence of salinity concentration in soil pore water on pH measures made with a soil acidity tester and with the combination electrode.

than at lower salinities. For example, at 5.44‰ salinity, the glass electrode read 5.9 and the soil acidity tester read 5.0, while at 30‰ salinity the respective readings were 6.05 and 5.0. This suggests that increasing salt content in the soil causes the soil acidity tester to underestimate pH as determined by a standard pH meter. This is not surprising because the manufacturer's instructions for the soil acidity tester stated that soluble salts in soils can cause erroneous readings and the instrument should not be used for measuring the pH of saline or alkaline soils. Of course, results in Figure 9 suggest that the device does not agree well with a standard pH meter even in non-saline soils.

Results of this study of pH measurements clearly show that the method used for measuring pH can have a marked influence on the pH value obtained for a given sample. Many different methods are used to assess pH in practical aquaculture, and even researchers may use different methods. There is an obvious need to standardize pond soil pH measurements to avoid differences in pH being introduced through varying methodologies. Based on the findings of this study, pond bottom soil measurement should be standardized as follows:

- Dry soil at 40°C in a forced-draft oven;
- Pulverize soil to pass a 2.36-mm sieve;
- Mix dry soil and distilled water in a 1:1 ratio (slightly more distilled water can be added if the mixture is not fluid enough to stir);
- Stir the mixture intermittently for 30 min with a glass rod;
- Insert a dual electrode or a combination electrode directly into the soil-water mixture; and
- Gently stir the soil-water mixture with a glass rod while measuring pH.

ANTICIPATED BENEFITS

Research conducted under this project is anticipated to have several benefits to pond aquaculture. A data base has

been accumulated that is sufficient to allow us to develop a concept of pond soil development and a system of pond bottom soil classification. The S horizon (upper few centimeters) is the most influential part of the pond soil profile affecting water quality. This layer has the highest concentration of reactive organic matter and the greatest respiration rate; phosphorus is also adsorbed by this layer. Thus, the recommendation to sample this soil layer (or the upper 5-cm layer of soil) should become a standard for future studies of pond soils.

Measurement of pond soil pH in 1:1 mixtures of dry soil (40°C) and distilled water also will become a standard procedure as a result of this research. Improved understanding and management of pond soils should result from the following conclusions of this research:

- 1) Pond soils do not accumulate organic matter as rapidly as often thought by practical aquaculturists;
- 2) Pond soils are sinks for phosphorus;
- 3) Microbial activity in many pond soils may be nitrogen-limited; and
- 4) Although pond bottom soils of this study exhibited a wide range in chemical and physical characteristics, it was still possible to successfully culture fish and shrimp.

LITERATURE CITED

- Boyd, C.E. and P. Munsiri, 1996. Phosphorus adsorption capacity and availability of added phosphorus in soils from aquaculture areas in Thailand. *J. World Aquacult. Soc.*, 27:160–167.
- Boyd, C.E., J. Queiroz, and C.W. Wood, 1998. Pond soil characteristics and dynamics of soil organic matter and nutrients. In: D. Burke, J. Baker, B. Goetze, D. Clair, and H. Egna (Editors), Fifteenth Annual Technical Report. Pond Dynamics/Aquaculture CRSP, Oregon State University, Corvallis, Oregon, pp. 11–25.
- Boyd, C.E., J. Queiroz, and C.W. Wood, 1999. Pond soil characteristics and dynamics of soil organic matter and nutrients. In: K. McElwee, D. Burke, M. Niles, and H. Egna (Editors), Sixteenth annual Technical Report. Pond Dynamics/Aquaculture CRSP, Oregon State University, Corvallis, Oregon, pp. 1–7.
- Boyd, C.E., M.E. Tanner, M. Madkour, and K. Masuda, 1994. Chemical characteristics of bottom soils from freshwater and brackishwater aquaculture ponds. *J. World Aquacult. Soc.*, 25:517–534.
- Boyd, C.E., C.W. Wood, T. Thunjai, and S. Sonnenholzner, 2000. Pond soil characteristics and dynamics of soil organic matter and nutrients. In: K. McElwee, D. Burke, M. Niles, X. Cummings, and H. Egna (Editors), Seventeenth Annual Technical Report. Pond Dynamics/Aquaculture CRSP, Oregon State University, Corvallis, Oregon, pp. 1–8.
- Dent, D., 1986. *Acid Sulphate Soils: A Baseline for Research and Development*. Publication 39. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands. 200 pp.
- Munsiri, P., C.E. Boyd, and B.J. Hajek, 1995. Physical and chemical characteristics of bottom soil profiles in ponds at Auburn, Alabama, and a proposed method for describing pond soil horizons. *J. World Aquacult. Soc.*, 26:346–377.
- Soil Survey Staff, 1994. *Keys to Soil Taxonomy*, Sixth Edition. United States Department of Agriculture, Soil Conservation Service, Washington, DC, 306 pp.
- SPSS, 1997. *SigmaStat Statistical Software*. SPSS Marketing Department, Chicago, Illinois.