Pond Fertilization: Ecological Approach and Practical Application

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by

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For Fritzi, who taught me the value of a productive life, and
For John, who taught me how to reason

Preface

Pond aquaculture has evolved from traditional farming practices in ancient China to a position of global significance, particularly regarding efforts to increase sustainability of human food production in lesser-developed, tropical countries. Rapid increases in human populations have contributed to the corresponding destruction of natural aquatic habitats and subsequent losses of native animal and plant species. Consequently, pond aquaculture is becoming increasingly relied upon as an important source of dietary protein and as a means for rural farmers to gain economic wealth.

The purpose of pond fertilization is to enhance natural food production within the pond for consumption by aquatic culture organisms. The foundation of natural food production in culture ponds is the growth of tiny aquatic plants, collectively known as algae. The production of other natural foods, such as microscopic animals, increases proportionally with algal production. Therefore, fertilizers are typically selected for their abilities to provide essential algal nutrients and stimulate algal productivity. The sustainability of such as aquaculture system depends on:

1) How efficiently the fertilizer(s) deliver(s) soluble algal nutrients when needed;
2) The relative magnitudes of positive and negative impacts on pond ecology when using the chosen fertilizer(s); and
3) How economical the fertilizer(s) is(are) with respect to actual farm costs, and in light of 1) and 2) above.

This book provides an ecological overview of pond fertilization, and examines the above-listed general issues of pond-culture sustainability with respect to relevant, dynamic processes within a pond ecosystem. The focus here is on freshwater earthen ponds, but most

discussions are also applicable to brackish water ponds. Because the principles of freshwater ecology are universal, emphasis is placed on understanding basic biological, chemical, and physical mechanisms and interrelationships (i.e., pond dynamics) which ultimately guide the formulation of rational fertilization strategies. Economic issues are raised to highlight direct and potentially hidden farm costs associated with fertilizers selections and their consequential impacts to pond ecology, but discussions are intentionally brief and non-quantitative.

The emphasis in this book on dynamic processes within a pond ecosystem is in contrast to the traditional "results" approach to aquaculture experimentation, where a pond is treated as a "black box," where dynamic processes are essentially ignored or just summarized in tables, and where meaningful analyses are often limited to fish yield comparisons. A fertilization strategy is usually deemed successful if more and bigger fish are harvested, and unsuccessful if the opposite occurs. Conclusions/recommendations are often applied to broad geographic regions or national borders, completely failing to appreciate the importance of each pond's unique ecological characteristics in understanding seemingly random responses to different fertilization strategies.

The main difference between most fertilization research and this book is focus. Fertilization research emphasizes the production of culture organisms under very controlled and site-specific experimental conditions, whereas the focus here is on general ecological factors which influence the production of natural foods for culture organisms. Stimulating algal growth and producing natural foods are the purposes of fertilizing ponds. Consequently, fertilization research which did not focus on or provide additional knowledge regarding principles of pond dynamics was not discussed in this book. On the other hand, the wide variety of seemingly incompatible conclusions generated from fertilization studies are best understood/harmonized with the context of pond ecology.

The general approach used in this book is to first describe the ecological components necessary to better understand potential applications and limitations of existing fertilization strategies. If pond fertilization can be thought of as a jigsaw puzzle, then the various aspects of pond dynamics are the puzzle pieces. In order to produce a

clear picture with the pieces, however, emphasis is placed on relevant ecological concepts and how interrelationships between these dynamic processes (i.e., puzzle pieces are discussed only to the extent necessary to appreciate their ecological significance in pond fertilization. Not only does this keep the book considerably shorter, but it avoids needless repetition of detailed analyses more thoroughly presented in standard limnology text books (e.g. Wetzel, 1983; Goldman and Horne, 1983) and Boyd's (1990) book on water quality for aquaculture ponds.

Specifically, the book is organized as follows: After a brief introduction of aquaculture's historical roots and ever-increasing need for economic efficiency, Chapter 2 focuses on relevant concepts of pond ecology. Topics in this chapter include aspects of biological production (e.g., primary and secondary production, detritus, decomposition) and physical factors (e.g., thermal stratification, turbidity) which affect algal nutrient availability. Chapter 3 examines algal nutrient dynamics, emphasizing phosphorous, nitrogen, and carbon cycling, and a discussion of the factors which limit and control the rate of algal production. Chapter 4 presents a comparative analysis of organic (i.e., animal and green manures) and chemical fertilizers commonly used in pond fertilization. Included in these analyses are such considerations as costs per unit of algal nutrient, associated labor and transport costs, and consequential impacts on pond ecology. Chapter 5 examines pond characteristics that can affect pond fertilization decisions. Included in this chapter are discussions of pond location, pond size, source water, pond sediments, and the use of specialized structures (e.g., cages and hapas) in ponds. Chapter 6 focuses on actual fertilization strategies within the framework of pond ecology. Discussions of commonly used approaches are distinguished by whether fertilization needs are determined before pond filling (i.e., fixed predetermined input rates) or during or during the culture period (i.e., water/sediment chemistry, computer modeling, and algal bioassays). Chapter 7, which comes at the request of one of the reviewers, summarizes my thoughts on possible research directions to further the scientific understanding of pond aquaculture and the production of natural foods for culture organisms, and how to approach fertilization research in general. This chapter is organized along the same lines as the rest of the book, with separate discussions

on pond ecology, fertilizers, and methods for determining pond fertilization requirements. The final discussion focuses on the nature of experimentation I feel fertilization research should be taking to fill in the gaps in our collective knowledge. Appendix 1 provides a detailed description of an algal bioassay method suitable for rural farmers, which is used to identify pond-specific fertilization requirements. Appendix 2 is a summary guideline which incorporates pond ecology and farm economics in the identification and selection of optimal fertilization strategies on an individual-pond basis.

This book was written under the premise that only by incorporating principles of pond ecology in fertilization decisions can a farmer or aquaculturist reasonably hope to optimize natural resource utilization, and attain predictably high and cost-efficient yields for each individual pond. For that reason, this book was written primarily for regional extension workers and educated farmers, as well as aquaculture students and scientists. No prior science background beyond high school biology and chemistry should be necessary to appreciate the general ecological concepts necessary for determining appropriate fertilization strategies. However, technical terminology and scientific concepts are presented in sufficient detail to enable the reader to better analyze and more knowledgeably benefit from previous and future aquaculture research.

This book is not a fertilization manual, and by ecological necessity avoids simplistic fertilization recipes. However, the book does provide the ecological knowledge and logical approach to fertilization which should help fish farmers worldwide achieve economic growth through more sustainable pond aquaculture.

Acknowledgments

The scientific foundation of this book is grounded in basic limnology (freshwater ecology). Limnologists and ecologists who have helped shape my understanding of limnology include Charles M. Weiss, Charles R. Goldman, William M. Lewis, Jr., Jay Windell, Cal McNabb, and Ted Batterson. Much of the aquaculture research discussed in this book was a product of the Aquaculture Collaborative Research Support Program (Aquaculture CRSP), funded by the United States Agency for International Development, and a project with which I have been associated since 1985.

Conceptually, this book has been in development since 1988, when I began five years of pond fertilization research at the Asian Institute of Technology (AIT, Bangkok, Thailand). Important in my conceptual understanding of pond ecology and fertilization theory were a great number of valuable discussions with fellow AIT faculty including Peter Edwards, David Little, C. Kwei Lin, Amararatne Yakupitiyage, and Joseph Gartner, as well as with several AIT graduate students including Hans Guttman and Latha Shevgoor. Equally important were discussions with other CRSP scientists including Raul Piedrahita, Cal McNabb, Ted Batterson, Kevin Hopkins, and Jim Szyper.

The actual production of this book could not have been possible without the help and technical assistance of Hillary Egna, Director of the Aquaculture CRSP. For her enthusiastic and total support I am sincerely grateful. My sincere gratitude also goes to three anonymous reviewers, whose insights and technical comments significantly improved the quality of this book. A special thanks goes to Kevin Hopkins for his candor, thoughtful criticism, and friendship. I am also grateful to Sayea Jenabzadeh, Kris McElwee, John Baker, Matt Niles, Danielle Crop, and Danielle Clair, all the Aquaculture CRSP, for their individual contributions to seeing the manuscript through to publication. Finally, heartfelt thanks go to my wife Dhori and our two children, Marissa and Brent, for their encouragement, patience, and tolerance in this effort.

Chapter 1. Introduction

Aquaculture is the cultivation of aquatic species under controlled or semi-controlled conditions. The origins of aquaculture date back millennia. The tomb of Ktihetep (about 2500 BC) contains a bas-relief which appears to show men removing tilapia from a pond (Landau, 1992). In addition, tilapia may have been the fish Saint Peter caught in the Sea of Galilee, and pond culture of tilapia may have been responsible for Christ's "miraculous" feeding of the masses (Borgese, 1977). In China, aquaculture's roots go back to between 1135 and 1122 BC when Wen Fang, besides being the founder of the Chou Dynasty, was reportedly the first to build aquaculture ponds and raise carp. Fan Li wrote the first treatise on carp culture, titled *Yang Yu Ching (Treatise on Fish-breeding)*, in 475 BC (Borgese, 1977; Landau, 1992).

Contemporary aquaculture systems can be categorized based on sources of nutrients/food used to raise the culture organisms. Aquaculture classified by food source falls into the three different culture techniques of extensive, semi-intensive, and intensive. Extensive aquaculture occurs where naturally occurring microflora and fauna supply all nutritional requirements. Semi-intensive culture occurs when ponds are intentionally fertilized with nutrients (e.g., manures, urea, phosphates) to stimulate natural food production, or when supplemental feed is added. Intensive culture is when the entire nutritional requirement is derived from external sources, such as complete moist pelleted feeds (Landau, 1992).

This book focuses exclusively on semi-intensive culture through the intentional addition of fertilizers to increase natural food production. This type of culture system is common throughout tropical Asia, Africa, and to a lesser degree, Latin America and the Pacific Islands. These systems are limited geographically to these tropical and semitropical regions because of the dual requirements of sufficiently high water temperatures and ample sunlight. It is important to keep in mind that the purpose of pond fertilization is to maximize/optimize natural food production without creating harmful environmental conditions for the culture organisms.

As will be discussed in following sections, natural food production is directly related to the rate of growth of tiny microscopic plants called algae—the greater the algal rate of growth, the greater the rate of natural food production. Natural foods include living

algae, microscopic animals which feed on algae, and detritus (particulate organic matter colonized by attached algae, bacteria, and fungi) formed upon the death and decay of algae, higher plants, and animals. Within environmental constraints, the growth rate of the culture organisms increases proportionally to increasing rates of natural food production. Insufficient light and cold water generally retard the growth of warmwater algal species, so the utility of pond fertilization decreases outside tropical regions of the world. Nevertheless, some of the most economically and nutritionally poor countries on the planet are in the tropics where efficient fertilization can have the greatest economic impact.

As the pursuit of sustainable development reaches a global scale, it is imperative that aquaculture farmers in these lesser-developed regions utilize the most nutrient-efficient, cost-effective, and environmentally friendly fertilization strategy(ies) to maximize both fish yields and personal incomes. Traditionally, fertilization research has been essentially trial-and-error studies evaluated primarily by yield comparisons, rather than focusing on actual dynamic processes which really determine the effectiveness of a particular fertilization strategy (Anderson, 1993a). Consequently, recommendations and conclusions based on such research are frequently too general and sometimes contrary to established ecological relationships.

Each pond is unique and will respond differently to identical fertilizations. By understanding basic principles of pond ecology and the limited number of identifiable variables which impact fertilization responses, the farmer can make intelligent decisions on a pond-by-pond basis as to what fertilizer(s) to use, the frequency and rate of application, when not to fertilize, how to most efficiently utilize avaiable natural resources, and how to maximize fish yields while minimizing expenses and environmental degradation. Empowering aquaculture extension workers and fish farmers with this knowledge is the overriding objective of this book.

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:

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

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:

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

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-

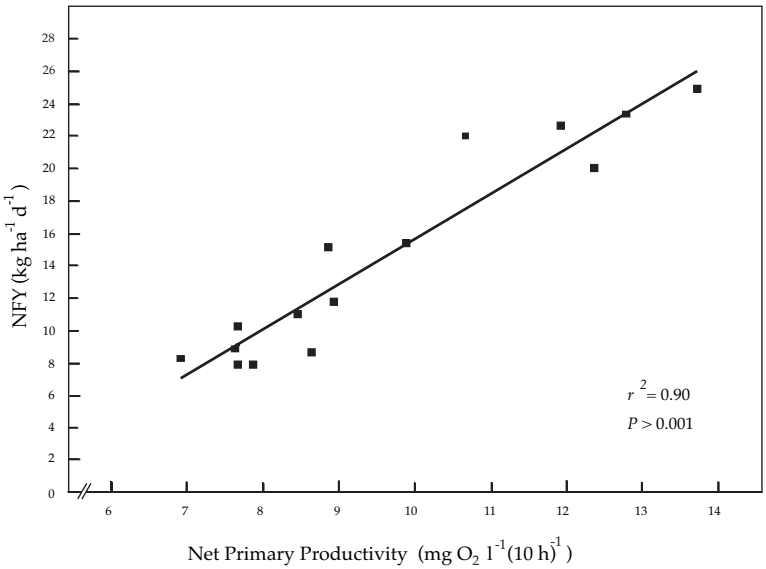


Figure 1. The relationship between net fish yield (NFY) and net primary productivity (NP) in a five-month grow-out of Nile tilapia in earthen ponds (adapted from Knud-Hansen and Batterson, 1994).

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

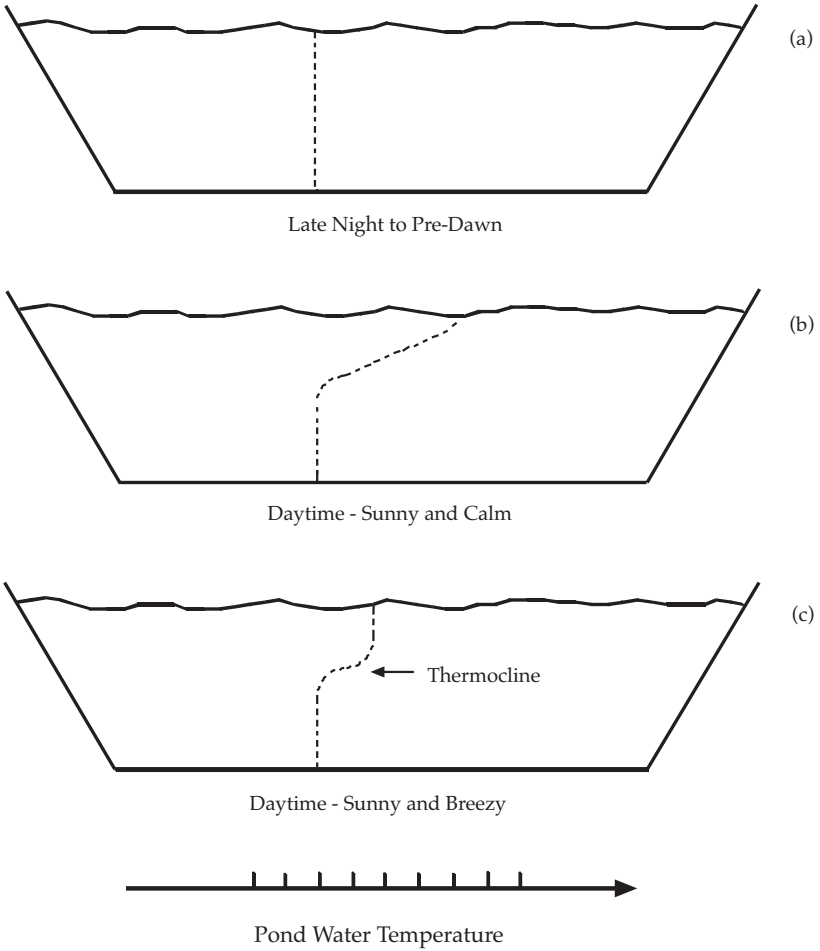


Figure 2. Typical temperature curves in a 1-m pond illustrating (a) whole pond mixing from late night to pre-dawn, (b) daytime warming of surface waters on a calm day, and (c) the establishment of a daytime thermocline as surface waters mix down to the cooler bottom waters.

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, phospho-

rus, 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.

Chapter 3. Managing Algal Productivity

The preceding overview on biological productivity and physical processes sets the stage for a closer look at what makes algae grow. It should be clear that algal primary productivity is the driving force behind secondary productivity in a fertilized pond. By understanding what algae require to grow efficiently, we can direct our pond management towards creating the most favorable environmental conditions for algal productivity. This chapter first discusses those algal nutrients we are most concerned with in pond fertilization, and then presents the concept of nutrient limitation as a means of controlling algal productivity with greater fertilizer utilization efficiency.

Algal Nutrient Dynamics

As a general principle, algae require a supply of inorganic nutrients, sufficient light, and favorable temperatures to grow (Fogg, 1975; Bold and Wynne, 1978). The primary inorganic nutrients are P, N, and C. Of course hydrogen (H) and oxygen (O) are also essential for algal growth, but water (H_2O) provides an abundance of these elements and no further discussion of H and O is necessary in regards to algal nutrient requirements. Many other elements are needed for algal growth in lesser or often trace amounts, and are collectively referred to as micronutrients. For example, silica (Si) is needed by diatoms as a structural component for their rigid cell walls. Other micronutrients required for growth and enzymatic activity include calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), iron (Fe), manganese (Mn), sulfur (S), zinc (Zn), copper (Cu), and cobalt (Co) (Goldman and Horne, 1983).

It is also important to understand that different algal species do not have identical nutritional needs. The fertilization approach in this book, however, addresses the needs of the algal community as a whole. No attempt is made here to manipulate interspecific competition for algal nutrients, or to promote a particular algal species by managing resource availability. With that in mind, the following section examines in more detail the three primary algal nutrients: P, N, and C. Discussions focus on their sources, biological availabilities, and recycling dynamics in a productive pond.

Phosphorus

Of the three primary nutrients, phosphorus (P) is the most scarce in the natural environment. Weathering of phosphorus-containing rocks, agricultural and urban drainage, and atmospheric dust are the principal mechanisms for P to reach the aquatic environment. Phosphorus is also found in the waste products of animals and is released during the decomposition of organic matter (Boyd, 1971).

Once in the pond, however, P can be very dynamic (Hepher, 1958; Hepher, 1966; Syers et al., 1973). To best understand P dynamics it is important to recognize the different forms in which P can be found. Most broadly, P can be found either in particulate matter or in a soluble form (Table 1). Particulate forms can either be organic, such as phytoplankton, zooplankton, bacteria, fish, or detritus, or inorganic. Inorganic particulate P is represented largely by P adsorbed (i.e., attached by chemical ionic bonding) to suspended and settled sediments in the pond, or as precipitates formed with phosphate (PO_4) and iron (Fe), aluminum (Al), and calcium (Ca) (Hepher, 1965; McKee et al., 1970; Syers et al., 1973). Soluble P is also found in both organic and inorganic forms. The organic form consists of dissolved organic molecules such as polypeptides, enzymes (e.g., alkaline phosphatase), adenosine triphosphate (ATP), and organophosphates released into the water through decomposition, excretions, and secretions from

	Organic	Inorganic
Particulate	Living biomass Detritus Feces, etc.	P adsorbed to suspended sediments P precipitated in Ca, Fe, and Al complexes
Soluble	Enzymes Amino acids Waste products	Orthophosphate Polyphosphates

Table 1. Different forms of phosphorus (P) commonly found in ponds.

algae and the rest of the aquatic biological community. Inorganic forms of dissolved P are principally orthophosphate (PO_4) and, to a lesser degree, polyphosphates (Syers et al., 1973; Goldman and Horne, 1983; Brabrand et al., 1990).

Analytically, P is first separated into particulate and soluble fractions by filtering the water through a filter with an effective pore size of between 0.45 and 1.0 mm (APHA, 1985). It was once generally believed that only orthophosphate passed through the filter, and represented the only utilizable form of P for algae. However, neither assumption has endured. It is now known that many forms of soluble and colloidal P can pass through the filter, and for the last several decades the conventional term for the dissolved fraction has been soluble reactive phosphorus (SRP) (APHA, 1985). This is the most appropriate term because it describes only the amount of analytically measured P which passes through the filter.

Because of the relative scarcity of phosphorus in the aquatic environment, algae have become quite adept in extracting it from its various forms for nutrient uptake. Determining biological availability of the different forms of P, therefore, can be quite difficult. Algae are certainly capable of taking up soluble inorganic P from the water, as well as many forms of soluble organic P produced by the enzymatic breakdown of organic molecules. Algae colonizing detrital particles utilize dissolved organics released from the microbial decomposition of the detritus (Rodina, 1963; Rodina, 1966; Fry, 1987). Furthermore, some algae are capable of extracting P adsorbed to sediments resuspended in the water column (Grobbelaar, 1983).

After recognizing the various forms of P suitable for algal uptake, the next step is to examine a few of the more important dynamic processes which affect P availability in the pond. Many of these processes have already been mentioned above, and the more basic pathways are illustrated schematically in Figure 3. In addition to intentional fertilization, P enters pond water from runoff from pond banks and atmospheric precipitation, groundwater seepage, and from pond sediments.

