Reviews in Fisheries Science, 15:327–360, 2007

ISSN: 1064-1262 print
DOI: 10.1080/10641260701624177

Indicators of Resource Use Efficiency and Environmental Performance in Fish and Crustacean Aquaculture

CLAUDE E. BOYD,[1] CRAIG TUCKER,[2] AARON MCNEVIN,[3] KATHERINE BOSTICK,[3] AND JASON CLAY[3]

[1]Department of Fisheries and Allied Aquacultures, Auburn University, Alabama, USA
[2]Delta Research and Extension Center, Mississippi State University, Stoneville, Mississippi, USA
[3]World Wildlife Fund, Washington, D.C. USA

The aquaculture industry is under increasing pressure to make production more resource efficient and environmentally responsible. Application of better management practices is the main approach for improving the environmental performance of aquaculture. There are, however, few numerical indicators for comparing resource use and waste generation for culture of common species and by different grow-out techniques. Indicators are proposed for evaluating the efficiency with which feed, protein, fish meal, nutrients, liming materials, water, land, and energy are used in aquaculture. In addition, methods for evaluating amounts of nutrients and other possible pollutants generated by production facilities are suggested. The indicators are designed to reveal the quantities of resources used, or of waste discharged, per tonne of production. This will simplify comparisons among species and production systems and facilitate comparisons with other kinds of animal agriculture.

Keywords aquaculture and environment, sustainable aquaculture, aquaculture BMPs, aquaculture certification

Introduction

Aquaculture has been criticized widely by environmentalists for wasteful use of resources and for causing negative environmental impacts (Clay, 1997; Naylor et al., 1998, 2000). Addressing some of the concerns—such as farming high-value, carnivorous species in response to consumer demand in developed countries—will require changes in social values. Many of the problems identified by environmentalists can be addressed by changing or improving culture methods. Many aquaculture organizations have suggested changes in production practices that can be adopted voluntarily by producers to lessen negative environmental impacts (Boyd, 2003). Improvement of production practices is a common approach to environmental management in other areas of agriculture (Clay, 2004). Practices considered to be the most practical means currently available for solving a pollution or resource management problem are known as best or better management practices (BMPs).

Address correspondence to Claude E. Boyd, Department of Fisheries and Allied Aquacultures, Auburn University, Alabama 36830. E-mail: boydcel@auburn.edu

Environmental management agencies of some nations have imposed aquacultural regulations. For example, the United States Environmental Protection Agency developed a national effluent rule for aquaculture (Federal Register, 2004), and the Department of Fisheries in Thailand made aquaculture effluent standards (Tookwinas, 1996). Application of BMPs often is recommended or mandated by environmental management agencies as a means of compliance with environmental regulations.

Large-scale seafood buyers are seeking products resulting from responsible methods to satisfy an increasing consumer demand for such items (Seafood Choices Alliance, 2003). The Aquaculture Certification Council (ACC), Global Aquaculture Alliance (GAA), World Wildlife Fund (WWF), Environmental Defense (ED), and other organizations are developing codes of conduct, purchasing policies, standards, and labeling programs for ecolabeled products. The most rigorous programs will be certification programs that require third-party verification of compliance with environmental, social, and food safety standards (Chamberlain 2005, 2006; Boyd et al., 2005). Compliance with the standards will require adoption of BMPs.

Aquaculture and the environment have been widely discussed in the press, on websites, at aquaculture meetings, and in the scientific literature. Most large-scale producers have in some way become a part of the responsible aquaculture movement, and their production practices have improved as a result. Voluntary adoption of BMPs tends to be cosmetic, governmental regulations may not be vigorously enforced (especially in third-world countries), and certification is not yet a common practice. The emphasis on responsible aquaculture is directed almost entirely at production in developed nations or for export to them. The majority of world aquaculture is conducted by small-scale producers in developing nations for family consumption or local markets. These producers have essentially been left out of the responsible aquaculture movement.

Most discussions of aquaculture and the environment involve identifying impacts and attempting to define the concept of "sustainable aquaculture"; however, the issue should not be how sustainability is defined, but rather how it can be measured. The lack of focus on useful metrics of environmental performance is also evident in most aquaculture "codes of practice" and BMP compilations. Goals are often "soft" and qualitative, making it difficult to measure improved production efficiency and reduced impacts when the practices are adopted. Quantitative indicators of the efficiency of resource use and of the quantities of waste produced in aquacultural facilities are therefore needed. These indicators could be used to obtain a better understanding of the normal ranges in amounts of land, water, nutrients, and energy used per unit production of different species by different methods. Indicators also could provide an assessment of the amounts of nitrogen, phosphorus, organic matter, total suspended solids, and possibly other pollutants released into natural waters per unit of production. Acquisition of these data would allow comparisons of the environmental demands of different types of aquaculture and allow comparisons of aquaculture with other kinds of animal production. Most importantly, quantitative indicators provide tools that aquaculturists can use to assess the benefits of adopting new production methods.

