Chapter 2. Ecological Concepts Related to Pond Production

There are a variety of aquaculture facilities used to raise fish from fingerlings to marketable size. For semi-intensive culture systems, the most common facility is the earthen pond. Although concrete tanks may also be used, they are more frequently associated with recirculating systems raising culture organisms in intensive, feedlot operations. Because recirculating systems commonly have some form of water treatment as part of the water recirculation, which greatly alters natural processes, this topic is beyond the scope of this book. The focus here is on the earthen pond ecosystem, and the biological, chemical, and physical interrelationships which can direct the aquaculturist/farmer towards a resource-efficient fertilization strategy.

The central ecological concept in a fertilized pond is biological production, or the creation of organic matter. Ponds are fertilized to grow natural foods, which in turn are used to grow culture organisms. Biological production in ponds is best viewed as part of a dynamic process of algal nutrient uptake, incorporation, and recycling, rather than a linear production model of nutrient inputs and organic outputs. Therefore, the ecological focus of this book is on the mechanisms and factors that control algal nutrient cycling in a pond, and their impacts on nutrient availability and algal production. The first section of this chapter discusses biological production, formation of detritus, and decomposition of organic matter. The second section examines physical properties of pond ecology which affect biological production.

Biological Production

Primary and Secondary Production

The biological production of organic matter requires an independent source of energy. The source of this energy, either from solar radiation or from the oxidation of previously created organic matter, distinguishes primary from secondary production, respectively.

More specifically, primary production refers to the production of plant organic matter through photosynthesis. Photosynthesis is a photobiochemical process in which light energy is utilized to convert water (H_2O) and carbon dioxide (CO_2) into organic matter, with oxygen (O_2) released as a by-product (Bold and Wynne, 1978). Equation 1 illustrates the photosynthetic process, with organic matter generically represented by the molecule CH_2O.

$$H_2O + CO_2 \xrightarrow{\text{light energy utilized}} \underset{\text{organic matter}}{CH_2O} + O_2 \qquad [1]$$

Plant material produced through photosynthesis is called primary production because of its utilization of light/solar energy in the process.

In contrast, secondary production refers to the creation of living organic matter by an organism from the breakdown of other organic matter. The energy released in this breakdown becomes available for the organism's metabolic needs, for production of new organic matter from ingested nutrients, and for physical activities. Growth of animals, bacteria, and fungi occurs through this process. Equation 2 illustrates the general process, which conceptually is the reverse of the photosynthetic equation above.

$$\underset{\text{organic matter}}{CH_2O} + O_2 \xrightarrow{\text{biochemical energy released}} H_2O + CO_2 \qquad [2]$$

Equation 2 also represents the biological process known as respiration. With the exception of anaerobic (i.e., able to live without oxygen) microorganisms, essentially all living organisms require oxygen to respire. The uptake of carbon dioxide and release of oxygen during photosynthesis, together with the subsequent uptake of oxygen and release of carbon dioxide during respiration, represent a core dynamic process in pond ecology.

Primary production in a pond can be accomplished by several types of plants. For the fish farmer, production of tiny microscopic plants called algae is usually of most concern. Although there are thousands of different species, algae can be divided into three general groups based on their physical location in the pond. The first group of microscopic plants is called phytoplankton, which are nearly buoyant in the water column with little or no ability to control their movements (Fogg, 1975). When phytoplankton production in a freshwater pond is great, the pond takes on a greenish color. A green pond is desirable when primarily natural foods produced in the pond are used for raising culture organisms, e.g., filter-feeding fish such as Nile tilapia (*Oreochromis niloticus*).

