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Fertilizers in aquaculture

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2.1 Introduction

Pond fertilization is an important component of semi-intensive to intensive aquaculture pond management that supports successful production of the culture organism. Semi-intensive and intensive aquaculture pond management fall along the extensive to hyperintensive management continuum and are characterized by high stocking rate of the culture animal, limited use of fertilizers, use of compound or complete feeds, and water quality monitoring and management, including use of mechanical aeration (Hickling, 1971; Bardach et al., 1972; Avault, 1996). Slightly lower stocking rates, relatively greater use of fertilizer and compound feed, and lower rates of mechanical aeration distinguish semi-intensive from intensive pond management strategies.

Fertilization contributes to establishing and maintaining a pond environment that allows the culture organism to efficiently utilize the compound or complete feeds (see other chapters in this volume) offered. Fertilizer sources are chemical fertilizers and organic (matter) fertilizers, which include agricultural by-products and animal manures. Chemical fertilizer typically is composed of nitrogen, phosphorus, and potassium compounds that dissolve readily to provide nutrients to phytoplankton. Organic fertilizer includes agricultural by-products, for example, rice bran, cottonseed meal, and animal manures, for example, poultry litter, cow manure, which first must undergo decomposition to release nutrients for phytoplankton growth. Among the benefits of pond fertilization are the production of natural food organisms that contribute to culture organism nutrition, the development of phytoplankton blooms that provide dissolved oxygen, utilize excreted feed nitrogen, shade out benthic vegetation, and provide contrast for fish to locate and consume floating, extruded feed, and the control of clay turbidity.

This chapter presents information on pond food webs, sources and form in water of macronutrients required by phytoplankton, chemical and organic fertilizers, fertilizer solubility, fertilization frequency, and examples of pond fertilization regimes.

2.2 Pond natural food web

Pond fertilization supplies exogenous sources of key nutrients to stimulate primary and secondary productivity that form the base of the aquaculture pond food web. In the context of aquaculture ponds, primary producers refers to microscopic algae and other photosynthetic organisms, collectively termed *phytoplankton*. Primary production in

chemically fertilized fish ponds was 4–5 times greater than in unfertilized ponds (Hepher, 1962). Secondary production refers to all the heterotrophic organisms that convert the chemical energy of their food into biomass, and are comprised of grazers and decomposers such as zooplankton, protozoa, nematodes, oligochaetes, insects, mollusks, and bacteria.

A generalized aquaculture pond natural food web is presented in Figure 2.1. Through photosynthesis, phytoplankton transform solar energy and inorganic nutrients into biomass, which forms the base of the natural food web. Phytoplankton populations in aquaculture ponds can be comprised of unicellular and colonial species of Cyanobacteria (blue-green algae), Chlorophyta (green algae), Bacillariophyta (diatoms), Euglenophyta (euglenoids), and Chrysophyta (golden-brown algae). Zooplankton are planktonic animals that graze on phytoplankton, protists, and detritus. The three most common types of zooplankton are rotifers, cladocerans, and copepods. Insect life stages from larva through adult are found in aquaculture ponds and can include species of Odonata, Coleoptera, Hemiptera, Plecoptera, and Ephemeroptera, among others. Benthic organisms can include nematodes, oligochaetes, snails, and bivalves. The components of the food web utilized by the culture species depend on the feeding habits of the fish or crustacean grown (Boyd and Tucker, 1998; Milstein, 2012).

The contribution of natural food organisms to semi-intensively and intensively cultured organisms will be minor in most instances. However, some species such as shrimp, carp, and tilapia may obtain significant levels of nutrients for growth from primary production. Production of natural food organisms stimulated by fertilization can contribute substantially to growth of larval stages or when biomass is low, for example, during the first weeks following fingerling or post-larvae stocking. Rapid growth will continue until the critical standing crop for the fertilized system is reached, then compound or complete feeds must be provided for continued rapid growth (Hepher, 1978). Fertilization, therefore, is necessary in order to stimulate and sustain the pond's food web.

Figure 2.1 Generalized schematic diagram of an aquaculture pond natural food web.

2.3 Nutrients and forms in water

Phytoplankton require many elements, classified either as macronutrients (C, N, P, K, H, O, Ca, Mg, Na, S, Cl) or micronutrients (B, Cu, Co, Fe, Mn, Mo, Si, V, Zn), for growth (Reynolds, 1984; Lin et al., 1997; Boyd and Tucker, 1998). Silica is a macronutrient for the Chrysophyta, especially diatoms (Reynolds, 1984). Concentrations of these elements in surface water will vary geographically and will depend upon the local geology and climate. Ground water concentrations of these elements are more variable than in surface waters, even at the same geographic location. The carbon dioxide concentration, geology of the formations through which the water infiltrates and of the destination aquifer, and retention time in the aquifer are factors that affect concentrations. For example, in a study of aquifers in four contiguous counties in west Alabama, Boyd et al. (2009) found great variability in ground water chloride concentration both within and among the different geologic formations in which the aquifers were located.

Of the many macro- and micronutrients required for growth by phytoplankton, phosphorus, nitrogen, and carbon are most likely to limit primary productivity. All three occur in various forms in pond water that are described in the following paragraphs.

Dissolved phosphorus is present in water in organic and inorganic forms. Organic forms generally are of biogenic origin, for example, enzymes, nucleic acids, and adenosine triphosphate, whereas orthophosphate ions (H_2PO_4^- , HPO_4^{2-}) derived from weathering of phosphate-containing minerals are the predominant inorganic forms. Orthophosphate ions are ionization products of orthophosphoric acid:

The ionic form varies with pH and H_2PO_4^- and HPO_4^{2-} are the forms present at aquaculture pond pH values. Dissolved orthophosphate is the main source of phosphorus for phytoplankton.

Nitrogen, too, is present in water in dissolved inorganic and organic forms. Enzymes, free amino acids, and peptides are among the forms of organic nitrogen and are products of biological activity. Ammonia-ammonium, nitrite, and nitrate ions are common forms of inorganic nitrogen. Dissolved ammonia is in equilibrium with ammonium and the proportions of each are affected mainly by pH and temperature:

Bacterial decomposition of organic matter and excretion by animals are the main sources of ammonia. Through nitrification, which occurs under aerobic conditions, bacteria oxidize ammonia first to nitrite and subsequently to nitrate. Although phytoplankton can assimilate ammonium, nitrite, and nitrate, ammonium is the most favorable energetically because nitrite and nitrate must be reduced prior to assimilation.