The purpose of this paper is to suggest a series of indicators that might be used in assessing aquaculture production methods. These indicators focus on the main resources needed for aquaculture: land, water, nutrients (fish meal, plant meals, protein, fertilizers, and liming materials), and energy. These indicators also provide ways to assess the potential of aquaculture discharges to pollute local waters. Some environmental concerns regarding aquaculture, e.g., use of non-indigenous species, escapes of farm animals, bird and predator control, antibiotic use, and others would be more difficult to address with numerical indicators.

Aquafeed Issues

Production of trout, salmon, tilapia, channel catfish, marine shrimp, and several other species popular with consumers in developed countries depends upon the use of aquafeeds. Aquafeeds usually are the most costly aquacultural input, and feed ingredient procurement and feed manufacture may constitute the largest energy inputs to aquaculture production. Aquafeeds also are the source of organic matter, ammonia, and phosphorus that impair water quality in culture systems and bodies of water receiving aquaculture effluents.

The most widely used indicator of production and feed use efficiency in aquaculture probably is the feed conversion ratio (FCR). This indicator is calculated as follows:

$$\text{FCR} = \frac{\text{Feed, kg}}{\text{Net aquacultural production, kg}}. \tag{1}$$

A facility where 1,800 kg of feed typically are used to produce 1,000 kg of fish operates with a FCR of 1.8. This indicator is important because it indicates the efficiency with which feed is converted to animal biomass. A facility that produces fish at an FCR of 1.8 obviously is much more efficient than one where the FCR is 2.5, and 2,500 kg of feed must be used to obtain 1,000 kg fish. It also is significant to note that the amount of waste generated per unit of production decreases as the FCR declines.

An important caveat regarding the FCR is that feed usually is about 90% dry matter and 10% moisture while culture animals contain about 25% dry matter and 75% moisture (Boyd and Tucker, 1998). This matter is not relevant economically, for producers sell culture animals on a live weight (wet weight) basis. The difference in dry matter between feed and culture animals is a major ecological issue. In the case of production with a FCR of 1.8, 1.62 kg dry feed (1.8 kg $\times$ 0.9) are used to obtain 0.25 kg dry animal biomass (1 kg $\times$ 0.25). The dry weight (water removed) FCR is 6.48, and it takes 6.48 kg dry matter in feed to produce 1 kg of dry matter in aquatic animal biomass.

The FCR provides a basis for calculating several other useful ratios related to aquacultural production. The dry matter ratio (DMR) is an indicator of the efficiency with which nutrients in feed are converted to animal biomass:

$$\text{DMR} = \text{FCR} \times \frac{\%\ \text{DM in feed}}{\%\ \text{DM in culture species}}. \tag{2}$$

If a fish culture facility normally reports an FCR of 1.8, the DMR will be about 6.48. This suggests that 6.48 of dry matter in feed would be needed to produce 1 kg dry matter of fish.

The waste production ratio (WPR) is the ratio of waste to live weight production of the culture species. The WPR can be estimated from the DMR as follows:

$$\text{WPR} = (\text{DMR} - 1) \times \frac{\%\ \text{DM in culture species}}{100}. \tag{3}$$

In our example, the WPR would be 1.37. This indicates that for each kilogram of live aquacultural product, 1.37 kg of waste (dry matter basis) is produced.

Protein feedstuffs are expensive, and efficient use is an important objective in aquafeed manufacturing and feeding practices. The protein conversion ratio (PCR) is the ratio of protein applied in feed to aquatic animal production:

$$\text{PCR} = \text{FCR} \times \frac{\%\ \text{Feed protein}}{100}. \tag{4}$$

Continuing the example of a fish culture operation with an FCR of 1.8, assume that the feed contains 32% crude protein. The PCR would be 0.576, indicating that 0.576 kg crude protein must be applied in feed to obtain 1 kg of fish.

