Aquaculture Pond Bottom Soil Quality Management

by

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INTRODUCTION

Water quality management has been considered one of the most important aspects of pond aquaculture for many years, but less attention has been given to the management of pond bottom soil quality. There is increasing evidence that the condition of pond bottoms and the exchange of substances between soil and water strongly influence water quality (Boyd, 1995). More attention is being devoted to the study of pond soils, and practical aquaculturists are beginning to seek information on pond bottom management.

The purpose of this small manual is to provide a practical guide to the management of aquaculture pond soils.

POND SOILS

Development

During pond construction, surface soil in the area to become the pond bottom usually is scraped off and used as earth fill for embankments. The newly finished pond bottom normally is subsoil low in concentrations of organic matter and nutrients. In tropical and subtropical areas with highly leached soils, pond bottoms often are high in clay content and of low pH.

After filling with water, various processes begin to transform the bottom of a new pond into a pond soil. Erosion of the watershed results in suspended particles of mineral soil and organic matter entering a pond in runoff. Wave action, rainfall, and water currents from mechanical aeration erode embankments and shallow edges to suspend soil particles. In addition, nutrients added to ponds in fertilizers, manures, and feeds cause phytoplankton blooms that increase the concentration of suspended organic particles. Suspended particles settle in ponds with large sand particles settling first, followed by

Table 1. United States Department of Agriculture (USDA) and International Society of Soil Science (ISSS) classifications of soil particle size separates.

Particle Fraction Name	**USDA** (mm)	**ISSS** (mm)
Gravel	> 2	> 2
Very Coarse Sand	1–2	
Coarse Sand	0.5–1.0	0.2–2.0
Medium Sand	0.25–0.50	
Fine Sand	0.10–0.25	0.02–0.20
Very Fine Sand	0.05–0.10	
Silt	0.002–0.05	0.002–0.020
Clay	< 0.002	< 0.002

silt-sized particles, and finally clay particles and fine-divided organic matter. The names and sizes of soil particle classes are provided in Table 1. Water currents and activity of fish and other organisms continually resuspend particles from the bottom, and these particles settle again. Boyd (1976, 1977) reported that continuous input, deposition, resuspension, and redeposition of particles in a pond result in a sorting of particles with the fine clay and organic matter particles settling in the deeper water and the coarser particles settling in shallower water (Figure 1). Deeper areas gradually fill in, and ponds may decrease in volume. Sediment thickness in deep areas of aquaculture ponds usually increases at 0.5 to 1 cm yr^{-1} (Munsiri et al., 1995; Tepe and Boyd, unpublished data).

Organic matter settles to the bottom and is decomposed by microorganisms. Easily decomposable organic matter, such as simple carbohydrates, protein, and other cellular constituents, is quickly degraded. More resistant material, such as complex carbohydrates and other cell wall components, accumulates because it is degraded slowly. There is a continuous input of organic matter to the bottom, so microorganisms are continually decomposing both fresh, easily degradable (labile) organic matter and older, resistant (refractory) organic matter. Because there is a more or less continuous resuspension and redeposition of particles and stirring of the surface sediment by fish and other organisms, the organic matter becomes rather uniformly mixed in the upper layer of sediment. Nevertheless, there usually is a layer of fresh organic matter at the sediment surface that has not been completely mixed into the sediment. Organic matter concentration usually is greatest near the sediment surface (Munsiri et al., 1995). The ratio of labile organic matter to refractory organic matter also is greatest near the sediment surface (Sonnenholzner and Boyd, 2000).

Organic matter concentrations in pond soils do not continue to increase indefinitely. If aquaculture practices—e.g., species; stocking, fertilization, and feeding rates; water exchange; amount of mechanical aeration; and treatment of fallow bottom between crops—remain about the same, the annual

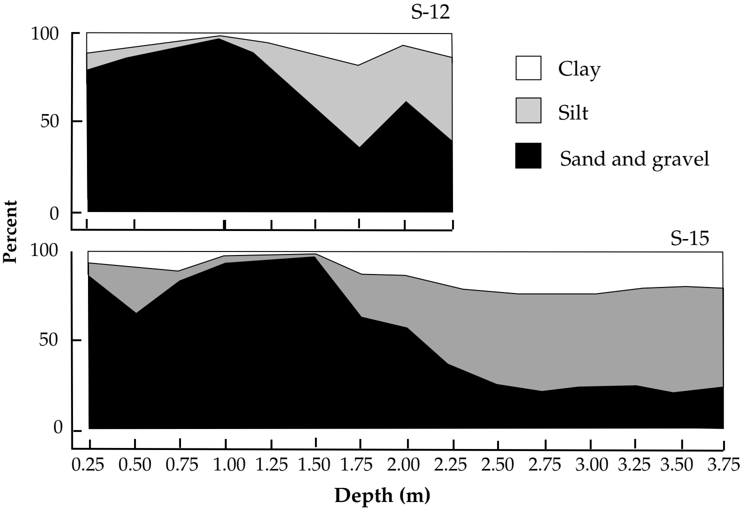

Figure 1. Relationship between water depth and particle size fractions in two ponds at Auburn, Alabama. Source: Boyd (1976).

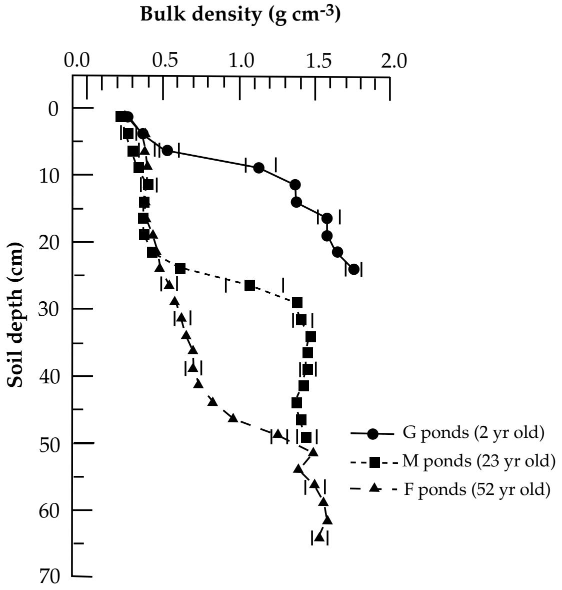

Figure 2. Dry bulk density in samples from different depths in cores from three ponds at Auburn, Alabama. Source: Munsiri et al. (1995).

input of organic matter and rate of organic matter decomposition also will remain about the same (Avnimelech et al., 1984; Boyd, 1995). New ponds usually have little organic matter in bottom soil, and the labile organic matter added each year will largely decompose, while a considerable proportion of refractory organic matter will accumulate (Boyd, 1995). Over a fairly short period, often only four or five crops, organic matter in the soil will reach a high enough concentration that the annual rate of decomposition of organic matter will equal the annual input of organic matter. At this time, equilibrium will occur and soil organic matter concentrations will remain about the same from year to year.

Dissolved oxygen cannot enter rapidly in bottom soil because it must diffuse through the tiny, water-filled pore spaces among soil particles. At a depth of only a few millimeters below the soil surface, the demand for dissolved oxygen by microorganisms will exceed the rate that dissolved oxygen can move to that particular depth, and anaerobic conditions will develop. The oxidized (aerobic) layer of surface sediment will have a lighter color than the deeper, reduced (anaerobic) sediment. The anaerobic sediment usually will be gray or black, and this color results from the presence of ferrous iron.

Processes described above result in sediment forming distinct layers with respect to bulk density (weight of soil per unit volume, usually given in grams dry soil per cubic centimeter) (Figure 2), organic matter concentration (Figure 3), and color.