The aim in culture ponds, of course, is to get as much fertilizer-P into algal biomass as possible. The recycling of P between dissolved and particulate forms through uptake, excretion, secretion, and decomposition benefits algal productivity (Brabrand et al., 1990). Biological competition for P, however, is complicated by the two

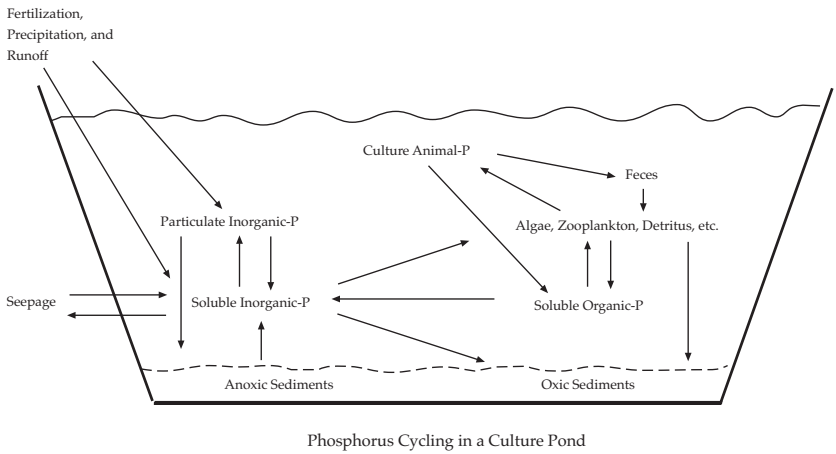


Figure 3. Schematic diagram showing major ecological pathways of phosphorus (P) transformations and cycling in a culture pond. For purposes of illustration, pond sediments are simultaneously represented as both anoxic and oxic.

chemical processes of adsorption and precipitation, which can take soluble P out of solution.

Phosphorus adsorption, as used here, refers to the chemical bonding of P to particulate matter suspended in the water or in the sediments (Boyd, 1971; Boyd and Musig, 1981). Phosphorus adsorption is affected by pond water and sediment characteristics. Soluble P adsorbs primarily to $CaCO_3$, and to Al and Fe oxides (McKee et al., 1970; Syers et al., 1973; Furumai and Ohgaki, 1989). Adsorption is greater when water has dissolved oxygen present (i.e., the water is said to be oxic), and when P is in the presence of particulate inorganic matter, especially fine clays (Stumm and Morgan, 1970; Syers et al., 1973; Boyd, 1995a; Shrestha and Lin, 1996). Adsorption of soluble P can take as little as 30 seconds to occur, with the rate of adsorption increasing as the pH of the water increases (Furumai et al., 1989).

In newly dug ponds, the relatively large exposure of inorganic sediments to overlying water facilitates P adsorption and removal from the water column. The rate of P removal by sediments decreases as bonding sites are filled and as organic matter (e.g., detrital particles) settles on the bottom. Organic matter reduces the crystallization

of Al and Fe oxides, and proportionally greater amounts of input-P remain in solution, available for algal uptake (Borggaard et al., 1990). In a statistical analysis of 16 culture ponds with widely varying fertilization histories, Knud-Hansen (1992) found that those ponds which had previously received greater organic (chicken manure) inputs required significantly less P input to maintain high algal productivities. Therefore, newly dug ponds generally require more P input to stimulate algal productivity than older ponds (Boyd, 1971; Boyd and Musig, 1981; Knud-Hansen, 1992).

On the other hand, when the environmental conditions are more acidic (i.e., pHs around 5.0) and void of dissolved oxygen (i.e., the water is anoxic), P desorption occurs and P becomes more soluble again (McKee et al., 1970; Stumm and Morgan, 1970; Furumai and Ohgaki, 1989). These conditions are often found in the interstitial or pore water, which surrounds the particulate matter in pond sediments. Decomposition of settled organic matter strips the oxygen out of the interstitial water, and the release of organic acids and carbon dioxide creates more acidic conditions (see following discussion on inorganic carbon). If the pond is thermally stratified, these more acidic and anoxic conditions may occur in the overlying bottom water as well. When this water is mixed with surface water, more P becomes available for algal growth through this internal fertilization mechanism (i.e., nutrients coming from within the pond).

The second mechanism which removes soluble P from solution is precipitation of phosphate by calcium, iron, and aluminum as $CaPO_{4(s)}$, $FePO_{4(s)}$, and $AlPO_{4(s)}$, respectively. Calcium phosphate precipitates out in waters with high pHs and high Ca concentrations, and becomes more soluble at lower pHs, particularly with the addition of carbon dioxide (CO_2) (Hepher, 1965). In a productive pond, therefore, $CaPO_{4(s)}$ precipitated during the daytime when pHs are high and CO_2 concentrations are low becomes soluble again during the night when respired CO_2 accumulates and lowers the pH.

In contrast, $FePO_{4(s)}$, and $AlPO_{4(s)}$, are least soluble at pHs of around 5 to 6 (Stumm and Morgan, 1970; Syers et al., 1973). Therefore, the high soluble P concentrations found in anoxic bottom waters with pHs of around 6 come from the desorption of P from metal oxides (and the solubilization of $CaPO_{4(s)}$ in ponds with high Ca concentrations), rather than from the solubilization of Al and Fe precipitates. With more acidic waters (pHs of 3 to 4) associated with acid sulphate soils, however, the solubility of Fe and Al increases. When these acidic

waters in the sediments mix into oxygenated pond water, Fe and Al oxides form and remove soluble P from solution through adsorption (Gaviria et al., 1986). Except perhaps in waters with very high calcium concentrations, P adsorption to metal oxides is likely a more significant cause of P loss than by precipitation (Syers et al., 1973). This is in part due to the relatively slow chemical reactions causing precipitation, and the higher solubility of Al and Fe precipitates at the higher daytime pHs normally found in productive freshwater ponds (Stumm and Morgan, 1970).

Nitrogen

Nitrogen is a major component of proteins and amino acids, and is, after C, H, and O, the most abundant element in living cells. Similar to P, the different forms of N can be separated into organic and inorganic, as well as particulate and dissolved components (Table 2). Particulate organic N is found in living biomass and detritus, while soluble organic nitrogenous materials are released into the water from excretions, secretions, and decomposition processes (Keeney, 1973). Soluble inorganic nitrogen is represented primarily by four different molecules: nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_3/NH_4^+), and nitrogen gas (N_2). Particulate inorganic N is largely represented by ammonium (NH_4^+) ions adsorbed to suspended sediments.

Figure 4 presents a simplified version of the nitrogen cycle in ponds. Nitrogen can enter the pond water through atmospheric

	Organic	Inorganic
Particulate	Living biomass Detritus Feces, etc.	Ammonia adsorbed to suspended sediments
Soluble	Enzymes Amino acids Organic acids Waste products	Nitrate Nitrite Ammonia Dissolved N_2 gas

Table 2. Different forms of nitrogen (N) commonly found in ponds.

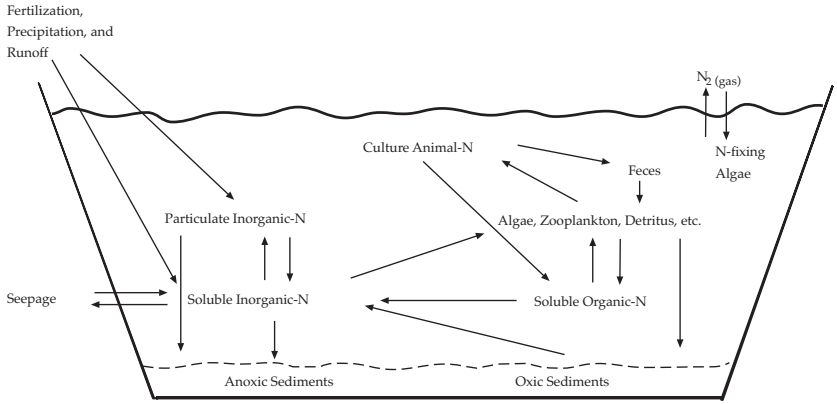


Figure 4. Schematic diagram showing major ecological pathways of nitrogen (N) transformations and cycling in a culture pond. For purposes of illustration, pond sediments are simultaneously represented as both anoxic and oxic.

precipitation and dry fallout, through runoff into the pond, from groundwater seepage, and through the chemical solubility and biological incorporation of atmospheric nitrogen gas (N_2). For relatively leaky culture ponds, the continual addition of source water can also contribute a significant amount of algal nutrients. For example, aquaculture ponds in Indonesia received an average of about 0.4 kg N ha^{-1} d^{-1} from the additional source water needed to compensate for daily evaporation and seepage losses (Knud-Hansen et al., 1991b).

The three primary N molecules utilized for algal growth are ammonia, nitrate, and nitrogen gas (Fogg, 1975; Bold and Wynne, 1978). Essentially all algae can take up nitrate and ammonia, and ammonia is the preferred form for plant growth because the incorporation of nitrate requires additional metabolic energy and enzymatic activity (Goldman and Horne, 1983). Both algae and bacteria incorporate ammonia very rapidly (Sugiyama and Kawai, 1979). In addition, some algae can metabolize various forms of dissolved organic N, as well as remove ammonium ions adsorbed to suspended particulate matter (Grobbelaar, 1983).

The incorporation of N_2 into algal biomass occurs through a process known as nitrogen fixation. The only algae capable of

extracting and fixing N_2 are certain blue-green algae, and they can do so only under limited environmental conditions (Fogg, 1975; Bold and Wynne, 1978; Oláh et al., 1983; Paerl and Tucker, 1995). These algae often have gas vacuoles which enable them to float to the water's surface. Not only does flotation provide these algae with direct access to atmospheric nitrogen and carbon dioxide, but it also gives them a competitive advantage for solar radiation. The importance of N-fixation as a mechanism for nitrogen input in fertilized ponds is generally quite limited. El Samra and Oláh (1979) reported fixation rates of < 0.005 g N m^{-2} d^{-1} (= 0.05 kg N ha^{-1} d^{-1}), while Lin et al. (1988) observed rates from 0.06 to 0.57 kg N ha^{-1} d^{-1}. These rates are relatively low when compared to typical fertilization input rates.

Similar to P, transformations between different forms of N in ponds are influenced by pond environmental conditions (Keeney, 1973). For example, ammonia is the principal nitrogenous by-product of organic decomposition, and experiences different fates depending on where in the pond the ammonia is produced. In waters containing dissolved oxygen, ammonia not incorporated by algae can be oxidized (i.e., add oxygen) through microbial processes. The oxidation of ammonia first to nitrite and then to nitrate is called nitrification, and is schematically shown in Equation 5:

$$NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^- \qquad [5]$$

In this two-step process, the microbial transformation of ammonia to nitrite is much slower than the subsequent microbial transformation of nitrite to nitrate (Cavari, 1977; Goldman and Horne, 1983). This fact has two implications. First, algal uptake of ammonia can be relatively fast, and competition for ammonia between algae and bacteria is predominantly in favor of the algal community. Second, the relatively rapid oxidation of nitrite to nitrate means that very little nitrite accumulates in oxic waters. Analytically, nitrite and nitrate are commonly measured together, and reported as mg l^{-1} NO_3-NO_2-N (APHA, 1985). If analyzed separately, the actual percentage of nitrite in such measurements should be negligible in most surface waters, and proportionally higher in the more chemically reduced conditions often found in anoxic pond sediments (Cavari, 1977).

Anoxic water with sufficient organic matter, an environment often found in pond sediments and in the bottom waters of a produc-

tive pond experiencing persistent thermal stratification, creates a biochemically reducing condition. Ammonia is already in a chemically reduced form and accumulates under these conditions. On the other hand, oxidized forms of N, such as nitrate and nitrite, become reduced (i.e., lose oxygen) as by-products of another two-step, biological process. This process is called denitrification, and is schematically represented in Equation 6.

$$NO_3^- \rightarrow NO_2^- \rightarrow \underset{(gas)}{N_2 \uparrow} \qquad [6]$$

First, NO_3^- loses an atom of oxygen to form NO_2^-. Then, the nitrite produced in the first step is further reduced to nitrogen gas (N_2), which may go back into solution or escape from the pond's surface water (schematically shown in Figure 4 and Equation 6) (Bouldin et al., 1974). The bacterial metabolic processes responsible for denitrification occur in anoxic pond sediments worldwide.

The last transformation of nitrogen to be mentioned is the purely chemical transformation between two forms of ammonia, namely the ionized (NH_4^+) and the un-ionized (NH_3) forms. The equilibrium reaction is shown in Equation 7:

$$NH_4^+ + OH^- \rightleftarrows NH_4OH \rightleftarrows NH_3 + H_2O \qquad [7]$$

The implications of this transformation in aquaculture systems are great because whereas the ionized form is generally safe for culture organisms, the un-ionized form can be highly toxic (Colt and Armstrong, 1981; Meade, 1985). A more thorough discussion of ammonia toxicity and the environmental factors which affect this chemical transformation is presented in the subsection on maintaining a favorable growth environment in Chapter 4.

Inorganic Carbon

Carbon is the dominant element in organic matter. Recall from the last chapter that primary producers such as algae incorporate inorganic carbon, while secondary producers such as fish incorporate organic carbon from biological sources (e.g., algae, algae-derived

detritus, zooplankton). In pond fertilization we are trying to optimize algal productivity, so our focus on carbon dynamics will naturally focus on inorganic carbon.

The three principal forms of dissolved inorganic carbon (DIC) are carbon dioxide (CO_2), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}), as indicated in Equation 8:

$$\mathrm{DIC} = CO_2 + HCO_3^- + CO_3^{2-} \qquad [8]$$

The three major sources of soluble CO_2 are the solution of atmospheric CO_2 into surface water, equilibrium reactions of dissolved CO_2 in the water with bicarbonate and carbonate, and the decomposition of organic matter in the pond. The solution of atmospheric CO_2 into water and the corresponding equilibrium reactions are presented below in Equation 9:

$$\underset{\text{(atmospheric)}}{CO_2} + H_2O \leftrightarrows \underset{\text{(aqueous)}}{H_2CO_3} \leftrightarrows HCO_3^- + H^+ \leftrightarrows CO_3^{2-} + 2H^+ \qquad [9]$$

As illustrated in Equation 9, two things happen when CO_2 is added and dissolves into water. First, bicarbonate and carbonate are produced. Second, hydrogen ions (H^+) are released, increasing their concentration in the water.

In addition to CO_2 solubility, primary sources of carbonate and bicarbonate are from the dissolution of the common rock limestone, which consists primarily of calcite (calcium carbonate [$CaCO_3$]) and may contain magnesium carbonate ($MgCO_3$). Once in the water, the carbonate and bicarbonate become part of the same equilibrium relationship described in Equation 9. Equation 10 illustrates this equilibrium by showing what happens when carbonate and/or bicarbonate are added to water.

$$\begin{array}{l} CO_3^{2-} + H_2O \leftrightarrows HCO_3^- + OH^- \\ \qquad\qquad\qquad\quad \downarrow \\ \qquad\qquad\qquad\quad HCO_3^- \leftrightarrows CO_2 + OH^- \end{array} \qquad [10]$$

When carbonate is added, bicarbonate and the hydroxyl ion (OH^-) are produced. Bicarbonate in the water either from carbonate or added independently (e.g., as sodium bicarbonate, $NaHCO_3$) produces CO_2 and another OH^- molecule.

The H^+ produced with the addition of CO_2 (Equation 9) and the OH^- produced with the addition of CO_3^{2-} and HCO_3^- (Equation 10) demonstrate the very important role of pH in carbonate equilibria. The pH is a measure of the H^+ concentration, which is a product of the equilibrium between water (H_2O) and concentrations of H^+ and OH^- (Equation 11).

$$H_2O \leftrightarrows H^+ + OH^- \qquad [11]$$

Theoretically, pH ranges between 0 and 14 pH units. A pH value between 0 and 7 indicates chemically acidic water (i.e., H^+ concentration > OH^- concentration); a value from 7 to 14 indicates water which is chemically basic (i.e., H^+ concentration < OH^- concentration), and a pH of 7 is considered chemically neutral (i.e., H^+ concentration = OH^- concentration). Adding H^+ or removing OH^- increases the concentration of H^+ in the water, and consequently lowers the pH. Similarly, removing H^+ or adding OH^- decreases the concentration of H^+ in the water, and increases the pH.

These pH shifts due to carbonate equilibria are clearly demonstrated in a productive pond. For example, when CO_2 is produced through respiration, total DIC concentrations increase and the corresponding release of H^+ causes a decrease in pH. In fact, CO_2 produced from organic decomposition is a major reason (along with the production of organic acids) why pond sediments are generally more acidic than overlying waters. On the other hand, algal uptake/removal of CO_2 during photosynthesis increases OH^- concentrations and raises the pH of the water. This relationship is shown in Equation 10; as CO_2 is removed by algae, the reaction moves to the right andand OH^- are produced from the reactions involving HCO_3^- and water. This equation demonstrates why surface-water pHs of productive ponds increase during sunny afternoons.

In the same way adding and removing any of the three forms of DIC can affect the pH, adding and removing H^+ or OH^- (i.e., changing the pH) can affect the relative amounts of CO_2, HCO_3^-, and CO_3^{2-} in the water (Stumm and Morgan, 1970). As the pH shifts, the

pH	CO_2	HCO_3^-	CO_3^{2-}
5	95.7	4.3	0.0
6	69.2	30.8	0.0
7	18.3	81.6	0.0
8	2.2	97.4	0.5
9	0.2	95.3	4.5
10	0.0	68.1	31.9
11	0.0	17.6	82.4

Table 3. Relationship between pH and approximate relative percentages of total dissolved inorganic carbon (DIC), based on equilibrium reactions between dissolved carbon dioxide (CO_2), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}) at 25°C (see text and Equations 8 to 10).

percent of total DIC represented by each of the three inorganic forms also changes (Table 3). At pHs below 5, dissolved CO_2 represents about 100% of the DIC; at pH of about 8.3, nearly 100% of the DIC is HCO_3^-; and at pH 12, approximately 100% of the DIC is in the form of CO_3^{2-}. Total DIC concentrations generally remain the same as the pH shifts, unless some CO_2 is lost to the atmosphere when surface water CO_2 concentrations become saturated at low pHs, or if some carbo-

	CO_2	HCO_3^-	CO_3^{2-}
DIC	X	X	X
Alkalinity		X	X
Utilized by Algae	X	X	

Table 4. Identification of different forms of dissolved inorganic carbon (DIC) in relation to total alkalinity and forms of inorganic carbon generally available for algal uptake. The three forms of DIC are dissolved carbon dioxide (CO_2), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}).

nates precipitate out of solution (e.g., with calcium, discussed below) at high pHs (Stumm and Morgan, 1970).

Because algae can not utilize all forms of DIC equally (Table 4), these changes in the forms of DIC as the pH shifts can have great importance to algae. Carbon dioxide is readily taken up by algae, and HCO_3^- can be utilized by many algal species (Talling, 1976; Boston et al., 1989; Prins and Elzenga, 1989). Carbonate, however, is generally

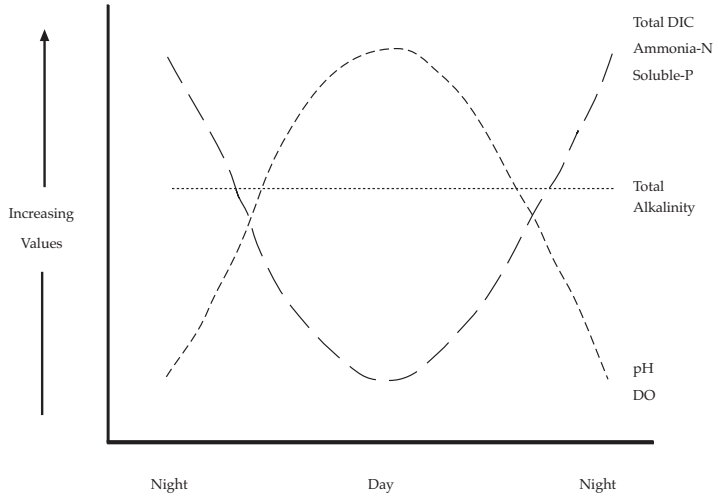


Figure 5. Typical diel (24-hour) curves of total dissolved inorganic carbon (DIC), ammonia-N, alkalinity, pH, and dissolved oxygen (DO) in a productive pond. Ecological reasons for curves and potential factors which could cause diel alkalinity values to vary are discussed in the text.

an unusable form and not available for algal uptake. In most waters this is not a problem, since about 95% of the DIC in waters with pHs below 9 is in the form of either CO_2 or HCO_3^-, and HCO_3^- still represents approximately 50% of the total DIC (the other 50% is CO_3^{2-}) at pHs of around 10.4 (Table 3). Nevertheless, DIC availability can be an issue in highly productive rain-fed ponds, where pond water is naturally low in both DIC concentration and total alkalinity (i.e., buffering capacity, see discussion below).