In aquaculture, feed protein is changed to aquatic animal protein for human consumption. The efficiency of this conversion can be estimated by the protein efficiency ratio (PER):

$$\text{PER} = \text{FCR} \times \frac{\text{\% Feed protein}}{\text{\% Protein in culture species}} \tag{5}$$

Assuming that the species in our example is tilapia containing about 14% crude protein (Table 1), the PER is 4.11. Thus, 4.11 kg of crude protein in feed is needed to produce 1 kg of fish protein. The PER does not give a true estimate of the amount of fish protein that is available for human consumption. Fish and other aquaculture species are processed, and only a portion of the protein is useful as human food. The remaining offal can be rendered to meal and used in animal feed.

Protein is about 16% nitrogen, and crude protein in plants, animals, and feedstuffs is calculated by multiplying total nitrogen concentration by 6.25 (100/16). The crude protein content of feed usually is printed on the feed label or bag. Aquafeeds vary in crude protein concentration depending upon the species for which they are intended. Tilapia and channel catfish feed often contain 28 to 32% crude protein while feeds for trout, salmon, and shrimp usually contain over 40% crude protein. The whole body crude protein composition of some aquaculture species is provided in Table 1. Concentrations range from 13.9 to 18.9%.

Fish meal is an essential component of most aquafeeds, for many culture species will not grow well without a certain percentage of fish meal in the feed. The fish meal concentrations in typical feeds for some common aquaculture species are provided in Table 2. Fish oil also is a component of some of these feeds. There is a finite supply of fish meal and oil. According to statistics provided by the Food and Agriculture Organization (FAO) of the United Nations, about 40% of fish meal and 80% of fish oil presently are used in aquafeeds. Because fish oil has traditionally been viewed as a by-product of fish meal production, more concern has been expressed in the past about the fish meal supply than the fish oil supply. The yield of fish oil from reduction fisheries is significantly lower than the yield of fish meal. This suggests that fish oil may in the future be a scarcer commodity than fish meal for use in aquafeeds.

The fish meal ratio (FMR) indicates the quantity of fish meal from aquafeed necessary to produce 1 kg of the culture species. This ratio can be calculated as follows:

$$\text{FMR} = \text{FCR} \times \frac{\text{\% Fish meal in feed}}{100}. \tag{6}$$

Tilapia feed often contains about 6% fish meal. Thus, the FMR for the example is 0.108.

Fish used for making fish meal are called feed fish or the reduction fishery. In fish meal manufacturing, the ratio of live fish to fish meal is about 4.5. The feed fish equivalence (FFE) of the fish meal in aquafeed can be computed as:

$$\text{FFE} = \text{FMR} \times 4.5. \tag{7}$$

Tilapia production with an FCR of 1.8 and 6% fish meal in the feed would require 0.486 kg feed fish for the amount of fish meal needed from feed to produce 1 kg fish.

Table 1

Percentage whole body composition on a fresh weight basis for some common aquaculture species

Species	Common name	Dry matter	Ash	Carbon	Crude protein	Nitrogen	Phosphorus	Reference
Ictalurus punctatus	Channel catfish	26.0	3.74	—	14.9	2.38	0.68	Boyd and Tucker (1995)
Oncorhynchus mykiss	Rainbow trout	26.0	2.50	—	15.6	2.50	0.35	Liu et al. (2004)
Litopenaeus vannamei	Pacific white shrimp	25.5	3.37	11.0	17.8	2.86	0.32	Boyd and Teichert-Coddington (1995)
Oreochromis aureus	Blue tilapia	25.0	4.95	10.9	13.9	2.22	0.70	Boyd and Green (1998)
Oreochromis niloticus	Nile tilapia	26.5	5.01	11.7	14.1	2.12	0.75	Boyd and Green (1998)
Penaeus monodon	Black tiger prawn	27.1	5.34	12.4	18.9	3.02	0.25	Gomes and Boyd (2003)
Salmo salar	Atlantic salmon	28.0	2.00	—	18.5	2.96	0.40	Shearer et al. (1994)

Table 2
Major ingredients and typical feed conversion ratios in feeds for common aquaculture species

	Ingredient content (%)				
	Atlantic salmon	Trout	Shrimp	Tilapia	Channel catfish
Soybean meal	14.0	15.0	24.5	38.3	34.5
Cottonseed meal	—	—	—	—	12.0
Corn meal	10.0	—	—	48.8	20.4
Wheat middlings	18.0	27.0	27.5	4.0	20.0
Fish meal	30.0	25.0	19.0	6.0	2.0
Shrimp head meal	—	—	13.5	—	—
Squid meal	—	—	5.0	—	—
Rendered products	—	15.0	—	—	4.0
Oil	24.0	16.0	4.5	1.5	2.0
Feed conversion ratio	1.0	1.2	2.0	1.8	2.2

Source: Boyd and Polioudakis (2006).