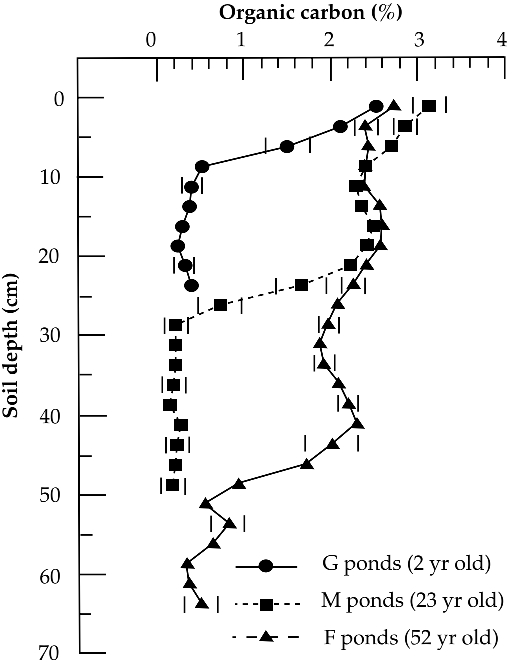

Figure 3. Organic carbon concentration in samples from different depths in cores from three ponds at Auburn, Alabama. Source: Munsiri et al. (1995).

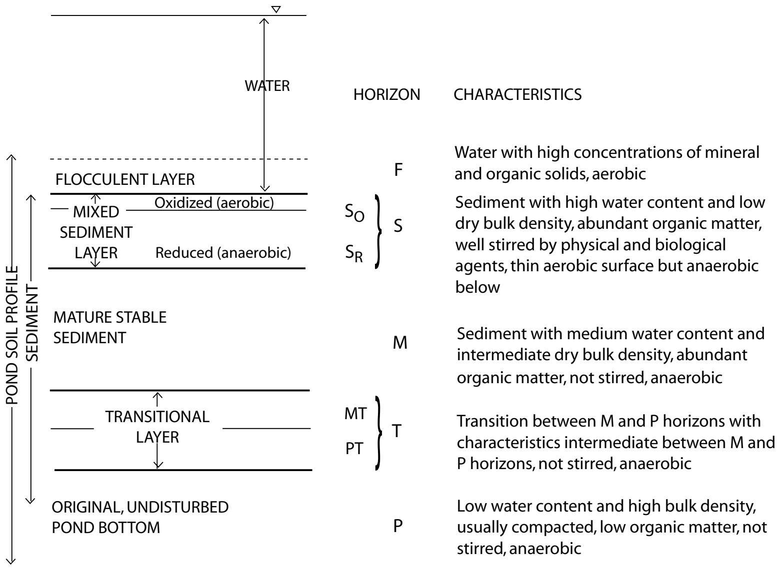

Figure 4. System for delineating soil profiles. Source: Munsiri et al. (1995).

A core taken through the sediment and extending into the original bottom soil is called a profile. Layers in the profile are known as horizons. Munsiri et al. (1995) described these horizons and assigned letters to them to facilitate discussion (Figure 4). For practical purposes, the F and S horizons are most important in aquaculture because they exchange substances with overlaying water to influence water quality (Munsiri et al., 1995; Boyd, 1995).

Research conducted in ponds at PD/A CRSP sites and vicinity has demonstrated that aquaculture ponds typically develop profiles shown in Figure 4 and attain equilibrium concentrations of soil organic matter within a few years. A procedure for classifying pond soil based on the characteristics of horizons has been formulated (Boyd et al., 2002), but pond soil classification is beyond the scope of this report.

The word soil is used for the weathered surface layer of the earth's crust in which plants grow, various animals burrow, and humans have frequent contact. Sediment is used to refer to geological material that has been suspended and transported by water to another place where it settles from the water and forms a deposit. In many places, the soil was formed by sedimentation. All aquaculture pond bottoms become covered with sediment, and this sediment can be considered an aquaculture pond soil. In describing various physical, chemical, and biological processes occurring in the pond bottom, it is convenient to refer to bottom deposits as sediment. However, in the discussion of management of pond bottoms, we usually will refer to the sediment layers in the bottom of an aquaculture pond as pond soil.

The Oxidized Layer

The oxidized layer at the sediment surface is highly beneficial and should be maintained throughout the aquaculture crop. Metabolic products of aerobic decomposition are carbon dioxide, water, ammonia, and other nutrients. In anaerobic sediment, some microorganisms decompose organic matter by fermentation reactions that produce alcohols, ketones, aldehydes, and other organic compounds as metabolites. Other anaerobic microorganisms are able to use oxygen from nitrate, nitrite, iron and manganese oxides, sulfate, and carbon dioxide to decompose organic matter, but they release nitrogen gas, ammonia, ferrous iron, manganous manganese, hydrogen sulfide, and methane as metabolites (Blackburn, 1987). Some of these metabolites, and especially hydrogen sulfide, nitrite, and certain organic compounds, can enter the water and be potentially toxic to fish or shrimp. The oxidized layer at the sediment surface prevents diffusion of most toxic metabolites into pond water because they are oxidized to non-toxic forms by chemical and biological activity while passing through the aerobic surface layer. Nitrite will be oxidized to nitrate, ferrous iron converted to ferric iron, and hydrogen sulfide will be transformed to sulfate. Thus, it is extremely important to maintain the oxidized layer at the sediment surface in aquaculture ponds.

Methane and nitrogen gas pass through the layer and diffuse from the pond water to the atmosphere. These two gases do not cause toxicity to aquatic organisms under normal circumstances.

Loss of the oxidized layer can result when soils accumulate large amounts of organic matter and dissolved oxygen is used up within the flocculent layer (F horizon) before it can penetrate the soil surface. Even in ponds without high concentrations of organic matter in sediment, high rates of organic matter deposition resulting from large nutrient inputs and heavy plankton blooms can lead to oxygen depletion in the F horizon. Ponds should be managed to prevent large accumulations of fresh organic matter in the F horizon, at the soil surface, or in the upper few millimeters of soil.

Toxic metabolites entering well-oxygenated pond water will be quickly oxidized. However, if the rate of release of toxic metabolites into water exceeds the rate that metabolites are oxidized, equilibrium levels of metabolites in the water may be high enough to have detrimental effects on culture animals.

Soil Organic Matter Concentration

It is difficult to assess organic matter concentrations in soil because there are different kinds of organic matter. Organic soils have high concentrations of often recognizable plant remains that are quite resistant to decomposition by bacteria and other microorganisms. Organic soils have 15 to 20% organic carbon (about 30 to 40% organic matter). Such soils are not good for pond aquaculture and should be avoided. Soils with less organic matter are known as mineral soils, and as previously discussed, organic matter in mineral soils is considered to be labile if microorganisms can decompose it readily or refractory if it decays slowly. Methods of soil organic matter analysis do not distinguish among coarse plant remains, refractory organic matter, and labile organic residues. They only measure the total concentration of organic matter. Thus, a soil with 10% organic matter may be perfectly acceptable for pond aquaculture if most of the organic matter is refractory but unacceptable if the organic matter is mostly labile.

A classification of soil organic carbon concentrations for pond aquaculture (Boyd et al., 2002) follows:

Organic Carbon (%)	**Comment**
> 15	Organic soil
3.1 to 15	Mineral soil, high organic matter content
1.0 to 3.0	Mineral soil, moderate organic matter content, best range for aquaculture
< 1	Mineral soil, low organic matter content

Soil organic matter is about 45 to 50% carbon, so a rough approximation of organic matter may be obtained by multiplying soil organic carbon by two.

Nutrient Exchange between Soil and Water

The two most important nutrients in pond aquaculture are nitrogen and phosphorus because these two nutrients often are present in short supply and limit phytoplankton growth. These two nutrients are added to ponds in fertilizers, manures, and feeds.