Organic and inorganic forms of carbon are found dissolved in water. Dissolved organic carbon compounds are numerous and varied and include, among others,

enzymes, nucleic acids, peptides, proteins, and carbohydrates. Carbon dioxide and bicarbonate and carbonate ions are the main forms of dissolved inorganic carbon. Carbon dioxide diffuses into water from the atmosphere and is produced by respiration. Because it comprises only 0.03% of the atmosphere, equilibrium concentration of carbon dioxide in water is low. And, only a small quantity ($\approx 0.2\%$) of dissolved carbon dioxide reacts with water to form carbonic acid, which dissociates to form bicarbonate:

As pH increases, bicarbonate dissociates into carbonate. Bicarbonate is released when limestone is dissolved by carbon dioxide and is the largest source of this ion in water. Phytoplankton uptake carbon dioxide and bicarbonate ion as carbon sources.

The nutrient present in the smallest concentration relative to its requirement will limit phytoplankton growth. Deficiencies in more than one nutrient concentration can limit phytoplankton growth, and supplying the deficient nutrients in needed concentrations will allow rapid growth. Because phytoplankton growth in aquaculture ponds is limited most commonly by carbon, nitrogen, and phosphorus, liming and fertilization strategies focus on providing these nutrients. Although liming technically is not fertilization, it does ensure that a fertilization program is successful by ensuring phosphorus availability and providing adequate dissolved inorganic carbon concentrations.

2.4 Liming

Sometimes a fertilizer application does not produce the desired response by phytoplankton. One possible cause may be acidic pond muds and low total alkalinity. Total alkalinity is a measure of the titratable bases in natural waters, of which bicarbonate, carbonate, and hydroxide are taken as predominant. Other than dissolved carbon dioxide, bicarbonate and carbonate comprise the largest pool of dissolved inorganic carbon in aquaculture ponds. Calcite (CaCO_3) and dolomite ($\text{CaMg}(\text{CO}_3)_2$) are the two primary limestone sources of bicarbonate, and alkalinity, in aquaculture ponds.

Gross primary productivity and phytoplankton abundance in fertilized ponds with very low (2–10 mg/L as CaCO_3) total alkalinity were significantly lower than in ponds with moderate (33 mg/L as CaCO_3) total alkalinity (Murad and Boyd, 1991). Algal productivity did not appear to be limited by phosphorus concentration, which was similar among all treatment ponds, but rather by carbon dioxide. Available carbon dioxide concentration at dawn was significantly higher in the moderate total alkalinity treatment compared to the low alkalinity treatments in which total alkalinity was similar.

Limestone is added to aquaculture ponds to increase the pH of pond soils and total alkalinity of pond water (Arce and Boyd, 1975; Boyd, 1997; Boyd and Tucker, 1998). Low pH of pond soils usually is caused by exchangeable aluminum (Boyd, 1995; Boyd and Tucker, 1998). Under these conditions, phosphorus reacts with aluminum

to form insoluble aluminum phosphate. Pond soils can adsorb fertilizer phosphorus quickly, especially when granular fertilizer broadcast over the pond surface sinks to the bottom, and phosphorus adsorption is similar across a variety of soil types (Boyd and Musig, 1981). When limestone is added to mitigate pond soil acidity, hydrogen ions that result from the hydrolysis of aluminum are neutralized by reaction with calcium carbonate, and the resulting calcium ion replaces the exchangeable aluminum on the soil. The soil pH increases as exchangeable aluminum is replaced by calcium. Pond soils are limed to achieve a final pH of 6.5–7. The analysis of pond soil samples to determine the lime requirement exceeds the scope of this chapter, but is described fully by Boyd and Tucker (1998) and Silapajarn et al. (2005).

The purity, ability to neutralize acidity, and the rate at which limestone reacts to neutralize acidity are important quality factors. Liming material purity is given by calcium carbonate equivalent (CCE), with pure calcium carbonate equal to 100%. The neutralizing value, also called total neutralizing value, is expressed as CCE and is the percentage of the liming material capable of neutralizing acidity because all liming materials contain impurities. For example, 1 kg of limestone with a neutralizing value (CCE) of 87% will neutralize as much acidity as 0.87 kg of pure calcium carbonate. Fineness determines how quickly the liming material will react with acid and is given by the percentage of the material that passes through or is retained by standard testing sieves. Silapajarn et al. (2004) reevaluated fineness of limestone for aquacultural use and developed new efficiency values. They found that soil pH in a soil–water microcosm increased from 5.0 to 6.9–7.1 in 1 week for soil treated with limestone particles smaller than 0.106 mm (passing a No. 140 US standard sieve), whereas soil treated with particles smaller than 0.25 mm (passing a No. 60 sieve) needed 10 weeks to attain pH 6.5. Limestone particles smaller than 0.106 mm were assigned an efficiency of 100% because they increased total alkalinity in a soil–water microcosm to 54.74 mg/L as CaCO_3 , almost the equilibrium concentration in water with solid calcium carbonate and normal carbon dioxide concentration. Lower efficiency values were assigned to larger limestone particle sizes. The particle size analysis and efficiency values can be used to calculate an effective neutralizing value or fineness value for a liming material (Table 2.1). The lime requirement determined analytically for a pond is divided by the neutralizing value (CCE) and fineness value of the liming material to be used, in order to arrive at the final lime application.

Limestone is added to ponds along with dissolved carbon dioxide to increase total alkalinity and total hardness:

Water in equilibrium with pure calcium carbonate and atmospheric carbon dioxide will have a pH of 8.3. Early morning pH and pH during intensive summer photosynthesis was greater than 8.4, which indicated that bicarbonate was the dissolved inorganic carbon source for photosynthesis (Arce and Boyd, 1975). Carbon dioxide

Table 2.1 Example of particle size distribution and efficiency factor for a sample of agricultural limestone

Size range (mm)	US Standard sieve number		Limestone sample		Efficiency factor (%)	Weighted efficiency (%)
	Passed	Retained on	Mass (g)	% of total		
>0.85		20	2.00	0.032	7.3	0.23
0.85–0.42	20	40	4.50	0.072	22.4	1.61
0.42–0.25	40	60	6.00	0.096	49.0	4.70
0.25–0.106	60	140	17.75	0.284	86.7	24.62
<0.106	140		32.20	0.516	100.0	51.60
Effective neutralizing or fineness value (%): $\sum =$						82.76

Adapted from [Silapajarn et al. \(2004\)](#).

generated by bacterial decomposition of organic matter added to ponds can speed the dissolution limestone. Sufficient quantities of organic matter should be added so that bacterially generated carbon dioxide prevents pH from increasing to harmful levels. In ponds that are drained often, meet the lime requirement based upon initial soil analysis and subsequently apply lime annually at 25% of the initial lime requirement (Boyd and Tucker, 1998). Boyd (1997) cautions against overapplication of lime, especially burnt (CaO) or hydrated (Ca(OH)₂) lime, because at the resulting high pH values ammonia toxicity becomes a problem. Boyd and Tucker (1998) provide a thorough discussion of liming aquaculture ponds.