It is useful at this point to summarize DIC transformations in light of pond dynamics. When algae remove CO_2 and HCO_3^- from pond water during daytime photosynthetic activity, the pH goes up, dissolved oxygen concentrations go up, and total DIC concentrations go down (Equations 9 and 10) (Talling, 1976; Goldman et al., 1974). As the pH goes up, forms of the remaining DIC shift towards a higher percentage of CO_3^{2-}, a form not useful to algae. Then, as nighttime respiration dominates DIC activity, dissolved oxygen is consumed and CO_2 is released back into the water, increasing DIC while decreas ing pH. Figure 5 illustrates these diel cycles, or cycles which occur over a 24-hour period. The two main points to remember from the above discussion are: 1) the forms of DIC shift with changing pH values (Table 3); and 2) the typical diel cycles of pH, DIC, and dissolved oxygen (Figure 5) are due to the fact that photosynthetic uptake of DIC occurs only during daylight hours.

The DIC equilibrium equations discussed above illustrate another very important concept in aquatic ecology. Notice that if an acid (i.e., H^+) is added to water containing bicarbonate and carbonate (i.e., water with a pH above 5), the H^+ concentration does not increase by the exact amount that is added. Some of the H^+ is used to convert CO_3^{2-} to HCO_3^-, and then to convert HCO_3^- to $CO_2 + H_2O$ (Equation 9). Likewise, adding a base (i.e., OH^-) will result in the conversion of CO_2 to HCO_3^-, and of HCO_3^- to $CO_3^{2-} + H_2O$ (Equation 10). In this way, carbonate equilibria act as a buffer to prevent large changes in pH when an acid or base is added to the water. This buffering capacity is also referred to as total carbonate alkalinity.

Although other negatively charged molecules such as phosphate (PO_4^{3-}), borate ($B(OH)_4^-$), nitrate (NO_3^-), and the hydroxyl ion (OH^-) are also part of total alkalinity, concentrations of these compounds are nearly always substantially less than 1% of the concentration of carbonate and bicarbonate in fresh water (Stumm and Morgan, 1970). For that reason, total alkalinity measurements are conveniently given in terms of mg l^{-1} of $CaCO_3$ (APHA, 1985). The simplified equation for total alkalinity can be expressed as follows:

$$\text{Total Alkalinity} = [HCO_3^-] + 2[CO_3^{2-}] + [OH^-] - [H^+] \qquad [12]$$

Equation 12 illustrates the loss of alkalinity when acid is added to water. If enough H^+ is added to the water, all the carbonate and bicarbonate molecules are converted to CO_2 and there is no more carbonate alkalinity left in the water (Equation 9). This is precisely what happens with acid rain or with alkalinity measurements using acid titration (APHA, 1985). The pH will decrease slowly due to carbonate alkalinity until the buffering capacity is gone at about pH of 5—then the pH drops rapidly and proportionally to acid input.

It is important to appreciate that CO_2 is not a part of alkalinity, and adding CO_2 to water has no impact on total alkalinity (Stumm and Morgan, 1970). Recall from Equation 9 that adding CO_2 to water produces equal amounts of HCO_3^- and H^+. Although DIC will increase with the addition of CO_2, for every molecule of HCO_3^- produced there is also a molecule of H^+ produced, canceling any net increase in alkalinity (Equation 12). Therefore, there are typically no diel changes in alkalinity with CO_2 removal during photosynthesis or with CO_2 production during respiration (Figure 5).

A simple laboratory experiment illustrates the relationship between alkalinity and CO_2. Measure alkalinity in a pond water sample before and after blowing bubbles (we exhale CO_2 produced from our own respiration) with a straw through the water for about a minute. The pH drops and a higher percentage of the DIC is in the CO_2 form (Table 3), but the alkalinity remains unchanged. Total DIC measurements, however, show an increase due to CO_2 added from blowing bubbles. The added CO_2 is available for algal uptake, but this increased DIC availability is not reflected in the alkalinity measurements, which stay the same.

A decrease in pond water alkalinity can occur, however, when HCO_3^- is removed by algae, as might occur during periods of high photosynthetic activity (Boston et al., 1989). Under these conditions, total DIC will still exhibit the same diel variability shown in Figure 5, but alkalinity may gradually decrease over time. Bicarbonate incorporated into decomposable algal biomass is subsequently released as CO_2, thus increasing DIC concentrations, but alkalinity will remain low until additional alkalinity is provided (e.g., adding lime to the pond).

Productive ponds with high calcium concentrations may show daytime losses of alkalinity through the formation and precipitation of $CaCO_3$ following high afternoon pHs (Boyd, 1990). The equilibrium reaction is given in Equation 13:

$$Ca^{2+} + 2HCO_3^- \leftrightarrows CaCO_{3(s)} + CO_2 + H_2O \qquad [13]$$

This white precipitate can be seen around the pond's edges below the water surface, or as a fine suspension of $CaCO_3$ particles (a phenomenon known as lake whitening), which can significantly reduce light penetration in the water (Goldman and Horne, 1983). However, the lower pHs and higher CO_2 concentrations resulting from nighttime respiration activity cause the precipitate to dissolve, restoring water clarity and alkalinity.

Competition for carbonates from other aquatic organisms can also reduce alkalinity and carbon availability in a pond. For example, organisms which incorporate calcium carbonate ($CaCO_3$) in their shells, such as snails and clams, are capable of seriously lowering alkalinity measurements in the pond water. This was observed with both snails and clams in culture ponds in Thailand (Knud-Hansen et al., 1993). The impact on algal productivity varies, depending upon the initial amount of alkalinity present and whether other sources of DIC are provided. Fertilization strategies designed to minimize this potential problem are discussed in Chapter 5.

A practical problem for aquaculturists is how best to quantify DIC availability for algal uptake. We have seen that algae utilize CO_2 and bicarbonate (HCO_3^-), but not carbonate (CO_3^{2-}). Therefore, neither total alkalinity nor total DIC can be automatically assumed to accurately represent DIC availability for algal growth since they both include carbonate, and alkalinity measurements do not include CO_2 (Table 4). Total CO_2 and bicarbonate concentrations can be calculated directly by using carbonate equilibrium equations together with water pH, water temperature (which affects solubility rate constants), and either total alkalinity or total DIC measurements (Stumm and Morgan, 1970). However, this approach is often not very practical.

Under certain environmental conditions, total DIC and alkalinity measurements can also provide reasonably accurate indications of DIC availability for algae. Total DIC measurements are very good approximations in waters with pHs below about 9, where > 95% of the DIC is CO_2 and bicarbonate (Table 3). On the other hand, total alkalinity can accurately indicate DIC availability for algae only in waters with pHs close to 8.3 under equilibrium conditions, when essentially 100% of DIC is in the form of bicarbonate, and assuming

only an insignificant amount of non-carbonate alkalinity (e.g., silicates, borates, nitrates) is present in the water. However, pHs in productive fertilized culture ponds are quite dynamic, and diel pH shifts of several units are common (Figure 5). Waters with pHs above 8.3 contain carbonate, and waters with pHs below 8.3 contain CO_2, so alkalinity measurements alone do not accurately indicate DIC availability for algal uptake.

Total alkalinity may directly indicate dissolved CO_2 and bicarbonate concentrations in some natural waters where nearly all the DIC enters from the dissolution of carbonaceous rocks. But this assumption is not appropriate when additional organic matter (e.g., compost, manures, wastewater, and pelleted and other feeds) is added to a pond. These organic materials decompose, adding CO_2 to the pond and increasing DIC availability for algae. When lime (calcium carbonate) has been added to animal manures to reduce odors, a common practice with chicken manure, manure fertilization contributes both alkalinity and DIC. Lime increases pond alkalinity, and both the added carbonate from lime and carbon dioxide from manure decomposition increase total DIC availability to algae.

Although pond alkalinity has serious limitations regarding its ability to quantitatively assess DIC availability for algae, it can still be a useful measurement qualitatively. Recall that adding CO_2 to water does not affect total alkalinity, but adding carbonate alkalinity does increase CO_2 availability through equilibrium reactions. Statistical analyses of nutrient limitation in dozens of very productive fertilized ponds in Thailand suggest that alkalinities above about 75 mg l^{-1} of $CaCO_3$ provided sufficient algal DIC so as not to limit algal productivity (Knud-Hansen and Batterson, 1994; Knud-Hansen, unpublished data). It has been suggested that alkalinities below 100 mg l^{-1} of $CaCO_3$ may still be insufficient (Boyd, 1997). On the other hand, a pond with low alkalinity (e.g., 10 to 20 mg l^{-1} of $CaCO_3$) may still have sufficient DIC for algae if enough DIC is provided from organic decomposition and release of CO_2. Alkalinity measurements above an experimentally established threshold value *should* indicate sufficient DIC, whereas values below *may* indicate potential carbon limitation with high algal productivities.

Low alkalinities in water also reflect poor buffering capacity. Carbon dioxide removal during photosynthesis raises the pH more quickly in poorly buffered waters, increasing the percentage of carbonate in the DIC pool (Table 3). Converting part of a pond's DIC

to a form not suitable for algae (i.e., carbonate) furthers the risk of having insufficient inorganic C for algal uptake in waters with low alkalinities. Adding alkalinity increases the buffering capacity as well as available DIC for algae, since algae can utilize bicarbonate.

When the pH is raised, either by adding alkalinity or from daytime CO_2 removal during photosynthesis, then the solubility of CO_2 increases, enabling more atmospheric CO_2 to enter the pond's surface waters (Equations 9 and 10, Stumm and Morgan, 1970). However, any net gain of DIC to a productive pond from increased CO_2 solubility is likely temporary, since some of the nighttime accumulation of respired CO_2 returns to the atmosphere when aquatic concentrations reach saturation levels (Stumm and Morgan, 1970; Talling, 1976). In fact, if the transfer of atmospheric CO_2 into pond water at high pHs was efficient, then DIC availability would not be a concern in culture ponds. Unfortunately, that is not the case.

Finally, and to complete the discussion on terminology regarding DIC, one last concept should be mentioned briefly. Water hardness is the capacity of water to precipitate soap, and is measured by the sum concentration of positive bivalent ions (e.g., Ca^{2+}, Mg^{2+}, Fe^{2+}) and trivalent ions (e.g., Al^{3+}, Fe^{3+}) (APHA, 1985). Dissolved ions in the water combine with soap to form insoluble precipitates, which retard the formation of suds.

Alkalinity and water hardness are related terms considering that most of the alkalinity and hardness in natural fresh water usually comes from the dissolution of $CaCO_3$ and $MgCO_3$ in the water. For that reason, measurements of hardness, like those of alkalinity, are commonly given in equivalent units of mg l^{-1} of $CaCO_3$. Both total hardness and alkalinity will decrease in ponds with snails or clams present, due to the incorporation of $CaCO_3$ in the shells. In ponds with very hard water (i.e., high calcium concentrations), high algal productivity can result in the precipitation of $CaCO_3$ (Equation 13), again reducing hardness, alkalinity, and DIC.

Controlling Algal Productivity

The above discussion on the dynamics of P, N, and C in a freshwater pond sets the stage for the key question in pond fertilization: How do you most efficiently make the pond green and abundant with algae? The simple answer is to give the algal community only

what it needs to grow—nothing more and nothing less. We have already seen that algae require:

- Primary nutrients (C, N, P) as well as hydrogen and oxygen;
- Minor and micronutrients;
- Sufficient light energy in the water column; and
- Suitable water temperatures for growth.

Algae will continue to grow rapidly as long as *all* of the above requirements are met. When one or more of the stated requirements are not available for growth, then algal productivity is said to be limited by that condition.

Limitation of algal growth is best described by Liebig's Law of the Minimum, which says that algal productivity will be limited by the element present in least supply relative to algal requirements (O'Brien, 1974; Goldman and Horne, 1983). Note that this principle says "least supply" and not "least concentration." In other words, the *rate* of algal production is determined by the *rate* of nutrient availability. It should be clear from the above discussion on nutrient dynamics that P, N, and C recycle extensively between algae, animals, the water column, and the sediments before becoming ultimately "lost" to the pond system through release into the atmosphere, from water seepage out of the pond, by being permanently bound up in the sediments, or being incorporated into harvestable fish biomass. Therefore, measurements of nutrient concentrations have limited value as indicators of the *supply* of algal nutrients available for uptake.

For purposes of this book, limitation of algal productivity is viewed broadly from an algal community perspective. Although different algal species have widely varying abilities and demands for nutrient uptake and light utilization (Fogg, 1975), here the purpose is to make ponds green without necessarily trying to promote a particular algal species in the pond.

Algal productivities in natural freshwater located in temperate climates are most typically limited by the supply of P (Schindler, 1978), whereas N has been frequently found limiting in tropical fresh water (Setaro and Melack, 1984). Natural nutrient limitation, however, has little practical importance in pond fertilization, where nutrient input rates may be hundreds or thousands of times greater than natural input rates. In pond fertilization, objectives include giving the algal community all it needs to keep growing at high rates, and not

fertilizing when the algae already have a sufficient supply of available nutrients in the water.

From a pond management perspective, however, only a few algal growth requirements need to be met through pond fertilization. Suitable water temperatures can be dealt with by selecting appropriate geographical regions to conduct semi-intensive aquaculture. There is plenty of hydrogen and oxygen in the water, so fertilization of these elements is not necessary. The supply of essential micronutrients has never been shown to limit algal growth in fertilized ponds—although species of diatoms require silica for their cell walls, diatoms are generally found in cooler waters and are not usually a dominant group in warm, freshwater ponds (Fogg, 1975; Goldman and Horne, 1983). Therefore, the only four algal growth factors which the aquaculturist/farmer needs to manage are the availability of suitable forms of P, N, and C, and sufficient light energy. The next chapter examines different types of fertilizers and their relative abilities to efficiently and economically meet these algal growth requirements.

Chapter 4. Comparative Analysis of Fertilizers

At this point in our ecological analysis of pond fertilization, we have examined principal algal nutritional and environmental requirements, and the basic dynamic processes in a pond system which affect the availability of these essential growth factors. It is now time to discuss different fertilizers commonly used in aquaculture and examine their abilities to meet the farmers' needs for efficient production of algae.

Fertilizers enter the pond in either soluble or particulate form, and deliver soluble P, N, and/or C for algal uptake and growth (Figure 6). All the pathways indicated in this figure have been discussed in earlier chapters, and now should be quite familiar. Fertilizers analyzed in this chapter can be divided into organic and chemical varieties. Organic fertilizers are either animal manures or plant compostings (green manures), while chemical fertilizers include

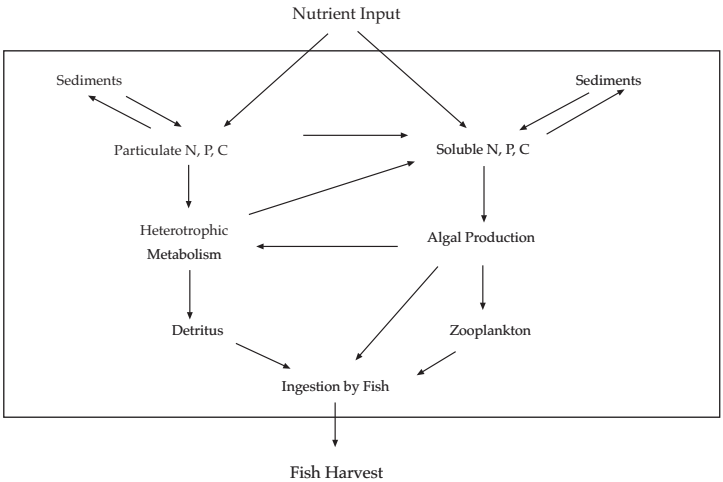


Figure 6. Schematic diagram showing major ecological pathways of fertilizer nutrients added to a culture pond (adapted from Knud-Hansen et al., 1993).

nitrogen-phosphorus-potassium (N-P-K) fertilizers, triple superphosphate (TSP), sodium nitrate, and urea. This chapter first discusses the analytical factors, based on the objectives of pond fertilization, used to evaluate the relative merits or problems of using different fertilizers. The remainder of the chapter incorporates these factors to analyze the relative utility of animal manures, green manures, and chemical fertilizers in helping the farmer get the most benefit from a particular fertilization strategy.

Analytical Factors

Fertilization Goals

The goal of pond fertilization can be viewed simply as maximizing the causal link between fertilizer inputs and ultimate yields of culture organisms at harvest, while minimizing economic and environmental costs. This general goal encompasses the four specific objectives in fertilization theory, namely:

1) To increase natural food production by stimulating algal productivity;
2) To optimize nutrient utilization efficiency;
3) To optimize cost efficiency; and
4) To maintain a favorable growth environment for culture species.

The first objective needs no further elaboration beyond Chapters 2 and 3. The second objective of optimizing nutrient efficiency refers to providing *only* what the algae need without wasting nutrients through excess or unnecessary fertilization. The third and fourth objectives of optimizing cost efficiency and maintaining favorable growth environments are discussed in the two subsections below.

Cost-Efficiency Analysis

Too often a fertilization strategy is evaluated solely on its ability to increase yields of culture organisms. If you get bigger fish, it works; if you did not get bigger fish, it did not work. This is rarely the most cost-efficient approach. For example, researchers have put high

inputs of N and P into shallow, turbid ponds, and then made general recommendations that high nutrient input rates are not beneficial because fish did not grow any better. That may be true for shallow, turbid ponds. By appreciating the fact that light limitation was preventing further algal productivity, however, a more useful recommendation would have been to deepen the ponds (or raise the banks) so the turbidity would settle out of the surface waters. This approach increases light availability and allows the algal community to benefit from higher rates of nutrient input. Only by understanding dynamic processes in the pond and *why* a particular fertilization strategy did or did not give expected results can more accurate costs and benefits be evaluated.

The cost-benefit approach taken in this chapter is broad but intentionally superficial and non-quantitative. The aim here is to highlight impacts on pond ecology and additional costs of mitigating resulting problems which should be considered by farmers and/or extension workers when making fertilization strategy decisions, and by researchers when making fertilization recommendations to rural farmers. Just getting bigger fish or higher yields is not enough if actual economic and environmental costs are too great. It is critically important that farmers appreciate the broad economic and ecological implications of choosing one fertilization strategy over another. That is the extent of the cost-benefit analysis in this book. For technical assistance in making more quantitative, in-depth economic analyses of aquaculture systems, the reader should consult more comprehensive sources (e.g., Shang, 1981; Shang, 1990; Jolly and Clonts, 1993; Engle et al., 1993; Engle et al., 1997).

Economic factors considered in the following comparative analysis of fertilizers include:

1) Market cost of biologically available N, P, and C (e.g., on-farm production versus off-farm purchase);
2) Transport and labor costs, including lost opportunity costs and integration of aquaculture with other farm activities;
3) The need for additional capital expenses, such as for pondwater aeration or mixing;
4) Market value of culture organisms (e.g., social acceptance/ marketability of manure-raised fish); and
5) Impacts on pond ecology, including water quality (e.g., dissolved oxygen, ammonia, turbidity, diseases) and the filling of ponds with organic matter.

Getting the most "economical" fertilizer is site-specific. Fertilizer requirements should be evaluated on a farm-by-farm basis, and can even be done on individual ponds (see Chapter 6). To illustrate, three ponds located side by side would require totally different approaches to fertilization if we assume they have different depths of 0.7 m, 1.2 m, and 3 m. Individual pond differences in thermal stratification characteristics and ecological impacts of resuspended bottom sediments greatly influence each pond's response to identical fertilizations. Before adopting any country-wide or regional fertilizer recommendation, therefore, its ecological foundation/assumptions should be examined critically to ensure that the suggested fertilization strategy is appropriate for each pond or farming system in question.

Maintaining a Favorable Growth Environment

This fourth goal of fertilization is a rather broad topic, and is covered more extensively elsewhere (e.g., Boyd, 1990). The focus here is limited to two areas of pond ecology where the choice of fertilizers can have a substantial influence on the health and welfare of culture organisms: 1) the need to maintain sufficient dissolved oxygen in the pond water; and 2) the need to minimize the presence of toxic, un-ionized ammonia concentrations.

Dissolved Oxygen

Most aquatic organisms require dissolved oxygen (DO) for metabolism and growth, and without oxygen these organisms will quickly die. Since air is about 21% oxygen (≈ 300 mg l^{-1} of air), oxygen depletion is rarely an issue for terrestrial organisms unless they are suffocated. Depletion of dissolved oxygen in aquatic environments, however, is a serious, ever-present concern. The solubility of oxygen in water is less than 1% of its solubility in air, and decreases further with increasing water temperatures. Saturated DO concentrations in water at 1 atmosphere of pressure range from about 9.1 mg l^{-1} at 20°C to about 7.0 mg l^{-1} at 35°C (Wetzel and Likens, 1979). These values show that there is not a lot of DO in the water when compared to O_2 concentrations in air.

Different aquatic organisms require different minimal levels of DO in order to survive, or at least not be detrimentally affected. For example, freshwater prawns may suffer when DO falls below 3 to 4

mg l^{-1}, whereas Nile tilapia can easily tolerate DO concentrations below 1 mg l^{-1} for short periods of time (Teichert-Coddington and Green, 1993). Fertilization should be conducted in a way to maintain DO levels above minimal acceptable values for the target culture species.

We have already discussed at some length DO dynamics in ponds. Oxygen production during daytime photosynthetic activity and oxygen uptake for biological respiration and biochemical oxidative reactions (e.g., nitrification) create the typical diel DO curve illustrated in Figure 5. Minimum DO concentrations are normally found at pre-dawn, just before photosynthetic activity begins with sunrise. Maximum DO concentrations can reach over 30 mg l^{-1} in very productive ponds in the late afternoon. Supersaturation of DO can exist because of water pressure, but eventually some DO bubbles out when subsurface water is brought to the surface (Wetzel and Likens, 1979).