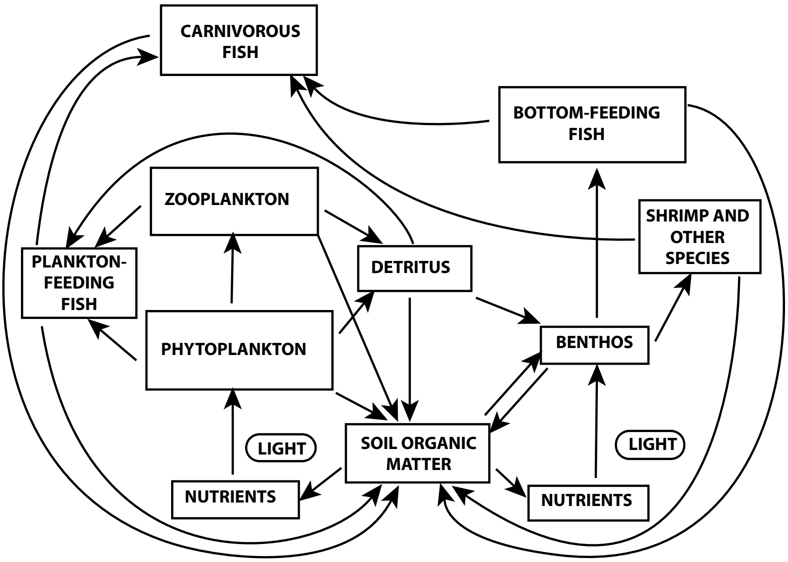

Figure 5. Food web in aquaculture pond.

Fertilizer nitrogen usually is in the form of urea or ammonium, and urea quickly hydrolyzes to ammonium in pond water. Ammonium may be absorbed by phytoplankton, converted to organic nitrogen, and eventually transformed into nitrogen of fish protein via the food web (Figure 5). Ammonium may be oxidized to nitrate by nitrifying bacteria, and nitrate may be used by phytoplankton or denitrified by anaerobic microorganisms in the sediment. Nitrogen gas formed by denitrification diffuses from sediment to pond water to the atmosphere. Ammonium is in equilibrium with ammonia, and ammonia also can diffuse from pond waters to the atmosphere. A small amount of ammonium may be adsorbed on cation exchange sites in pond bottom soils. Organic nitrogen in plankton and in aquatic animal feces may settle to the bottom to become soil organic nitrogen. Nitrogen in soil organic matter may be mineralized to ammonia and recycled to the pond water. Studies conducted under the PD/A CRSP suggest that decomposition in bottoms of aquaculture ponds usually does not result in mineralization of significant amounts of nitrogen (Boyd et al., 1999, 2000, 2001).

Phosphorus usually is present in fertilizer as calcium or ammonium phosphate. Phytoplankton can rapidly remove phosphate from water, and phosphorus in phytoplankton may enter the food web culminating in fish or shrimp (Figure 5). Pond soil strongly adsorbs phosphorus, and the capacity of pond soil to adsorb phosphorus increases as a function of increasing clay content (Boyd and Munsiri, 1996). Masuda and

Table 2. Distribution of phosphorus within different pools and fractions for a fish pond constructed on Ultisols at Auburn, Alabama. From Masuda and Boyd (1994).

Phosphorus Pool	**Phosphorus Fraction**	**Concentration** ($g\ m^{-2}$)	%
Pond Water [a]	**Total Phosphorus**	**0.252**	**0.19**
	Soluble Reactive Phosphorus	0.019	0.01
	Soluble Non-Reactive Phosphorus	0.026	0.02
	Particulate Phosphorus	0.207	0.16
Soil [b, c]	**Total Phosphorus**	**132.35**	**99.81**
	Loosely-bound Phosphorus (Water Soluble)	1.28	0.96
	Calcium-bound Phosphorus	0.26	0.20
	Iron and Aluminum-bound Phosphorus	17.30	13.05
	Residual Phosphorus	113.51	85.60
Pond	**Total Phosphorus**	**132.60**	**100.00**

[a] Average pond depth = 1.0 m.
[b] Soil depth = 0.2 m.
[c] Soil bulk density = 0.797 g m^{-3}.

Boyd (1994) found about two-thirds of phosphorus applied to ponds in feed accumulates in bottom soils. They also showed that most of soil phosphorus was tightly bound, and only a small amount was water soluble (Table 2). Studies on phosphorus adsorption and release by soil conducted under the PD/A CRSP also revealed pond soils are not a major source of phosphorus to water because soil-adsorbed phosphorus is highly insoluble (Boyd and Munsiri, 1996; Boyd et al., 1998, 1999). Phosphorus released by decomposition of organic matter in pond bottoms is rapidly adsorbed by soil and little of it enters the water. Soils that are near neutral in pH have less capacity to adsorb phosphorus and a greater tendency to release phosphorus than do acidic or alkaline soils (Boyd, 1995). Nevertheless, even neutral soils remove phosphorus from the water and are a sink rather than a source of phosphorus.

Manures often are applied to ponds in tropical nations as a substitute for chemical fertilizers (Hickling, 1962; Lannan et al., 1986; Green et al., 1990). These organic materials decompose, releasing nitrogen and phosphorus into the water. Once dissolved in the water, nitrogen and phosphorus originating from manures will enter the same pathways as nitrogen and phosphorus applied in chemical fertilizers.

Feeds are used in aquaculture to increase aquatic animal production above that possible with fertilizers and manures. Most of the feed is eaten directly by fish or shrimp, but usually only 10 to 30% of phosphorus and 20 to 40% of nitrogen applied in feed is retained by culture animals (Boyd and Tucker, 1998). The remainder of the nitrogen and phosphorus enters pond ecosystems in feces or other metabolic products—much of the nitrogenous wastes of fish and other aquatic animals is excreted as ammonia. Organic metabolites and uneaten feed are decomposed by microorganisms, and nitrogen and phosphorus are mineralized. The ultimate fate of nitrogen and phosphorus applied in feed but not contained in

Table 3. A nitrogen budget for four channel catfish ponds (each 400 m^2) on the Auburn University Fisheries Research Unit, Auburn, Alabama, during the period 30 May to 9 October 1997. From Gross et al. (2000).

Variable	**Nitrogen** (g $pond^{-1}$)	%
N GAINS		
Initial Water	480	4.65
Fish Stock	189	1.83
Feed	9,069	87.89
Rain	378	3.67
Pipe Inflow	197	1.91
Nitrogen Fixation	5	0.05
Total	**10,318**	**100.00**
N LOSSES		
Fish at Harvest	3,354	31.53
Overflow	167	1.57
Draining for Harvest	1,482	13.93
Loss to Pond Bottom	2,400	22.57
Seepage	56	0.53
Ammonia Volatilization	1,331	12.51
Denitrification	1,846	17.36
Total	**10,636**	**100.00**

culture animals at harvest is the same as for nitrogen and phosphorus applied in chemical fertilizers and manures.

Ponds overflow after heavy rains, water may be exchanged, and ponds may be drained for harvest. Outflowing water will contain nutrients and may represent a significant loss of nutrients from ponds (Schwartz and Boyd, 1994; Gross et al., 2000).

Budgets for nitrogen and phosphorus have been made for aquaculture ponds, as illustrated in Tables 3 and 4. Nutrient budgets reveal that most phosphorus not contained in aquatic animals at harvest is adsorbed by bottom soil or contained

Table 4. A phosphorus budget for three channel catfish ponds (each 405 m^2) on the Auburn University Fisheries Research Unit, Auburn, Alabama, during the period 2 March to 3 October 1983. From Boyd (1985).

