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 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

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}.

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.