Even in the most productive ponds, pre-dawn DOs will usually remain about 3 mg l^{-1} as long as the organic matter in the pond is produced *only* within the pond (Knud-Hansen et al., 1993). In other words, very green ponds which do not receive any additional organic matter (e.g., manures or feeds) should not experience early morning DO levels below 3 mg l^{-1}. This assumes that ponds are shallow enough to experience nighttime destratification and whole-pond mixing. As more organics are added to the pond, the oxygen demand increases and nighttime DO concentrations decrease. If too much organic matter is added to the pond, DO can be depleted, causing potentially lethal, anoxic conditions to develop (Ram et al., 1982).

It is possible to add DO to pond water through appropriate pond management, but with additional corresponding costs and risks. For example, mechanical aerators, such as paddlewheels, propeller-aspirator pumps, and vertical-pump aerators can be particularly effective in adding DO (Boyd and Watten, 1989). Oxygen diffusion from air into calm water is quite slow, but can be accelerated substantially by agitating the water's surface (Boyd and Teichert-Coddington, 1992). Included in the farmer's decision whether or not to use organic fertilizers, therefore, are considerations of the financial and labor costs associated with the purchase, operation (including energy costs), and maintenance of these devices. Furthermore, ponds which require aerators to maintain minimal DO concentrations above lethal levels

put the farmer at a greater risk, particularly if fish survival depends upon not having any mechanical or power failures.

Un-Ionized Ammonia Toxicity

The second major environmental concern is with un-ionized ammonia toxicity. Remember that ammonia occurs in water in two soluble forms, namely ionized (NH_4^+) and un-ionized (NH_3). To facilitate discussion, the equilibrium reaction introduced in Equation 7 is repeated:

$$NH_4^+ + OH^- \rightleftarrows NH_4OH \rightleftarrows NH_3 + H_2O \qquad [7]$$

This transformation between the ionized and un-ionized forms of ammonia is a function primarily of water pH and, to a lesser degree, water temperature. The equation moves to the right (i.e., the transformation of the ionized to the un-ionized form) with increasing pHs and, to a much lesser extent, with increasing temperatures. Table 5 illustrates this relationship, showing the different percentages of un-ionized ammonia in the total ammonia pool with variable pH at 25°C (Trussell, 1972; Emerson et al., 1975).

pH	NH_4^+	NH_3
5	100.0	0.0
6	99.9	0.1
7	99.4	0.6
8	94.7	5.3
9	64.2	35.8
10	15.1	84.9
11	0.8	99.2

Table 5. Relationship between pH and relative equilibrium concentrations of total dissolved ammonia. Values are approximate percentages of total dissolved ammonia based on equilibrium reactions between the ionized form (NH_4^+) and the un-ionized form (NH_3) at 25°C (see text and Equation 13) (adapted from Trussell, 1972).

This transformation has importance in aquaculture systems because, unlike the ionized form, the un-ionized form can be highly toxic to culture organisms (Colt and Armstrong, 1981; Ruffier et al., 1981; Meade, 1985). However, a word of caution is necessary before assuming that reduced fish growth may be related to high ammonia levels in the pond. For example, in a fertilization study using fixed weekly inputs of N and P, tilapia net fish yields (NFY) in some ponds were comparatively low and total ammonia concentrations were several milligrams per liter (Knud-Hansen and Batterson, 1994). Upon further examination, it was shown that lower fish yields corresponded directly to lower natural food production as indicated by lower algal net productivities (NP). Low NPs were related to both DIC and turbidity-induced light limitations, conditions which caused the accumulation of unused ammonia-N in the pond water (Figure 7). Therefore, there was no direct causal connection between observed high ammonia concentrations and low NFYs.

The above example further illustrates how an ecological understanding of pond dynamics can provide direction for a more efficient fertilization strategy. Rather than reduced N inputs, these ponds needed more DIC and reduced inorganic turbidity to stimulate

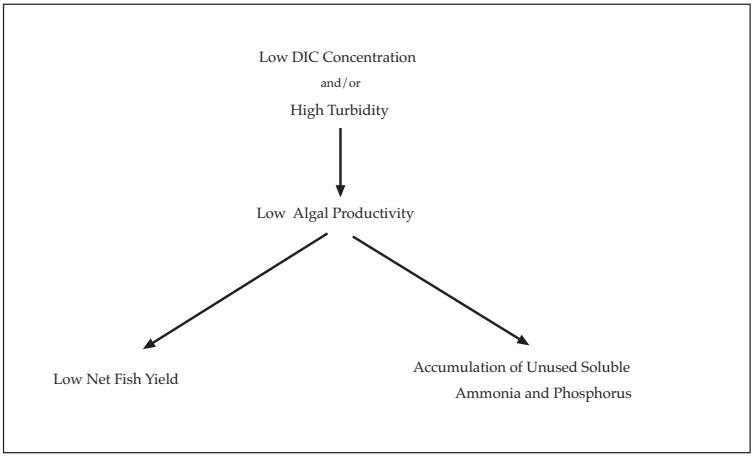


Figure 7. Schematic diagram showing impacts on algal and fish productivity when a production pond fertilized with N and P is limited by the availability of dissolved inorganic carbon (DIC) and/or availability of light by high inorganic turbidity.

algal productivity. Fertilization with DIC would allow the algae to utilize surplus N, thus reducing ammonia concentrations while at the same time increasing both NP and NFY.

Further evidence that un-ionized ammonia may not be as serious a problem as generally attributed, at least for tilapia culture, was shown in a statistical residual analysis of the relationship between NFY and NP from over 60 fertilized ponds (Knud-Hansen, unpublished data). This analysis found no lethal or sublethal effects on growth when Nile tilapia were exposed to afternoon, un-ionized ammonia concentrations of between 2 and 3 mg l^{-1}. These results conflict with published 48-hour LC_{50}s of around 2.1 to 2.4 mg l^{-1} un-ionized ammonia for tilapia based on static or continual-exposure toxic bioassays (Redner and Stickney, 1979; Lin and Liu, 1990), although Daud et al. (1988) reported higher values for red tilapia fry.

To understand why ammonia toxicity may not be as great a problem in fertilized culture ponds, it is important to review toxicity testing methodology. Ammonia toxicity for different culture species is typically determined in laboratory experiments, subjecting test organisms to *continual exposure* to a gradient of un-ionized ammonia concentrations. The concentration which is lethal to 50% of the test organisms is called the LC_{50} (Ruffier et al., 1981; APHA, 1985). Toxicity tests usually determine either acute (e.g., 24-hour LC_{50}) or chronic (e.g., 30-day LC_{50}) toxicities. Toxin concentrations which kill 50% of the test organisms in 24 hours are often several times greater than concentrations which kill 50% of the same test organisms over longer time periods (APHA, 1985; Daud et al., 1988).

The difficulty in applying the results of ammonia toxicity tests to organisms raised in fertilized ponds becomes clear when you consider pond ecology. Recall that pH rises during the day, sometimes up to a pH of 10 in very productive ponds, with the removal of dissolved CO_2 due to photosynthetic uptake by the algal community (Equation 9). Excess ammonia not taken up by algae is converted to the un-ionized form in greater percentages as the pH rises (Table 5). But this high pH is a temporary condition, and after sunset the pH begins to drop back to about 7 in most ponds. In highly productive ponds, high pHs may be found only in the upper 20 to 30 cm since photosynthetic activity is light-limited in subsurface waters due to algal self-shading.

From a fish's perspective, un-ionized ammonia concentrations may be elevated in the surface waters for only a few hours during the

day. The fish have most of the day and all of the night to recover from any sublethal effects and to acclimate to sublethal concentrations. Moreover, fish can swim to refuge areas (e.g., deeper water) when ammonia concentrations in surface waters are high. This recovery period is not incorporated in ammonia toxicity tests, and relying on 72- or 96-hour LC_{50}s based on continual exposures may overestimate the importance of ammonia toxicity in fertilized ponds. A 4-hour LC_{50} may more realistically reflect un-ionized ammonia concentrations harmful to fish raised in outdoor, fertilized ponds.

However, the fact that un-ionized ammonia may be of lesser importance in fertilized ponds does not mean that the farmer should not reduce any potential risks. The two management options are to keep afternoon pHs lower, or to keep afternoon total ammonia concentrations lower. Increasing the buffering capacity by increasing alkalinity (e.g., with addition of lime) will reduce pH fluctuations. However, a more cost-efficient approach would be to fertilize with nitrogen more efficiently. In nitrogen-limited ponds, the algae utilize essentially all the dissolved inorganic N available to them. Ideally, however, the pond should be so productive that light limitation from algal self-shading controls algal productivity (Knud-Hansen et al., 1991a). Under these conditions it is important to supply only as much N as the algal community requires, which is the simplest way to avoid the possibility of un-ionized ammonia toxicity in culture ponds. The discussion of various fertilization strategies in Chapter 6 indicates ways to help the farmer avoid overfertilizing culture ponds.

Before examining the fertilizers themselves, it is useful to reflect on what we have already learned, and what we need to know to best evaluate a given fertilizer's utility in a culture pond. We know that:

- Algal productivity is generally limited by availability of P, N, C, and/or light;
- Fertilizers provide soluble P, N, and/or C for algal uptake;
- It is not desirable to have high inorganic turbidity, critically low DO concentrations, or high un-ionized ammonia concentrations; and
- The relative utility of a fertilizer is based on comparative economics, including potentially negative impacts on pond ecology.

With this in mind, it is time to evaluate the more common fertilizers used in warmwater aquaculture. The three categories examined are animal-based organic fertilizers, plant-based organic fertilizers, and chemical fertilizers.

Animal Manures

Types

Animal manures have a long history in aquaculture as sources of soluble P, N, and C for algal growth and natural food production, and as sources of particulate organic matter for rotifer production (Wohlfarth and Schroeder, 1979; Colman and Edwards, 1987). This section does not examine every possible source of animal manure suitable for aquaculture, but instead focuses on how different types of manure provide soluble algal nutrients, impact pond ecology, and satisfy the farmer's need for cost-efficient fertilization. For purposes of discussion, animal manures are categorized as either poultry (e.g., chickens and ducks) or mammal. Manures from mammals are either from ruminants (e.g., cows and buffaloes) or non-ruminants (e.g., pigs and rabbits).

Nutrient Availability

The first consideration is determining how well each fertilizer provides soluble P, N, and C for algal uptake. It must be appreciated that only a fraction of the P, N, and C in the manure will become available for algal growth. Most of the nutrient release occurs within a few days of adding the manure to the pond, primarily through leaching and the breakdown of soluble organic molecules (Amir Ullah, 1989; Nath and Lannan, 1992). A certain percentage of manure-P, -N, and -C will remain bound in particulate matter, and will eventually be buried in pond sediments. Economic analyses of fertilizers must reflect the cost per molecule of only the nutrient pool made available for algae, without including the percentage of nutrients lost to the sediments and never made available to algae.

Manure nutrient concentrations, and the percentage of manure-P, -N, and -C which becomes available for algal uptake, depend primarily on the animal's diet, whether the manure is liquid or solid, and the age and storage conditions of the manure (Muck and

Steenhuis, 1982). First, the source-animal's diet is important because what comes out of an animal is directly influenced by what it consumed (Little and Muir, 1987; Amir Ullah, 1989). Animals fed high-protein diets typically have manures richer in N and P than manure from similar animals who rely on scavenging for their sustenance. Appreciating the relationship between animal feed quality and resultant manure quality helps the farmer reduce the risk of over-fertilizing the ponds, which could result in ammonia toxicity and pond water deoxygenation.

Second, nutrient availability is related to the consistency or form of the manure. Liquid excretions (e.g., urine) already contain algal nutrients in soluble forms, and more nutrients will be released with the decomposition of soluble organic matter. Algal nutrients are generally more tightly bound in particulate manure, and so a smaller percentage of the total manure-N, -P, and -C in solid wastes will become available for algal uptake (Colman and Edwards, 1987; Knud-Hansen et al., 1991a).

The third factor affecting the percentage of available nutrients is the age and storage conditions of the manure. Fresh manure contains more nutrients than manure which has been stored. During manure storage, aerobic decomposition results in the release of CO_2 and ammonia, reducing both the total amount and percentage of N and C available to algae when the manure is eventually put in the pond (Muck and Steenhuis, 1982; Amir Ullah, 1989). The loss of CO_2 may be compensated somewhat by lime (calcium carbonate), which is often added to stored manures to reduce noxious odors. If the stored manure is not protected from the weather, leaching of soluble nutrients will further decrease the fertilization value of the manure. Table 6 compares nutrient concentrations of several typical animal manures.

There are many benefits of using animal manures for pond fertilization. Manure can be a good source of CO_2, which may be needed in rain-fed or other ponds with low alkalinities. Although manures do not increase alkalinity unless lime was added during storage, the CO_2 released during decomposition will be available for algal uptake. Manure can supply soluble N and P for algal utilization, and provide a substrate for zooplankton production (Colman and Edwards, 1987; Wohlfarth and Schroeder, 1979; and Mims et al., 1995). Manure additions may also help clarify clay turbidity in pond water (K. Hopkins, personal communication). Furthermore, a layer of

Animal	% Moisture	% N	% P
Poultry litter[a]	28	2.8	1.2
Chicken[b](bagged)	38	2.0	3.0
Duck[c](fresh)	82	3.7	1.7
Buffalo[d] (fresh)	77	1.7	0.1
Dairy cattle[a] (fresh)	86	0.5	0.1
Swine[a](fresh)	89	0.6	0.2
Sheep[e] (fresh)	77	1.4	0.2

Table 6. Representative availabilities of nitrogen (N) and phosphorus (P) in various animal manures.

organic matter on the pond bottom can help reduce the rate of P adsorption to pond sediments (Borggaard et al., 1990) and may reduce seepage of pond water (Teichert-Coddington et al., 1989). The final benefit of manure may be its availability and easy production on the farm.

It may be argued that manure can be consumed directly, thus providing an additional benefit for culture organisms (e.g., Noriega-Curtis, 1979; Oláh et al., 1986; Colman and Edwards, 1987; Green et al., 1989). In fact, Knud-Hansen et al. (1991b) demonstrated utilization of particulate chicken manure by Nile tilapia in ponds fertilized only with chicken manure. In highly productive ponds receiving primarily chemical fertilizers, however, there was no significant benefit to tilapia when the fertilization regime was supplemented with chicken manure (Knud-Hansen et al., 1993; see also Schroeder et al., 1990).

This latter conclusion is not surprising, since there is no reason to believe that the direct consumption of manures is more advantageous for filter-feeding organisms than feeding on natural foods produced in the pond. The nutritive value of animal manure is poor when compared to living algae, zooplankton, and algal-based detrital aggregates. In fact, suspended particles of manure may actually impair fish productivity by diminishing the overall nutritive quality of the filterable organic matter in the pond. Furthermore, adding additional manure for purposes of direct consumption may unnecessarily degrade the quality of pond water (see below). Manures

can be beneficial in providing algal nutrients to stimulate primary productivity, and decisions to add manure should be based on its utility for producing natural foods.

Environmental Impacts

Although manures may represent a readily available source of algal nutrients, they contain other elements which can have serious and undesirable impacts on pond ecology. First, manures contain organic matter. Other than the possibility that culture organisms may in fact consume particles of manure, the main problem with introducing organic matter to a pond is the depletion of DO required for its utilization and decomposition (Wohlfarth and Schroeder, 1979; Shevgoor et al., 1994; Qin et al., 1995). As more manure is added to a pond, pre-dawn DO levels can reach 0 mg l^{-1}, causing severe stress or mortality of the culture organisms. The mixing of anoxic bottom water back into the water column can potentially increase ammonia and hydrogen sulfide concentrations to toxic levels (Ram et al., 1982).

Pond filling is an additional consideration associated with fertilizing with particulate manures. The depth of accumulated organic solids increases over time, thus reducing the effective volume of water available for culture organisms. Organic accumulation is less of a problem in tropical ponds where water temperatures remain relatively warm all year, and when bottom sediments are resuspended into oxygenated waters above. Nevertheless, heavily manured ponds may periodically require the costly shoveling-out of bottom sediments.

Manures produced by ruminants, such as cows and buffaloes, release dissolved organic compounds which can also degrade the pond environment. The plant material consumed by these animals contains complex organic molecules, which are passed into the manure. These soluble organic molecules impart a dark color to the water, thereby reducing the amount of light available for algal photosynthesis. The more these manures are used, the lower the potential net algal productivity, and the lower the resultant net fish yields. Shevgoor et al. (1994) reported increasing water color and decreasing dissolved oxygen with increasing rates of buffalo manure fertilization. Figure 8 illustrates the positive and negative effects on pond ecology when putting buffalo manure in a pond. These dissolved organic

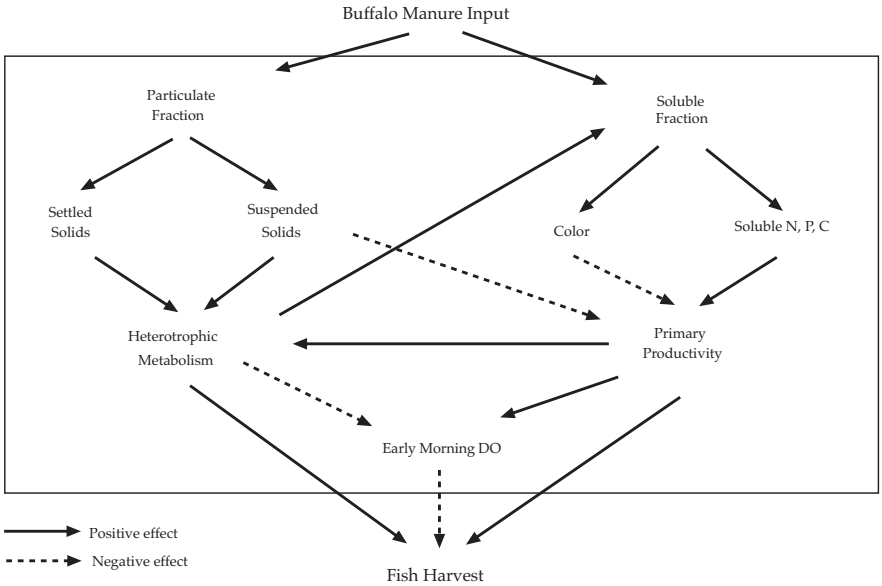


Figure 8. Schematic diagram showing the positive and negative ecological impacts with the addition of buffalo manure in a culture pond. Heterotrophic metabolism refers to decomposition and secondary production processes (adapted from Shevgoor et al., 1994).

molecules will eventually decompose over time, but until then they represent an undesirable ecological impact on natural food production.

Farm Costs

Although the animals do not charge anything for giving it, from the farmer's perspective manure is not free. Manure available for aquaculture is either purchased off-farm, or produced on-farm. If purchased off-farm, associated costs include the actual purchase price, transportation costs to the farm, labor for hauling and shoveling the manure into ponds, and lost opportunity costs. Here, lost opportunity costs refer to opportunities for economic improvement the farmer no longer has because of time and financial expenses devoted to obtaining and putting fertilizers in his/her ponds (Engle et al., 1993). These

costs vary with each farmer and locale, but it is incorrect to assume that the farmer has nothing better to do than shovel manure—it should be up to the farmer to make that determination. Additional farm costs may include the purchase, maintenance, and operation of mechanical aerators, as well as costs associated with removing accumulated bottom sediments from the pond.

When buying manure off-farm, purchase-price comparisons with other fertilizers are best accomplished by calculating the actual cost of the available algal nutrients released by the fertilizer. A cost comparison between chicken manure and chemical fertilizers (TSP and urea) in Thailand showed that chicken manure was over seven times more expensive as a source of available N than urea, and over four times more expensive a source of available P than TSP (Table 7; Knud-Hansen et al., 1993). This result was surprising in that a 50-kg bag of chicken manure cost only 20 baht (US$1 = 25 baht at the time), while 50-kg bags of urea and TSP cost 240 baht and 450 baht, respectively. But because of the concentrated nature of urea and TSP, 1 kg of urea and 1 kg TSP together provided an amount of available N and P equivalent to about 100 kg of chicken manure. This ratio will vary depending upon the quality of manure and the solubility of algal nutrients contained therein. For example, Nath and Lannan (1992) found 60 to 80% of the total N and P in chicken manure was available. Such a price comparison is only one aspect of the economic analysis, however, and the other relevant factors of associated farm expenses (e.g., manual labor, time, and impacts on pond ecology) must also be considered when choosing the most appropriate fertilizer. The easiest way to eliminate the purchase price of manure is to produce it on-farm. Using the output of one farming subsystem as input for

Fertilizer	**Cost** (baht (50 kg)$^{-1}$)	**Available N** (baht kg^{-1})	**Available P** (baht kg^{-1})	**Available C** (baht kg^{-1})
Chicken manure	20 [a]	76 [b]	194 [c]	7 [d]
Urea	240	10	—	24
TSP	450	—	45	—
$NaHCO_3$	1000	—	—	140

Table 7. Economic comparison of different fertilizers with respect to available nitrogen (N), phosphorus (P), and carbon (C) (US$1 = 25 baht) (from Knud-Hansen et al., 1993).

another is a common component of an integrated farming system. In this case, animals can be raised adjacent to aquaculture ponds so that waste products can be conveniently washed into the pond. If waste disposal is an economic/labor cost to the farmer, then integrated aquaculture can provide an additional benefit (Edwards, 1983; Little and Muir, 1987; Edwards, 1991).