Variable	**Phosphorus** (g $pond^{-1}$)	%
GAINS		
Fish Stock	36	2.05
Feed	1,682	95.89
Inflow from Pipe	35	2.00
Rainfall	1	0.06
Total	**1,754**	**100.00**
LOSSES		
Fish Harvest	521	29.70
Overflow and Draining	119	6.78
Seepage	145	8.27
Uptake by Mud	969	55.25
Total	**1,754**	**100.00**

in organic matter that settles to the bottom. Nitrogen not removed in the harvest of animals is lost primarily through denitrification, ammonia volatilization, or outflow. A significant portion of the nitrogen also may accumulate in bottom soil.

Soil pH

The pH is the negative logarithm of the hydrogen ion concentration, and the pH range usually is given as 1 to 14. A pH of 7 indicates a neutral condition (neither acidic or basic), where hydrogen ions equal hydroxide ions in concentration. A pH below 7 indicates more hydrogen ions than hydroxide ions and acidic conditions. Above pH 7, there are more hydroxide ions than hydrogen ions and basic or alkaline conditions exist. Pond bottom soil pH can range from less than 4 to more than

9, but the best pH for pond soils is considered to be about neutral (Boyd, 1995). Maximum availability of soil phosphorus usually occurs at about pH 7. Most soil microorganisms, and especially soil bacteria, function best at pH 7 to 8.

The source of acidity in most pond soils is aluminum ion. Clay and organic matter particles in soil are negatively charged and attract cations to their surfaces. Aluminum ions on cation exchange sites in soil are at equilibrium with aluminum ions in the pore water surrounding soil particles. Aluminum ion hydrolyzes to aluminum hydroxide, releasing hydrogen ions (Figure 6). The greater the proportion of aluminum ions on cation exchange sites in soil, the greater the acidity. Other exchangeable ions that occur on cation exchange sites, mainly calcium, magnesium, sodium, and potassium, are basic. Pulverized limestone, called agricultural limestone, often is applied to acidic soils to neutralize them, as illustrated in Figure 6. Limestone neutralizes the acidity and calcium ions replace aluminum ions of cation exchange sites to make soil less acidic in reaction.

Waters in ponds with acidic soils typically have low concentrations of bicarbonate, carbonate, calcium, and magnesium.

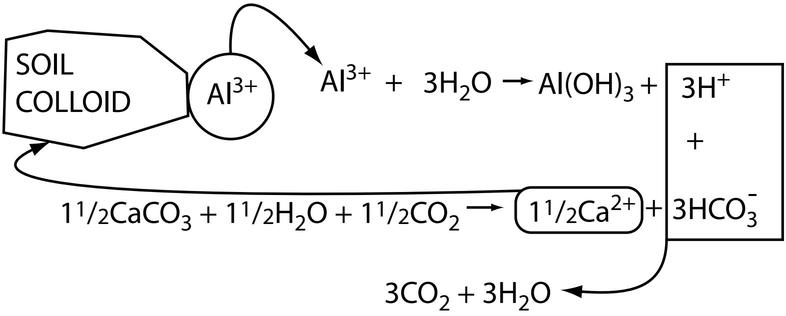

Figure 6. Model for neutralization of exchangeable acidity in soil by calcium carbonate.

Waters with low concentrations of bicarbonate and carbonate will have low total alkalinity, and those with low concentrations of calcium and magnesium have low concentrations of total hardness. Usually, water with low alkalinity also is low in hardness. Such waters are not well buffered against pH change, and they do not have large reserves of inorganic carbon to support phytoplankton photosynthesis. Application of agricultural limestone to acidic ponds can increase soil pH, increase concentrations of total alkalinity and total hardness in waters, increase the availability of inorganic carbon for photosynthesis, and buffer waters against wide diurnal changes in pH. Thus, aquaculture ponds with acidic bottom soils and low alkalinity water should be treated with agricultural limestone.

Soils in humid areas tend to be highly leached of exchangeable bases and therefore acidic. However, if soils in humid areas contain a source of carbonate, such as limestone, they will not be acidic. In semi-arid and arid regions, evaporation exceeds precipitation and salts tend to accumulate in soils. Such soils will be neutral or basic in reaction. In coastal aquaculture, ponds often are filled with seawater or water from estuaries that usually have moderate total alkalinity (75 to 120 mg l^{-1}) and high total hardness (1,000 to 6,000 mg l^{-1}). Nevertheless, soils in coastal ponds may still be acidic and respond positively to liming.

Soils in some coastal areas contain iron pyrite. When such soil is exposed to air, pyrite oxidizes releasing sulfuric acid. These soils are known as acid-sulfate soils. They may have pH values of 5 to 7 when wet, but when dried, pH may fall to 2 or 3 (Fleming and Alexander, 1961; Dent, 1986). Acid-sulfate soils should not be used for aquaculture ponds if other alternatives are available.

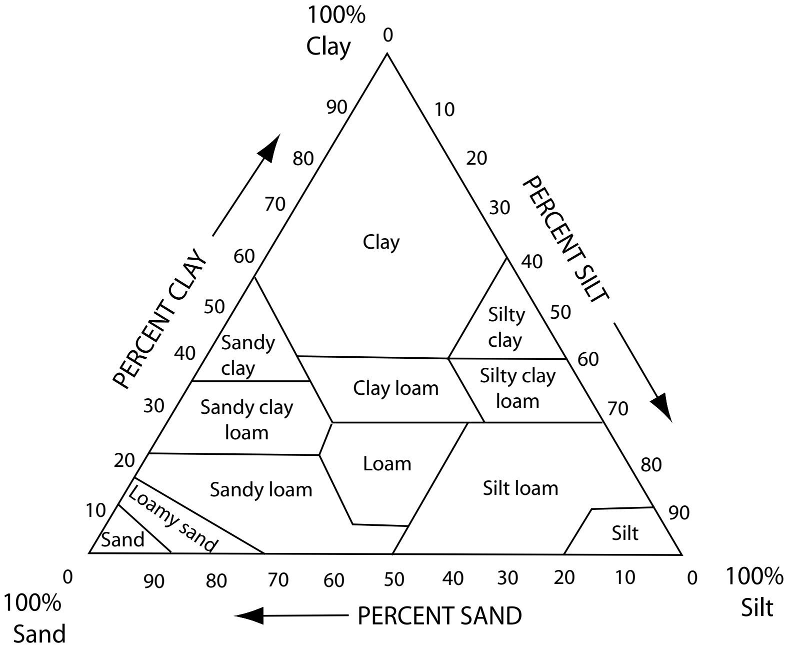

Figure 7. A soil triangle.

Soil pH sometimes is intentionally increased to 10 or 11 in order to destroy pathogenic organisms harbored in the pond bottom. Calcium oxide or calcium hydroxide is applied to the bottoms of fallow ponds for this purpose. After a few days, soil pH will decline and ponds can be filled and stocked.

Soil Texture

The term texture refers to the particle-size distribution in soil. A soil texture name can be assigned with a soil triangle (Figure 7) using data on percentages of sand, silt, and clay. The concept of soil texture was developed for terrestrial soils, and the large number of textural classes is useful in describing agricultural soils. There does not appear to be a need for so many soil texture classes for aquaculture pond soils.

