

Chapter 5. Pond Characteristics that Affect Fertilization Decisions

When examining the various pond characteristics that may affect fertilization decisions, it is worth remembering the five primary requirements for algal growth: sufficient supplies of soluble P, N, and C, sufficient sunlight, and favorable water temperatures. Pond characteristics that negatively affect any of these requirements will decrease the pond's algal community's response to fertilization. Discussions below focus on pond location, pond source water, pond morphometry, and pond sediments; the management of which can help the farmer maximize fertilization efficiencies. The last section in this chapter examines the ecological implications of using specialized aquaculture structures (e.g., cages and pens) in ponds.

Pond Location

Ponds should be located in climates warm enough to maintain favorable temperatures for both high algal productivities and economically sufficient growth of the culture organisms. Ambient water temperatures are in part functions of both latitude and altitude, so mountainous regions in the tropics may not be as suitable as lowland areas in the same geographic area. Colder climates may still be suitable for production of natural foods, but augmentation with pelleted feeds may be necessary to grow the culture organisms to marketable size within a reasonable time. Again, the choice of pond location is ultimately a question of farm economics.

Where ponds are physically constructed can affect the availability of sunlight and favorable temperatures for algal growth. Common sense clearly indicates that ponds surrounded by shade trees or buildings will receive less sunlight than those with full daytime exposure. In the northern hemisphere, therefore, crop trees planted next to ponds should be situated along the north side of ponds to reduce shade, and ponds should be located to the south of nearby buildings.

Exposure to wind is important because of pond mixing. Ponds exposed to high winds should be both relatively small in area

and somewhat deeper to prevent pond sediments from being continuously resuspended into surface waters, thus blocking out light otherwise available for algal photosynthesis. If high winds are not a problem, then exposure to gentler breezes may actually benefit the pond by mixing waters, facilitating internal fertilization, oxygenating organic sediments, and reducing the risk of continuous thermal stratification. Once a suitable location has been identified, the next consideration is pond source water.

Pond Source Water

The quality of source water used to fill culture ponds can influence subsequent pond fertilization requirements. Maintaining our focus on pond ecology and algal productivity, the concern with source water quality is primarily with the availability of algal nutrients, light, and favorable water temperatures. Additionally, sources of pond water should be selected to minimize the presence of toxic substances such as agricultural biocides and heavy metals. Initial concentrations of dissolved N and P have little practical value because fertilization rates will typically overwhelm any N and P deficiencies in the source water. Viewed from a fertilization perspective, therefore, the two primary water quality variables of source water are its dissolved inorganic carbon (DIC) availability and its inorganic turbidity.

Common sources of aquaculture pond water include direct rainfall, channeled surface waters diverted from rivers, lakes, and reservoirs, and groundwater pumped from wells. Typically, rainwater has both low DIC concentrations and low turbidity. Alkalinities are often close to zero, and diffusion of atmospheric CO₂ into water is relatively too slow to make a significant contribution of DIC to rainwater (Stumm and Morgan, 1970). As surface runoff collects in streams, manmade canals, and reservoirs, water can pick up additional DIC and often much inorganic turbidity from the soil. Some inorganic turbidity may settle out if surface water first goes into a reservoir or settling basin. Source water may carry a high sediment load, however, if it comes directly from earthen canals or ditches.

There are ways to treat turbid source water before it enters culture ponds. For example, at the Institut Pertanian Bogor in Indonesia, a passive, gravity-flow water treatment facility was designed to deal with highly turbid, low-alkalinity source water also suspected of carrying unacceptable concentrations of agricultural

biocides. Canal water first flowed into an open, cement-walled container of about 10 m² in area and 1 m deep. The box contained vertical cement baffles, which slowed water speed and allowed heavier suspended materials to settle out. Water exited through a weir at the top of box into a 200-m² pond partitioned into three equal sections. The first section contained sand for additional filtering, the second had limestone for adding DIC and alkalinity to the water, and the third section was filled with activated carbon for removing biocides. Treated source water was crystal clear, sufficiently rich in DIC, and responded predictably well to fertilization. After a year, the treatment facility was still operating smoothly with minimum maintenance (McNabb et al., 1990).