Integrated farming with poultry can be as simple as putting chicken coops over a pond, or allowing ducks to spend the day swimming on the pond (Barash et al., 1982; Edwards, 1986). In the former, spilled feed will also contribute algal nutrients through decomposition as well as through direct ingestion by fish and subsequent excretion. With ducks, it is best to have duck houses also over water (e.g., on stilts) to prevent the ducks from eroding the pond banks with daily traffic. Pond bank erosion will increase inorganic turbidity, and thus reduce available light for algal productivity. Duck houses should not inhibit water movement underneath, and ponds should be large enough so that duck houses do not cause significant shading of pond water.

When evaluating the economics of an integrated system, the focus should be on the individual subsystems (e.g., pond, crop, poultry, pig). If all subsystems are showing a profit, then using integrated farming to supply pond fertilizers can improve farm profitability. For example, if raising pigs is profitable, then the corresponding pig manure available for pond fertilization is an additional value of the pig operation (Edwards, 1985; Teichert-Coddington et al., 1990). If the pig subsystem loses its profitability due to increasing production costs or a significant drop in the market value of pork, however, it makes little economic sense to raise pigs just to fertilize ponds if the net loss from the pig production is greater than the cost of other available fertilizers. Even if all subsystems are profitable, an itemized review of total farm expenses may indicate that some other available sources of pond fertilizers are more economical in the long term.

Green Manures

The use of terrestrial and aquatic macrophytes for aquaculture is a very broad topic, which includes direct feeding on freshly cut plant material and the composting of plants both in and outside the

pond (Edwards, 1987). Composted plant materials provide a pond with decomposed particulate matter, and release soluble algal nutrients and dissolved organic matter during decomposition (Biddlestone and Gray, 1987). Since the central theme of this book is the relationship between pond fertilization strategies and pond ecology, discussion of green manures is limited to the utility of macrophytes as a direct source of algal nutrients in a culture pond.

Decomposition of macrophytes in a pond/lake system is a two-stage process. The first stage of plant decomposition is characterized by the leaching of soluble organic compounds during the first several days after submersion into pond water (Gasith and Hasler, 1976; Gasith and Lawacz, 1976; Gadshalk and Wetzel, 1977). These leachates are rapidly decomposed and release ammonia, soluble P, CO_2, and other by-products (Wetzel and Manny, 1972). Microbial oxygen demand remains high while the easily decomposable materials are broken down. This first stage is followed by the considerably slower decomposition of remaining particulate plant matter and more complex dissolved organics. Included in the latter group are tannins and other dissolved organic materials, which impart a dark and lasting color to the water (Christman and Ghassemi, 1966).

Types

Plants utilized as green manures include both terrestrial grasses and nitrogen-fixing legumes, as well as rooted aquatic macrophytes. The best plants are low in fiber (e.g., aquatic macrophytes) so decomposition is faster, and high in soluble algal nutrients (e.g., nitrogen-rich legumes) (Biddlestone and Gray, 1987). Plants which have been chopped into pieces decompose relatively faster than unchopped plants because of increased surface area for microbial attachment and decomposition. Plant material may be added directly to the pond, or put into separate composting areas. Composting may be conducted in the pond in a number of different ways. In China, farmers pile plant biomass in 150-kg heaps along the pond banks (Edwards, 1987). After three to four days the heaps begin to leach into the water, turning the pond a greenish-brown color. Heaps are spread several times to distribute organic matter throughout the pond. Within ten days, the partially decomposed plant material is removed from the pond and incorporated into the soil for

terrestrial farming. Another technique involves using bins in the corner of a pond. Plant matter in the bin leaches dissolved organic matter into the pond, but keeps the particulate matter out of the culture area. Composting bins may also be located outside the pond with the leachate either filtered out or washed directly into the pond.

Nutrient Availability

Nutrient availability from green manures depends on a number of factors. Different plants have different amounts of N and P, and the concentrations of N and P vary with the different parts of the plant (Biddlestone and Gray, 1987). For example, leaf biomass generally has greater concentrations of leachable N and P than woody stems or roots (Gasith and Hasler, 1976). Plants fertilized with N and P will have greater concentrations in their biomass than similar plants

Plant	% Moisture	% N	% P
Alfalfa (dry)	10	2.4	0.2
Alfalfa (fresh)	76	0.7	0.1
Mixed grass (dry)	11	1.1	0.2
Mixed grass (fresh)	69	0.8	0.1
Rice hulls	8	0.5	0.1
Rice straw	7	0.6	0.1
Sugar cane leaves	74	0.2	0.1
Cottonseed meal	7	6.9	1.1
Soybean meal	10	7.3	0.6

Table 8. Representative availabilities of nitrogen (N) and phosphorus (P) in various plants (adapted from Boyd, 1990).

grown with reduced N and P availability. Table 8 provides N and P concentrations for several different plants.

Whether plants decompose in composting bins or directly in the pond, the decomposition processes are the same and the amount of nutrients eventually released from the plants should be reasonably

similar. There are two exceptions to this general assumption. First, placing compost bins outside the pond can cause some of the released ammonia and carbon dioxide to be lost to the atmosphere through volatilization. Second, stocking a herbivorous fish (e.g., *Tilapia rendalli* or silver carp, *Hypophthalmichthys molitrix*) with a filter-feeding fish such as Nile tilapia can provide plant N and P more quickly than would otherwise be available from passive leaching and slower microbial decomposition. Plant material, such as napier grass (*Penniselum pururеum*), added to the pond is fed upon directly by the herbivorous species, accelerating the decomposition process and release of algal nutrients through fish excretions (Chikafumbwa, 1996). Rapid plant consumption would reduce both the oxygen demand in the pond from the added organic matter, and the amount of color-forming soluble organics released during decomposition (see below).

Environmental Impacts

Adding green manures to a pond has several direct consequences for pond ecology. First, the amount of light energy in the water column is diminished through absorption both by the dark water color imparted by dissolved organics and by the suspended particulate matter from decomposing plants (Mims et al., 1993). Second, there is an additional microbial oxygen demand to decompose organic matter introduced into the pond (Schroeder, 1975). The increased need of DO for microbial respiration is often made more acute by reduced oxygen production from algal photosynthesis because of decreased light availability.

The severity of these impacts on pond ecology depends in part on the method used to put the green manure into the pond. Direct application of chopped plant biomass is likely the least effective way to fertilize a pond, except when culture organisms consume the plants directly. Otherwise, the chopped plants can exert a high oxygen demand, increase water color, and physically block out sunlight for algae. Partially decomposed plant material eventually settles to the pond sediments, promoting anoxic conditions in bottom waters while filling the pond with organic matter. Extensive use of green manures could necessitate mechanical aerators or other means of pond reaeration.

Negative ecological consequences of using green manures can be reduced by decomposing the plant matter in bins outside the pond and devising an efficient collection system for the leachate. In this way, atmospheric oxygen is used for decomposition and the partially decomposed particulate matter (which could be used to improve agriculture soils) is kept out of the pond. Furthermore, if the leachate can be exposed to sunlight for several days before it is used to fertilize the pond, the breakdown of soluble organics will be faster and there will be less color imparted to the pond water (Shevgoor et al., 1994). Although some CO_2 and ammonia is lost to the atmosphere, minimizing negative environmental impacts makes leachates more effective fertilizers.

Farm Costs

The deciding factor on the utility of green manures is probably based on farm-specific economics. There are several costs and labor demands which must be considered before adopting a green manure fertilization strategy. For example, in addition to construction and maintenance costs for compost bins, the potential requirement for mechanical aerators should also be included in the budget analysis. Although in-pond composting might be less expensive to set up, the associated environmental impacts discourage that approach.

The plants used as green manures also come at a price. There are both out-of-pocket and labor costs incurred for growing, maintaining, harvesting, and transporting plants to composting areas. These expenses can be reduced by growing marketable food crops (e.g., vegetables) along the pond banks, and then composting the non-consumable parts of plants otherwise raised for food. There are essentially no additional production costs of this approach, and it is a convenient way to recycle nutrients from decomposing plants back into living biomass (e.g., algae and other natural foods). It is better to compost fresh, green plant matter, because dried by-products (e.g., rice straw) have already lost most of their leachable nutrients (Biddlestone and Gray, 1987). As an alternative to composting, some agricultural by-products may be suitable as a supplementary food source for farm animals. A portion of the P, N, and C contained in the plant material is incorporated in animal biomass, while another

portion is excreted, which then becomes available for pond fertilization.

For all these different ways of integrating plant crops, livestock, and aquacultural production systems, there are labor costs involved. If the farmer has to hire the labor, then these expenses become quantifiable and more readily incorporated into a comprehensive economic analysis. But if, for example, the farmer plants legumes to be used as a pond fertilizer, then determinations of the actual price of available P, N, and C for algal productivity must include: 1) all legume production costs (including seeds and/or transplanted cuttings); 2) more profitable alternative uses for the land and water used to grow the plants; and 3) more profitable uses of the farmer's time and labor (i.e., lost opportunity costs).

The appreciation of lost opportunity costs is of paramount importance for the farmer's economic development. A farmer who spends hours a day collecting and/or processing manures (both animal and green) for aquaculture should do so only if it makes economic sense to that farmer. Otherwise, it becomes a very high price to pay for algal nutrients if the land, water, and labor could be used for more profitable endeavors. To help the farmer make this analysis, Appendix 2 is a summary of the economic and ecological factors which should be considered when choosing a particular fertilization strategy at the individual farm (or farm pond) level.

Chemical Fertilizers

Types

Chemical fertilizers are concentrated sources of P, N, and C which are manufactured, distributed, and sold in package form. The ones used in aquaculture are identical to those used in terrestrial agriculture. The more commonly used chemical fertilizers for P include mono superphosphate (MSP), triple superphosphate (TSP), and the various combinations of nitrogen-phosphorus-potassium (N-P-K) fertilizers. Note that N-P-K fertilizers are designated by the content weight of N, P_2O_5, and K_2O, so a 20-16-8 grade fertilizer has actual N-P-K contents of 20%, 7%, and 6.6%, respectively (Lin et al., 1997). In addition to the N-P-K fertilizers, other N fertilizers include urea and sodium nitrate. Fertilization to increase inorganic carbon

availability is accomplished by adding carbonaceous minerals such as lime ($CaCO_3$) and sodium bicarbonate ($NaHCO_3$). Lime should be added with the appreciation that adding too much calcium facilitates

Fertilizer	Formula	% N	% P
Urea	$CO(NH_2)_2$	45	0
Ammonium nitrate	NH_4NO_3	35	0
Ammonium sulphate	$(NH_4)_2SO_4$	21	0
Sodium nitrate	$NaNO_3$	20	0
Calcium nitrate	$Ca(NO_3)_2$	17	0
Ammonium phosphate, monobasic	$NH_4H_2PO_4$	12	27
Ammonium phosphate, dibasic	$(NH_4)_2HPO_4$	21	23
N-P-K (20-16-8 grade)		20	7
Calcium phosphate, dibasic	$CaHPO_4$	0	23
Triple superphosphate (TSP)	$10Ca(H_2PO_4)_2 + 2HF$	0	19-24
Mono superphosphate (MSP)	$3Ca(H_2PO_4)_2 + 7CaSO_4 + 2HF$	0	8-9

Table 9. Availability of nitrogen (N) and phosphorus (P) in several chemical fertilizers. Actual fertilizer concentrations of N and P may vary or be slightly lower due to impurities. List below adapted from more complete listings found in Boyd (1990) and Lannan (1993).

the precipitation of $CaCO_3$ during afternoon increases in pH (Boyd, 1997, discussed in Chapter 3).

Nutrient Availability

Table 9 summarizes the content of each algal nutrient in several common chemical fertilizers. Since under typical pond water conditions these fertilizers eventually release 100% of each nutrient, the amount of soluble P, N, and C made available for algal uptake is readily calculable. It is better to dissolve the fertilizer in a bucket or put granules on a submerged platform to maximize soluble nutrient availability in the water column (Boyd, 1990).

It is important to remember that only part of the chemical fertilizer actually contains the desired algal nutrient(s). For example, urea is 46.7% N, and therefore 1 kg urea contains 0.467 kg of urea-N. Due to the prevalence of counterfeit fertilizers in some developing countries (e.g., some bags of urea produced in Thailand were found to contain considerably less than 46.7% N), it may be prudent to verify either the source or the actual nutrient concentration when first using a particular chemical fertilizer.

Environmental Impacts

The dominant impact on pond ecology from the use of chemical fertilizers is the corresponding rise in algal productivity, the exact result a farmer wants from pond fertilization. Since no additional organic matter is added to the pond, deoxygenation is not a problem. In highly productive, warmwater ponds (afternoon DO levels around 20 to 30 mg l^{-1}) fertilized only with urea and TSP, predawn DO concentrations typically average around 3 mg l^{-1} during a five-month grow-out of Nile tilapia (Knud-Hansen et al., 1993). The pond microbial community has sufficient DO to metabolize the daily production of algae-derived detritus and soluble organic molecules.

In addition to not containing organic matter, a second benefit of chemical fertilizers over most organic fertilizers is that they do not affect light availability to algae. Chemical fertilizers dissolve in water, so there is no additional particulate matter suspended in the water column, such as that observed with manures. Nor are there tannins or other dissolved organic substances which impart significant color to the water, as is the case with green manures and animal manures from ruminants.

Furthermore, the rate of P adsorption by pond sediments can be reduced more quickly by applying a P fertilizer such as TSP. As discussed in Chapter 3, organic matter on the pond bottom adsorbs P less readily than bare inorganic sediments. Adding TSP will more rapidly fill remaining P adsorption sites in the sediments. Reducing net P losses to the pond sediments will increase the availability of subsequent P fertilization to the pond's algal community (Boyd, 1971; Boyd and Musig, 1981; Knud-Hansen, 1992).

One common misconception is that chemical fertilizers increase acidity in outdoor culture ponds. In fact, the addition of nitrates, phosphates, and carbonates actually increases alkalinity in

water (Stumm and Morgan, 1970). A likely source of this confusion may be the misapplication of a laboratory investigation by Hunt and Boyd (1981) which examined the decomposition of urea and ammonia-based fertilizers in water.

Ammonia-based fertilizers and urea both add ammonia to water. Urea can also be directly utilized by many species of algae, bacteria, and fungi (Healey, 1977), or broken down through enzymatic reactions using urease (Leftley and Syrett, 1973; Morris, 1974). Equation 14 gives the general chemical reaction for the production of ammonia from urea:

$$\underset{\text{urea}}{CO(NH_2)_2} + H_2O \underset{\text{urease}}{\leftrightarrows} CO_2 + 2NH_3 \qquad [14]$$

Ammonia in water goes between the un-ionized (NH_3) and (NH_4^+) ionized forms, as discussed earlier in this chapter and shown again in Equation 15:

$$NH_3 + H_2O \rightarrow NH_4^+ + OH^- \qquad [15]$$

This reaction shows that adding ammonia to water actually *increases* alkalinity with the addition of each hydroxyl ion (OH^-, see also Equation 11). If ammonia remains in oxygenated water, however, the slow microbial oxidation of NH_4^+ to nitrate (NO_3^-) releases two hydrogen ions (H^+) for every molecule of ammonia, thus causing a net increase in the water's acidity. Hunt and Boyd (1981) conducted their experiments in the *dark*, and were able to demonstrate this acidification of water with the addition of ammonia-based fertilizers.

If ammonia is taken up biologically before it gets slowly oxidized to nitrate, then H^+ ions are not released and there is no additional acidity. For example, in the presence of sunlight, ammonia released from urea (or from any other source of ammonia, including the decomposition of manures and detritus) is rapidly taken up by algae during photosynthesis (Sugiyama and Kawai, 1979). Alkalinity increases with the addition of OH^- (Equation 12) when ammonia chemically reacts with water (Equation 15), but algal uptake of NH_4^+ prevents any further oxidation to nitrate, and therefore H^+ ions are not produced. Recent research confirmed both the loss of alkalinity when

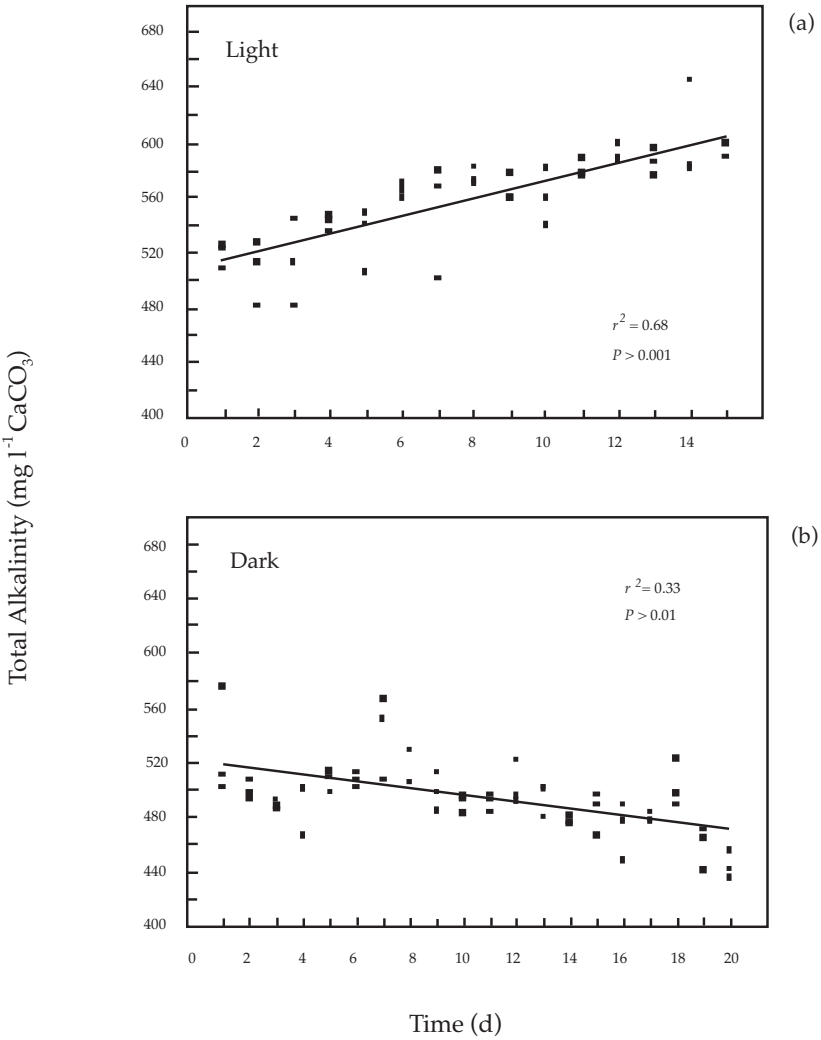


Figure 9. Graphs illustrating changes in total alkalinity with the addition of urea, an ammonia-based chemical fertilizer. Alkalinity increases in the presence of light (a) because of photosynthetic uptake of ammonia and decreases in the dark (b) because of the oxidation of ammonia to nitrate and nitrite (see text for discussion; graphs adapted from Knud-Hansen and Pautong, 1993).

urea is decomposed in the dark, and the expected increase in alkalinity when sunlight is present (Figure 9; Knud-Hansen and Pautong, 1993). Vlek and Craswell (1979) also reported a similar increase in pH and alkalinity in flooded rice fields fertilized with urea. Because these increases in alkalinity are due to additions of OH^-, there is no effect on total DIC beyond the additional CO_2 which is produced during urea decomposition (Equation 14).

Because Hunt and Boyd's (1981) study was conducted in the dark, its practical application to pond fertilization is severely limited. Since algae utilize ammonia, regardless of the source, research clearly shows that acidification does not take place in fertilized ponds. In fact, if ammonia were a significant source of acidity in culture ponds, the continual release of ammonia from decomposition should have an observable effect. Decades of fertilizer research has yet to document acidification in a pond which could be attributed *directly* to ammonia oxidation. Figure 9 indicates that it could take weeks for acidification to occur even in the dark. As a practical issue, the need to replace ammonia-based fertilizers with sodium nitrate to prevent pondwater acidification (e.g., Boyd, 1995b) has been overstated.

Conditions are rare which would permit acidification of pond water due to fertilization with ammonia. The accumulation of ammonia in unproductive ponds (e.g., due to inorganic turbidity) which have been heavily overfertilized with ammonia-based fertilizers (including manures) can cause both a loss of alkalinity through the oxidation of ammonia to nitrate and potentially toxic levels of un-ionized ammonia. Oxidation of ammonia can also occur in the dark, bottom waters of a thermally stratified pond, but probably only to a small degree since microbial respiration of organic matter will rapidly deplete available DO. Therefore, any reasonable application of commonly used agrochemical fertilizers should not increase pond water acidity.

Farm Costs

Chemical fertilizers suitable for aquaculture can be found in all countries of the world where such fertilizers are used for raising land crops. In fact, chemical fertilizers are often produced in developing countries located in the tropics. The fact that these fertilizers are marketed in a country does not mean, however, that they are sold in remote villages. Farmers should include in their

economic analysis the cost of getting fertilizers to the farm, which may include transportation costs if not locally available.

