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Management of acidity in mangrove sited aquaculture

by

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Abstract: Potential acid sulfate soil in mangrove areas is generated by a combination of several chemical, microbiological, and physical processes. Acid is formed when the soils are disturbed during pond construction.

A specific instance of acid development in the ponds of a penaeid shrimp aquafarm located in the coastal zone at Chomes, Puntarenas, Costa Rica, is presented. The known consequences on the operation of the ponds are analyzed; remedies and their ecological and economic costs are evaluated.

Several people have suggested that the flat coastal areas in the tropics are well suited for extensive pond aquaculture (Pillay 1967, Ryther 1975, Webber 1975). Since mangrove forests are common on tropical coasts, the building of new aquafarms there will often require siting ponds in mangrove soils. Special problems can arise. In this paper we discuss one such problem, the development of acidity in some penaeid shrimp ponds owned by Maricultura, S. A., a Costa Rican company. Similar problems have arisen in aquaculture ponds in the Philippines (Potter 1976), in Indonesia, and in Malaysia (Tropical Fish Culture Research Institute, Malacca 1959-1969). In fact, the conditions that lead to the formation of acid are likely to be present in many mangrove soils. Solutions are needed for new aquaculture developments in former mangrove soils to succeed. We describe here some techniques for the management of acidity in aquaculture ponds. We would like to acknowledge the help of H. R. Schmittou of Auburn University who suggested the cause of the problem and provided us with information on the experience in the Philippines.

THE AQUAFARM SITE

The aquafarm is near Chomes in Provincia de Puntarenas on the Pacific coast of Costa Rica. It is on the northeastern shore of Golfo de Nicoya at 10°3'N latitude and 84°55'W longitude. The gulf is roughly rectangular, 40 km long and 5 to 10 km wide. The long axis runs northwest to southeast parallel to the main mountain ranges in the country. At its southeastern end, where it opens into the Pacific, the gulf is 50 m deep. Off Chomes it reaches a depth of 20 m. The mean tidal range at Chomes is 2.3 m.

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Many rivers and streams drain into the gulf from the Cordillera de Tilarán and the highlands of the Península de Nicoya. The Río Lagarto, 4 km north of Chomes, and the Río Guacimal, 2 km to the south, together with surface runoff and rainfall make the coastal waters brackish at the farm site during certain periods of the year. The runoff waters carry clay and silt, especially during the rainy season from May to November. As is typical of tropical runoff waters, only a small fraction of the suspended particulate matter is organic. The area around Chomes is an alluvial plain with mangrove growing on the coast. The land has a declination of 2 to 4 m/km, so the mangrove zone reaches back from the coast about 1 km, the extent of the mean tidal incursion. Many tidal creeks meander through the zone. The gulf bottom falls away at the same rate for about 1 km where a steeper decline begins. A sandy beach ridge runs in stretches along the coast.

The land- and soil-forming processes in the area are typical of mangrove areas. The parent soil settles out of the gulf water. This sediment is predominantly mineral clay and silt, including kaolinite and metal sesquioxides. The red mangrove, *Rhizophora mangle,* is the dominant species at the water's edge. Further landward, at higher elevations, the black mangrove, *Avicennia germinans,* becomes dominant. As the forest develops, two soil forming processes become important. First, the extensive prop roots of the red mangrove reduce wave turbulence and slow longshore and tidal currents. Sand and large silt settle out of the water at the edge of the mangrove zone, forming a sand ridge there. The fines, clay and small silt, are carried into the far reaches of the forest on flood tides where they settle out on the the higher elevations. The elevation rises gradually and the coast line, with colonizing mangrove, moves out into the gulf. Second, mangrove leaves, litter, and roots are incorporated in the soil. The major portion of the organic matter comes from the extensive fibrous root system that is characteristic of *Rhizophora* spp. Decomposition quickly turns the soil anoxic just below the surface. Under anoxic conditions, organic matter decomposes slowly, even in tropical climates. Anaerobic decomposition, primarily by sulfate reducing bacteria, takes over. Thus, reduced, clayey, peaty, water-logged, saline soils are formed.

FARM CONSTRUCTION AND OPERATION; THE ACID PROBLEM

Shrimp production at Chomes has three phases, a hatchery phase, a nursery phase, and a growout phase. At the beginning of the nursery phase, 20 day-old postlarval shrimp from the hatchery are stocked in nursery ponds. The ponds are 1 m deep and have an area of 0.4 ha. In 45 days the shrimp grow into juveniles weighing about 2 gm. The juveniles are then transferred to 4 ha growout ponds, also 1 m deep. They grow to market size in 90 days.