Manmade reservoirs and lakes can provide a very good water source for aquaculture ponds. If the lake is deep enough to be thermally stratified, then care must be taken not to pump bottom water, which may be anoxic with toxic levels of hydrogen sulfide. This precaution is especially true for ponds located very near the lake. On the other hand, lake bottom water may be preferred if the culture ponds are located some distance (e.g., > 1 km) from the lake and the water is pumped into surface ditches. Remember that anoxic bottom waters often contain large concentrations of dissolved P, ammonia, and CO₂ (Chapter 3). If bottom waters are allowed to re-oxygenate in the canals before entering the ponds, then this water will be both safer for fish and remain higher in dissolved algal nutrients when compared to lake surface water.

Pumping groundwater from wells is another option for source water. Well water has the advantages of generally lower turbidities and higher concentrations of dissolved solids, particularly DIC (Stumm and Morgan, 1970). Wells may also provide a more consistent and dependable supply of good quality water for aquaculture than ditches or lakes. Although in tropical climates well water can be considerably cooler than surface water, groundwater put into ponds or temporarily stored in above-ground tanks is quickly warmed by ambient air and solar radiation. The main problem for the farmer is the high capital cost of the well, and the labor and finances for its maintenance.

Once pond location and pond source water have been identified, the next issue is pond morphometry. The two aspects of pond morphology discussed below are pond depth and pond surface area.

Pond Size

Pond Depth

Pond depth is one of the most critical factors within the aquaculturist's control. The optimal pond depth balances practical considerations and potential ecological consequences. Practical considerations include costs for pond excavation (which would be greater in rocky or more mountainous soils), and convenience to the farmer with respect to harvesting fish during the culture period. The two main ecological considerations with respect to pond depth focus on the need to minimize inorganic turbidity in the photic zone (upper part of water column in which light penetrates), and the need to avoid prolonged thermal stratification of pond water.

The possibility for sediment resuspension into the photic zone generally decreases with increasing pond depth. As discussed in Chapter 2, inorganic turbidity is undesirable in the photic zone because it promotes light limitation of algal productivity, thus reducing fertilization efficiency. Experience has shown that shallow ponds (e.g., 0.5 to 0.8 m) are likely to have significant inorganic turbidities throughout the culture period, whereas sediment resuspension into the photic zone is not common in ponds with depths of about 1.0 m or greater. Although pond location and surface area (see below) also influence the likelihood of sediment resuspension, maintaining depths above 1.0 m should be a reasonable management approach for most ponds to reduce unwanted inorganic turbidity.

Fish raised in shallower ponds, however, may benefit from warmer water temperatures due to absorption of solar radiation by pond sediments (Van Someren and Whitehead, 1959). This may not be a very practical approach because it would be quite difficult to regulate water temperature by managing pond depth. Furthermore, water which becomes too warm may jeopardize the health and survival of culture organisms. It is doubtful that the potential growth benefits of warm water exceed the associated risks of sediment resuspension in shallow ponds.

The second ecological consideration is the direct relationship between pond depth and the risk of persistent thermal stratification of the pond's water column. Recall from Chapter 2 that the continual separation of surface and bottom waters by a thermocline is undesirable for many reasons, particularly when bottom waters

become anoxic from organic decomposition, accumulate toxic substances (e.g., hydrogen sulfide), and cause massive fish kills when they eventually mix with surface waters. In Northeast Thailand, for example, fertilized ponds 2.0 to 2.5 m deep and stocked only with Nile tilapia were green without noticeable problems until a large rain storm passed through two weeks after stocking. The next day all the fish were dead, and several days after the storm the ponds turned brilliant green due to internal fertilization from bottom waters mixed into the photic zone.

The farmer basically has three options to avoid fish kills:

- 1) Maintain thermal stratification during the entire culture period;
- 2) Make ponds sufficiently shallow to prevent long-term stratification; or
- 3) Find a convenient way to routinely mix the pond's water column.

As for the first option, small, deep ponds protected from the wind could remain thermally stratified throughout the grow-out period without necessarily harming the fish. However, the continual loss of nutrients to the bottom through sedimentation of detritus and the prevention of internal fertilization from nutrients generated from pond sediments make this situation relatively inefficient.