The second group is floating algae, which have gas vacuoles enabling them to rise to the pond's surface, and thus giving them a competitive advantage by providing greater access to atmospheric carbon dioxide, atmospheric nitrogen (see discussion of nitrogen fixation in Chapter 3), and sunlight (Bold and Wynne, 1978). Although only a limited number of species have this ability (found in the taxonomic group commonly known as blue-green algae or cyanobacteria), high production of these algae can produce surface scums which can block light and reduce algal productivity in the waters below (Fogg, 1975; Paerl and Tucker, 1995). With reduced photosynthesis there is less oxygen produced in the water, and therefore less oxygen available for fish respiration and microbial decomposition of organic matter. Surface scum not only reduces primary production in the water column, but can also create conditions causing severe oxygen stress for aquatic animals.

The third group, attached algae, lives on rocks, pond sediments exposed to sunlight, and rooted aquatic plants growing along the banks. Many species of attached algae, which often appear as a brown or greenish slime, can be found in the phytoplankton community as well. Some fish, such as Nile tilapia, have the ability to scrape attached algae off rocks (Bowen, 1982; Lowe-McConnell, 1982; Shrestha and Knud-Hansen, 1994).

As illustrated in Equation 1, plants require carbon (C) in the form of carbon dioxide (or other forms of inorganic carbon as discussed later), water, and sunlight to grow photosynthetically. Additionally, plant growth requires nitrogen (N), phosphorus (P), micronutrients, and suitable water temperatures. Micronutrients, such as manganese (Mn), iron (Fe), copper (Cu), silica (Si), potassium (K), cadmium (Cd), and zinc (Zn), are essential elements required only in trace amounts (Bold and Wynne, 1978; Goldman and Horne, 1983). Plant growth can be described by Equation 3:

$$C+N+P+\text{micronutrients}+\text{water}+\text{light}+\text{favorable temperature} \rightarrow \text{plant growth} \qquad [3]$$

Biological production can also be referred to as biomass, or standing crop. A measurement of biomass is like a photograph or snapshot in time, and only tells you the amount of organic matter present at the time of measurement. Biomass values do not indicate anything about the condition or quality of the organisms measured. In aquatic ecology, biomass is often given as weight per unit volume (e.g., kg m^{-3}), or per unit surface area of the water (e.g., kg m^{-2} or kg ha^{-1}). Fish harvest yields or chlorophyll *a* concentrations are examples of biomass measurements. Concentrations of chlorophyll *a,* the primary pigment used by algae for the capture of light energy for photosynthesis, are often used to estimate algal biomass in water (Wetzel and Likens, 1979; APHA, 1985).

In contrast to biological production or biomass, biological productivity describes the *rate* of biological production. Productivity indicates how fast biomass is produced within a given time period (e.g., kg ha^{-1} d^{-1}). High algal standing crop, as indicated by high chlorophyll *a* concentrations, does not necessarily indicate high algal productivities. In fact, algal productivities can be quite low following an algal bloom (i.e., period of high algal productivity and high production) due to a depletion of algal nutrients and light in the water column (Fogg, 1975). On the other hand, coral reefs have very little algal standing crop but are among the most productive ecosystems on the planet. Filter feeding organisms and fish scraping attached algae off rocks keep the algal biomass low, but the rapid recycling of algal nutrients through digestion and elimination keeps algal productivities high.

Productivities can be described in terms of changes in production over time. Equation 4 illustrates this relationship:

$$\text{Productivity} = \frac{(\text{Standing crop at time } T_1) - (\text{Standing crop at time } T_0)}{T_1 - T_0} \qquad [4]$$

For example, if 10 kg of fish were stocked in a 0.5-hectare pond (i.e., 20 kg ha^{-1}), and 100 days later 1,000 kg of fish were harvested (i.e., 2,000 kg ha^{-1}), the net fish yield (NFY) would be:

$$\frac{2{,}000 \text{ kg ha}^{-1} - 20 \text{ kg ha}^{-1}}{100 \text{ d} - 0 \text{ d}} = 19.8 \text{ kg ha}^{-1} \text{ d}^{-1}$$

Since the goal is to grow small fish into big fish as quickly as possible, increasing fish productivity, and not necessarily fish production, should be the objective. Fish production (here, 2,000 kg ha^{-1}) is only a snapshot in time without any indication of how long it took to reach that value. Fish productivity (here, NFY = 19.8 kg ha^{-1} d^{-1}) measures how quickly fish biomass is being produced, and allows the farmer to estimate how long it should take to reach a desired level of fish production. Although fish growth rates are not necessarily linear during the culture period (Hopkins, 1992), NFYs can provide a convenient way to estimate economic rates of return based on average daily fertilization rates and expenses.