In the past, many authors, including the senior author of this manual, have stated that soils for pond embankments and bottoms should contain at least 20 or 30% clay (Hajek and Boyd, 1994; Boyd and Bowman, 1997). From an engineering standpoint, a high clay content is undesirable, for such soils are difficult to spread in layers and to compact. Embankments with a high clay content may not be stable or have a good weight-bearing capacity when wet. Moreover, soils with a high clay content are sticky, easily erodible, slow to dry, and difficult to till. A clay content as low as 5 to 10% is preferable to a higher clay content for constructing embankments if soils have a good mixture of particles of different sizes (McCarty, 1998). Such soils can be worked more easily during construction than soils of higher clay content, and water-tight ponds with stable embankments can still be built. Management procedures such as drying, tilling, fertilization, and control of soft sediment also can be applied more easily in soils of lower clay content. Most of the soil texture classes from the soil triangle can be used in aquaculture, but sands, which are highly permeable, and soils of high clay content can be problematic. The earlier references to the superiority of heavy clay soils in aquaculture should be disregarded or at least reconsidered.

POND SOIL TREATMENTS

Liming

The reason for liming aquaculture ponds is to neutralize soil acidity and increase total alkalinity and total hardness concentrations in water. This can enhance conditions for productivity of food organisms and increase aquatic animal production. Freshwater ponds with less than 40 or 50 mg l^{-1} total alkalinity, brackishwater ponds with total alkalinity below 60 mg l^{-1}, and any pond with soil pH below 7 usually will benefit from liming (Boyd and Tucker, 1998).

Samples of bottom soil may be analyzed for lime requirement (Boyd, 1974; Pillai and Boyd, 1985), but if this is not possible, the general guidelines given below are suggested:

Total Alkalinity ($mg\ l^{-1}$)	**Soil pH** (standard units)	**Agricultural Limestone** ($kg\ ha^{-1}$)
below 5	below 5.0	3,000
5–10	5.0–5.4	2,500
10–20	5.5–5.9	2,000
20–30	6.0–6.4	1,500
30–50	6.5–7.0	1,000

Either total alkalinity or soil pH may be used to estimate the agricultural limestone dose. If both are available but values are not in agreement, use the variable that gives the greatest agricultural limestone dose. To illustrate, suppose total alkalinity is 15 $mg\ l^{-1}$ but soil pH is 5.1 in a freshwater pond. The agricultural limestone dose for pH 5.1 (2,500 $kg\ ha^{-1}$) should be used. For a brackishwater pond with 80 $mg\ l^{-1}$ total alkalinity and soil pH of 5.5, the liming rate should be 2,000 $kg\ ha^{-1}$ because of the pH.

Agricultural limestone should be spread uniformly over bottoms of empty ponds, or alternatively, it may be spread uniformly over water surfaces. Agricultural limestone should be applied at the beginning of the crop, and it should be applied at least one week before fertilization is initiated.

Agricultural limestone will not react with dry soil, so when applying over the bottoms of empty ponds, it should be applied while soils are still visibly moist but dry enough to walk on without soiling your shoes. Tilling after liming can improve the reaction of agricultural limestone with soil, but no studies have been made to verify benefits of tilling.

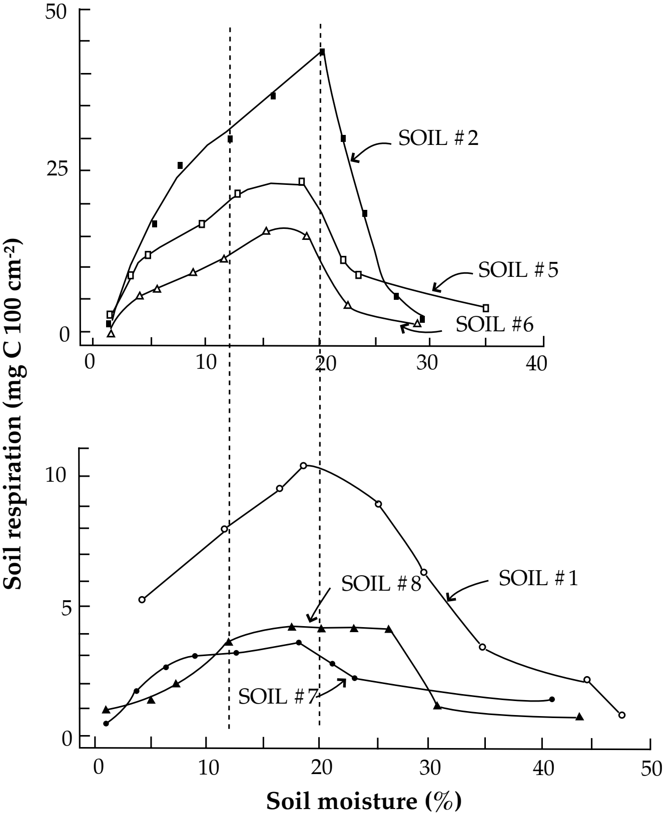

Figure 8. Relationship between soil respiration and soil moisture. Source: Boyd and Pipoppinyo (1994).

Drying

The purpose of drying pond bottoms between crops is to reduce the moisture content of soil so that air can enter pore spaces among soil particles. Better aeration will improve the supply of oxygen and enhance aerobic decomposition of organic matter. By drying for two to three weeks, most of the labile organic matter remaining in the bottom soil from the previous crop will decompose and reduced inorganic compounds will be oxidized (Boyd and Pippopinyo, 1994). The main benefit of this practice is to reduce oxygen demand of bottom soil as much as possible before beginning the next crop.

The time required to dry a bottom soil depends upon soil texture, air temperature, wind conditions, rainfall, and infiltration of water from adjacent ponds or shallow water tables. Light-textured soils dry faster than heavy-textured soils. Warm, dry weather and windy conditions hasten drying, while rainy weather or infiltration of water into ponds retards drying. The decomposition rate in soil will increase up to the optimum moisture content and then decline if soils are dried more (Figure 8). Because of the relationship depicted in Figure 8, usually it is not useful to dry pond bottoms for periods of many weeks.

In soils with a high clay content or in deep layers of silty or clayey sediment, the soil will crack into columnar blocks upon drying. Surfaces of blocks of soil may appear oxidized and quite dry, but if blocks are broken, soil inside will still be black and wet. Additional drying of the soil usually will not be of much benefit, because dry surfaces serve as a barrier to further evaporation. Tilling with a disc harrow can break up blocks of soil or penetrate dense soils to enhance drying and aeration.

Tilling

Tilling bottom soils can enhance drying to increase aeration and accelerate organic matter decomposition and oxidation of reduced compounds. Soil amendments such as agricultural limestone or burnt lime can be mixed into soil by tilling. Accumulations of organic matter of other substances in the surface layer of soil also can be mixed with deeper soils to reduce concentrations of the substances in the surface layer.

Figure 9. Tractor with extra wide tires to prevent rut forming during tillage of pond bottoms.

Pond bottoms should not be tilled when they are too wet to support tillage machinery. Ruts caused by machinery will fill with soft sediment and be likely sites for anaerobic conditions. Ruts also interfere with draining and increase the difficulty of drying pond bottoms. Where tractors are used for tilling, dual tires or extra-wide tires are recommended to prevent causing ruts (Figure 9).

Depth of tillage usually should be 5 to 10 cm, so a disc harrow can be used. Rototillers require much more energy than disc harrows, and they are destructive of soil texture. Mould board plows, often called turning plows, can be used to turn soil over. They could be useful if surface soil has unacceptably high concentrations of one or more substances and deeper soils are of better quality. A mould board plow should not be used for routine tilling for it requires more energy than a disc harrow.

Tilling can be counterproductive in ponds where heavy mechanical aeration is used. Tilling will loosen the soil particles and aerator-induced water currents will cause severe erosion of the pond bottom. Thus, if bottoms of heavily aerated ponds are tilled, they should be compacted with a heavy roller before refilling.