2.5 Chemical fertilizers

Nutrients added by use of commercially formulated chemical fertilizers generally are limited to the primary macronutrients nitrogen, phosphorus, and potassium. Commercial fertilizer labels specify the guaranteed minimum percentage, in order, of nitrogen (N), phosphorus (as phosphate, P₂O₅), and potassium (potash, K₂O). By convention, fertilizer phosphorus and potassium content are quantified as percent phosphate and percent potash, respectively. For example, a fertilizer with the formula 12-24-12 contains 12% nitrogen, 24% phosphate, and 12% potash. Formulations of commonly used commercial fertilizers are shown in Table 2.2.

Secondary macronutrients are calcium, magnesium, and sulfur (Table 2.2). Gypsum contains both calcium and sulfur, as does superphosphate. Agricultural limestone is a source of calcium and often serves as filler in blended granular fertilizers. Dolomitic limestone provides both calcium and magnesium.

2.5.1 Nitrogen

Industrial production of nitrogen fertilizer begins with the synthesis of ammonia by reacting under pressure atmospheric nitrogen and a source of hydrogen, usually from natural gas, using the Haber–Bosch process. Ammonia is then reacted with additional compounds to manufacture nitrogen-based fertilizers (Figure 2.2). Ammonium nitrate is a white, granular fertilizer whose use is being supplanted by the less expensive, easier to handle urea; the US Department of Homeland Security regulates the sale of ammonium nitrate because it can be used in explosives. Urea and ammonium sulfate are white, granular fertilizers. Monoammonium phosphate (MAP) and diammonium phosphate (DAP) are greyish, granular fertilizers. Ammonium polyphosphate is a liquid in its 10-34-0 form and has a density of 1.37 kg/L but is granular in its 11-57-0 form.

2.5.2 Phosphorus

Phosphorus fertilizers are manufactured from rock phosphate (Figure 2.2), but rock phosphate itself seldom is used directly as a fertilizer because of its low availability of phosphorus and transport cost. Instead, finely ground rock phosphate is treated

Table 2.2 Percent composition of primary macronutrients as percent nitrogen, phosphorus (as P_2O_5), and potassium (as K_2O) and equivalent elemental concentration of commonly available commercial fertilizers, and elemental concentrations of secondary macronutrients (calcium, magnesium, and sulfur) of commonly available commercial fertilizers and common nutrient sources

Nutrient source	Labeled % composition			Elemental % composition				
	N	P_2O_5	K_2O	P	K	Ca	Mg	S
Ammonium nitrate	34	0	0	0	0	0	0	0
Ammonium polyphosphate	10–11	34–57	0	15–25	0	0	0	0
Ammonium sulfate	21	0	0	0	0	0	0	24
Urea	46	0	0	0	0	0	0	0
Monoammonium phosphate	11	50	0	22	0	0	0	0
Diammonium phosphate	18	46	0	20	0	0	0	0
Superphosphate	0	20	0	9	0	18–21	0	11–12
Triple superphosphate	0	46	0	20	0	15	0	0
Potassium chloride	0	0	60	0	50	0	0	0
Potassium nitrate	13	0	44	0	37	0	0	0
Potassium sulfate	0	0	50	0	42	0	0	17–18
Potassium magnesium sulfate	0	0	22	0	18	0	11	22

Figure 2.2 Fertilizers manufactured from ammonia and rock phosphate.

with sulfuric acid to yield monocalcium phosphate monohydrate and is known as superphosphate. About 85–90% of phosphate in superphosphate is water soluble. In another process, finely ground rock phosphate is reacted with sulfuric acid to produce phosphoric acid (54% P_2O_5), also called green acid, and gypsum, which is removed as a by-product. Phosphoric acid usually is not used directly as a fertilizer because it is corrosive, but is used to manufacture other fertilizers. The reaction of phosphoric acid with finely ground rock phosphate yields triple superphosphate (TSP). MAP and DAP are the products of reactions between phosphoric acid and ammonia. Phosphoric acid can be heated to drive off water to produce superphosphoric acid (68–70% P_2O_5), which when reacted with ammonia yields ammonium polyphosphate.

Phosphorus fertilization rates often are given in terms of P, not P_2O_5 . The proportion of P in P_2O_5 is used to calculate the equivalent quantity of P in a fertilizer: $2P/P_2O_5 = (2 \times 31 \text{ g/mol})/142 \text{ g/mol} = 0.437$. Thus, the percentage of P in a 12-24-12 fertilizer is: $24\% P_2O_5 \times 0.437 = 10.5\% P$.

2.5.3 Potassium

Potassium chloride is the most common potassium source for fertilizers, is known as muriate of potash, and is highly water soluble. It is manufactured primarily from the

mineral sylvite, which is mined in New Mexico, Michigan, and Utah in the United States and Saskatchewan, Canada. Potassium chloride color ranges from white to pink to red—the pink and red colors caused by inclusions of hematite, which do not affect potassium availability. Three other potassium fertilizers are potassium sulfate, potassium nitrate, and potassium magnesium sulfate.

As with phosphorus, fertilization rates can be given in terms of K rather than K_2O . The proportion of K in K_2O is used to calculate the equivalent quantity of K in a fertilizer: $2 K/K_2O = (2 \times 39.1 \text{ g/mol})/(94.2 \text{ g/mol}) = 0.830$. Using the 12-24-12 fertilizer grade, the percentage of K is: $12\% K_2O \times 0.830 = 9.96\% K$.

2.6 Organic fertilizers

Organic fertilizers comprise a variety of plant-derived materials that range from fresh or dried plant material to animal manures and litters to agricultural by-products (Wohlfarth and Schroeder, 1979; Das and Jana, 2003; Kumar et al., 2004). The nutrient content of organic fertilizers varies greatly among source materials, and readily biodegradable materials make better nutrient sources. Nitrogen and phosphorus content is lower, often substantially lower, in organic fertilizers compared to chemical fertilizers. Moisture content is another factor that reduces or dilutes the nitrogen and phosphorus concentrations of organic fertilizers. Thus, it can be cost ineffective to transport high-moisture organic fertilizer long distances. However, use of locally available sources is perfectly reasonable if its use is consistent with the production strategy. Nutrient value of animal manures is more variable than that of agricultural by-products. The animal's diet, the use and type of bedding material, manure age, and how it was stored are factors that affect manure nutrient value; these factors can vary seasonally on and among farms, and regionally or on a larger geographic scale. In contrast, nutrient content of agricultural by-products is less variable but can be affected by the industrial process used to produce the by-product. However, it always is advisable to analytically determine the nutrient content of the organic fertilizer.