It takes 10 to 20 kg live fish to produce a kilogram of fish oil, but the quantity varies greatly by species and season (Tacon et al., 2006). However, "fish-oil ratios" and feed-fish equivalences that include oil are more difficult to calculate and interpret than those for fish meal because of the large variation in fish oil yield and the history of fish oil as a by-product of fish meal production. Nevertheless, the conservation benefit of substituting vegetable oil for fish oil in aquafeeds is obvious. The main problem with complete substitution is that marine species need long-chain polyunsaturated fatty acids in their diet and fish oils are an excellent source. Also, the fatty acid profile of fish produced on feeds containing only vegetable oil is different than fish produced with feeds containing fish oil, and this may change the taste of the fish.

Environmentalists are concerned over inefficient use of feed fish to make fish meal and fish oil for aquafeeds. Feed fish are a component of world fisheries production, and it can be logically argued that unless an FFE of 1.0 or less is obtained, feed-based aquaculture detracts from world fisheries production. The relationship among FFE, FCR, and fish meal concentration in feed (Table 3) shows that FFE increases with increasing FCR and fish meal concentration. At a fish meal concentration of 10%, FFE exceeds 1.0 at FCRs above 2.3, but at 20% fish meal concentration, FFE exceeds 1.0 above FCR of 1.1. Reducing FCR is important in lowering FFE, but if the fish meal concentration is high in feed for a particular species, an FFE of 1.0 will be impossible to attain. This is true for black tiger prawn (*Penaeus monodon*) for feeds usually have over 20% fish meal, and we are not aware of farms for this species that have FCRs below 1.5.

Fish meal can be produced from the offal from processing of wild-caught or aquacultured fish. Offal contains more ash and less protein than live fish, and fish meal from offal is of lower quality than that from live fish. Nevertheless, fish meal from offal can be used in many applications to spare marine fish meal. Shrimp heads from processing can be used to make shrimp head meal that can be used in animal feeds.

In tilapia processing for example, offal yield is about 67% of live weight—1,000 kg live fish yields 670 kg offal that can be processed into 149 kg offal meal (Alfonso Delfini Jr.,

Table 3

Calculated feed fish equivalence (FFE) of aquaculture production at different percentages of fish meal in feed and feed conversion ratios (FCR). It was assumed that 4.5 kg live fish were needed to make 1 kg fish meal