Algal productivities are most readily calculated by measuring changes in dissolved oxygen (DO) in the water (Oláh et al., 1978; Wetzel and Likens, 1979; Boyd, 1990). Oxygen is produced during photosynthesis (Equation 1), and increases in algal biomass are indicated by corresponding increases in dissolved oxygen concentrations during a specific time period (e.g., mg O_2 l^{-1} h^{-1} or d^{-1}).

Because algae, along with all other living organisms in the pond, also utilize dissolved oxygen at the same time, algal productivity can be described as net productivity (NP) or gross productivity (GP). NP indicates the net amount of organic matter produced over a given time, accounting for losses due to respiration. On the other hand, GP refers to the total amount of algal production theoretically assuming no respiration. Since organisms which comprise natural foods for culture fish do respire, NP more accurately indicates the rate of algal-based food availability.

Accurate and precise measurements of a pond's NP are very difficult, if not impossible, to obtain because of diel (i.e., 24-hour) variations in photosynthetic and respiration rates, rate differences with pond depth, and inherent methodological problems (Oláh et al., 1978; Chang and Ouyang, 1988). For comparative purposes, however, pond NP can be systematically estimated by net changes in DO concentrations between theoretical minimum and maximum values as measured in the water column just before dawn and at mid-afternoon (Hall and Moll, 1975). Although in highly productive ponds some DO may be lost to the atmosphere through oxygen supersaturation in surface waters (Boyd, 1990; Boyd and Teichert-Coddington, 1992), net changes in DO still provide a good relative parameter to compare algal productivities between ponds, or within the same pond over time (Knud-Hansen et al., 1993; Knud-Hansen and Batterson, 1994).

Not surprisingly, it is well established that the rate of production of fish raised on natural foods in a fertilized pond is directly related to the rate of net algal production (McConnell et al., 1977; Almazan and Boyd, 1978; Liang et al., 1981; Oláh et al., 1986). Figure 1 illustrates this relationship, with NP estimated from diel DO measurements (from Knud-Hansen and Batterson, 1994). In other words, NFY is proportional to NP, *not* to algal standing crop. As an analogy, visualize a snapshot of a child sitting in front of a large plate of food. The photo tells you only that there was a child in front of lots of food. However, food must be supplied on a daily basis or the child will not grow and may even starve, regardless of how much food is present at the time of the photograph. The *rate* of food availability will affect the rate of the child's growth, not how much food was observed in the snapshot. Given the added difficulty of accurately measuring repre-