The organic carbon content of organic fertilizer can be of equal or greater importance than its nitrogen and phosphorus contents. Application of organic fertilizer promotes increases in heterotrophic bacterial biomass, which stimulates other secondary productivity and mineralizes nutrients to stimulate primary productivity (Schroeder, 1978; Anderson, 1987; Colman and Edwards, 1987; Qin et al., 1995; Barkoh et al., 2005). Furthermore, through respiration the increased bacterial population generates carbon dioxide, which increases dissolved inorganic carbon available to phytoplankton, dissolves limestone to increase pond total alkalinity, and can moderate increases in pH during periods of intense photosynthesis. Also through respiration, the bacterial population consumes oxygen and heavy applications of organic matter can result in low predawn pond dissolved oxygen concentration (Qin et al., 1995). However, organic matter decomposition and nutrient mineralization occurs over days in contrast to immediate nutrient availability from chemical fertilizer.

Application of organic fertilizers to ponds depends on the fertilizer form and moisture content. The recommended application method for fresh animal manure,

Table 2.3 Nutrient composition (on an as is basis) and dry matter content of select animal manures and agricultural by-products that can be used as organic fertilizer

Material	Composition (% , as is)			Dry matter (%)
	N	P	K	
Manure				
Beef cattle	0.57	0.14	0.41	8
Dairy cow	0.52	0.12	0.36	13
Poultry—broilers ^a	3.08	1.28	1.82	74
Poultry—layers	1.68	1.06	1.20	42
Swine—grow-finish	0.93	0.31	0.48	11
By-products				
Alfalfa meal	2.77	0.25	2.46	90
Cottonseed meal	7.38	1.16	1.65	92
Rice bran	2.30	1.73	1.89	91

^aIncludes litter.

Rasnake et al. (2000), Sawyer (2009), ASABE (2010), Kirsten (2013), and Gadberry (No Date).

for example, cattle, swine, is to make a manure—water slurry that is splashed over the pond surface. Poultry litter can be applied by broadcasting over the ponds surface. Poultry litter bedding material such as wood chips/shaving or rice hulls, as opposed to sawdust, can decompose and accumulate on the pond bottom, which is undesirable. Agricultural by-products, for example, alfalfa meal, rice bran, can be broadcast over the pond surface along the windward bank or mixed with water to make a slurry that is splashed over the pond surface (Table 2.3).

2.7 Solubility of chemical fertilizer

Chemical fertilizer is available in granular, water soluble, and liquid forms. Granular fertilizer can be applied to ponds by broadcasting the granules over the water surface, allowing them to dissolve as they sink through the water column. Fertilizer granules vary in size, which affects their solubility as they sink through the water column. Particle size, as determined by sieve analysis, ranged from <0.25 mm to >2.00 mm, and nitrogen and phosphorus dissolution from DAP granules sinking through a 2-m freshwater column were 4.8 and 2.8 times greater, respectively, for granules 0.85 mm and smaller compared to larger granules (Boyd, 1981). However, particles 0.85 mm and smaller comprise only 3.1% of DAP granules and, on average, 4.3% of granules in 10 other fertilizers evaluated (Boyd, 1981). Nutrient dissolution of common fertilizers sinking through a 2-m column of freshwater is shown in Table 2.4.

Table 2.4 Percent of fertilizer nutrient that dissolved while sinking through a 2-m column of freshwater at 29 °C and percent of fertilizer granules larger than 0.85 mm

Fertilizer	Solubility (%)			Composition (%)
	N	P ₂ O ₅	K ₂ O	>0.85 mm
Ammonium nitrate	98.8	—	—	97.9
Ammonium sulfate	85.9	—	—	83.4
Monoammonium phosphate	5.1	7.1	—	99.9
Diammonium phosphate	11.7	16.8	—	96.9
Superphosphate	—	4.6	—	97.1
Triple superphosphate	—	5.1	—	99.6
Potassium chloride	—	—	87.0	91.5

Adapted from [Boyd \(1981\)](#).

Salinity also can affect solubility of fertilizer granules as they sink through the water column. Solubility of nitrogen from urea and MAP granules sinking through a 1-m water column averaged 89.7% and 12.4%, respectively, in freshwater, but decreased by 18% and 17%, respectively, in 30 ppt salinity water ([Teichert-Coddington et al., 1997](#)). Only a 2% decrease in nitrogen solubility was reported for DAP as salinity increased from 0 to 30 ppt. Phosphorus solubility averaged 4.6%, 11.7%, and 5.0% for TSP, MAP, and DAP, respectively, and decreased 7%, 22%, and 6%, respectively, in 30 ppt water compared to freshwater.

Most nitrogen in nitrogen-only fertilizer dissolves as the granules sink through the water column. However, only a small percentage of nitrogen and phosphorus from MAP and DAP and phosphorus from superphosphate and TSP dissolve as granules sink to the pond bottom. Once on the bottom, nutrients continue to dissolve, and after 24 h, 80% of nitrogen and 81% of P₂O₅ have dissolved ([Boyd, 1981](#)). However, since phosphates react with aluminium, calcium, and iron ions in pond muds, phosphorus solubilized from fertilizer granules that sink to the pond bottom will react to form insoluble phosphate compounds and become unavailable to phytoplankton ([Boyd and Musig, 1981](#); [Boyd and Tucker, 1998](#)).

Dissolving granular fertilizer in pond water and splashing the solution on the pond surface along the upwind pond bank rather than broadcasting it over the pond surface will increase availability of fertilizer nutrients to phytoplankton. [Lawrence \(1954\)](#) observed that wind currents would be sufficient to distribute fertilizer nutrients throughout the pond if the fertilizer were placed on a platform 30 cm below the pond surface. It is unlikely that a fertilizer platform is required today; the concept remains valid where granular fertilizers are applied. Nitrogen from nitrogen-only fertilizer dissolves readily and fertilizer solution can be applied directly to the pond

surface. Since MAP, DAP, superphosphate, and TSP do not dissolve as readily, the residual undissolved fertilizer can be placed in a burlap sack or woven plastic fertilizer sack and suspended in the top 30 cm of the water column, where it will dissolve completely. Water currents from a mechanical aerator or a water inlet structure can assist with dissolution and dispersal of these residual fertilizer nutrients.