	Fish meal (%)														
FCR	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30
3.0	0.270	0.54	0.81	1.08	1.35	1.62	1.89	2.16	2.43	2.70	2.97	3.24	3.51	3.78	4.05
2.9	0.261	0.52	0.78	1.04	1.30	1.57	1.83	2.09	2.35	2.61	2.87	3.13	3.39	3.65	3.92
2.8	0.252	0.50	0.76	1.01	1.26	1.51	1.76	2.02	2.27	2.52	2.77	3.02	3.28	3.52	3.78
2.7	0.243	0.49	0.73	0.97	1.22	1.46	1.70	1.94	2.19	2.43	2.67	2.92	3.16	3.40	3.64
2.6	0.234	0.47	0.70	0.94	1.17	1.40	1.64	1.87	2.11	2.34	2.57	2.81	3.04	3.28	3.51
2.5	0.225	0.45	0.68	0.90	1.12	1.35	1.58	1.80	2.02	2.25	2.48	2.70	2.92	3.15	3.38
2.4	0.216	0.43	0.65	0.86	1.08	1.30	1.51	1.73	1.94	2.16	2.38	2.59	2.81	3.02	3.24
2.3	0.207	0.41	0.62	0.83	1.04	1.24	1.45	1.66	1.86	2.07	2.28	2.48	2.69	2.90	3.10
2.2	0.198	0.40	0.59	0.79	0.99	1.19	1.39	1.58	1.78	1.98	2.18	2.38	2.57	2.77	2.97
2.1	0.189	0.38	0.57	0.76	0.94	1.13	1.32	1.51	1.70	1.89	2.08	2.27	2.46	2.65	2.84
2.0	0.180	0.36	0.54	0.72	0.90	1.08	1.26	1.44	1.62	1.80	1.98	2.16	2.34	2.52	2.70
1.9	0.171	0.34	0.51	0.68	0.72	1.03	1.20	1.37	1.54	1.71	1.88	2.05	2.22	2.39	2.56
1.8	0.162	0.32	0.49	0.65	0.81	0.97	1.13	1.30	1.46	1.62	1.78	1.94	2.11	2.27	2.43
1.7	0.155	0.31	0.46	0.61	0.76	0.92	1.07	1.22	1.38	1.53	1.68	1.84	1.99	2.14	2.30
1.6	0.144	0.29	0.43	0.58	0.72	0.86	1.01	1.15	1.30	1.44	1.58	1.73	1.87	2.02	2.16
1.5	0.135	0.27	0.40	0.54	0.68	0.81	0.94	1.08	1.21	1.35	1.48	1.62	1.76	1.89	2.02
1.4	0.126	0.25	0.38	0.50	0.63	0.76	0.88	1.01	1.13	1.26	1.39	1.51	1.64	1.76	1.89
1.3	0.117	0.23	0.35	0.47	0.58	0.70	0.82	0.94	1.05	1.17	1.29	1.40	1.52	1.64	1.76
1.2	0.108	0.22	0.32	0.43	0.54	0.65	0.76	0.86	0.97	1.08	1.19	1.30	1.40	1.51	1.62
1.1	0.099	0.20	0.30	0.40	0.50	0.59	0.69	0.79	0.89	0.99	1.09	1.19	1.29	1.39	1.48
1.0	0.090	0.18	0.27	0.36	0.45	0.54	0.63	0.72	0.81	0.90	0.99	1.08	1.17	1.26	1.35
0.9	0.081	0.16	0.24	0.32	0.40	0.49	0.57	0.65	0.73	0.81	0.89	0.97	1.05	1.13	1.22
0.8	0.072	0.14	0.22	0.29	0.36	0.43	0.50	0.58	0.65	0.72	0.79	0.86	0.94	1.01	1.08
0.7	0.063	0.13	0.19	0.25	0.32	0.38	0.44	0.50	0.57	0.63	0.69	0.76	0.82	0.88	0.94

personal communication). In the example used above, the feed for 1,000 kg tilapia contained 108 kg fish meal. This demonstrates that tilapia aquaculture can be a net source of fish meal albeit of somewhat lower quality than the fish meal used in tilapia feeds. All species will not yield as much offal as tilapia. Channel catfish usually yield about 38% offal (Ammerman, 1985). At an FCR of 2.2 with a feed containing 2% fish meal, 44 kg fish meal would be used in feed for 1,000 kg channel catfish. The offal from 1,000 kg channel catfish could yield 84 kg offal meal. The net increase in fish meal of 40 kg/1,000 kg fish is roughly the same as for tilapia in spite of the lower percentage offal from catfish processing.

Calculation of a fish meal credit in kilograms of offal meal per tonne of production would be useful in assessments of resource use by different kinds of aquaculture. An adjustment for the difference in the value of offal meal and marine fish meal should be applied to the credit. The adjustment could be made by multiplying offal meal yield by the ratio of the percentage crude protein in offal meal to that of the marine fish meal used in feed for the particular species.

The FCR is a critical variable because it governs the efficiency of feed ingredient use and the amount of wastes produced. Values for indicators improve with a decrease in FCR as illustrated for tilapia culture (Table 4). Nevertheless, a low FCR does not suggest there are no environmental concerns related to feed use for a particular species. The species with the lowest FCR usually are carnivorous and feed for carnivorous fish such as trout and salmon must contain a high percentage of fish meal. The trend in salmon feeds has been to lower the percentage fish meal and increase the percentage of fish oil in the feeds over time as the industry gained knowledge on optimizing feed utilization.

Percentage dry matter normally is similar among aquafeeds, and culture species do not vary greatly in dry matter content (Boyd and Tucker, 1998). The main reason that DMR and WPR differ among species (Table 5) is variation in FCR. The DMR increases with decreasing FCR, and salmon and trout have greater DMRs than do catfish, tilapia, and shrimp (Table 5). The WPR follows a trend opposite to DMR. Values for PCR and PER are influenced by FCR, protein composition of feed, and species. Calculation of PCR (Table 5) revealed that the least amount of crude protein was needed to produce salmon, while the greatest amount was needed for black tiger prawn. Salmon required the least amount of crude protein to return a unit of crude protein in fish biomass while channel catfish required the most. Much of the crude protein in salmon, trout, and shrimp feed is from fish meal, and FMR and FFE values for these three species were greater than those for catfish and tilapia (Table 5).