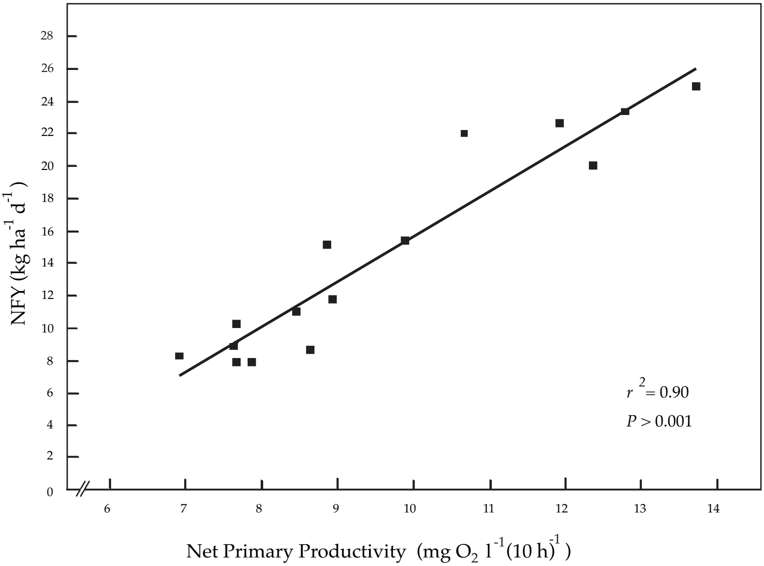

Figure 1. The relationship between net fish yield (NFY) and net primary productivity (NP) in a five-month grow-out of Nile tilapia in earthen ponds (adapted from Knud-Hansen and Batterson, 1994).

sentative chlorophyll *a* concentrations in a dynamic fish pond, the typically poor chlorophyll *a* versus NFY relationships often described in the literature are not surprising.

Detritus

Algal productivity is the cornerstone of biological productivity in a fertilized pond. Algae have life cycles of the order of several hours to several days (Fogg, 1975). Living algae, if not fed upon by animals, die and slowly settle to the bottom of the pond. This settling process may take many hours in a perfectly still pond, but with water mixing due to swimming fish, wind, and thermal density gradients (discussed more fully at the end of this chapter), dead and decaying algae can remain in the water column for days (Lorenzen et al., 1983). This non-living particulate organic matter is called detritus, and dead algae represent by far the dominant source of detritus in a productive fertilized pond (Rodina, 1963; Rodina, 1966; Golterman, 1972; Schroeder et al., 1990).

Although in a continual process of decomposition, algae-derived detritus generally represents a good source of food for filter-feeding culture organisms. The nutritional value of the detritus is enhanced by living bacteria, fungi, attached algae, and microinvertebrates (i.e., microscopic animals such as rotifers and Cladocerans) which colonize dead algae and detrital aggregates (Paerl, 1977; Halemejko and Chrost, 1986). Since this derivative food source comes from living algae, more detritus is generated in the water column as NP increases.

The microinvertebrates colonizing suspended detrital particles, together with microinvertebrates swimming freely in the pond, are collectively known as zooplankton. The growth of zooplankton is part of secondary production, as is the growth of other non-plants in the pond, including the culture organisms and unintentional inhabitants such as snails, clams, and crabs.

Zooplankton biomass is very difficult to measure in shallow, dynamically active culture ponds. In quiescent waters, zooplankton populations are often found in patches of dense concentrations, and representative samples are nearly impossible to collect. Furthermore, their swimming abilities enable them to migrate to the bottom during the day and back to the surface at night. This diel migration, an adaptive behavior to avoid predation, also enables zooplankton to avoid collection traps and devices (Goldman and Horne, 1983).

Aquaculture research often includes zooplankton concentrations, but without documentation of adequate and scientifically representative sampling techniques, the data are probably best evaluated qualitatively rather than quantitatively.

Decomposition

Decomposition can be thought of as another process of secondary production. Whether it occurs in the guts of animals, in detrital aggregates, in the breakdown of dissolved organic matter (e.g., from secretions, excretions, leaching of recently dead plants and animals), or in dead organisms settled on pond sediments, decomposition involves the growth of bacteria and fungi from the utilization of non-living organic matter.

The rate of decomposition is naturally related to the rate of organic matter availability. If ponds do not receive organic fertilizers, decomposition rates are proportional to algal productivity. Since oxygen is consumed during the breakdown of organic matter, the rate of oxygen consumption will be proportional to the rate of oxygen produced during the photosynthetic production of organic matter. Adding non-living organic matter (e.g., manures, pelleted feeds) to a pond can upset this balance; associated environmental consequences affecting water quality and pond management are discussed in Chapter 4.