Liquid fertilizers are commonly used in agriculture and increasingly in aquaculture. Ammonium polyphosphate (Table 2.2), a common liquid fertilizer, and other standard and custom liquid fertilizer blends are available from agricultural nutrient suppliers. The benefit of liquid fertilizer is especially pronounced for phosphorus because of its increased solubility (Metzger and Boyd, 1980; Musig and Boyd, 1980; Boyd and Hollerman, 1981). Application of the liquid fertilizer, ammonium polyphosphate, resulted in higher concentrations of soluble reactive phosphorus, total phosphorus, and chlorophyll *a* than broadcast applications of granular TSP plus ammonium nitrate or DAP (Boyd et al., 1981). The density of liquid fertilizer (1.3–1.4 kg/L) is heavier than water, which means it will sink to the bottom with minimal mixing with pond water if poured directly into a pond (Metzger and Boyd, 1980). Liquid fertilizer should be mixed with pond water (1:5–10 ratio) and this solution splashed along windward pond bank, drained into the outboard motor propeller wash as the boat moves about the pond, or sprayed over the pond surface using a power sprayer mounted on a boat or tractor (Boyd and Hollerman, 1981; Boyd and Tucker, 1998).

2.8 Fertilization frequency

Fertilizer can be applied on a fixed schedule or in response to some water quality variable or measure of phytoplankton productivity. Application frequency also can vary between chemical and organic fertilizers because nutrients from chemical fertilizers are available sooner for phytoplankton growth, whereas organic fertilizers first must undergo bacterial decomposition before nitrogen and phosphorus concentrations increase.

Net primary productivity was not affected by fertilization frequency (daily to biweekly) in tropical fish ponds that received the same total nitrogen and phosphorus inputs as chemical fertilizer (Knud-Hansen and Batterson, 1994). Availability of inorganic carbon (as measured by total alkalinity) and clay turbidity (as measured by total fixed solids) accounted for 60% of the variability in net primary production in these ponds. There was a similar inverse relationship between primary productivity and clay turbidity in organically fertilized ponds (Teichert-Coddington et al., 1992). Fertilization frequency becomes important when primary production is limited by nitrogen and phosphorus rather than by carbon limitation or clay turbidity (Knud-Hansen and Batterson, 1994). Consequently, fertilization frequency based upon sustaining high primary productivity rather than a set schedule or a fixed rate should result in more efficient nutrient utilization. Fixed-rate fertilization programs can lead to nutrient accumulation and primary production being limited light availability because of self-shading (Hepher, 1962; Knud-Hansen and Batterson, 1994; Mischke, 2012).

In organically fertilized ponds that each received the same quantity of fertilizer, net fish yield was significantly greater with applications made daily compared to once every 5–7 days (Zhu et al., 1990). Biochemical oxygen demand (BOD) and total ammonia nitrogen (TAN) concentration were significantly higher in ponds fertilized daily, but chlorophyll *a* and zooplankton concentration were unaffected by fertilization frequency. The substantial increase in fish yield gained by daily fertilization must be balanced against the increased BOD and TAN concentration, which could become growth limiting or toxic.

The rate of fertilizer application can affect primary productivity and production of the culture organism. It seems logical that the desired result of fertilization in newly filled ponds is a rapid increase in natural productivity. As the culture cycle progresses, nutrient concentrations can increase because of repeated fertilization and feeding. In order to evaluate how an organic fertilization rate affects primary productivity and tilapia production, Teichert-Coddington et al. (1990) applied liquid swine manure to culture units at a constant, increasing, or decreasing rate. All culture units received the same total quantity (2842 kg/ha total solids basis) of organic fertilizer over 14 weeks. Fertilizer was applied (on a total solids basis) 5 days/week at 29 kg/ha/day for the constant rate, and initially at 7.3 kg/ha/day or 51 kg/ha/day for the increasing and decreasing rates, respectively, and rates were adjusted biweekly by 6.2 kg/ha/day. Net primary productivity at the beginning of the culture period differed significantly among all treatments and was highest in the decreasing rate treatment, intermediate in the constant rate treatment, and lowest in the increasing rate treatment. Net primary production equalized among treatments over time, initially between the decreasing and constant rate treatments, and then among all treatments. Tilapia net yield was significantly higher in the constant and decreasing rate treatment compared to the increasing rate treatment. Thus, higher initial fertilizer application can increase primary productivity more quickly, but these higher rates require increased attention to dissolved oxygen concentration.

A pond-specific approach to determine the need for fertilization with nitrogen, phosphorus, or carbon, individually or in any combination, was adapted by Knud-Hansen (1998) from the algal bioassay methodology used by limnologists. In this approach, called the algal bioassay fertilization strategy (ABFS), eight 200–500 mL clear plastic bottles with screw caps are filled with pond water, a nutrient spike is introduced, and the loosely capped bottles are incubated for 2–3 days. Nutrients are added in excess such that phytoplankton growth will not be limited by that nutrient during incubation. One bottle serves as a control (no nutrient added) to the applied nutrient spikes (N, P, C, N + P, N + C, P + C, and N + P + C). After incubation, phytoplankton response in the spiked samples are compared to control and N + P + C to determine which, if any, nutrient limited productivity. Pond water samples should be analyzed weekly using the ABFS to determine need for fertilization.

The Secchi disk is another tool that can be used to determine the need (frequency) for fertilization. A Secchi disk is a 20-cm diameter disk with alternating black and white quadrants that can be affixed to the end of a 2-m-long pole marked in 1-cm increments. The black and white quadrants of the disk face the pole. Secchi disk visibility was highly correlated with chlorophyll *a* or particulate organic matter

concentrations in fertilized and unfertilized ponds and ponds in which fish were fed (Almazan and Boyd, 1978). Secchi disk visibility only is a valid index of plankton abundance in ponds that do not have clay turbidity. There was little variability ($CV = 1.8\%$) among repetitive Secchi disk readings made by the same observer and somewhat greater variability ($CV = 4.4\%$) among 10 observers taking readings in the same pond (Almazan and Boyd, 1978).

A consistent protocol for measuring Secchi disk visibility is required in order to obtain the best results. Measurements should be made at the same time of day since observed Secchi disk visibility varies with the time of day it is measured (Almazan and Boyd, 1978). Measurements taken between 11 a.m. and 1 p.m. are preferred because the sun is directly overhead. The observer should be in the same position relative to the sun, ensure that the measurement is taken outside of the observer's shadow, and use the same clothing accessories, that is, hat, sunglasses. Submerge the Secchi disk slowly in the pond until it just disappears, and record the depth. Submerge the disk about another 20 cm, and then slowly lift the disk toward the surface until the disk just reappears, and record the depth. The Secchi disk visibility is the mean of the two recorded depths. Secchi disk visibility can be measured weekly in ponds with established phytoplankton blooms and more often if bloom conditions warrant, for example, excessively sparse or dense blooms. A 20–40-cm Secchi disk visibility is an appropriate range for semi-intensive to intensive ponds, and the decision to fertilize can be based upon deviation from a specific visibility.