The depth at which a thermocline becomes established is a function of many environmental factors (Chang and Ouyang, 1988; and discussed in Chapter 2). However, a review of thermal data from PD/A CRSP ponds in Asia, Africa, and Latin America indicates that culture ponds maintained at depths of about 1 m should typically mix nightly and not experience persistent thermal stratification. In contrast, research in Thailand and China indicates that ponds deeper than about 1.5 m increase the likelihood that thermal stratification of the water column may persist for several days or weeks (Chang and Ouyang, 1988; Szyper et al., 1991). Although ponds with depths less than 1 m are not likely to exhibit continual thermal stratification, there are several reasons why a farmer may still find deeper ponds preferable.

Issues related to thermal stratification notwithstanding, deeper ponds provide several benefits and may even be necessary under certain circumstances. First, from a water management perspec-

Pond Depth (m)	Advantages	Disadvantages
0.5-0.8	<ul style="list-style-type: none"> • easy to harvest • pond water warms rapidly • less costly to construct • requires less water 	<ul style="list-style-type: none"> • high inorganic turbidity • less water for biological production
1.0-1.2	<ul style="list-style-type: none"> • harvest still manageable • less inorganic turbidity • diel stratification and internal fertilization 	<ul style="list-style-type: none"> • wind-induced resuspension of pond sediments
> 1.5	<ul style="list-style-type: none"> • low inorganic turbidity • greater volume of water for growth 	<ul style="list-style-type: none"> • higher risk of persistent stratification • more costly to construct • requires more water

Table 10. Summary of the ecological and practical advantages and disadvantages of maintaining culture ponds at different depths.

tive, rain-fed ponds in drier climates need to be deep enough to store sufficient water for the entire growing season. Second, inorganic turbidity is less of a problem in deeper ponds because the resuspension of bottom sediments into the photic zone is considerably more difficult in a 2- to 3-m pond than in a 1-m pond due to increased energy requirements for mixing. Reducing inorganic turbidity allows sunlight to penetrate deeper into the pond, and increases the volume of water in which photosynthetic activity can take place. And third, deeper ponds may give culture organisms more water volume and physical space in which to grow, although Szyper et al. (1991) did not find any significant differences in tilapia yields or size which could be directly related to differences in pond depths between 0.6 and 1.5 m. Table 10 summarizes how pond depth influences pond ecology and management.

To avoid the serious consequences associated with continual stratification in deeper ponds, pond water must be mixed regularly. The most common means of pond mixing in aquaculture is with the use of mechanical mixers and subsurface pumps (Szyper and Lin, 1990). Although they can be effective, the main problems with these devices are their capital costs, maintenance, energy requirements, and labor costs. For the rural farmer in the tropics, a single aerator could mean a significant financial commitment; a broken aerator could result in financial ruin.

An alternative to mechanical aeration is the biological mixing energy supplied by large fish. The same farm in Northeast Thailand where the massive tilapia kill occurred had many other fertilized ponds 2.5 m deep in which no mortality occurred. In fact, in addition to inorganic fertilizers, these ponds received swine manure flushed in daily from pens adjacent to the ponds. The difference was the presence of large carp, particularly common carp (*Cyprinus carpio*), which kept these ponds sufficiently mixed to prevent thermal stratification. Rather than recommending farmers to risk limited financial resources on relatively expensive technology, extension workers could help the farmer determine how many carp it takes to mix his/her ponds. Since the added carp can be eaten or sold, the answer does not have to be precise.

Pond Surface Area

The second variable of pond morphometry considered in this section is pond surface area. When choosing how large or small to make culture ponds, the farmer should consider several economic factors, including capital and maintenance costs, physical site constraints (e.g., land availability, existing buildings, other ponds), convenience (e.g., location of source water, proximity to animal pens), and desired size of farmer's aquaculture operation. The main ecological consideration focuses on the relationship between pond area and the risk of increasing inorganic turbidity in the pond.