Although much decomposition occurs in the water column, partially decomposed organic particles not resuspended through pondwater mixing will accumulate on the pond bottom. If the water immediately overlying the sediments is not mixed, then this water will also accumulate soluble by-products of decomposition. The two main by-products of decomposition are ammonia and carbon dioxide. If the overlying water has been stripped of its dissolved oxygen and becomes anaerobic, molecules such as phosphorus, iron, and sulfides become more soluble and will increase in concentration. Hydrsulfide (H_2S), which gives off a rotten egg odor, is particularly worrisome because of its high toxicity to fish and other aerobic (i.e., requiring oxygen to live) organisms (Boyd, 1990).

Physical Properties Related to Pond Production

Although a comprehensive discussion of this subject could extend to several volumes, discussion here is limited to only two general concepts which have important implications in pond ecology and fertilization theory. The first topic examines thermal characteristics of pond water, while the second section discusses water turbidity and its effects on pond productivity.

Thermal Characteristics of Pond Water

Pond water temperature is not static, but changes in relation to a pond's gains and losses of thermal energy (Wetzel and Likens, 1979). The primary source of heat is the sun. Solar radiation is absorbed directly by the water and by the suspended materials in the water column. Solar energy penetrates deeper in clearwater ponds than in waters with high concentrations of dissolved and particulate constituents, where energy is rapidly absorbed and only surface waters are warmed. Direct contact of air at the pond's surface can also cause transfer of some thermal energy, which can occur in either direction depending on the relative temperatures of the surface water and the air above.

In addition to direct contact with relatively cooler air, the primary ways a pond loses heat from its surface waters are from evaporative cooling and thermal radiation losses (Goldman and Horne, 1983; Chang and Ouyang, 1988). Evaporative cooling is a function of several factors including air temperature, relative humidity, and air movement over the water. A useful biological analogy is the evaporative cooling function of perspiration in humans. Thermal radiation losses occur when the surface water temperature is warmer than the air above it, similar to the heat radiated from a pie just out of the oven. In summary, ponds typically lose more heat during the nighttime, particularly when the air is relatively cool, the skies are clear (i.e., low relative humidity), and there is some wind (Chang and Ouyang, 1988).

Unless the pond water is completely mixed, water temperatures typically exhibit a vertical gradient or stratification with pond depth. Thermal stratification refers to the horizontal separation of a relatively warmer surface layer of water from the cooler bottom waters. The principle behind thermal stratification is that water increases in density (i.e., gets heavier per unit volume) as it gets colder, to about 4°C (Wetzel and Likens, 1979). Conceptually, warmer, less dense water floats on top of cooler, more dense water.

To illustrate, assume that a culture pond is completely mixed before dawn due to nighttime cooling (Figure 2a). On a calm day, a thermal density gradient may develop as soon as the morning sun begins to heat the pond's surface water (Figure 2b). If the pond has a lot of phytoplankton and/or suspended sediments, absorption of solar energy may be restricted to the upper 10 to 20 cm. As surface waters continue to warm, bottom waters remain cool because the particulate matter suspended in the surface waters has absorbed most of the incoming solar radiation. Even in a 1-meter-deep pond, differences between surface and bottom pond water temperatures on a sunny day can exceed 5°C.

If winds pick up during the day, surface waters can mix down only to the depth where the density gradient is not too severe to be overcome (Figure 2c). By mixing warmer water down to the point where the water density is too great to be disturbed, a relatively strong thermal/density gradient develops, which maintains the separation and prevents upward mixing of bottom waters. This severe density gradient, or thermocline, should be familiar to most people who have jumped into a lake on a warm afternoon.

The thermocline will persist as a barrier to whole-pond mixing until the energetics are such that this barrier can be overcome. There are two general ways that mixing can occur naturally. First, when the surface waters cool down, the thermal gradient between surface and bottom waters is reduced and mixing occurs. As discussed above, this can happen during nighttime heat loss to the atmosphere and from evaporative cooling. The second mechanism occurs when sufficient physical energy is supplied to break down the density gradient. This energy can come from such sources as wind or a cold driving rain, which would reduce surface water temperatures as well as provide energy for mixing (Goldman and Horne, 1983; Chang and Ouyang, 1988).