Several approaches to determining fertilization frequency are available. Fixed rate application strategies in which a defined rate of fertilizer usually is applied on a weekly basis derive from experimental station research and often are recommended regionally. However, broad application of recommendations may be inappropriate because of variation in soils, water, and climate (Mischke, 2012). Another strategy bases fertilization frequency on algal nutrient concentrations in water and requires weekly or biweekly analysis of pond water samples (Knud-Hansen, 1998; Qin, 2012). The ABFS, described above, is yet another strategy. The difficulty is to decide which strategy is most appropriate for a given situation. Knud-Hansen et al. (2003) compared these three strategies in a 120-day tilapia production study. In the fixed rate treatment, weekly applications of 30 kg N/ha and 15 kg P/ha as chemical fertilizer were made. Algal nutrient concentrations were measured biweekly and the PONDCLASS® computer program was used to determine fertilization rate. The ABFS was used weekly to determine nutrient requirements and application rates. Net fish yields did not differ significantly among treatments; the fixed rate treatment had the highest, but most variable net yield. The fixed rate strategy used about 20% more nitrogen than the other two strategies, which resulted in higher algal and fish productivity. The algal nutrient and ABFS strategies resulted in greater efficiency of phosphorus utilization but did not maximize fish production.

The decision as to which strategy to use can be viewed as falling along the continuum from extensive to intensive aquaculture systems (Mischke, 2012). In this context, the algal nutrient and ABFS strategies may be more appropriate for extensive aquaculture systems where there are a small number of ponds, the culture organism relies completely on natural food, fertilizer is applied throughout the culture cycle and is a

major cost of production, and labor is inexpensive. At the semi-intensive to intensive aquaculture systems end of the continuum where there are a large number of ponds, formulated rations provide the bulk of nutrients for growth and represent a major cost, fertilizer is applied on a limited basis, and labor is expensive, then the fixed rate strategy may be more appropriate. Use of the Secchi disk would be a valuable management tool in these circumstances.

2.9 Fertilization regimes

2.9.1 Pond preparation

Just as a farmer prepares land for planting a crop by liming the soil and eliminating weeds, so too must ponds be prepared in order for a fertilization program, and ultimately the production of the culture organism, to be successful. Liming of ponds is one important preparatory activity that was discussed earlier. Ponds are fertilized to stimulate primary and secondary production. Primary production in aquaculture refers to phytoplankton, not benthic and emergent macrophytes, which, if present, will out compete phytoplankton for fertilizer nutrients. Once established in ponds, macrophyte populations will flourish in response to nutrients from fertilizers and feeds, and require considerable effort to control. Dense macrophyte populations can impede the culture organism from accessing formulated feed, pond seining for sampling and harvest, and pond mechanical aeration. Thus, it is best to identify and control pond macrophyte populations early. Identification and control of aquaculture pond macrophytes is beyond the scope of this chapter, and the reader is referred to [Avery \(2012\)](#).

Light availability in the pond water column is another important requirement for algal photosynthesis. At times, ponds can become muddy because sediments from within the pond or the pond watershed enter and remain suspended in the water column ([Boyd, 1995](#)). These suspended sediments, referred to as clay turbidity, restrict sunlight penetration into the water column, which reduces primary productivity and the entire pond natural food web. Clay turbidity may impact the ability of certain fish to locate and consume floating feed. Most aquaculture ponds are levee ponds that have small watersheds. Clay turbidity that originates from levee runoff can be controlled by establishing a cover crop, such as grass, or by covering pond levees with straw ([Yi et al., 2003](#)). Clay turbidity may be controlled in ponds with low total hardness (often coincidental with low total alkalinity) by liming, which increases calcium ion concentration, which, in turn, can attract the negatively charged colloidal clay particles and promote flocculation ([Boyd, 1995](#)). However, lime takes time to dissolve, and wind action or mechanical aeration may diminish or deter any effect from liming. Application of organic fertilizer, for example, chicken litter, rice bran, at 500 kg/ha dry matter can reduce or eliminate clay turbidity ([Teichert-Coddington et al., 1992](#); [Lin et al., 1997](#)). Several applications of organic matter at 5–7-day intervals may be necessary, and addition of nitrogen fertilizer (20 kg N/ha) may speed development of an algal bloom. Intractable clay turbidity can be treated with gypsum (calcium sulfate) or alum (aluminium sulfate) ([Boyd, 1979](#); [Wu and Boyd, 1990](#); [Boyd and Tucker,](#)

1998). Treatment with 250–500 mg gypsum/L or 10–30 mg alum/L was used to reduce clay turbidity. Note that 0.5 mg/L of total alkalinity is destroyed per 1 mg/L alum added to the pond, so the pond may require additional liming.

2.9.2 Pond fertilization examples for young-of-year culture

Chemical and organic fertilizers are applied to increase natural productivity for young-of-year culture organisms as a means to promote rapid growth and improve survival before and during feed training. In addition to stimulating algal productivity, pond fertilization aims to increase zooplankton populations, since these often are preferred first foods. There exists a vast body of literature on pond fertilization, a review of which far exceeds the scope of this chapter. Some additional suggested readings that may be of interest to the reader are listed at the end of this chapter. A targeted literature search may be beneficial to readers seeking additional information.

Rice bran, cottonseed meal, distiller's dried grain, or a trout starter meal were evaluated as organic fertilizers and applied in combination with chemical fertilizer (10–34–0) to promote zooplankton for young-of-year paddlefish (*Polyodon spathula*) (Mims et al., 1991, 1995). Total nitrogen application over the 40-day nursery period was 43 kg/ha as organic fertilizer and 11 kg/ha as chemical fertilizer. Fertilizer was applied at 2–3-day intervals. Significantly greater biomass of large cladoceran zooplankters, which are preferred by paddlefish, were observed with rice bran or trout starter meal. Fish growth, survival, and yield were higher in these ponds. Combined application of organic and chemical fertilizer appears to increase zooplankton productivity, but the importance of each fertilizer type in stimulating zooplankton production cannot be determined without testing organic and chemical fertilization individually as well as in combination.

