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

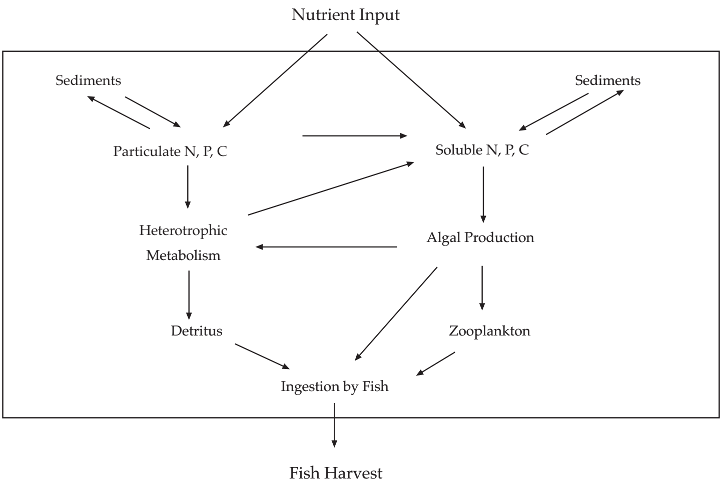

Figure 6. Schematic diagram showing major ecological pathways of fertilizer nutrients added to a culture pond (adapted from Knud-Hansen et al., 1993).

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:

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

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

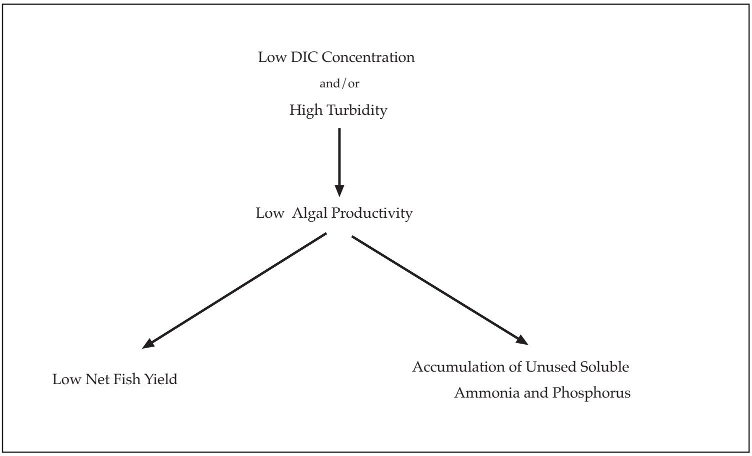

Figure 7. Schematic diagram showing impacts on algal and fish productivity when a production pond fertilized with N and P is limited by the availability of dissolved inorganic carbon (DIC) and/or availability of light by high inorganic turbidity.