The concept of thermal stratification has critical importance in fertilized, warmwater aquaculture ponds. Remember that oxygen is photosynthetically produced in surface waters exposed to light, and decomposition/respiration processes require oxygen to break down organic matter. If bottom waters are separated from surface waters by a thermocline, oxygen-rich surface waters cannot be used to meet the oxygen

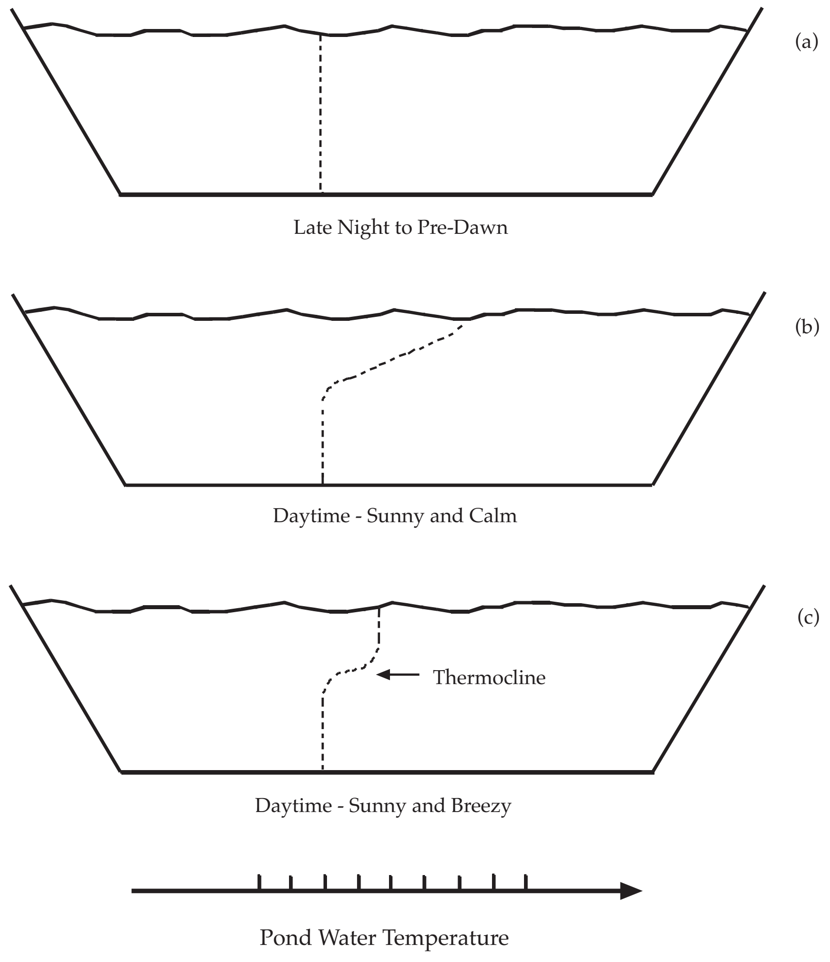

Figure 2. Typical temperature curves in a 1-m pond illustrating (a) whole pond mixing from late night to pre-dawn, (b) daytime warming of surface waters on a calm day, and (c) the establishment of a daytime thermocline as surface waters mix down to the cooler bottom waters.

demand for respiration in the pond sediments. In a productive pond, oxygen depletion at the sediment/water interface may occur within days if dissolved oxygen (DO) is not available from surface water. If the pond is thermally stratified, the layer of bottom water can become void of dissolved oxygen (i.e., anoxic) and rich in soluble carbon dioxide, ammonia, phosphorus, and hydrogen sulfide. The longer the pond remains stratified, the greater the accumulation of these dissolved compounds (Chang and Ouyang, 1988; Chang, 1989; Szyper and Lin, 1990).