For ponds with small surface areas (e.g., < 100 m² [0.01 ha]), pond banks can be the major contributor of total suspended solid (TSS) concentrations in the water. These ponds have greater shoreline-to-surface-area ratios than larger ponds. This means that erosion of earthen pond banks typically has a relatively greater impact on TSS levels in smaller ponds. Bank stabilization is always a concern with earthen ponds, but particularly if ponds are small and/or shallow.

Ponds with relatively large surface areas (> 1 ha), however, are not necessarily better. Unless ponds are several meters deep, the large surface area facilitates resuspension of bottom sediments through wind mixing. Large ponds also pose practical problems for the farmer, making it more difficult to distribute fertilizers evenly and to partially harvest fish without first draining the pond. The latter problem could be resolved by raising the culture organisms in cages, but that would incur additional capital and maintenance expenses.

Therefore, there is no single answer to the question of optimal pond area. A 200-m² (0.02-ha) pond with very stable earthen or concrete banks may work as well as a 5,000-m² (0.5-ha) pond located in a wind-protected valley. It is perhaps more important to understand how pond size can influence fertilization efficiency, and to recognize that brown, resuspended sediments are undesirable.

Pond Sediments

Pond sediments are an integral part of the pond ecosystem (Boyd, 1995a; Boyd and Bowman, 1997). They can act as a biological filter, adsorbing organic residues of food, fish excretions, and algal metabolites (Avnimelech and Lacher, 1980). Perhaps more importantly, pond sediments play a significant role in the cycling of nutrients in a fertilized pond (Avnimelech and Lacher, 1979; Boyd, 1995a).

Nutrient losses to sediments occur with the sedimentation of P, N, and C bound up in particulate organic matter, particularly algal-based detritus (Avnimelech, 1984). Sedimentation rates are higher in fertilized systems (Hepher, 1965). Other losses to the sediments include the rapid chemical adsorption of P and ammonia to inorganic sediments. As discussed in Chapter 3, the rate of P adsorption to pond sediments decreases as bonding sites are filled and a layer of organic matter (e.g., algae-derived detritus) covers the pond bottom. During the course of a culture period, pond sediments generally act as a net “sink” for algal nutrients (McKee et al., 1970; Boyd, 1971; Boyd and Musig, 1981).

Some of the nutrients “lost” to the system, however, can be returned to the water column and again become available for algal uptake. In fact, sediment conditions created in highly productive ponds facilitate nutrient transport from the pond bottom. Sediments in fertilized culture ponds typically become void of dissolved oxygen due to the accumulation of decomposing organic matter. Under anoxic conditions, the chemical solubilities of dissolved P, ammonia, and CO₂ increase in the interstitial water (i.e., water between sediment granules). Bottom water, overlying pond sediments, can have elevated concentrations of these algal nutrients that accumulate during day-time thermal stratification. Nighttime mixing brings this nutrient-rich bottom water upward, and at the same time transports oxygen-rich surface water down to the sediments. Pond water mixing facilitates both the internal

fertilization of pond surface water, and the decomposition of organic matter on the bottom. These processes reduce the net loss of algal nutrients to the bottom, and therefore increase fertilization efficiencies.

There are several sediment management options designed to help the farmer improve economic and nutrient efficiencies of pond fertilizers. In particular, three sediment-related activities are often conducted prior to filling the pond. The first is pond drying to allow pond sediments to air-dry between culture periods. The main function of this drying period is to facilitate the aerobic decomposition of organic matter accumulated in pond sediments (Ayub et al., 1993; Boyd and Teichert-Coddington, 1994). For ponds fertilized with manures, sediment air-drying reduces the rate of pond filling with organic matter and can extend the life of the pond before it has to be dug out.

Nevertheless, pond drying to decompose organic matter is not recommended under most circumstances. As we have seen, a layer of organic matter on the bottom sediments can increase fertilization efficiencies by reducing the rate of adsorption of soluble P to pond sediments. Furthermore, ammonia and CO₂ produced during decomposition of exposed sediments will be lost directly to the atmosphere through volatilization instead of being retained in the pond system. Hollerman and Boyd (1986) reported reduced algal productivities in ponds drained annually when compared to similar ponds left undrained.