Sediment Removal

Sediment accumulates in ponds for several reasons. There may be a large external sediment load from turbid water supplies. Erosion of embankments can result in large amounts of sediment in deep water areas even where there is not a large external sediment input. If ponds are left empty between crops, rain falling on bottoms can cause erosion of insides of embankments and shallow water edges and eroded material will settle in deep parts of the pond bottom. Mechanical aeration can cause erosion in front of aerators where water currents are strong, and deposition of eroded particles will occur in areas of the pond with weaker water currents.

Accumulation of soft sediment in ponds is undesirable for several reasons. It fills deeper areas and can cause ponds to lose volume. Soft sediment can trap feed pellets and fertilizer granules. Anaerobic zones often occur in soft sediment, and soft sediment is not good habitat for benthic organisms. Fish harvest also is hampered by soft sediment because it impedes seining operations. Soft sediment should be removed periodically before it reaches a troublesome thickness.

Sediment can be excavated with a variety of equipment ranging from shovels to bulldozers. Sediment in pond bottoms does not contain as much organic matter as farmers often think. There normally is no valid reason for disposing of sediment outside of ponds. Sediment often can be put back on the areas from which it eroded. Of course, the loose material should be compacted or protected from erosion by covering with vegetation, stone, or other barriers. When sediment must be disposed of outside of ponds, disposal should be done in a responsible way to prevent unsightly, ecologically degrading spoil piles and erosion.

Fertilization

There are ponds constructed on soils with high concentrations of fibrous organic matter. Decomposition in organic soils is slow because pH usually is low and the amount of carbon relative to nitrogen (carbon:nitrogen ratio) is high. Nevertheless, because of high organic matter content, such soil often becomes anaerobic during fish or shrimp culture. Application of agricultural limestone to increase pH and inorganic nitrogen fertilizers to supply nitrogen will increase soil organic matter degradation during fallow periods between crops. Nitrate also can be used to oxidize wet soils that cannot be dried.

Urea can be spread over pond bottoms at 200 to 400 kg ha^{-1} at the beginning of the fallow period to accelerate decomposition of organic soil. Agricultural limestone should not be applied until a few days after urea is applied to prevent a high pH. Urea hydrolyzes to ammonia, and if pH is above 8, much of the ammonia will diffuse into the air. Bottoms may be tilled to incorporate lime and urea into soil to avoid ammonia volatilization. Tilling also provides better aeration of the soil mass to encourage bacterial activity.

In some ponds there will be areas that will not dry sufficiently to enhance decomposition of organic matter and oxidation of reduced inorganic compounds. Sodium, potassium, and sodium nitrate can be applied to wet soil to encourage organic matter decomposition by denitrifying bacteria and to oxidize ferrous iron, manganous manganese, and hydrogen sulfide. The usual application rate is 20 to 40 g m^{-2} over wet areas.

Nitrate fertilizers are more expensive than urea and are not recommended where soils can be adequately dried.

Productivity of benthic organisms may be low in ponds with concentrations of organic carbon below 0.5 to 1.0%. Organic fertilizer can be applied to such soils to enhance organic matter concentration. Chicken and other animal manures have been applied at 1,000 to 2,000 kg ha^{-1} to pond bottoms during the fallow period. However, application of a higher quality organic matter such as plant meals—e.g., rice bran, soybean meal, and crushed corn—or low-protein-content animal feed at 500 to 1,000 kg ha^{-1} is more efficient. When organic fertilization of pond bottoms is practiced, ponds should be filled with 10 to 20 cm of water and a dense plankton bloom allowed to develop. Water level should be increased and one or two weeks allowed for development of the benthic community before stocking ponds.

Bottom Raking

During the culture period when the pond bottom is covered with water, the most common bottom soil problem is loss of the oxidized layer. Stirring of the sediment surface can improve contact with oxygenated water and help maintain the oxidized layer.

Several methods have been used to introduce oxygenated water into the surface sediment, but the two most practical techniques appear to be manual raking in small ponds and dragging a chain across the bottom of larger ponds. A chain with 2- to 3-cm-long links is heavy enough for this purpose. This practice should be applied at one- or two-day intervals to be effective.

Organic matter originating from dead algae, manure particles, or uneaten feed often accumulates in the windward corners of ponds and settles to the bottom to spoil the sediment surface. Where feasible, this material should be removed by hand and the bottom in the corner raked thoroughly.

Disinfection

Bottom soils can harbor aquatic animal pathogens or their vectors between crops and cause diseases in the succeeding crop. It is common practice to attempt to disinfect pond bottoms following disease outbreaks. Drying can eliminate most disease organisms, but the combination of drying and application of chemical disinfectant is more effective. The two most common treatments are chlorination with calcium hypochlorate to kill organisms by chlorine contact and application of lime (calcium oxide or calcium hydroxide) to cause a high soil pH and kill disease organisms and their vectors.

Calcium hypochlorite is expensive, so lime treatment is more feasible. Application of 1,000 kg ha^{-1} of lime is the minimum amount necessary to raise pH high enough for disinfection, and 1,500 to 2,000 kg ha^{-1} is a more reliable rate. Lime should not be applied after ponds are dry, for it will not dissolve and increase pH. Uniform coverage of bottom soil is necessary, and the distribution of lime over the bottom and its penetration into the soil mass can be facilitated by adding a few centimeters of water over the bottom.

Liming for disinfection also will improve pH in acidic soils, but it kills beneficial bacteria as well as pathogenic ones. Where pond soils are acidic, lime application will not enhance bacterial activity unless time is allowed for the pH to decline to 8 or 8.5 so that re-establishment of beneficial communities of soil microorganisms will occur. This usually takes only three or four days, but ponds should be left fallow for another two or three weeks to promote organic matter degradation.

Probiotics

A number of products are promoted to enhance beneficial chemical and biological processes and to improve soil quality. These products include cultures of living bacteria, enzyme preparations, composted or fermented residues, plant extracts, and other concoctions. There is no evidence from research that any of these products will improve soil quality. Nevertheless, they are not harmful to the culture species, surrounding environment, workers, or quality of aquaculture products.

GOOD PRACTICES

Major concerns in pond bottom soil management are low soil pH, high soil organic matter, loss of the oxidized layer, and accumulation of soft sediment. Although the procedures outlined above can be used to correct soil quality problems, pond managers should still strive to prevent severe soil quality problems from developing. Soil deficiencies should be identified and treated in new ponds instead of waiting until poor bottom soil quality develops later. For example, if soil in a new pond is acidic, it should be limed before initiation of aquaculture. Afterwards, liming material should be applied in a moderate quantity after each crop to maintain acceptable soil pH. In older ponds with impaired soil quality, problems should be corrected and prevented from recurring. Some good practices for protecting soil quality are provided in Table 5.

SOIL ANALYSIS

Monitoring of soil and water quality conditions can be valuable in aquaculture pond management, so some selected procedures will be provided. Most small-scale farmers will not be able to conduct these simple analyses, so comments about visual evaluation of soil also are provided.

Table 5. Good practices for use in maintaining acceptable pond bottom soil quality.