During the nursery and growout phases the shrimp feed on zooplankton, algae, and organic detritus, which is produced naturally in the ponds. They also feed on a supplemental artificial feed, which is supplied daily. Also, the pond water is exchanged regularly with gulf water to remove toxic metabolites.

Ponds are constructed in batches of 5 to 10 at a time on 25 to 50 ha parcels of land. A perimeter dike is built first around a parcel and the enclosed area is drained or pumped dry. It is then cleared of vegetation and leveled. Dikes are built to form ponds and supply and drain channels. Concrete water control structures are installed in each pond and channel. Pumps are also sometimes installed. During the construction period the soils are partially drained and dried to promote the decomposition of organic matter in order to lessen the oxygen demand by the soils during later use. Rain and seepage, however, keep the soils partially moist.

In the spring and summer of 1976, soon after shrimp production began, high acidity was measured in the ponds. The pH in most ponds was less than 5 and in a few extreme cases below 4. At that time no pumps had been installed yet so water was exchanged only with the tides by partially draining on ebb tides and refilling on flood tides. The long-period components of the tides, however, prevented the exchange of water in some ponds at high elevations for periods of up to two weeks. The acidity in these ponds became the highest, indicating that the acid was generated in the ponds and not brought in with the exchange water. A red-orange layer covered the bottoms of the ponds that had the highest acidity.

Shrimp growth was low in the acid water ponds and ceased when the pH fell below 5. Acidity can interfere with growth in many ways. Biochemical reactions, particularly enzymatic reactions, are highly sensitive to pH. The shrimp as well as other organisms of a normal pond ecosystem suffer. Acidity inhibits the growth of microorganisms that shrimp eat directly and that are food for protozoans upon which the shrimp also feed. Microorganisms also participate in the digestion of the artificial feeds. Some also remove metabolites. The beneficial microorganisms are often supplanted by other species when the pH changes. Important chemical processes are equally pH sensitive. For example, the equilibrium point shifts in the carbonate system, certain toxic heavy metals are released, and phosphate ions, necessary for algal growth, are immobilized when the pH is lowered. In short, a pH change effects most important components and processes of an aquatic ecosystem. The soil was the source of the acid. In the next section, we review the acid generating process.

ACID SULFATE SOILS

Acidity results from drying the soils during construction. Before they are disturbed the mangrove soils are classified as *thionic fluvisols* in the World Soil Map (FAO-Unesco, 1971) and *sulfaquents* in the Soil Taxonomy scheme (Soil Survey Staff, 1975). The common name is *potential acid sulfate soil.* This type of soil contains pyrite, cubic ferrous disulfide, which is chemically and biologically oxidized upon drying and exposure to the atmosphere.

The dried and oxidized soils, which have a pH of less than 3.5 when mixed with an equal weight of water, are called *sulfaquepts* in Soil Taxonomy or, more commonly, *acid sulfate soil* (Dost, 1973; Bloomfield and Coulter, 1973). Two processes are involved, the formation of pyrite over a long time span, which forms potential acid sulfate soil, and the oxidation of pyrite over a relatively brief period after the soil is disturbed, which transforms the soil to acid sulfate soil.

We shall describe the two processes in relation to the history of the soils at Chomes.

Pyrite is formed naturally in several settings. The mangrove ecosystem is only one of many (Berner, 1970), but one in which all essential factors are abundant. Pyrite has been reported to constitute up to 5% of the dry weight of some mangrove soils (Moorman and Pons, 1975). The continual action of the tides plays an important role in the production of large amounts of pyrite by bringing seawater and suspended mineral matter into the mangrove forest floor and carrying away reaction products. Another essential contribution is the continual incorporation into the soil of organic matter from the mangroves. Sulfur enters as sulfate ion in the seawater (sulfate is the second most common anion in the sea). In anaerobic reduced environments bacteria of the genera *Desulfomaculum* and *Desulfovibrio* use sulfate ion in their respiration analogously to the use of oxygen in aerobic respiration. The process can be represented by (Bloomfield and Coulter, 1973):

$$2CH_3\ CHOHCOOH + SO_4^{2-} = 2CH_3\ COOH + 2\ CO_2 + 2H_2O + S^{2-}$$

The sulfate-reducing bacteria are active only in an anaerobic reduced environment with a near neutral pH. These conditions are maintained in mangrove soil, so the virtually unlimited supply of sulfate brought in on each tide and the large amount of organic matter from the mangroves leads to the production of much hydrogen sulfide. Carbon dioxide is removed as bicarbonate by tidal flushing, preventing a large change in pH.