Channel catfish (*Ictalurus punctatus*) fry are stocked at high rates into recently filled and fertilized nursery ponds (Mischke, 2009). Although fry are offered a formulated feed immediately following stocking, natural productivity, especially zooplankton, comprise an important part of their diet during the first 3–4 weeks, after which formulated feed becomes the primary nutrient source for fish growth. Copepods (>650 µm total length, TL), cladocerans (450–700 µm TL), and ostracods (>450 µm TL) are preferred by channel catfish fry (Mischke et al., 2003). In order to determine whether organic fertilization would stimulate production of preferred zooplankton, Mischke and Zimba (2004) tested four fertilization regimes (no fertilizer, organic fertilizer only, chemical fertilizer only, and organic plus chemical fertilizer) in newly constructed ponds and ponds that had been in use for 16 years. Organically fertilized ponds received an initial application of 140 kg/ha cottonseed meal followed by 28 kg/ha applied twice weekly. Chemical fertilizer ponds received an initial application of 20.2 kg N/ha and 2.0 kg P/ha followed by 10.3 kg N/ha and 0.8 kg P/ha applied twice weekly. The organic-chemical fertilizer treatment combined the component applications. More nitrogen and phosphorus were available in ponds that received chemical fertilizer, either alone or with organic fertilizer, compared to organic fertilizer, and in old ponds compared to new ponds. Chlorophyll *a* and preferred zooplankton also were higher in ponds that received chemical fertilizer as well as in old ponds. Overall,

there appeared to be little benefit to organic fertilization, and although the authors admit that the rates they used were low, they and Mischke (2009) argue that increased rates of organic fertilization potentially increase risk and cost because emergency aeration may be needed in response to low dissolved oxygen. The use of organic fertilization in fry ponds merits further research. More importantly, though, this study demonstrated a much greater need for nitrogen fertilization and that a much higher rate of chemical fertilization than is recommended traditionally is required for fry ponds. The new recommendation calls for an initial application of 20 kg N/ha and 2 kg P/ha, followed by subsequent applications of 10 kg N/ha and 1 kg P/ha. Additionally, newly constructed ponds may need even higher fertilizer application rates given the differential response to fertilization between old and new ponds.

Nursery ponds for hybrid striped bass (*Morone chrysops* × *Morone saxatilis*) fry are filled and fertilized, and fry are stocked at high numbers several days later (Ludwig et al., 1998; Ludwig, 2002, 2004). Zooplankton, beginning with rotifers and transitioning over time to large cladocerans, are an important component of their diet. Formulated feed also is offered to fish. Organic and chemical fertilizers are applied together at recommended rates to stimulate pond productivity (Ludwig et al., 1998; Ludwig, 2004). Ludwig (2002) evaluated whether fry production could be increased by increasing (2X, 3X, and 4X) the recommended fertilization rates. Total nitrogen applied as organic fertilizer (rice bran) or chemical fertilizer ranged from 9.6 to 38.3 or 19.9–79.6 kg N/ha, respectively, for the 1X–4X treatments. Corresponding applications of phosphorus were 7.2–28.7 or 58.2–232.6 kg P/ha, respectively. Zooplankton abundance increased with increased fertilization rate, but fry survival and yield decreased with increasing stocking rate. However, fish survival and yield were high and did not differ statistically when the fertilization rate was doubled. Further increases in fertilization rate resulted in lower fish production. Poor fish production was attributed to increasingly poorer water quality as fertilization rate increased. Thus, there are limits to increasing production by increasing fertilization.

2.9.3 Fertilizer–feed combinations

Feeding a formulated feed often begins as soon as juvenile culture organisms are stocked into ponds for growth to stocker size or market size. However, juveniles may not require formulated feed until growth of the culture organism slows because it no longer can consume the natural food organisms efficiently or the biomass of natural food organisms no longer can support rapid growth. Culture organism food habits also will determine how well it is able to utilize natural pond productivity for growth. In a polyculture experiment, common carp (*Cyprinus carpio*), silver carp (*Hypophthalmichthys molitrix*), and tilapia (*Oreochromis aureus*) were stocked into ponds that were fertilized daily with liquid cow manure (114.5 kg/ha dry matter) or where fish were fed high-quality formulated ration daily (Moav et al., 1977). Species-specific stocking rate and initial size were similar for the two treatments. Examination of growth curves for common carp showed no difference in growth during the first month, but that growth in the fertilizer treatment had slowed substantially by week 6, and at harvest fish were less than half as large as those in the fed treatment. Growth curves for the silver carp

and tilapia did not diverge visibly between treatments. Final individual weight by treatment differed by 3% for silver carp and by 15% for tilapia. Natural food no longer could sustain rapid growth of common carp after the first month, and feeding a formulated ration was required to maintain rapid growth. Silver carp were able to maintain rapid growth consuming natural food and did not benefit from the formulated ration. Tilapia did appear to benefit somewhat from being fed. Thus, organic fertilization could substitute for feeding during the first month with no loss of productivity.

Nile tilapia (*Oreochromis niloticus*, monosex males, average weight = 15 g/fish) stocked at 2–3 fish/m² and grown in monoculture do not need to be fed a formulated ration for up to 80 days when ponds are fertilized intensively. Additionally, fertilization in combination with reduced feeding rate can be as productive as feeding alone. Nile tilapia in ponds fertilized weekly with chicken litter (1000 kg/ha dry matter) were significantly smaller after 60 days than fish fed a formulated ration 6 days/week at 3% of biomass (Green, 1992). Despite significantly higher primary productivity in fertilized ponds, tilapia growth was food limited. Rapid growth was reestablished with suspension of fertilization and provision of formulated ration. A reduced fertilization (500 kg/ha/week chicken litter) plus feed (1.5% of biomass) treatment also was tested. At harvest 151 days after stocking, individual weight and net yield did not differ significantly among treatments, although results for the reduced fertilization-feed treatment were about 12% less than the mean of the other two treatments.

Growth of tilapia fed at 50% or 75% of satiation in ponds that were fertilized weekly with urea (28 kg N/ha) and TSP (7 kg P/ha) did not differ from fish fed daily in ponds without fertilization (Diana et al., 1994). Final individual weight and net yield did not differ among these treatments in this 155-day study, although results for the 50% satiation treatment were about 10% less than the mean of the other two treatments. Delaying initiation of feeding until Nile tilapia attain specific target weights was evaluated in ponds fertilized weekly with chemical fertilizer (28 kg N and 7 kg P/ha) throughout the study (Diana et al., 1996). Fish growth was similar among treatments during the first 38 days of culture, at which time fish averaged 50 g/fish, the first target weight. Growth of the fed (50% of apparent satiation) fish diverged from that of unfed fish, and was significantly greater after 80 days, at which time fish in fertilized ponds averaged 100 g, the second target weight. Growth of fish in the second target group increased in response to feeding, similar to the response seen for the first target group as well as in Green (1992). Fish in the first and second target weight groups reached harvest size at the same time and had similar yields, but 22% more feed was fed to fish in the first target weight group. Growth of fish where feeding was delayed until fish averaged 150 g or 200 g increased as in the other treatments once feeding was initiated, but grow out duration increased about 13% and 26%, respectively. Thus, fertilization can substitute totally for feed during the early part of tilapia grow out, or partially substitute for feed throughout grow out. However, the production cycle will be increased if initiation of feeding is delayed too long.