Cost analysis should also include the price per kg of soluble algal nutrient(s) in the fertilizer. A seemingly inexpensive source may not be as economical as first perceived. As previously demonstrated in Table 7, the highly concentrated nature of chemical fertilizers can make them several times more cost-efficient sources of algal nutrients than purchased manures, even though manures are considerably less expensive on a per-kg basis (Knud-Hansen et al., 1993). Anderson (1993b) also reported the economic benefit of chemical fertilizers over organic sources.

However, purchasing the least expensive source of soluble N and P may be difficult in some cases. The market cost per kg of fertilizer generally increases as bag size decreases, and poorer farmers may not have the financial resources to purchase the more economical 50-kg bags. Furthermore, N-P-K fertilizers, typically available in remote villages, tend to be more expensive sources of soluble N and P than urea and TSP, respectively. This is in part due to the inclusion of K in the fertilizer, which has never been shown to limit algal productivity and represents an unnecessary expense to the farmer. If individual farmers cannot afford to purchase fertilizers in bulk, then joining a group of farmers or a farming cooperative would allow them to purchase only what they need.

With livestock-land crop-aquaculture integrated farming systems, it is more common to put chemical fertilizers on the land crops and manures in the ponds. Ecologically, and perhaps economically, it makes more sense to do the reverse. Manures decompose more readily in air, which has about 20 times more oxygen than does water at saturation. And rather than filling up ponds with organic matter and depleting waters of oxygen, composted manures applied on land can improve soil quality as well as provide a source of plant nutrients. Chemical fertilizers could supplement manure-treated soils as required.

On the other hand, chemical fertilizers applied to land crops can easily wash out once in solution; the high N and P content of agricultural drainage water is evidence of these losses. Directing this drainage into a culture pond would help reduce this potential loss to the farm while helping protect downstream environments from unwanted eutrophication. From a whole-farm perspective, adding chemical fertilizers to the pond (to intentionally create eutrophication)

and using pond water to irrigate land crops should further increase nutrient utilization efficiencies. A farm economic analysis which includes an assessment of ecological impacts should indicate which fertilization strategy is the most cost-effective.

Other economic benefits of using chemical fertilizers for pond fertilization include their consistency and predictability in nutrient concentrations, their long shelf-life when properly stored, and their relative ease of application (Boyd, 1997). Labor costs involved with applying chemical fertilizers are lower than those for organic fertilizers. Manures tend to be noxious, heavy, bulky, and required in much greater amounts. For example, a typical fertilization rate with chicken manure is about 500 kg ha^{-1} wk^{-1} (e.g., Green and Boyd, 1995), which provides approximately the same amount of soluble N and P as 5 kg ha^{-1} wk^{-1} of urea and TSP, respectively.

However, the farmer's decision whether to use organic or chemical fertilizers should be based primarily on farm economics, which necessarily includes relevant aspects of pond ecology. Although algae do not question the sources of P, N, and C, the farmer should question the environmental costs and economic benefits of each potential fertilizer. In making this analysis, the farmer should also consider several pond-specific characteristics which can affect the efficacy of a particular fertilization strategy. This is the subject of the next chapter.

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 CO_2 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 m^2 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-m^2 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 CO_2 (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	• easy to harvest • pond water warms rapidly • less costly to construct • requires less water	• high inorganic turbidity • less water for biological production
1.0-1.2	• harvest still manageable • less inorganic turbidity • diel stratification and internal fertilization	• wind-induced resuspension of pond sediments
> 1.5	• low inorganic turbidity • greater volume of water for growth	• 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 m^2 [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-m^2 (0.02-ha) pond with very stable earthen or concrete banks may work as well as a 5,000-m^2 (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 CO_2 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 CO_2 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 (FeS_2), which oxidizes to sulfuric acid (H_2SO_4) 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.

Chapter 6. Methods for Determining Fertilization Requirements

Pond management should maximize availability of soluble N, P, C, and light for algal uptake and utilization, while minimizing environmental and economic impacts. Earlier chapters have established the foundation for achieving this goal. Chapters 2 and 3 outlined the biological, chemical, and physical pond-dynamic processes relevant to understanding the ecological consequences of adding fertilizer to a pond for natural food production. We examined advantages and disadvantages of different fertilizers in Chapter 4, and in Chapter 5 we examined how pond location, morphometry, source water, and sediments can be managed to optimize a pond's ecological response to fertilization.

Now that we have looked at the why, what, and where, it is finally time to discuss the question of how much fertilizer should be added to a particular pond. Remember that the farmer wants to get the most for his/her money and labor. Also recall the well-established and very strong positive relationship between net algal productivity (NP) and the net fish yield (NFY) for fish whose diet consists of natural food produced in the pond. The short answer to the question, therefore, is that the farmer should fertilize *only* to the extent necessary to cost-effectively maintain high algal productivity throughout the *entire* culture period.

Fertilizers and fertilizer rates are selected to meet algal nutritional needs in highly productive culture ponds. Discussed below are a number of different methods available to the farmer for determining these nutritional needs. When comparing the relative utility of these different methods, several important considerations should be kept in mind. Among the key elements of comparison are:

1) How well does the method predict the desired algal response to the recommended fertilization?
2) How well does the method minimize the risk of underfertilization, or wasteful overfertilization?
3) How cost-efficient is the method with regards to time, labor, and its ability to predict algal responses? and
4) How well does the method account for the ecological diver sity of farm ponds in general?

The methods commonly used to determine a specific pond's fertilization requirements can be separated into two categories based on whether fertilization rates are determined before the pond is filled, or established from pond-specific measurements taken during the culture period. Methods in the latter category are further separated into those which rely on time-specific measurements, and a method which incorporates dynamic biological and chemical processes in the determination. Following this organizational format, discussions below identify the advantages and inherent problems of each approach, and demonstrate why the last method is the most effective in identifying a specific pond's variable fertilization needs throughout the entire culture period.

Predetermined, Fixed Fertilization Rates

Fixed Rates

A predetermined fertilization rate is usually a fixed recipe (e.g., 10 kg P ha^{-1} wk^{-1} and 30 kg N ha^{-1} wk^{-1}) selected prior to filling the culture pond with source water. Most often this recipe is based on previous fertilization research, and selected because it resulted in the best fish yields of the several treatments examined. The main advantages of this approach are that it is simple and routine. The main problem is that experimental results, gathered at institutional and university aquaculture research stations, may not be directly applicable to a farmer's fish pond.

The great variability among ponds worldwide with regards to latitude, altitude, morphometry, source water, soil profile, and fertilization histories precludes any reasonable reliance on recipes derived from a few studies conducted in relatively similar ponds. Experimental ponds for aquaculture research tend to be fairly uniform to reduce unwanted variability in grow-out experiments. In fact, pond uniformity and a fixed-input fertilization scheme are often essential *experimental* conditions for researchers to best study nutrient transport mechanisms and ecological relationships.

Farm ponds, however, are not uniform, and yields from experimental ponds indicate only what is possible in ponds under similar ecological conditions. Important, ecological variables that influence a fertilizer's ability to stimulate algal productivity include those factors that:

1) Affect nutrient uptake capabilities (e.g., the extent to which inorganic turbidity promotes light limitation);
2) Promote internal fertilization through nutrient recycling (e.g., whether pond sediments are oxic or anoxic, stratification and mixing characteristics in the pond, feeding and nesting habits of culture organisms);
3) Control thermal stratification (e.g., pond depth, pond's exposure to prevailing wind, local weather, size and feeding habits of culture organisms); and
4) Affect algal nutrient availability in the water column (e.g., sediment characteristics, fertilization history of each pond).

Not only is the relative importance of these factors pond-specific, but they can vary in importance in the same pond during a several-month culture period.

Fixed-rate recipes pay little attention to pond dynamics and the ecological differences between culture ponds that affect fertilization responses. As a result, these fertilizations are generally inefficient, often adding more nutrients than necessary. For example, wasteful nutrient accumulation in pond water can occur if ponds are light limited due to sporadic or seasonal increases in inorganic turbidity from rainfall or bioturbation of pond sediments (Knud-Hansen and Batterson, 1994; Knud-Hansen et al., in press). Also, recipes often do not account for changing nutrient requirements during grow-out, as may happen when P adsorption sites in pond sediments get filled, or when unwanted molluscs gradually remove carbonate from the water for shell growth.

Fixed-rate fertilization recommendations defined by national boundaries or geographic regions have little relevance to the farmer if his/her ponds are significantly dissimilar from experimental ponds. If the farmer's ponds are sufficiently similar ecologically to the experimental ponds from which the recommendations were derived, however, then it does not matter in which country the experimental ponds were located for the fertilization guidelines to be reasonably applicable. Individual pond ecology determines how fertilization affects that pond's productivity, not the pond's physical location in relation to international borders.

Since yields from experimental ponds indicate only what is possible in ponds under similar ecological conditions, it is worth examining the circumstances which have produced some of the

highest reported Nile tilapia yields when raised on naturally produced food only (Table 11). Data presented in Table 11 are extracted from three research studies conducted in Thailand during the early 1990s (Knud-Hansen et al., 1993; Knud-Hansen and Batterson, 1994; Knud-Hansen and Lin, 1996). Although experimental

Stocking Rate (fish m^{-2})	Mean Final Weight (g $fish^{-1}$)	NFY (kg^{-1} ha^{-1} d^{-1})	NFY (kg^{-1} ha^{-1} yr^{-1})	Reference
1.6	244	31.7	11,558	1
1.6	261	25.5	9,309	1
1.6	232	27.2	9,932	1
1.6	284	28.8	10,511	1
1.6	245	27.6	10,066	1
2.0	170	22.6	8,249	2
2.0	166	24.9	9,088	2
2.0	167	22.0	8,030	2
2.0	157	23.3	8,504	2
0.8	422	17.0	6,205	3
0.8	350	14.9	5,429	3
1.6	296	29.1	10,637	3
1.6	230	29.9	10,929	3
2.4	240	30.9	11,286	3

[1] Knud-Hansen et al. (1993) (200-m^2 ponds at Bang Sai, Thailand).
[2] Knud-Hansen and Batterson (1994) (400-m^2 ponds at AIT, Thailand).
[3] Knud-Hansen and Lin (1996) (200-m^2 ponds at Bang Sai, Thailand).

Table 11. Representative net fish yields (NFY) of sex-reversed male Nile tilapia raised for five months (initial stocking weights about 10 g $fish^{-1}$) in culture ponds with low inorganic turbidity and alkalinities above 75 mg l^{-1} $CaCO_3$, and where at least 90% of the fertilizer N and P came from chemical fertilizers. Fertilization input was at fixed rates of approximately 30 kg N ha^{-1} d^{-1} and 10 kg P ha^{-1} wk^{-1}.

designs and objectives differed among the three investigations, they all included some ponds fertilized with urea and TSP at similar high fixed rates of approximately 30 kg N $ha^{-1}wk^{-1}$ and 10 kg P $ha^{-1}wk^{-1}$. The 14 research ponds reported in Table 11 were located at two sites about 30 km apart, were maintained at about 1.0 m in depth, ranged in surface area from about 200 to 400 m^2, and were characterized by relatively low inorganic turbidity and alkalinity generally above 75 mg $CaCO_3$ l^{-1}. Sex-reversed male Nile tilapia were stocked at

approximately 10 g fish^{-1}, and culture periods were four to five months.

In these clearwater ponds, apparently with sufficient light and DIC availability, the algal communities were able to benefit from the high N and P fertilization rates. Ponds remained deep green, with afternoon DO, measured every two weeks, often greater than 20 mg l^{-1}. Pre-dawn DO levels averaged around 3 mg l^{-1} during the culture period. High algal productivity in these 14 ponds resulted in an average annually extrapolated NFY of 9,267 kg ha^{-1} y^{-1}, with a standard deviation of 1,770 kg ha^{-1} y^{-1}. At the time these experiments were conducted, the total cost of the fertilizer was about 25% of the total farm-gate price of the tilapia produced.

The fixed fertilization rates used in these investigations should be considered neither the maximum nor the most efficient possible rates. These rates worked well in 1-m ponds with good water quality, although accumulation of soluble N and/or P during the culture period in some ponds suggests that slightly lower fertilization rates could have produced similar yields, or perhaps adding more DIC could have increased the yields. Furthermore, productivities were substantially reduced in other experimental ponds limited by carbon and/or light, as indicated by consistently low alkalinities and/or high inorganic turbidities, and by significant accumulations of soluble N and P (Knud-Hansen and Batterson, 1994). It is also a reasonable hypothesis that deeper (i.e., 2- to 3-m) clearwater ponds, mixed daily to prevent persistent stratification, could give greater yields with higher rates of nutrient input. Table 11 only shows what is possible under stated water quality conditions and similar pond morphometry (particularly pond depth).

The last point of discussion related to fixed fertilization rates concerns how they are expressed. Fertilization rates are typically given on an areal basis; that is, rates are referenced to pond surface area (e.g., kg ha^{-1} wk^{-1}). Fertilization rates can also be expressed volumetrically (e.g., kg m^{-3} wk^{-1}), or as an anticipated concentration (e.g., mg l^{-1}) (Boyd and Daniels, 1993). Neither areal fixed rates nor volumetric fixed rates fully incorporate pond dynamics in their application, which is another problem using such recipes. Areal rates focus on fertilizing the photic zone where algal photosynthesis and nutrient uptake occur, usually in the top 20 to 30 cm of productive ponds. But areal rates do not account for variabilities in dilution of added nutrients depending upon actual pond depth and volume. On

the other hand, fertilization rates standardized to pond volumes account for dilution, but ignore pond dynamics with regards to stratification, actual zone of photosynthetic activity, internal fertilization and nutrient recycling processes, and constantly changing volumes from seepage, rainfall, and source-water additions which also affect nutrient concentrations in the water.

Since there are inherent problems with both approaches, the choice of whether to describe fertilization rates areally or volumetrically should be based on function and purpose. For example, in aquaculture research there are experimental protocols in which describing loading rates volumetrically is analytically preferable and even necessary, particularly in tank experiments or when culture water is continually mixed or recirculated. Scientific investigations of nutrient cycling dynamics in earthen ponds should examine fixed nutrient loading rates both areally and volumetrically to best understand the ecological system.

Farmers, however, are more interested in improving farm production and personal incomes than in conducting ecological research, so fertilization rates should be described as practically as possible without unnecessary confusion. Farms are defined by surface area (not volume), so it is not surprising that areal fertilization rates are standard in terrestrial agriculture, and harvests from both land- and aquatic-based farming systems are typically reported by area (e.g., kg ha^{-1}). Analyses comparing fertilization and economic efficiencies between different crops, ponds, or farming systems are much simpler to conduct using identical units for both inputs and outputs (e.g., system/pond comparisons of kg ha^{-1} biomass produced per kg ha^{-1} nutrient added). In addition, accurately measuring volumes of slope-sided earthen ponds is considerably more difficult than measuring their surface areas. It is conceptually less confusing, and analytically more beneficial, for farmers to use fertilizer application rates described on an areal basis rather than to use rates based on questionable, implicit assumptions about a specific pond's ecology.

Furthermore, when fertilization rates are determined during the culture period using a method which inherently incorporates nutrient cycling processes in the determination (e.g., algal bioassay, see below), fertilization requirements can be determined on a pond-by-pond basis. Since there can be no misapplication of a predetermined fixed recipe due to differences in pond morphometry (e.g., pond depth), the choice of units for fertilizer rates is made only for the

farmer's convenience and analytical benefit. Therefore, the preference in this book is to discuss fertilization rates areally and not volumetrically.

Frequency of Fertilization

When employing a fixed-rate fertilization strategy, a secondary issue is how frequently should the ponds be fertilized. For example, a 1-ha pond fertilized at 10 kg P ha^{-1} wk^{-1} for a 10-wk culture period will require 100 kg of P. Scheduling weekly inputs of 10 kg P may be convenient for the farmer, but that may not be the most efficient from the algal community's perspective. An algal cell's need for N, P, and C changes as it grows, divides/reproduces, and becomes senescent. Algal cell division and reproduction rates vary with species and environmental conditions, but are typically about every 3 to 4 days (Fogg, 1975). However, reproduction in a diverse algal community cannot be synchronized to any fixed fertilization schedule.

Fertilization frequency is best understood through pond ecology and farm economics. Algae should be "fed" as frequently as they need to be in order to maintain optimally high net productivities, while not incurring disproportionate labor costs for the farmer. Fertilization must be frequent enough to prevent nutrient depletion from limiting algal productivity—remember that there can be a net loss of P and N to the sediments through adsorption and from the sedimentation of algal-based detritus (McKee et al., 1970; Boyd, 1971; Boyd and Musig, 1981; Avnimelech, 1984). Daily input of soluble algal nutrients is likely the best way to keep NP high (Milstein et al., 1995), but labor costs may make this option impractical.

The type of fertilizer will help determine how practical daily fertilization really is. Chemical fertilizers are concentrated, and tossing in a small bucket of urea and TSP each day may not be too great a hardship. Although considerably more expensive, the use of controlled-release fertilizers may further reduce labor involved (Kastner and Boyd, 1996). Shoveling in much larger quantities of manure, however, is more labor-intensive and far less practical. On the other hand, with integrated farming systems, ponds can be fertilized more conveniently, often as a side benefit of hosing down animal pens.

The main problems with maintaining a fixed fertilization schedule are the disregard for dynamic fluctuations in algal nutrient

availability over time within a pond, and not accounting for the relevant ecological differences between ponds. For example, the inefficiency of a fixed frequency was demonstrated in an experiment which looked at the relationship between pond productivity and fertilization frequency (daily, 2x/week, 1x/week, 1x/1.5 weeks, 1x/2 weeks) (Knud-Hansen and Batterson, 1994). Again, NFY was strongly associated with NP, but neither productivity measurement had any relationship to fertilization frequency. Algal productivities apparently were limited in varying degrees by light and/or DIC availability, so soluble N and P accumulated up to several mg l^{-1} in some ponds. Since ponds were overfertilized with N and P, the frequency of application was not relevant. The relationship would be completely different, however, if N and P loading rates had been lower, or if DIC had not been diminished by clam shells, or if pond banks had not contributed suspended solids through erosion from rain storms.

When determining optimal fertilization frequencies using manures, emphasis is placed more on maintaining a favorable growth habitat than on maximizing availability of algal nutrients. Care must be taken not to overfertilize with manures, which can diminish the growth environment by causing oxygen depletion and the accumulation of light-absorbing dissolved organic matter (Schroeder, 1975). More frequent fertilizations with proportionally less manure used per application can reduce the overall negative impacts of adding manure, though this strategy may increase labor costs. The preselected manuring rate, the type of manure, labor costs, and the need to minimize undesirable changes in water quality are factors used to determine optimal manuring frequencies (Schroeder, 1975; Zhu et al., 1990; Teichert-Coddington et al., 1990; MacLean et al., 1994).

Fertilization Rates Based on Pond-Specific Measurements

Methods that incorporate pond-specific data in determining fertilization requirements recognize the ecological uniqueness of individual farm ponds. This is a distinct advantage over predetermined fixed rates. Discussions below examine four different methods designed to help the farmer identify algal nutrient requirements on a pond-by-pond basis. The first three methods (water chemistry, sediment chemistry, and computer modeling) attempt to predict algal

nutritional needs based on analytical measurements of what is present in the pond at the time measurements are taken. The fourth and last method discussed, the algal bioassay, involves adding algal nutrients individually and in combination to pondwater samples, and then using the algal growth responses in these water samples to indicate which nutrient(s) is(are) needed to stimulate algal productivity in that pond at that time.

Water Chemistry

The chemical analysis of pond water can indicate the pond's algal nutrient deficiencies and availabilities, and, therefore, can provide some guidance for fertilization. For example, pond water depleted of soluble reactive phosphorus (SRP) may be phosphorus-limited, and a dose of P-containing fertilizer would be beneficial at that time. Similarly, pond water found to contain several mg l^{-1} of ammonia-N during mid-afternoon would probably not require fertilization with N at that time. Relevant water chemistry variables include total phosphorus, SRP, ammonia-N, nitrate-nitrite-N, alkalinity, total DIC, and dissolved organic P, N, and C.

However, there are a number of serious problems with relying upon water chemistry measurements to indicate fertilizer requirements. The first problem is methodological. As discussed in Chapters 2 and 3, the availability of soluble P, N, and C is anything but a static condition. All three elements are highly dynamic in a productive pond system. Ammonia-N concentrations may be several milligrams per liter before sunrise, and near zero by noon. DIC concentrations may exhibit similar diel cycles (Figure 5). Furthermore, as the pond becomes thermally stratified during the day, vertical gradients in the concentrations of SRP, DIC, and dissolved N may also be several milligrams per liter, even in a 1-m deep pond. The unresolvable issues are: When, where, and how can a water sample be collected that accurately reflects nutrient availability for a pond's algal community?

The second problem with water chemistry as a predictive tool is that a measurement is only a "snapshot" in time. What is important for sustained algal productivity is a sustained supply of algal nutrients. Remember that the *rate* of nutrient supply controls the *rate* of algal production (i.e., NP), which controls the *rate* of fish production (i.e., NFY). Algal nutrients are supplied from fertilizers, but also are made available from within the pond system through excretion,

secretion, decomposition, mineralization, and adsorption-desorption processes. Water chemistry measurements do not give any indication of how extensive these dynamic processes are, they only indicate what was in the water sample at that particular time. The same way that chlorophyll *a* concentration is a poor indicator of NP (discussed in Chapter 3), water chemistry is a poor indicator of the rate of nutrient availability.