Among the minerals carried onto the soil by the tides are iron compounds. Goethite, limonite, and other hydrated iron oxides are often found in tropical runoff waters. Berner (1970) has investigated the natural formation of iron sulfides in systems containing iron oxides and hydrogen sulfide. He has shown that pyrite can be formed in quantity in environments similar to mangrove soils. Pyrite is stable and accumulates in the sediment so long as it remains anaerobic.

In general, *Rhizophora* spp. grow in the intertidal zone. As described above, sedimentation gradually raises the elevation to the high tide level. It is to be expected then that the depth of the soil stratum containing a high concentration of pyrite will nearly equal the tidal range. It will be thicker if organic matter is deposited in the sediment below the low tide level in front of the accreting beach in large quantities. For example, a sea grass bed off the mangrove coast can increase the depth of the layer containing pyrite.

The construction of the farm as described above disturbs the mangrove soils by partially drying and exposing them to the atmosphere. The pyrite is oxidized, producing four moles of hydrogen ion for each mole of pyrite consumed (Stumm and Morgan, 1970; Bloomfield and Coulter, 1973). The reaction is catalyzed by various bacteria. The first step is the chemical oxidation of pyrite to sulfate (Stumm and Morgan, 1970):

$$FeS_2 + \frac{7}{2}O_2 + H_2O = Fe^{2+} + 2\,SO_4^{2-} + 2H^+$$

Although this reaction is relatively slow, within a month or so, the soil pH falls to less than 4. Ferrous iron, one of the products, is chemically oxidized to ferric iron:

$$Fe^{2+} + \frac{1}{2}O_2 + H^+ = Fe^{3+} + \frac{1}{2}H_2O$$

The rate of this reaction is relatively slow. Stumm and Morgan report a halflife of about 1000 days at a pH of 3. However, the microorganism, *Thiobacillus ferrooxidans,* which thrives at a pH of less than 4 and appears to be ubiquitous in moist soils and sediments, oxidizes ferrous iron to ferric iron at a rate several times the rate of the chemical oxidation (Bloomfield and Coulter, 1973). Ferric iron then enters into two competing reactions:

$$Fe^{3+} + 3\,H_2O = Fe(OH)_3(s) + 3\,H^+$$

$$2\,Fe^{3+} + FeS_2 = 3\,Fe^{2+} + 2S^0$$

Both reactions are fast chemical reactions. Ferric hydroxide, one of the products of the first reaction, is nearly insoluble if the pH is greater than 3.5. The precipitation of ferric hydroxide removes hydroxide ion from the water. This reaction, producing three equivalents of acidity for each mole of iron, more than compensates for the oxidation of ferrous iron by *T. ferrooxidans.* The second reaction replaces the air oxidation of pyrite by a much faster reaction. Another bacterium, *Thiobacillus thiooxidans,* oxidizes the free sulfur produced by the second reaction to yield more acidity:

$$S^0 + \frac{3}{2}O_2 + H_2O = 2H^+ + SO_4^{2-}$$

T. thiooxidans similarly thrives in acid conditions.

Another product of the oxidation of pyrite in mangrove soils is jarosite, which is stable only in acid conditions. In dry soils it forms straw-yellow mottles. At Chomes, jarosite mottles are found on the crown and sides of the pond dikes. Also, a precipitated ferric oxide, hematite, produced by *Thiobacillus ferrooxidans* covers the pond bottom with a bright red-orange layer when the ponds are acid. Acid pond waters and the presence of yellow jarosite in dry soil and red hematite in the pond bottoms are good indications that the ponds were built in acid sulfate soils.