Similar fertilization–feeding strategies have been evaluated for freshwater and marine shrimp. Juvenile freshwater prawns (*Macrobrachium rosenbergii*; average weight = 4.4 g) were stocked in ponds at 6/m² in which prawns were offered only a

formulated ration based upon prawn biomass, a formulated ration at 50% of the feed-only rate plus organic and chemical fertilizer, and a formulated ration (none during the first month, and 25% and 50% of the feed-only rate during months 2 and 3, respectively) plus organic and chemical fertilizer (Correia et al., 2003). Specific growth rate and net yield of prawns did not differ significantly in the feed-only and 50% ration treatments, which indicated that natural productivity could substitute for half of the formulated feed ration. Feed conversion ratio was significantly lower in the 50% ration treatment compared to the feed-only treatment, which indicates that prawns in the feed-only treatment were overfed. However, natural productivity alone was unable to substitute completely for formulated ration during the first month, and lost growth never was recovered once feeding at a reduced rate was initiated; final individual weight and net yield were less than half those in the other treatments, and although the FCR was significantly lower, the prawns were not of marketable size. In another study, *M. rosenbergii* juveniles (0.05 g/prawn) were stocked at 10/m² in ponds that received formulated feed only, chicken manure only, or combinations of formulated feed plus manure (Maclean et al., 1989, 1994). Prawn growth in the formulated feed plus manure treatments was significantly faster than in the feed-only or manure-only treatments. Survival among the feed-plus-manure and manure-only treatments did not differ, but was significantly lower than in the feed-only treatment, which likely was affected by the significantly greater survival in the feed-only treatment. As a result, individual weight at harvest was significantly greater in the feed-plus-manure treatments than in the feed-only or manure-only treatments, which did not differ from one another. No treatment differences were detected for any water quality variable. While it appears that natural pond productivity enhanced by fertilization can substitute partially for formulated ration in prawn production, additional research is needed to confirm the results of these studies.

The effect of substituting organic fertilization for formulated feed during the first 4–9 weeks of penaeid shrimp grow out was investigated by Teichert-Coddington et al. (1991). Juvenile shrimp (average weight = 0.8 g/shrimp; 89% *Litopenaeus vannamei*, 11% *Litopenaeus stylirostris*) were stocked into ponds at 5/m². The standard protocol (60 kg/ha/week chicken litter during the first 8 weeks plus formulated ration) was compared to a feed-only treatment and treatments of weekly applications of only chicken litter (60 kg/ha) for the first 4 or 8 weeks, followed by feed only. Survival averaged 65% among treatments. After 99 days, final individual weight and yield in the standard and feed-only treatments were significantly greater than in the substitution treatments. Thus, the low rate of organic fertilization was insufficient to substitute for formulated ration during the first 4–8 weeks of grow out, and the inclusion of a low weekly dose of organic fertilizer did not appear to improve production compared to feed only. In a follow-on study, juvenile shrimp (average weight = 0.8–1.2 g/shrimp; 93% *L. vannamei*, 7% *L. stylirostris*) were stocked into ponds at 5.8/m² (Teichert-Coddington et al., 1991). A revised standard protocol (100 kg/ha/week chicken litter during the first 4–6 weeks plus formulated ration) was compared to weekly applications of chicken litter only (220 kg/ha) during the first 8–9 week of culture followed by feed only. Survival in the standard protocol (69%) was significantly less than the fertilizer then feed (79%) treatment. However, no significant treatment differences

were detected at harvest for mean individual weight and yield. Thus, organic fertilization was able to substitute for formulated feed during the initial 8–9 week of grow out.

Pacific white shrimp (*L. vannamei*) juveniles (0.5–1.0 g/shrimp) were stocked at 15, 25, or 35 shrimp/m² in culture units to evaluate the effect of a full and a restricted (50%) daily ration (Carvajal-Valdes et al., 2012). Culture units were fertilized twice per week with urea (16 kg N/ha) and TSP (2.4 kg P/ha); the high fertilization rate apparently was to compensate for 5–15% daily water exchange. Shrimp survival exceeded 90% in all culture units. Mean weight gain and yield did not differ significantly between the full and restricted daily ration but did decrease significantly as stocking rate increased. However, FCR (averaged across stocking rate) for shrimp fed the full ration (2.99) was nearly twice that for the shrimp fed the restricted ration (1.55) and demonstrates shrimp were overfed. These results indicate that the feed daily ration can be reduced by 50% when culture units are fertilized intensively.

Overall, these studies indicate that fertilization can substitute for feed for a defined period at the beginning of the culture cycle or partially substitute for feed throughout the culture cycle in semi-intensive production of fish or crustaceans as long as the culture organism is able to utilize the natural food organisms stimulated by fertilization. Natural productivity in ponds initially is driven by fertilizer nutrients, but the contribution from feed nutrients increases as the culture organism biomass increases and feed becomes the sole nutrient source once fertilization is suspended. Even in ponds where fertilization substitutes partially for feed throughout the culture cycle, feed becomes the predominant nutrient source and driver of natural productivity. However, the benefits of increased primary productivity, for example, increased natural food and utilization of excreted feed nitrogen, can be offset by increased phytoplankton respiration or feed nitrogen excretion that exceeds phytoplankton utilization. Thus, feed nutrient (N and P) retention (see other chapters in this volume) must be maximized so that pond water quality can be managed to ensure rapid growth of the culture organism.

2.10 Future trends

Fertilization recommendations for aquaculture ponds generally are derived from research conducted at aquacultural experiment stations. While such recommendations apply broadly to ponds with similar soil and water types, they often are generalized to an entire region or larger area. Consequently, fertilizer recommendations may not be optimal because of insufficient or excessive provision of key nutrients. Fertilizer verification trials, where fertilization recommendations are tested and compared on farm to existing practices, are needed. Through such trials, not only can data be collected on the effectiveness of the fertilizer recommendation, but also on pond history, and local pond soil and water quality. Collectively, these data will allow for refinement of fertilizer recommendations with the goal of optimizing fertilizer nutrient utilization.

Pond fertilization strategies that target production of desirable populations of phytoplankton and zooplankton for the culture organism's life stages of interest need further development and refinement. There is a need for a better understanding

of fertilizer nutrient dynamics in the water column and in interactions with pond muds, of successional dynamics of desirable natural food organisms, of the role of pond history, and of frequency of fertilization. There is a need to reevaluate the role of nitrogen fertilization as recent research has demonstrated that it may be required in much higher quantities than recommended previously. Similarly, it may be possible to reduce phosphorus application rates, particularly in concert with higher nitrogen application rates. Fertilizer application at cool and cold water temperatures also requires additional research. Micronutrients typically are not included in chemical fertilizers, and while there is some indication that their inclusion may be beneficial for pond fertilization, additional research is needed. Both chemical and organic fertilizers should be considered as pond fertilization strategies are developed and refined in order to optimize nutrient utilization in the most economically efficient manner possible.

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