Problem	Preventative Measure
Low soil pH	• Neutralize acidity of new pond bottom soil before initiating aquaculture. • In old ponds that have never been limed, apply agricultural limestone according to the soil pH or total alkalinity of water (see text). • Use urea and ammonium fertilizers conservatively because they are acid forming. • Monitor total alkalinity of pond waters and soil pH to assure that total alkalinity is above 40 mg l^{-1} in fish ponds (75 mg l^{-1} in marine shrimp ponds) and soil pH is above 7. • After initial correction of soil pH, apply agricultural limestone to bottoms of empty ponds at 1,000 kg ha^{-1} during fallow period between crops. If ponds are full, make the application to the water.
High soil organic matter	• Select sites without organic soil. • Where soils are organic, apply agricultural limestone and urea (200 to 400 kg ha^{-1}) to encourage degradation of organic matter during fallow periods. Repeat after each crop. • Use moderate stocking rates to avoid high inputs of nutrients and organic matter in fertilizers, manures, and feeds. • Dry ponds between crops, apply agricultural limestone according to soil pH (see text), and till heavy-textured soils to encourage oxidation of organic matter by bacteria. • In areas of the pond bottom where soils cannot be dried, apply nitrate fertilizer at 20 to 40 g m^{-2}. • Monitor soil organic matter concentrations annually. More than 3% organic carbon (about 6% organic matter suggests excessive organic matter.
Loss of oxidized layer	• Practice preventive measures for avoiding accumulation of organic matter in soil listed above. • Where a surface layer high in organic matter has developed in bottom soils, use a mould-board plow (turning plow) to bury this layer and expose higher quality soil. • Monitor the appearance of the soil. The upper few milliliters should be natural soil color or brownish. A gray or black color at surface indicates reduced (anaerobic conditions).

Table 5 (cont.). Good practices for use in maintaining acceptable pond bottom soil quality.

Problem	Preventative Measure
Loss of oxidized layer	• Use a rake or chain to scarify surface soil during the crop if it appears anaerobic. • Remove accumulation of organic matter from corners of ponds. • Maintain adequate plankton blooms to restrict light and prevent mats of benthic algae. • Remove soft sediment from ponds as suggested below.
Excessive accumulation of soft sediment	• If water supply has high concentrations of suspended solids, pass water through a settling basin before putting it in ponds. • Establish grass cover to minimize erosion on watersheds and embankments of ponds. • Use proper side slopes and compaction when constructing new ponds or renovating old ones. • In ponds with mechanical aeration, install aerators to prevent water currents from eroding insides of embankments. • Install rip-rap (stone) on bottom in front of aerators to prevent scouring. • If sites of active erosion are observed, measures for lessening erosion should be installed. These measures may include installation of rip-rap, proper sloping and compaction, grass cover, etc. • When ponds are empty between crops, remove sediment from deep areas and place it on the areas from which it eroded. Proper sloping and compaction, establishment of grass above water level, or installation of rip-rap will lessen erosion potential. • Do not leave ponds empty longer than necessary during rainy weather to prevent erosion of soil from shallow area with deposition of soil in deeper areas. • If bottoms of heavily aerated ponds are tilled between crops, compact bottoms with heavy roller before refilling. • Do not allow livestock to walk on pond embankments or wade in shallow water edges. • Avoid operating equipment that will cause ruts and other inundations in pond bottoms. • Monitor pond bottoms for soft sediment and remove such sediment periodically instead of waiting until a severe problem has developed.

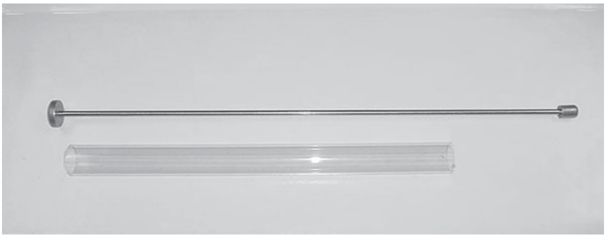

Figure 10. Clear plastic core liner tube and sediment core removal tool.

Visual Evaluation

A clear plastic core liner tube (Figure 10) can be pushed into the pond bottom by hand until it extends into the original soil. The tube can be capped and carefully removed to provide an undisturbed soil core with water above it. The outside of the tube can be washed clean to permit visual observation of soil

Figure 11. Use of plunger to push core from liner tube.

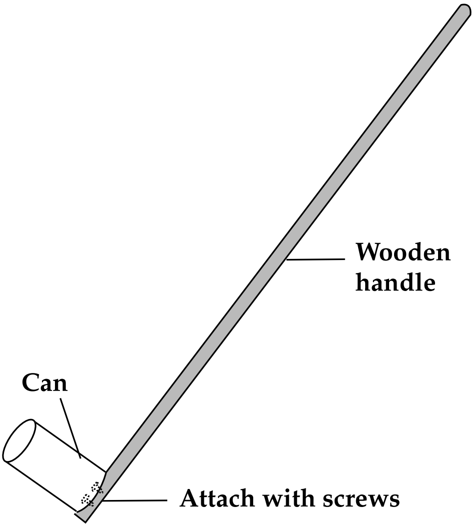

Figure 12. Sediment sampler made from a wooden handle and empty can.

horizons. The presence and thickness of the oxidized layer can be determined. A rough approximation of sediment softness can be determined by tilting the tube and observing the sediment. Extremely soft sediment will pour out of the tube like water. Very soft sediment is more viscous, but it can be easily poured from the tube. Soft sediment cannot be poured from the tube unless the tube is agitated. Firm sediment will remain in the tube even when it is inverted, and hard sediment must be pushed from the tube with a plunger. Use of a custom-made piston-shaped plunger to push the core from the liner tube is illustrated in Figure 11, but a plunger can be improvised if necessary.

If a clear plastic tube is not available, soil samples can be removed with a sampler made from an empty can (Figure 12). The sampler should be removed from the water very slowly to prevent disturbing the soil so that meaningful observations on color and softness can be made.

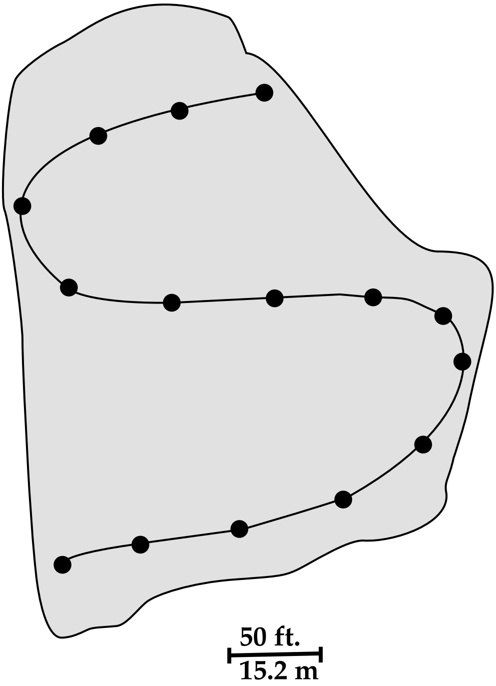

Figure 13. Illustration of S-shaped pattern for taking pond soil samples.

Soil Samples

Samples for measurements of soil pH and organic matter should be taken soon after ponds are drained. Samples should be taken to a depth of 5 cm. Samples generally should be taken randomly from about ten places in each pond. A convenient method is to take samples along an S-shaped pattern as illustrated in Figure 13. Equal volumes of samples taken from the different locations in a pond should be placed in a clean plastic bucket and thoroughly mixed to provide a single composite sample for analysis. The composite sample may be dried in an oven at 60°C, or it can be spread on a plastic sheet and allowed to dry in the sun. The sample should be crushed with a mortar and pestle or rolling pin, sieved through a 20-mesh (0.85 mm) screen, and stored in a clean plastic container or bag.

Soil pH

Soil pH can be estimated *in situ* with a soil acidity tester (Figure 14). These devices may be inserted directly into sediment to read pH, but they are notoriously inaccurate and their use is discouraged (Thunjai et al., 2001). Litmus paper can be used to obtain a rough estimate of soil pH. The pH can usually be estimated to the nearest pH unit with universal pH paper, but we do not consider this adequate for pond management.

The acceptable way to measure pH is with a pH meter and glass electrode. Standard pH meters are the most reliable, but small pocket pH meters can provide suitable estimates of pH.