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

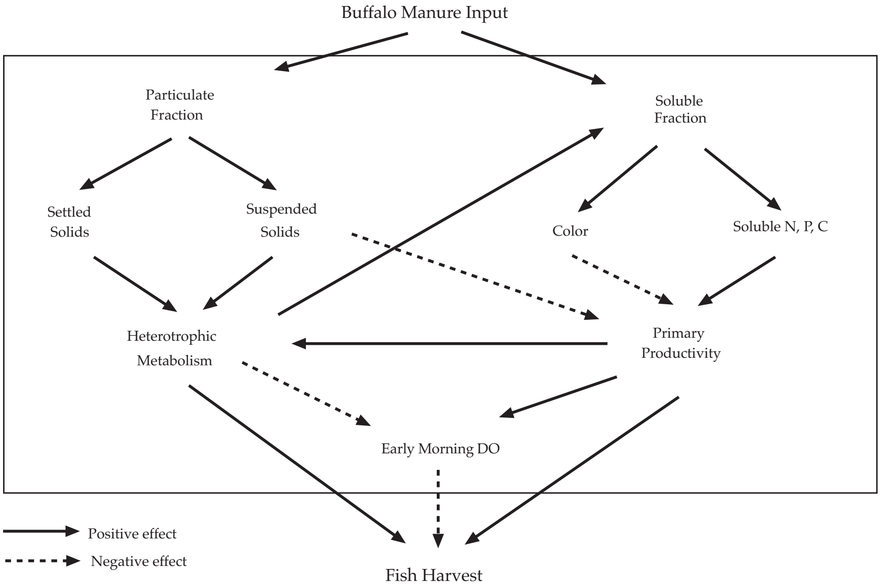

Figure 8. Schematic diagram showing the positive and negative ecological impacts with the addition of buffalo manure in a culture pond. Heterotrophic metabolism refers to decomposition and secondary production processes (adapted from Shevgoor et al., 1994).

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 purureum*), 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

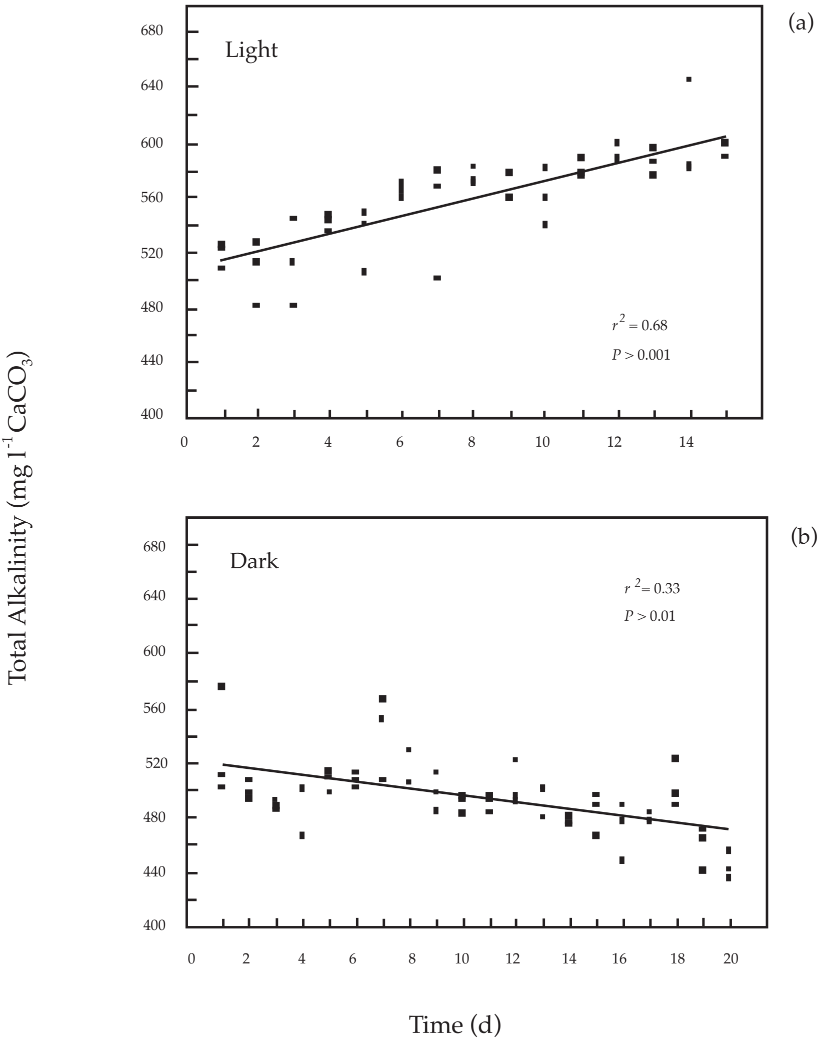

Figure 9. Graphs illustrating changes in total alkalinity with the addition of urea, an ammonia-based chemical fertilizer. Alkalinity increases in the presence of light (a) because of photosynthetic uptake of ammonia and decreases in the dark (b) because of the oxidation of ammonia to nitrate and nitrite (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.