Analytical deficiencies aside, conducting accurate water chemistry measurements is far beyond the economic scope and technical expertise of rural farmers. The training, equipment cost and maintenance, and time involved in conducting reliable water chemistry (i.e., accurately measuring what is in a sample of water, and collecting scientifically representative water samples) prohibits its use at the farm level. Water chemistry is an essential scientific tool for understanding pond dynamics, but is not practical in predicting fertilization requirements for earthen ponds.

Pond Sediment Chemistry

Pond sediments influence algal nutrient availability in the pond water above, and there are times when sediment chemistry may be useful in determining some fertilization requirements. For example, sediment analysis conducted prior to filling a pond with source water is used to determine the pond's lime requirement for increasing buffering capacity (reviewed in Chapter 5). Recent research has shown that measuring sediment P adsorption capacity and clay content can indicate to what extent soluble P will be removed by pond sediments (Boyd and Munsiri, 1996; Shrestha and Li, 1996). And, there are studies which examine the positive relationship between sediment respiration rates and organic (manure) loading rates to culture ponds (e.g., Boyd and Teichert-Coddington, 1994), although their practical importance with regards to fertilization is limited to documenting that manures can provide a source of DIC to ponds.

Many of the problems associated with water chemistry as a method for determining nutrient input rates also apply to sediment chemistry. Methodologically, there is the same question of collecting a representative sample. Pond bottoms are not homogenous, and fish activities such as nest building or bottom feeding can increase sediment heterogeneity. Combining multiple samples may help, but unless individual subsamples are also analyzed there is no way to get

a quantitative estimation of pond sediment variability. There is also the problem of deciding how deep sediment cores should be. Furthermore, how can the farmer determine the appropriate time to collect pond sediments, since the quality of pond sediments is likely to change during the culture period?

These sampling issues are particularly relevant when trying to apply results derived from controlled laboratory experiments. For example, there may be a clear relationship between sediment P-adsorption capacity and clay content in sediments, but how does the farmer collect a representative pond sediment sample for analysis? Equally troubling, how does the farmer account for dynamic changes in pond sediment organic content, as well as fluctuations in the pH and dissolved oxygen of interstitial water, which also affect the P-adsorbing capacity?

Another disadvantage of relying upon sediment chemistry is that, like water chemistry, measurements give only "snapshots" in time. There is no accounting for dynamic processes across the pond sediment/water interface, or for changes in sediment composition and algal nutrient requirements during the culture period. Furthermore, the prohibitive cost and technical expertise required to conduct sediment chemistry is similar to that of water chemistry. Consequently, the beneficial value of sediment chemistry to the farmer (other than determining lime requirements) is probably not cost-effective, considering that sediment analyses can be even more expensive than water quality analyses and the representativeness of sediment samples is highly questionable.

Computer Modeling

In its simplest form, a model describes the relationship between two variables. The NP versus NFY relationship illustrated in Figure 1 is a good example. The positive effect NP has on NFY can be represented with a mathematical equation, which describes how changes in the input variable (i.e., NP) correspondingly affect a response variable (i.e., NFY). More complicated models may involve many independent and inter-related relationships, each described by mathematical equations derived from theory and/or scientific research. Computers have enabled all the equations to be calculated simultaneously or in a specified sequence, allowing the researcher/modeler to see how input variables affect response variables and the

system as a whole.

There are three general benefits from computer models. First, they can be effective teaching tools for understanding how dynamic processes interrelate within a particular system. Second, they can be great experimental tools to see how a system may respond to changes in rates or input variables. Third, they can be used for predicting responses as inputs vary.

Computer modeling has a significant place in aquaculture research (Piedrahita et al., 1997), but not necessarily as an efficient tool to predict fertilization requirements. The predictive value of computer models for pond aquaculture is limited by the type of input data required by the model. Such models, for example PONDCLASS© (Lannan et al., 1993) and its successor POND© (Bolte et al., 1994) produced by the CRSP, rely principally on water chemistry data for predicting fertilization requirements. Therefore, all the above-stated problems and inaccuracies with using water chemistry also apply to computer models which depend on such data.

The extremely dynamic nature of productive, fertilized ponds further reduces the predictive value of complex computer models for aquaculture. For example, the rate of algal production is affected by the availability of light energy, the availability of algal nutrients, and water temperature. Availability of solar energy is affected by inorganic turbidity, self-shading by algae, and the light-absorbing properties of the pond water. Algal nutrient availability is affected by a large number of biological and biochemical variables, some of which are illustrated in Figures 3 and 4, as well as by sediment chemistry and mixing characteristics of the pond. There is statistical uncertainty associated with each mathematical relationship, so the numerical precision of a response variable (e.g., fertilization rate) generally decreases as the model increases in complexity.

However, these models do treat ponds individually, and their predictive abilities should improve as ecological relationships become better defined through focused research. In fact, fertilization according to PONDCLASS© (Lannan et al., 1993) was found to be significantly more efficient with regards to P inputs than with predetermined fixed rates (Table 12) (Knud-Hansen et al., in press). Although computer models may increase fertilization efficiencies when compared to fixed-rate recipes, there is still the problem of transferring this technology from a subsidized research facility to the independent rural farmer.

	Algal Bioassay	PONDCLASS©	Fixed Input
Nitrogen Utilization Efficiency			
kg fish (kg N added)$^{-1}$	4.1	3.6	4.3
% N incorporated into fish flesh[a]	9	8	10
Phosphorus Utilization Efficiency			
kg fish (kg P added)$^{-1}$	51.5	28.5	8.3
% P incorporated into fish flesh[a]	30	16	5
Total fertilizer costs[b]			
baht (kg live fish)$^{-1}$	4.7	3.4	8.6

[a] Assumes tilapia composition of 9.5% N, 2.4% P, and 76% water (Tan, 1971).
[b] Based on 1993 conversion rate of US$1 = 25 Thai baht.

Table 12. Nutrient utilization and cost efficiencies for the three fertilizer determination strategies of algal bioassay, the computer model PONDCLASS©, and fixed input used in a four-month culture of Nile tilapia (adapted from Knud-Hansen et al., in press).

For the farmer there are serious issues of having:

1) The necessary analytical instrumentation/reagents and the technical expertise to conduct weekly water quality measurements;
2) The ability to ensure analytical quality control;
3) Access to a suitable computer;
4) The technical ability to use a computer and appropriate software; and
5) The time to do all the required field, laboratory, and computer work competently.

These issues reflect enormous amounts of capital expense, technical knowledge, and labor generally found only in universities and research institutes receiving research grants or donations. Rural farmers in developing countries need to maximize the fertilization value of their labor and limited economic resources; computer modeling has yet to provide cost-effective answers.

Algal Bioassay

Based on the concept of algal nutrient limitation (Chapter 3), the algal bioassay is a responsive test designed to examine a lake/pond's algal growth response to nutrient enrichment (Gerhart and Likens, 1975; Goldman, 1978). Concentrated solutions (nutrient spikes) of N, P, and sometimes C and micronutrients are introduced into separate water samples collected from a lake or pond. If after two to three days the algae grow in response to enrichment by a particular nutrient, then that nutrient is said to limit algal productivity for that water at that time.

Algal bioassays have been used extensively by limnologists (freshwater ecologists) for several decades to identify what *not* to put in a lake to keep algal productivities low and waters clear (e.g., Goldman, 1960; Gerhart and Likens, 1975; Middlebrooks et al., 1976; Knud-Hansen and Goldman, 1987). For example, algal bioassay research has shown that P availability limits algal growth in most fresh water located in temperate climates (Vollenweider, 1968; Middlebrooks et al., 1976).

Rather than for finding how to keep/get waters clear, the algal bioassay is also a very practical tool for determining how to efficiently get waters green. By identifying the particular nutrient(s) that will stimulate algal growth, the farmer can tailor fertilization directly to pond-specific algal requirements. There have been only a few investigations using algal bioassays to identify nutrient limitations for aquaculture fertilization (e.g., Kemmerer, 1968; Msiska, 1983; Yusoff and McNabb, 1989; Guttman, 1991), and only recently has a practical algal bioassay method been described which is directly applicable to determining actual pond fertilization requirements (Knud-Hansen et al., in press).

The Knud-Hansen and Guttman algal bioassay method is technologically simple (i.e., no water or sediment chemistry measurements, no computers or technical software, and even literacy is not necessary), analytically sensitive, and can be conducted using local materials. Sufficient technical competency can be acquired in a single afternoon, and the entire method should take a total of only a couple of hours of the farmer's time to conduct. Bioassay results indicate whether a pond should be fertilized at that time with N, P, and/or C at full loading, half loading, or not at all. The method is successfully being used to improve fertilization efficiencies at the Tha Ngone farm in Lao

PDR (H. Guttman, personal communication). A detailed description and an example of the method's application are given in Appendix 1.

The theory behind the algal bioassay is logical and straightforward. Algal productivity in an algal bioassay water sample is the product of nutrient enrichment from the spikes (additions of concentrated nutrient solutions), as well as excretion, secretion, and decomposition activities occurring in the assay bottle. For example, zooplankton grazing and release of algal nutrients can have a significant impact on algal growth and productivity (Porter, 1976). If a nutrient is not limiting, there will be no additional growth beyond the control (i.e., water sample without nutrient spikes), and no fertilization of that nutrient is recommended at that time. There is no guesswork involved, only visual comparisons of actual fertilization responses in the farmer's own pond water referenced to an easy-to use table indicating fertilization requirements (Appendix 1, Table A1.2).

Furthermore, algal bioassays inherently incorporate such important ecological considerations as nutrient fluxes between pond sediments and pond water, and light limitation of algal productivity. For example, nutrient concentrations in pond water reflect P adsorption/desorption processes and ammonia release from sediments. When the accumulation of algal nutrient(s) in the pond water creates a surplus beyond the nutritional needs of the pond's algal community, the algal bioassay shows this (these) nutrient(s) to be non-limiting. That is, nutrient spikes do not cause any additional algal growth beyond what is observed in the control water sample. The method also accounts for light-limiting conditions due to high algal productivity or high turbidity from inorganic suspended solids. Elevated nutrient accumulations are common under these environmental conditions, and corresponding algal bioassay results correctly indicate that no fertilizers should be added at such times (Appendix 1, Table A1.2).

Besides being a simple and accurate test, the advantages of algal bioassays are numerous. First, unlike inferring algal nutritional needs from water or sediment chemistry measurements, the algal bioassay method looks at how the algal community present in a farmer's pond *actually responds* to specific fertilizers when added individually and in combination.

Second, determining fertilization requirements from algal bioassays can improve fertilization efficiencies. Algal bioassays are

both pond- and time-specific, allowing the farmer to fertilize different ponds individually according to each pond's actual algal requirements during the culture period. Each pond is fertilized with only the nutrients that the bioassay results indicate will stimulate algal productivity in that pond. This approach improves the percentage of added nutrients taken up by algae, and reduces potentially wasteful and unnecessary fertilizations.

For example, in a four-month Nile tilapia grow-out trial, ponds fertilized according to algal bioassay results had much greater P fertilization efficiencies than found using either a fixed-input fertilization strategy or the computer model PONDCLASS© (Table 12) (Knud-Hansen et al., in press). Fertilizer expenses per kilogram of harvested fish were similar between algal bioassay and PONDCLASS© approaches, which were better than the fixed-rate approach (Table 12). More efficient pond fertilization benefits the farmer economically by maximizing pond productivity with minimal nutrient inputs, and benefits the environment by reducing the amount of unused N and P discharged into natural waters when ponds are drained at harvesting.

Third, by correlating routine bioassays with visual observations, farmers can gain a deeper understanding of their individual ponds, and how each pond responds to nutrient inputs. Pond- and time-specific fertilization requirements vary due to differences in important ecological factors, e.g., pond morphometry, fertilization history, pond sediments and inorganic turbidity, concentration of algal nutrients, and algal biomass and productivity. The sum effect of these ecological variables is inherently reflected in the pond's algal community and the availability of algal nutrients. The algal bioassay takes advantage of this by utilizing the pond's current algal community and nutrient availability when determining the pond's actual response to selective nutrient enrichment (Goldman, 1978).

By relating trends in algal bioassay results to ecological observations, the farmer can better anticipate fertilization needs. For example, experience over time may show how brown or green a pond must be to be confident that light limitation exists, and that no fertilization (or algal bioassay) is necessary at that time. This approach is conceptually different from fertilization strategies based on water chemistry measurements to predict fertilization requirements. Ecological measurements are not necessary with the algal bioassay method, but they can be analyzed together with nutrient enrichment responses to help better understand the pond ecosystem.

Lastly, using algal bioassays to determine fertilizer requirements can give the farmer more independence. The entire analysis can be conducted using locally available materials (Appendix 1) and is simple to perform. Rather than rely on others for broad, often unreliable recipes, farmers are empowered to determine for themselves exactly what their individual ponds require for efficient fertilization and sustainably high productivities.

Chapter 7. Fertile Areas for Practical Fertilization Research

Aquaculture is a relatively new scientific discipline. There are an infinite number of uncharted directions on which researchers can focus their attention and energies. Although I have attempted to answer some ecological questions regarding the fertilization of earthen ponds, this book best serves as a platform for further scientific exploration. Discussed below are some possible research directions and ideas categorized under the familiar headings of pond ecology, fertilizers, and methods for determining pond fertilization requirements, and a final section on experimental design.

Pond Ecology

Perhaps the strongest research need for aquaculturists with respect to pond ecology is to develop a better understanding of primary and secondary productivity from a limnological perspective, i.e., through ecological relationships. This can be best accomplished by conducting library, not laboratory, research. There exists a tremendous wealth of knowledge in the limnological and oceanographic literature with direct relevance to understanding the dynamics of pond aquaculture—literature which has been largely ignored in pond aqua culture research. Ecological studies on nutrient cycling, algal productivity relationships, nutrient limitation, sediment/water interactions, predator/prey relationships, and the ecological importance of thermal stratification are among the many areas of published research which can benefit aquaculture scientists.

The easiest way to begin is to review general limnology texts, e.g., Wetzel (1983) and Goldman and Horne (1983), for a synthesis of the topic and to find citations of relevant research. A more comprehensive, and likely more interesting, way is to go to a university or institutional library and scan article titles of the more recently published research in journals such as: *Limnology and Oceanography*, *Canadian Journal of Fisheries and Aquatic Sciences*, *Oikos*, *Ecology*, *Aquatic Botany*, *Hydrobiologia*, etc. Searching on-line through the Internet may even be simpler and more efficient. Those aquaculture scientists who have not looked much beyond the aquaculture literature would be

surprised at the great number of relevant and interesting articles related to their research interests, and research funds are too scarce to be "reinventing wheels."

An important area of field research is the effect of pond depth on nutrient recycling (i.e., internal fertilization) and algal productivity. The regeneration of algal nutrients from algal and detrital decomposition reduces the need for external fertilization, thereby increasing fertilization efficiencies. Understanding how pond depth and pond mixing characteristics affect internal fertilization processes may provide an additional pond management strategy for farmers.

Fertilizers

Fertilizer research should focus on improving the knowledge and potential application of organic fertilizers. Although inorganic fertilizers have a number of advantages over using organic inputs to stimulate algal productivity (discussed in Chapter 4), the potential use of organic by-products produced locally or on-farm should be explored more fully. In particular, nitrogen-fixing legumes have a real potential for providing a relatively economical source of algal nutrients. Criteria for evaluation should include actual costs (including labor) of production and application; nutrient release characteristics; and ecological impacts on oxygen demand, turbidity, and discoloration of pond water. Included in this line of research is an examination of how different types of storage and composting techniques affect nutrient release characteristics of the manure or leaf biomass.

Methods for Determining Pond Fertilization Requirements

A prime area of research would be to fine-tune fixed-rate recipes. As previously discussed, current use of fixed-rate recipes is seriously flawed because generally the only determinative criterion is the country the pond happens to be located in or where the fertilization research took place. Since the relationship between country and ecological parameters which actually determine the efficacy of a particular fertilization strategy is tenuous at best, these recipes may have little relation to ecological reality. However, by relating recipes to actual pond conditions (e.g., pond depth, mixing characteristics,

culture fish behavior related to pond-water mixing, prevalence of inorganic turbidity, source water chemistry), sources of variation can be reduced and more predictive recipes can be established. This would be a very good use of computer modeling together with global experimentation (i.e., identical experiments conducted in a variety of environmental conditions).

A second area of research would be to examine further the relationship between areal and volumetric loading rates on predicting algal productivity, and therefore NFY. In Chapter 5, I made clear my reasons why I believe areal rates are more useful to the farmers for whom fertilization rates are intended. Nevertheless, these ecological relationships have not been well examined for pond culture, and further research may produce valuable insights and understanding regarding nutrient dynamics of fertilized ponds. The roles and relationships of internal fertilization, pond morphometry, and pond mixing characteristics should be included in any such research.

A third area of research would be to look at the role of calcium additions, through liming and/or fertilization, on pond productivity. The precipitation of calcium carbonate may become more important as calcium concentrations increase over years of pond culture. This relationship between calcium inputs and pond productivity merits further study.

Experimental Design

My final word on research directions concerns experimental designs. Scientific research is simply a systematic way to understand the universe in which we live. Research designs to provide answers can be loosely divided into two approaches based on two general hypotheses. The first can be described as the "Is this *significantly different* from that?" hypothesis. Different treatments are selected, and responses are evaluated by comparing the results of one treatment with another. Depending on how treatments were selected and replicated, significant differences between response variables may or may not be revealed. This emphasis on treatment comparisons, and limiting data analyses to these comparisons, characterizes most fertilization research. Unfortunately, such comparisons generally provide little insight into the ecological relationships which actually govern algal productivity, and therefore NFY.

The second approach can be described as the "What is the *relationship* between this and that?" hypothesis. The emphasis here is not on significant differences, but on significant relationships. Rather than comparing treatment means, statistical analyses focus on regression and correlation analyses. Relationships may be the stated objective of fertilization research, but research designs are most frequently of the significant-difference variety. For example, the typical design for examining the relationship between chicken manure input and fish yield (or oxygen depletion) would have four treatment levels of manure input with three replicates per treatment. Trying to describe a relationship (e.g., linear, quadratic, exponential, nonexistent) with just four manure levels is difficult at best, and subject to the limited range of manure inputs selected. If the goal is to examine the relationship, then there should be twelve different levels of manure, equally spaced, ranging from zero to obviously excessive. Statistically, this can be viewed as one treatment (i.e., manure input) with twelve replicates (with experimental error determined from variability about modeled relationships), and is clearly more likely to reveal the presence and nature of an existing ecological relationship.

If scientific research is thought of as a body, then statistics is the skeleton which gives the body structure and support. A more grounded understanding of experimental designs and corresponding analyses can only improve the quality of research. Hard work and mountains of data can not overcome analytical deficiencies in poorly designed or unfocused research. The entire conceptual approach to aquaculture research from hypothesis formulation, to selecting response variables, to optimizing experimental units (e.g., ponds), to minimizing experimental error through appropriate experimental designs, to data analysis, and finally to publication of results is systematically presented in Knud-Hansen (1997). Interested readers should find this relatively short (50 pages) presentation a good place to begin formulating research ideas, or strengthen existing research capabilities. Lastly, it is important to keep in mind the rural farmers in the developing tropics, who are the ultimate beneficiaries of quality fertilization research.

Appendix 1. Algal Bioassay Methodology to Determine Pond Fertilization Requirements

The algal bioassay method described below is essentially identical to the procedure described by Knud-Hansen et al. (in press). This paper discusses more extensively the scientific justifications and applications of algal bioassays in aquaculture, and examines each aspect of the methodology in more detail. The method as described below emphasizes the use of locally available materials.

Pond Water Collection

Several liters of subsurface pond water are collected in a prerinsed container or bucket. It is better to collect the water soon after dawn, before ambient N, P, and C are stripped from the water column by phytoplankton through photosynthetic activity. The method described here uses 500-ml pondwater subsamples for individual treatment determinations, but this volume and the corresponding nutrient spike volumes can be scaled up or down if more convenient. Larger sample volumes may be preferable, however, in that they reduce potential sources of variability from contamination and/or bottle effects (Mitchell and Malthus, 1984).

Nutrient Spikes

Nutrients are added to pondwater samples in the form of concentrated solutions called spikes. The spike volume and nutrient concentrations are designed to approximate reasonable input rates of N, P, and/or C, and can be made with analytical reagents or directly from chemical fertilizers (Table A1.1). Spikes can be made with either distilled (D) or deionized (DI) water, which can often be found in grocery stores or is available at automobile service stations for filling car batteries. Spike concentrations do not have to be analytically precise, but care must be taken to avoid unwanted contamination of algal nutrients. All containers should be prerinsed with D/DI water, and solutions should be kept covered and refrigerated when not in

Algal Nutrient	Spike Source	Spike Source Concentration (mg l^{-1})	N,P, or C Concentration in Spike (mg l^{-1})	Spike Volume (ml)	Increased N, P, or C Concentration in Spiked Sample (mg l^{-1})	Nutrient Fertilization Equivalent[1] (kg ha^{-1} wk^{-1})
N	NH_4Cl	575	150	10	3.0	30
N	Urea	325	150	10	3.0	30
N	$NaNO_3$	910	150	10	3.0	30
P	K_2HPO_4	280	50	10	1.0	10
P	TSP	230	50	10	1.0	10
P	MSP	75	50	10	1.0	10
C	$CaCO_3$	1000	1000 [2]	10	20 [2]	200 [2]
C	$NaHCO_3$	845	1000 [2]	10	20 [2]	200 [2]
Initial	D/DI water	-	-	20	-	-
Control	D/DI water	-	-	20	-	-

[1] Loading rate assumes a 1.0-m deep pond.
[2] Carbon spikes and fertilization given in units of alkalinity (mg l^{-1} of $CaCO_3$).