Ponds built on acid sulfate soils are especially at risk when dried. These soils contain iron pyrite (FeS₂), which oxidizes to sulfuric acid (H₂SO₄) when exposed to air (Watts, 1969; Gaviria et al., 1986; Boyd and Daniels, 1993). Since deep cracking of dried sediments may expose these acid soils to air, and then to pond water upon filling, it is better to keep such pond sediments moist (Watts, 1969; Gaviria et al., 1986). Not only does pond ecology discourage the air-drying of ponds, but farm economics can suffer if an otherwise productive pond is allowed to remain empty longer than necessary.

A second pre-filling activity is to add a layer of manure to the pond bottom and cover it with water to a depth of about 10 to 20 cm. As noted above, this organic layer will reduce the rate of P adsorption by pond sediments. Although using TSP to fill P adsorption sites may be more effective both ecologically and economically, the layer of

organics helps create a physical separation of pond water from inorganic sediments below (Knud-Hansen, 1992). Using only a thin layer of water to cover pond sediments allows for greater atmospheric oxygen diffusion to help decompose the organic matter—both the added manure and the settled organic matter accumulated from the previous culture period. Algae, utilizing soluble nutrients from decomposing organic matter, also contribute DO through photosynthesis. Most of the oxygen demand for decomposition occurs within the first four to five days, and ponds can then be filled without reasonable fears of pondwater deoxygenation.

Additional benefits from conducting a pre-filling manure treatment result from the nighttime anoxic conditions likely to occur during the first couple days. This layer of anoxic water can kill snails, bivalves, and other unwanted molluscs which would otherwise remove CaCO_3 from the water for shell development, hence reducing both alkalinity and DIC availability. Better still, the relatively lower pH and higher CO_2 concentrations typical of these anoxic waters help dissolve existing shells in the sediments, increasing the pond's alkalinity and DIC pool.

When the pond is filled, source water should be added during the daytime after the water covering the pond bottom has had time to re-oxygenate through algal photosynthesis. The mixing of this highly productive, nutrient-rich bottom water with incoming source water enables the pond to produce natural foods more rapidly than similar ponds not receiving the pre-filling manure treatment. And finally, a layer of manure can improve water conservation by reducing pond water seepage (Teichert-Coddington et al., 1989).

The third pre-filling activity is to add agricultural limestone (CaCO_3) to the sediments—liming the pond. Liming benefits the pond in two ways. First, it increases alkalinity (or buffering capacity) in the water. Increasing buffering capacity is especially important in ponds built on acid sulfate soils, common in some tropical coastal areas. Negating soil acidity keeps pond water pHs within acceptable ranges for algae, zooplankton, and culture organisms (Boyd, 1990; Boyd and Daniels, 1993). Second, liming increases the DIC pool by adding carbonates to the water, which can increase algal productivities in rain-fed ponds and other ponds with low alkalinities or DIC availabilities.

There are a number of published guidelines on determining lime requirements (e.g., Boyd and Cuenco, 1980; Pillay and Boyd, 1985; Boyd, 1990). Lime requirements are best calculated according to individual pond sediment characteristics, however, because generalized liming recipes may not adequately address a culture pond's specific needs. For example, Bowman and Lannan (1995) developed simplified methods for estimating lime requirements which account for local soil types. Interactive computer models are also available for determining lime requirements for specific pond conditions (Lannan et al., 1993; Bolte et al., 1994).

The final pond-sediment management technique discussed here involves the stirring or mixing of pond sediments during the grow-out or culture period. This can be accomplished with large rakes, and is done to increase decomposition of settled organic matter and to mix nutrient-rich interstitial water into the water column (Costa-Pierce and Pullin, 1989).

The net utility of this activity depends in great part on how long pond sediments remain resuspended in the water column. Ponds with very sandy soils may benefit because sand settles very quickly. In most ponds, however, increased turbidity from pond-sediment raking will lower algal productivity due to reduced light availability, reduce the percentage of algae and algal-derived detritus in the total suspended solid concentration, potentially increase sediment P adsorption by exposing inorganic sediments, and likely disturb culture organisms with the raking and subsequent inorganic turbidity. When factoring in the labor required together with the above detrimental environmental impacts, pond raking is considered more as a remedial option to rehabilitate ponds already heavily fertilized with manures.