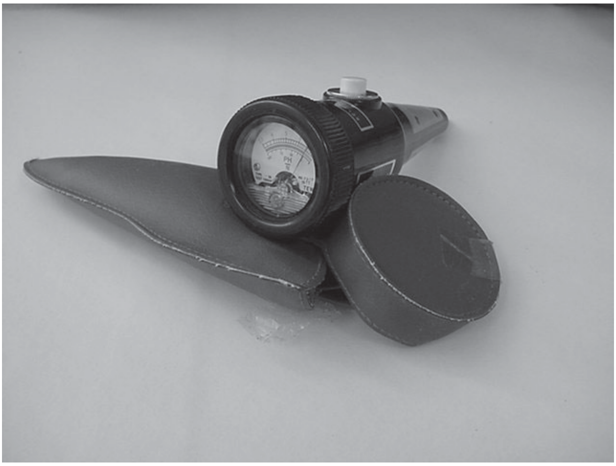

Figure 14. Soil acidity tester.

Apparatus
pH meter

Reagents
Standard pH buffers for calibrating pH meters. Solutions of pH 5.0 and 7.0 usually are employed.

Procedure
Use a dry, pulverized sample (0.85 mm) prepared as described above. Equal weights of soil and distilled water should be combined. For most purposes, either 10 g or 20 g of dry soil and 10 ml or 20 ml of distilled water should be placed in a beaker and stirred intermittently with a glass or plastic rod for 20 min. The pH electrodes should be inserted into the soil–distilled water mixture and the pH measured while gently stirring. High-clay-content soils may be too sticky for pH measurement in a 1:1 soil–distilled water mixture. A 1:1.5 or 1:2 soil–distilled water mixture can be used when this situation is encountered.

Lime Requirement

The decision to lime a pond should be based on total alkalinity of water, bottom soil pH, or both. At the farm level, the best way to measure total alkalinity is to purchase a water analysis kit for this variable. The water sample may be dipped from the surface of the pond, and a single sample from a pond is sufficient.

There are several methods for determining the lime requirement of pond soils (Boyd and Tucker, 1992), but only the general method of Pillai and Boyd (1985) will be provided.

Apparatus
pH meter

Reagents

Buffer. Prepare a p-nitrophenol buffer of pH 8.0 ± 0.1 by dissolving 10 g of p-nitrophenol, 7.5 g of H_3BO_3, 37 g of KCl, and 5.25 g of KOH in distilled water and diluting to 1,000 ml in a volumetric flask.

Procedure

Preparation of sample. Soil for lime requirement analysis should be collected, dried, and crushed according to the guidelines given above. For most accurate results, the proportion of the entire sample that passes the 20-mesh screen should be estimated and used in establishing the liming rate. However, this step normally is omitted.

Determination of lime requirement. Weigh 20 g of dry, pulverized soil into a 100-ml beaker and add 40 ml of buffer. Stir the mixture intermittently for one hour. After setting the pH meter at pH 8.0 with the buffer, measure the pH of the mud-buffer mixture to the nearest 0.01 pH unit. If the pH is below 6.8, repeat the procedure with 10 g of soil and 40 ml of buffer. For a 20-g sample, the equation for the lime requirement is:

$$\text{Lime requirement (kg CaCO}_3\text{ ha}^{-1}) = (8.00 - \text{pH}) \times 5{,}600.$$

For a 10-g sample, double the value obtained with the above equation.

Organic Carbon

Principles

The potassium dichromate–sulfuric acid oxidation technique used for measuring the chemical oxygen demand of water can be applied equally well for the determination of organic carbon content of soil (Nelson and Sommers, 1982). The general reaction is:

$$2Cr_2O_7^{2-} + 3C^0 + 16H^+ = 4Cr^{3+} + 3CO_2 + 8H_2O.$$

The amount of potassium dichromate consumed in the above reaction is equivalent to the amount of readily oxidizable organic carbon in the soil sample. As in the chemical oxygen demand analysis of water, a known amount of potassium dichromate is introduced into the digestion mixture. The portion of the dichromate consumed in the oxidation of organic carbon is measured by back-titration with ferrous iron:

$Cr_2O_7^{2-} + 6Fe^{2+} + 14H^+ = 2Cr^{3+} + 6Fe^{3+} + 7H_2O$.

Reagents

Potassium dichromate, 1.00 N. Dry $K_2Cr_2O_7$ at 105°C and cool in desiccator. Weigh 49.04 g $K_2Cr_2O_7$, dissolve in distilled water and dilute to 1,000 ml.

Concentrated sulfuric acid. Must be at least 96% H_2SO_4. If soils are expected to contain appreciable chloride, add Ag_2SO_4 to sulfuric acid at the rate of 15 g l^{-1}.

Ferroin indicator. Dissolve 1.485 g of 1,10-phenanthroline monohydrate and 0.70 g of $FeSO_4 \cdot 7H_2O$ in water and dilute to 100 ml. An alternative is to purchase the 1,10-phenanthroline-ferrous complex already combined as an indicator solution called ferroin.

Ferrous sulfate solution, 0.5 N. Dissolve 140 g of $FeSO_4 \cdot 7H_2O$ in water, add 15 ml of concentrated sulfuric acid, cool, and dilute to 1,000 ml.

Procedure

Grind the dry soil sample to pass a 60-mesh sieve. Weigh out a 0.50-g or a 1.00-g sample and place in a 500-ml Erlenmeyer flask. Add 10.00 ml of 1.00 N $K_2Cr_2O_7$ and swirl gently to mix soil with the reagent. Add 20 ml of concentrated H_2SO_4 and swirl vigorously for 1 min. Let flask and contents stand for 30 min. Add 100 ml of distilled water to the flask. Filter the suspension through Whatman No. 1 filter paper. Wash the filter and residue with 100 ml of distilled water. Capture the wash water in the flask with the filtrate. Add 3 or 4 drops of ferroin indicator and titrate with ferrous sulfate solution. The solution will assume a greenish cast and then turn dark green near the end point. When this occurs, add ferrous solution drop by drop until the color changes from dark green through blue to red. The ferrous sulfate solution must be standardized daily against 10 ml of 1.0 N $K_2Cr_2O_7$ using the same procedure described above for the organic carbon analysis.

Calculate results with the following equation:

$$\text{Organic carbon (\%)} = \frac{(\text{meq } K_2Cr_2O_7 - \text{meq } FeSO_4)\,(0.003)\,(100)}{\text{Sample weight in grams}}.$$

If 10.00 ml of 1.00 N $K_2Cr_2O_7$ is used, the equation may be expressed as:

$$\text{Organic carbon (\%)} = \frac{(10 - NV)\,(0.3)}{W}$$

where N = normality of ferrous sulfate, V = volume of ferrous sulfate in milliliters, and W = sample weight in grams.

Comments

The equivalent weight of carbon is 3 in its reaction with $K_2Cr_2O_7$ because each carbon atom has a valance of 0 in organic matter and is oxidized to carbon in carbon dioxide with a valance of +4. Hence, 12 g carbon per atomic weight divided by 4 electrons lost per atom in the reaction equals 3 g carbon per equivalent weight. Thus, in the equation above, 0.003 g is the milliequivalent weight of carbon. The factor, 100, is to convert results to a percentage.

The amount of organic carbon recovered by the procedure is variable. In surface soils, it ranges from 75 to 85%. The organic matter in soil is 45 to 55% carbon. Some investigators incorporate a recovery factor in the equation for calculating organic carbon, and in addition, some convert organic carbon to organic matter by assuming a carbon percentage for the organic matter. These factors have been developed for agricultural soils based on results of studies of percentage recovery of carbon from specific soils and percentage of carbon in the organic matter of specific soils. Such investigations have not been conducted for pond soils, so it is best to attempt no corrections for recovery and to express results as organic carbon instead of organic matter.

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