MANAGEMENT OF AQUACULTURE PONDS IN MANGROVE SOILS

The purpose of pond management is to optimize shrimp production by continuously adjusting the values of controllable pond variables. Here we will consider only five variables, pH, redox potential, dissolved oxygen concentration, dissolved ammonia concentration, and dissolved hydrogen sulfide concentration. Shrimp grow best when the pH is near neutrality, when the redox potential is positive, when the oxygen concentration is near saturation, and when the concentrations of ammonia and hydrogen sulfide, which are both toxic to shrimp, are low. The variables are interdependent. Shrimp consume oxygen and excrete ammonia, so these variables are influenced by the shrimp biomass density. If the oxygen concentration is high, then, in general, the redox potential will be positive in the pond water and the hydrogen sulfide concentration low. But, a large amount of organic matter on the pond bottom, due to high residual amounts in the soil, shrimp feces, and uneaten artificial feed, will lead to anaerobic conditions in the sediments even when the water above is saturated with oxygen. Sulfate reducers will begin to produce hydrogen sulfide a few centimeters below the water-sediment boundary (Jorgensen, 1977). The free sulfide will either form metal sulfides or be oxidized to sulfuric acid when it diffuses to the oxygen-rich overlying water. As we have seen, once the process is started, pyrite in the sediment will continue to generate acid even without a supply of oxygen, although a high oxygen concentration in the sediment will greatly speed the reaction. Thus in potential acid sulfate soils, oxygen in the pond water has both good and bad effects. On the one hand, shrimp grow best in oxygenated water, toxic gasses are removed, and the redox potential is kept high. On the other hand, oxygen willlead to acid waters if it comes in contact with bottom material.

We can divide the possible remedies into those applied during the construction of the ponds and those used during the culture operations.

Two strategies can be applied during construction, burying the problem soils and removing the potential acidity. The first includes methods of construction that disturb the soil as little as possible. For example, mangrove roots can be left in the soil and the bottoms can be left unleveled. Ponds in Asia have been built this way for centuries. Fishkills in aquaculture ponds after heavy rains in the Philippines have been attributed to acid soil washing off the exposed surfaces of the dikes into the ponds during rain storms (Potter, 1976). As discussed above, potential acid sulfate soil produces acid at a much faster rate when exposed to the atmosphere than when continuously submerged under water. So, dikes can be built with non-mangrove soil brought to the site, or fabricated walls made, for example, from concrete or cement-asbestos board. Non-toxic soil can be brought in and spread over the bottoms of the ponds to isolate the potential acid soils. Synthetic pond liners can be used. In most circumstances, each of these remedies will be too costly.

The second strategy is to oxidize the soils to lower the amount of pyrite and then to flush with sufficient water to remove the acid. The application of agricultural lime or another base to neutralize the acidity is an alternative to flushing. It has been estimated that this strategy may require up to 10 years of conditioning before the mangrove soils are acceptable for agriculture (Bloomfield and Coulter, 1973). Again, this is not an economic strategy in most cases. There may be times, however, when one or more of these techniques is justified.

Even if the potential for acid generation is removed during construction, the normal operation of seawater aquaculture ponds will regenerate potential acid conditions. Thus the management of the ponds must compensate. In our opinion, continuous and abundant flushing of the ponds with seawater is the only effective and economic means of diluting and removing the generated acid. At Chomes, water exchange rates of 25% per day are adequate to maintain the pH at neutrality. Since water exchange removes other toxic substances and brings in oxygenated water, it has other benefits. However, there are also disadvantages: 1) either the design of the ponds must permit tidal exchange of water every day, or pumps of sufficient capacity must be installed. In the latter case, there will be a continuous pumping expense; 2) silt may accumulate in the ponds if the incoming water carries much suspended matter; 3) the water must be carefully screened or filtered to prevent predator and competitor species from entering the ponds; 4) beneficial plankton will be washed out of the pond.

The experience at Chomes and other sites shows that potential acid sulfate soils, in particular mangrove soils, can be used for aquaculture. However, the additional cost of treatment and operation must be anticipated. Large areas of mangroves, unsuitable for agriculture, may still have value for coastal aquaculture.

RESUMEN

Se revisan informes sobre aguas ácidas en estanques de acuacultura localizadas en antiguos manglares. La acidez es producida por los suelos aparentemente sulfatados del manglar y es generada por varios procesos químicos, microbiológicos y físicos. El ácido se forma cuando se "alteran" los suelos durante la construcción de los estanques. Se presenta un caso específico del desarrollo del ácido en los

estanques de acuacultura del camarón en la zona costera de Chomes, Costa Rica. Se analizan las consecuencias de la operación en estanques y finalmente, se evalúa la solución de estos problemas y su costo ecológico y económico.

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