Structures for Pond Culture

The complexity and diversity of a pond culture system can increase with the addition of specialized structures in the pond. Discussed below are three structures (cages, pens, and hapas) used to segregate or contain culture organisms in a pond, and a fourth device (bamboo and baffles) used to increase attached algal biomass. The beneficial utility of these structures depends in part on the farmer's awareness of associated ecological and economic implications.

Cages

A common aquaculture practice is to raise culture organisms in floating cages suspended in rivers, canals, and ponds. When in ponds, there is an opportunity to increase fish yields by stocking planktivorous fish outside the cages. A good example is raising catfish in cages situated in a pond filled with Nile tilapia (Lin, 1996). The catfish are fed pelleted food. The tilapia outside the cages benefit from spilled pelleted food, as well as from natural foods produced through pond fertilization from N and P released from decomposing feeds and from catfish excretions. Additional fertilization necessary to maintain high algal productivities in the pond may be reduced considerably. Initial research on intensive feeding of large Nile tilapia in cages placed in ponds stocked with Nile tilapia fingerlings also looks promising (Yi et al., 1996).

In making the decision whether to use cages in ponds, the farmer should consider potential ecological and economic consequences. The addition of organic matter (i.e., pelleted feed) increases the oxygen demand in the water, as well as in pond sediments if the pellets sink to the bottom. Water beneath cages should be sufficiently deep to permit lateral water movement and avoid stagnation. Capital investment costs include the construction and maintenance of cages. Nevertheless, additional yields of marketable fish could make polyculture with durable cages economically beneficial for the farmer.

Pens

Pens are established in ponds by attaching plastic netting to vertical poles inserted into pond sediments, thus forming net enclosures. Similar to cages, these enclosures can segregate fish of different sizes or different species to allow for more diverse aquaculture in a single pond. Pens are open both at the bottom and top, enabling water to mix vertically down to pond sediments within the enclosure. The primary ecological concern with pens is the potential restriction of horizontal water movement if the netting becomes clogged with attached microbial growth. Restricted lateral water movement could increase the possibility of incomplete vertical

mixing, which could create a potentially toxic bottom layer of deoxygenated water in the pen. Routine monitoring of the netting, however, should reduce this risk considerably.

Hapas

Hapas are net containers often put in ponds or large tanks to raise fish fingerlings (e.g., Argue and Phelps, 1995). Unlike pens, there is netting on the bottom as well as the sides of the hapas. Ponds are fertilized, and the fingerlings feed on natural foods which pass through the netting. The main issue is water circulation in and out of the hapa, which is necessary for waste removal, water temperature control, and prevention of deoxygenation in the hapa. Similar to pens, keeping the netting clean and unclogged is essential. Relatively large hapas can physically restrict water movement and wind mixing within the pond, so organic fertilizers should be used cautiously in these systems. As with cages, there should be sufficient water movement beneath the hapas to reduce the threat of deoxygenation of bottom waters.

Bamboo and Baffles

Some culture species (e.g., Nile tilapia) are capable of scraping attached algae off submerged rocks and rooted aquatic plants (Bowen, 1982; Lowe-McConnell, 1982). Aquaculturists have taken advantage of this fact by placing vertical substrates in ponds to increase growth of attached algae. In extensive systems (i.e., without fertilization), the addition of bamboo poles inserted vertically into pond sediments has had some apparent benefit for farmers of the Ivory Coast (Welcomme, 1972; Hem and Avit, 1996). The principal drawback is the amount of labor required to insert the poles and remove them again for harvesting.

Although there may be a benefit in extensive aquaculture systems, research on the utility of vertically placed baffles discourages their use in fertilized culture ponds. Shrestha and Knud-Hansen (1994) reported that yields of Nile tilapia were actually lower (though not significantly) in ponds with baffles. Baffles hindered water movement and reduced light availability for planktonic algae, thus negating any additional benefit with respect to overall pond productivity. Additionally, baffle fabrication, installation, maintenance, and removal for harvesting culture organisms would represent a significant labor cost to the farmer.