When the pond does finally mix, perhaps after a good rain or wind storm, anoxic waters with high hydrogen sulfide concentrations may be sufficiently lethal to kill all the culture organisms (Chang, 1989). However, the influx of soluble inorganic P, N, and C from the bottom waters, a mechanism also referred to as internal fertilization, usually causes high algal productivity and a subsequent algal bloom (i.e., high algal biomass concentrations). When the thermocline forms again and these algae die off, the cycle repeats itself. Through these observations, farmers mistakenly associate a causal relationship between fish mortality and green ponds. It is important to recognize, however, that persistent thermal stratification followed by whole-pond mixing is the determinative factor which can result in a mass mortality, *not* high algal productivities.

Experience has shown that thermoclines that develop on warm sunny days and disappear when nighttime cooling causes surface water to sink to the bottom may actually provide some benefit to the pond. Carbon dioxide, soluble phosphorus, and ammonia accumulated in bottom waters during the day internally fertilize the pond during nighttime mixing, while oxygen-rich surface waters are transported to the sediments, facilitating decomposition of settled organic matter. If stratification persists for more than a few days, however, the farmer risks a massive fish kill.

Turbidity

Turbidity refers to the concentrations of particulate organic and inorganic matter suspended in the water column of a pond. Organic turbidity consists primarily of phytoplankton and algae-derived detritus, zooplankton, and fecal matter from culture organisms. Sedimentation of this organic matter can take days, and even longer if the material is resuspended through wind mixing and biological activity.

Inorganic turbidity usually consists of fine clays and silts which enter the pond from surface runoff from rainfall and from pond bank erosion. Suspended inorganic matter in pond water is also caused by within-pond activities including resuspension of pond sediments from wind mixing, and bioturbation from culture organisms. For example, the nesting behavior of Nile tilapia (even sex-reversed males) involves scouring half-meter-diameter craters in the pond sediments. Fish that feed on bottom-dwelling organisms and sedimented organic matter, such as the mud carp

(*Cirrhina molitorella*) and mrigal (*Cirrhina mrigala*), also stir up pond sediments (Havens, 1991; Riise and Roos, 1997). The amount of bioturbation is proportional to fish size (Krom et al., 1985), and a significant amount of dissolved nutrients can also be transported from the sediments through this activity (Blackburn et al., 1988).

Analytically, the organic and inorganic suspended matter collectively is called total suspended solids (TSS). TSS can be quantitatively determined by measuring the difference in filter dry weight before and after filtering a measured volume from a representative water sample (APHA, 1985). The weight loss of the filtered material after combustion in a high-temperature oven can provide a reasonable approx imation of the organic component of the TSS. The organic matter is combusted primarily to carbon dioxide, leaving the inorganic ash remaining on the filter (the filter is made of glass fibers so as not to combust). This weight loss is therefore referred to as ash free dry weight (AFDW) (APHA, 1985).

Determining the percent organic fraction of the TSS provides additional understanding of a pond's ecology. Fertilized ponds with high percentages of AFDW are generally quite green, and not a muddy brown as when inorganic sediments dominate the water column. High TSS concentrations may not be desirable if the percent of AFDW of the TSS is relatively low (e.g., less than 20%). This would indicate high inorganic turbidity, which is not desirable in a pond fertilized to raise filter-feeding organisms.

There are several reasons why inorganic turbidities should be avoided in culture ponds. First, the suspended sediments absorb light radiation which would otherwise be available for algal photosynthesis. Diminished light availability caused by increased turbidity reduces photosynthesis and nutrient uptake by algae, and therefore creates a surplus of algal nutrients in the water. Second, clay particles readily adsorb phosphorus and ammonia making them less available for algal nutrition, and the settling of these particles may remove algal nutrients from the water column (Grobbelaar, 1983). And third, filter-feeding organisms must contend ener getically with reduced concentrations of digestible matter in the filtered material. Consequently, inorganic turbidity can reduce both fertilization efficiency and economic return. Pond management considerations for minimizing inorganic turbidity are discussed in Chapter 5.