Table A1.1. Spike sources, volumes, and approximate concentrations used in the algal bioassay procedure. Controls and spike solutions are made with distilled or deionized (D/DI) water. Spike volumes are appropriate for 500ml pondwater samples, but can be scaled accordingly (e.g., 1 ml of nutrient spike would be appropriate for a 50ml pondwater sample).

use to prevent contamination.

Thoroughly mix the pondwater sample, and twice rinse nine (9) 1-l clear plastic, screw-capped water bottles with the pond water. Almost any translucent-glass or plastic containers may also be used. Transfer 500-ml pondwater subsamples into each of the nine plastic bottles. Each bottle should be clearly labeled indicating the nutrient spike to be applied: N, P, C, N+P, N+C, P+C, N+P+C, initial, and control.

Add the appropriate spike(s) to each of the nine pond water subsamples according to Table A1.1. For example, the N+P flask would receive 1 ml of the N spike and 1 ml of the P spike. The initial and control treatments receive D/DI water spikes instead of nutrient spikes. Each bottle is then mixed. The water in the initial treatment is immediately filtered (see below), while the remaining eight treatments are incubated to evaluate algal responses to nutrient enrichment. Bottles should be loosely capped to allow limited air exchange while preventing airborne contamination.

Incubation of Culture Bottles

Since the response variable of algal production only needs to be examined relatively and not absolutely (see discussion below), the two primary incubation criteria are that 1) culture bottles are in a light/temperature environment conducive to algal growth; and 2) all culture bottles are placed in identical environmental conditions during the incubation period.

Incubation should be done under artificial lighting or indirect sunlight. If bottles are placed under direct sunlight, photoinhibition will reduce photosynthetic activity and water samples could quickly overheat, killing the phytoplankton (Fogg, 1975). Outdoor exposure under a white cotton cloth with sufficient lateral ventilation is preferable to complete shade (Guttman, 1991). In areas with low nightly temperatures, bottles should be taken indoors at sunset and returned outdoors after sunrise. Guttman (1991) also demonstrated that swirling the vessels at least twice daily enhanced the algal response in cultures where limiting nutrient(s) were supplied in the spike. A two- to three-day incubation period is sufficient for most ponds, although clear water ponds may require up to four days incubation due to the initially low algal standing stock in the culture vessels.

Algal Biomass Comparisons

Bioassay results are primarily the comparisons of algal growth in the initial and control bottles with the seven nutrient-spiked pondwater samples. Algal growth during the incubation period can be measured by various physical (e.g., weight, optical density) or biochemical (e.g., fluorescence, ATP, radioactive carbon uptake) analytical techniques. However, the relatively high algal productivities and densities found in fertilized culture ponds enable algal biomass to be easily and effectively analyzed through visual comparisons of the nine filters after individually filtering each spiked pondwater sample.

The filtering apparatus can be easily created out of local materials. For example, cut a circular section out of a lid from a wide-mouthed jar or bottle with a screw-on top (Mason jars already have

lids with removable center sections). Replace the sectioned part of the lid with a circular filter and a screen/plastic mesh, which supports the filter. A white paper coffee filter works well as a bioassay filter. With the cap inverted, insert the mesh with the filter on top. Both mesh and filter should be cut to fit closely along the inside of the jar's lid. To filter, put a measured amount of thoroughly mixed sample water in the jar, screw the lid on tightly, and invert the bottle to allow gravity filtration. On-farm filtering may be facilitated with a commercially available hand-operated vacuum or bicycle tire pump. For field trials, a Whatman GF/C glassfiber filter (47 mm) was placed in a plastic Millipore Swinnex filter holder, and culture water was pushed through using a 50-ml plastic syringe (Knud-Hansen et al., in press)

If algal growth has been great or the culture volumes were large, thoroughly mixing the sample and filtering only 10 to 20 ml may be advisable in order to better distinguish treatment differences, and to save time on filtering. Although it does not really matter how much water is filtered, the filtrate volume *must* be identical for all treatments to permit meaningful visual comparisons. In fact, since there are only three different possible levels of algal growth in the culture bottles (see below), treatment differences may be discernable simply by comparing the relative greenness in the bottles after mixing, and filtering would not even be necessary.

Filter Interpretation for Determining Fertilization Requirements

The unaided human eye can easily separate treatment differences of algal biomass, as indicated by relative greenness on filter paper (Guttman, 1991), and posed no problem in a four-month field trial (Knud-Hansen et al., in press). Visual separation becomes ambigous only in extremely green or turbid ponds, in which case fertilization would not be recommended at that period (discussed below). To aid in the visual comparison of filters, filters should be laid out in a format to conveniently apply Table A1.2 for interpretation. Placing filters in a straight line in the same order as the treatment heading in Table A1.2 is one option; the layout in Figure A1.1 illustrates another. Once the filters are in order, then visual color comparisons are made.

	Bioassay Response									Limiting Nutrient		Relative Input		
	Control	N	P	C	N+P	N+C	P+C	N+P+C		1°	2°	N	P	C
1.	○	●	○	○	●	●	○	●	:	N		2	0	0
2.	○	⊙	○	○	●	⊙	○	●	:	N	P	2	1	0
3.	○	⊙	○	○	⊙	●	○	●	:	N	C	2	0	1
4.	○	⊙	○	○	⊙	⊙	○	●	:	N	P+C	2	1	1
5.	○	○	●	○	●	○	●	●	:	P		0	2	0
6.	○	○	⊙	○	●	○	⊙	●	:	P	N	1	2	0
7.	○	○	⊙	○	⊙	○	●	●	:	P	C	0	2	1
8.	○	○	⊙	○	⊙	○	⊙	●	:	P	N+C	1	2	1
9.	○	○	○	●	○	●	●	●	:	C		0	0	2
10.	○	○	○	⊙	○	●	⊙	●	:	C	N	1	0	2
11.	○	○	○	⊙	○	⊙	●	●	:	C	P	0	1	2
12.	○	○	○	⊙	○	⊙	⊙	●	:	C	N+P	1	1	2
13.	○	○	○	○	●	○	○	●	:	N+P		2	2	0
14.	○	○	○	○	⊙	○	○	●	:	N+P	C	2	2	1
15.	○	○	○	○	○	●	○	●	:	N+C		2	0	2
16.	○	○	○	○	○	⊙	○	●	:	N+C	P	2	1	2
17.	○	○	○	○	○	○	●	●	:	P+C		0	2	2
18.	○	○	○	○	○	○	⊙	●	:	P+C	N	1	2	2
19.	○	○	○	○	○	○	○	●	:	N+P+C		2	2	2
20.	●	●	●	●	●	●	●	●	:	None		0	0	0
21.	○	○	○	○	○	○	○	○	:	Other		0	0	0

Table A1.2. Guide for determining primary (1°) and secondary (2°) limiting nutrient(s) based on algal bioassay results. When visually compared to the control filter color after 2 to 3 days growth, bioassay responses are indicated by: ° = algal response similar to control filter, ⊙ = partial algal response, and ● = maximum algal response. Corresponding relative nitrogen (N), phosphorus (P) and/or carbon (C) fertilization input requirements are given as: 2 = full amount, 1 = half amount, and 0 = no inputs for that fertilization period. "Other" in line 21 refers to other possible limitations of algal growth such as temperature, light, and/or micronutrient availability. See text for further discussion.

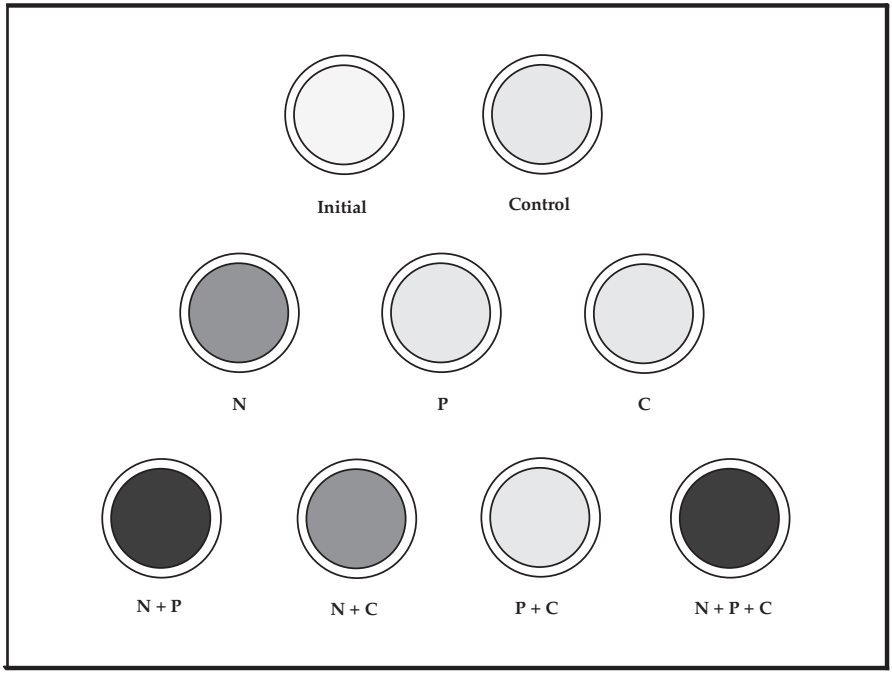
The first comparison is between the initial filter, the control filter, and the N+P+C treatment filter. If the control filter is noticeably greener than the initial filter, and looks indistinguishable when compared to the N+P+C nutrient-spiked treatment, then this result indicates that the availability of N, P, or C did not limit algal growth, and there is no need to fertilize that pond at that time (line 20, Table A1.2). If the N+P+C treatment filter is noticeably greener than the control filter, however, then there are 20 different results which are theoretically possible based on the nutrient spike combinations (Table A1.2).

The amount of greenness on the N+P+C filter represents what is considered the full response to the nutrient enrichment from spikes, and is indicated by the filled circles in Table A1.2. Other spiked samples may also show the same full response, a partial response (indicated by a half-filled circle), or a response equal to the control (i.e., no additional stimulation of algal growth, as indicated by an open circle).

Relative algal responses indicate which nutrient(s) is(are) both primarily and secondarily limiting (Table A1.2). For example, the filters illustrated in Figure A1.1 show a pond where N is primarily limiting and P is secondarily limiting. The P, C, and P+C treatments show the same response as the control, but the N+P response is greater than the N response and equal to the N+P+C response (line 2, Table A1.2). Phosphorus is secondarily limiting because it becomes limiting only after the N demand has been met; but there is not enough ambient P to satisfy algal needs once sufficient N has been added.

Table A1.2 also indicates suggested relative fertilization requirements based on algal bioassay results. If a nutrient is shown to be primarily limiting, then the pond receives the full input amount for that fertilization interval period. If a nutrient is secondarily limiting, only half the full amount is put in the pond at that time. No fertilizer is applied for a nutrient when no limitation is indicated. For example, results in Figure A1.1 indicate that the pond should be fertilized at the full rate for N, half the full rate for P, and no inputs for C for that fertilization period.

As discussed throughout this book, there is no universal recipe of "maximum" fertilization rates because of pond-specific variability. As a practical issue, however, this is not a problem. Initial maximum loading rates could be around 30 kg N ha^{-1} wk^{-1} and 10 kg P



Example Algal Bioassay Result

Figure A1.1. Schematic representation of results from a typical algal bioassay. Results are filter comparisons after pond water samples were spiked with nitrogen (N), phosphorus (P), and/or inorganic carbon (C). Results here show pond water with N as the primary limiting nutrient and P as the secondary limiting nutrient (see text and Table A1.2; adapted from Knud-Hansen et al., in press).

ha^{-1} wk^{-1}, although one should check to see if ecologically applicable, predetermined fixed rates are available. Actual fertilzation rates are scaled quantitatively to cover the period between algal bioassays. Nevertheless, if these rates are too high for a particular pond, then dissolved N and P will accumulate in the water and the next algal bioassay will indicate that no N or P fertilization is necessary because of the lack of nutrient limitation. Subsequent algal bioassays will reveal when a nutrient is again limiting, and should be added to the

pond to stimulate algal productivity. On the other hand, if maximum loading rates are too low for a given pond, then subsequent algal bioassays will reveal a continued demand for nutrient inputs and the farmer should fertilize accordingly.

Frequency of Algal Bioassay Testing

Algal bioassays should be conducted as frequently as reasonable and economical. Routine schedules for both algal bioassays and fertilization are certainly preferable from a farm-management perspective. If the farmer has only a few ponds, weekly analyses should be sufficient. This schedule was shown to be effective in a four-month experiment (Knud-Hansen et al., in press), as well as at the Tha Ngone farm in Lao PDR (H. Guttman, personal communication). As the farmer visually correlates algal bioassay results with pond appearance, the farmer will better understand when a pond is light-limited due to high algal productivity or high inorganic turbidity, and neither algal bioassay nor fertilization would be necessary at that time. Ultimately, the individual farmer must determine the economic trade-off between improved fertilization efficiency and the effort required to attain it.

Appendix 2. General Guide for Pond Fertilization Based on Pond Ecology and Farm Economics

The central theme of this book has been the relationship between pond ecology and making cost-effective, intelligent decisions regarding pond fertilization strategies. It should be clear that ponds are individual, dynamic ecosystems, and the variabilities among and within ponds prevent any generalized fertilization recipes from having much reliable benefit to the farmer. Efficient fertilization and high, sustainable yields are not difficult to attain as long as ponds are not treated simply as "black boxes." Optimizing fertilization means identifying and satisfying deficiencies in algal nutrient and light requirements; it also means minimizing capital and labor costs, wasteful fertilization, and detrimental impacts to the pond ecosystem.

The following summary outline represents a guide to help farmers determine the optimal fertilization strategy for each culture pond with regards to pond characteristics, pre-filling activities, choosing a fertilizer, and identifying pond fertilization requirements. Recommendations are based on identified benefits and problems with common approaches to pond fertilization, evaluated using ecological consequences and potential impacts on farm economics as the only criteria. It is assumed that the ponds are located in the appropriate climatic region for warmwater aquaculture, and that at least one of the culture species in the pond utilizes natural foods for growth.

The guideline below focuses on relevant, general questions and concepts the farmer should consider. It may take the farmer a modest effort to answer all necessary questions adequately, particularly in Section C, but working together with an extension agent would certainly help. Some parts of the economic analysis may have local or even regional application, and could be kept updated at the local aquaculture extension office. The farmer's answers to these questions will help determine what is most appropriate for each individual pond system. But even if some questions remain unanswered, focusing their attention on important ecological and economic considerations gives farmers a greater (and valuable) understanding of fertilization theory, of pond dynamics, and of their individual farming system as a whole.

I. Pond characteristics

A. Location of pond

1. Maximize pond exposure to sunlight.
2. Minimize pond exposure to wind in shallow ponds to reduce resuspension of pond sediments. Exposure to wind may benefit deeper ponds by reducing risk of persistent thermal stratification of the water column.

B. Size of pond

1. Pond area of convenient size, though not so small that pond bank erosion noticeably increases pondwater turbidity. Make sure banks of earthen ponds are stabilized.
2. Pond depth no less than 0.8 m if possible, to reduce impact of resuspended pond sediments.
3. Pond depth no more than about 1.2 m because of risk of prolonged thermal stratification, unless able to keep water mixed through mechanical mixers or bioturbation (e.g., large carp).
4. If mechanical or biological mixers are used, pond depths of about 2 to 2.5 m for minimal impact of pond sediment resuspension and greater volume for biological productivity.

C. Source water for pond

1. If high in inorganic turbidity, consider having source water first go through a settling basin before putting in pond.
2. If subsurface lake water is used, determine if it is anoxic (rotten egg odor present)—if source water is anoxic, allow it to re-oxygenate before putting it in ponds.

II. Pre-filling activities

A. Determine liming requirement, then lime accordingly.

B. Add layer of organic fertilizer on pond bottom and fill pond to about 10 to 20 cm of source water. This activity reduces the amount of fertilizer-P adsorbed to pond sediments, can reduce pondwater seepage, and provides a concentrated dose of algae and soluble algal nutrients when the pond is completely filled.

C. Wait about 5 to 7 days, then fill pond to appropriate level with source water. Fill pond during the day for photosynthetic re-oxygenation of water.

D. Evaluate need for polyculture.
   1. Molluscivores (e.g., Chinese black carp) eat snails and other animals which strip the water of calcium carbonate for shell production.
   2. Large fish (i.e., common carp) keep deep ponds reasonably mixed in order to avoid prolonged thermal stratification.

III. Choosing fertilizers

A. On-farm fertilizer sources (integrated farming systems)
   1. Separate each subsystem (e.g., aquaculture, land crops, each type of land animal) for economic evaluation.
   2. In the economic evaluation for each subsystem, identify:
      a. All shared and individual expenses, including:
         (1) All capital costs for equipment and facilities.
         (2) All input costs (e.g., feeds, fertilizers, antibiotics).
         (3) All labor (both farmer's and hired help).
         (4) All marketing costs (e.g., transportation, time).
      b. Identify all potential savings (e.g., farm waste disposal).
      c. Evaluate potential profitability of each subsystem.
   3. Find nutrient availability for each potential farm input to the ponds (check local extension office).
   4. Estimate actual cost per kg P, N, etc. for pond fertilization.
   5. Examine sources of off-farm fertilizers according to the criteria below.

B. Off-farm fertilizer sources
   1. Estimate actual cost of each potential fertilizer.
      a. Animal manures—for each source identify:
         (1) Nutrient availability in manure (check extension office).
         (2) Market cost per kilogram N, P, etc. available for algae.
         (3) Transportation and labor costs for application to ponds.
         (4) Lost opportunity costs (i.e., potential economic value of farmer's time used in activities to get

fertilizer).
(5) Environmental costs (need for aerators, frequency of redigging ponds).
(6) Estimate total cost per kilogram N, P, etc. available for algae.

b. Green manures—for each plant candidate identify:
(1) Nutrient availability in plant (check extension office).
(2) Market cost per kilogram N, P, etc. available for algae.
(3) Transportation and labor costs for acquiring plants.
(4) Cost of composting facilities.
(5) Labor for harvesting and composting for application to ponds.
(6) Lost opportunity costs (i.e., potential economic value of farmer's time used in activities to get fertilizer).
(7) Environmental costs (need for aerators, frequency of redigging ponds).
(8) Estimate total cost per kilogram N, P, etc. available for algae.

c. Chemical fertilizers—for each source identify:
(1) Nutrient availability (check extension office).
(2) Market cost per kilogram N, P, etc. available for algae.
(3) Transportation and labor costs for application to ponds.
(4) Lost opportunity costs (i.e., potential economic value of farmer's time used in activities to get fertilizer).
(5) Environmental costs (need for aerators, frequency of redigging ponds).
(6) Estimate total cost per kilogram N, P, etc. available for algae.

2. Choose the most economical source of fertilizer. This analysis may be applicable for a community or region, and updated only when necessary.

IV. Identifying pond fertilization requirements

A. Check aquaculture extension office for existence of any fixed, predetermined fertilization rates that may be applicable for initially fertilizing specific farm ponds. Use fertilizer(s) selected by economic analysis in C above.

B. If no applicable fixed rates are available, choose *initial* N and P fertilization rates based on pond water transparency:

1. Clear water: 30 kg N ha^{-1} wk^{-1} and 10 kg P $ha^{-1}wk^{-1}$
2. Visibility down to 0.5 m: 20 kg N ha^{-1} wk^{-1} and 4 kg P $ha^{-1}wk^{-1}$
3. Visibility down to 0.2 m: 10 kg N $ha^{-1}wk^{-1}$ and 2 kg P $ha^{-1}wk^{-1}$

C. If ponds are rainfed or suspected/known to have low alkalinities, add an *initial* fertilization of agricultural lime at about 200 kg ha^{-1}, particularly if ponds are not green 2 to 3 days after following step A or B above.

D. Identify which nutrient(s) limit algal productivity for each pond using the algal bioassay method (Appendix 1).

1. Set up own algal bioassay test using available materials.
2. Conduct algal bioassay about once per week, or as often as practical or seems necessary.

E. Fertilize each pond according to algal requirements as indicated by algal bioassay results. Adjust total inputs to cover the period between algal bioassays.

Appendix 3. Acronyms

AFDW	ash free dry weight
AIT	Asian Institute of Technology
BCE	before common era
D/DI	distilled/deionized
DIC	dissolved inorganic carbon
DO	dissolved oxygen
GP	gross productivity
LC_{50}	median lethal concentration
MSP	mono superphosphate
NFY	net fish yield
NP	net productivity
PD/A CRSP	Pond Dynamics/Aquaculture Collabortive Research Support Program
PDR	People's Deomocratic Republic (Laos)
SRP	soluble reactive phosphorus
TSP	triple superphosphate
TSS	total suspended solids

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