Table 4

Influence of FCR on other feed use efficiency ratios for *Oreochromis aureus* provided a 32% protein feed containing 90% dry matter and 6% fish meal. The data were generated using equations presented in the text

FCR	DMR	WPR	PCR	PER	FMR	FFE
2.5	9.0	2.00	0.80	5.76	0.15	0.68
2.25	8.1	1.78	0.72	5.62	0.14	0.63
2.00	7.2	1.55	0.64	4.60	0.12	0.54
1.75	6.3	1.32	0.56	4.03	0.10	0.45
1.50	5.4	1.10	0.48	3.45	0.09	0.40
1.25	4.5	0.88	0.40	2.88	0.075	0.34

Table 5
Feed use efficiency values for several common aquaculture species. These data were generated using equations presented in the text

	Species				
Variable	*Salmo salar*	*Ictalurus punctatus*	*Oreochromis aureus*	*Oncorhynchus mykiss*	*Penaeus monodon*
FCR	1.0	2.2	1.8	1.2	2.0
Crude protein in feed (%)	43	28	32	45	35
Fish meal in feed (%)	30	2	6	25	19
DMR	3.21	7.62	6.48	4.15	6.64
WPR	0.62	1.72	1.37	0.82	1.53
PCR	0.43	0.62	0.58	0.54	0.70
PER	2.32	4.13	4.14	3.46	3.70
FMR	0.3	0.044	0.108	0.30	0.38
FE	1.35	0.20	0.49	1.35	1.71

Water Use

Water use in aquaculture may be classified as either total use or consumptive use (Boyd, 2005). Total water use is the sum of all inflows (precipitation, runoff, seepage, and management additions) to production facilities. Much of the water entering production facilities passes downstream in overflow or intentional discharge from culture units. Consumptive water use includes reduction in stream flow as a result of increased evaporation and seepage from the aquaculture facility, freshwater from wells, and water removed in biomass of aquatic animals at harvest (Boyd, 2005). Water in harvest biomass averages about 0.75 m^3/t, a minor quantity that usually can be ignored.

Boyd (2005) proposed indices for water use and water value that can be calculated for either total or consumptive use as follows:

$$\text{Water use index, m}^3/\text{t} = \frac{\text{Water use, m}^3}{\text{Production, t}} \tag{8}$$

$$\text{Water value index, \$/m}^3 = \frac{\text{Production, t} \times \text{crop value, \$/t}}{\text{Water use, m}^3} \tag{9}$$

Total water use varies greatly in aquaculture depending mainly upon the culture method used. Cage and net pen culture use the least water, and raceway culture uses the most. Water use in ponds varies with the intensity of production, frequency of draining, and amount of water exchange employed (Table 6). Embankment ponds use less water than watershed ponds (Boyd and Gross, 2000), and embankment ponds that are drained annually use more water than those from which fish are seine-harvested without annual draining (Boyd et al., 2000). Providing storage volume to capture rainfall and runoff in ponds during the summer and fall in the southeastern United States can conserve considerable water and lessen the amount of water needed from other sources (Boyd, 1982).

Consumptive use of freshwater in aquaculture is an important conservation issue. Total and consumptive water use is the same for cage and net pen culture, for the only water consumed is that incorporated into biomass. In raceway culture, water in biomass plus

Table 6
Total water use in different aquaculture production systems. Modified from Yoo and Boyd (1994)

System	Water use (m^3/t)
Cages and net pens	≈ 0.75
Pond culture of channel catfish	
Embankment ponds	
Seine-harvested without draining	1,200–1,800
Drained annually for harvest	3,800–5,000
Watershed ponds	6,500–10,000
Brackish water culture of shrimp	
Semi-intensive (5% daily water exchange)	50,000–100,000
Intensive (10% daily water exchange)	20,000–40,000
Trout raceway	
Un-aerated	85,000–120,000
Mechanically aerated	16,000–42,000

evaporation from raceways is consumptive use. According to Boyd et al. (2005), trout culture consumes 30 to 35 m^3/t as compared to total water use of 16,000 to 120,000 m^3/t (Table 6). Boyd (2005) also found that consumptive use in embankment ponds for annually drained channel catfish ponds in the southeastern United States averaged 3,667 m^3/t. Channel catfish culture in watershed ponds (regardless of annual draining) and undrained embankment ponds was estimated at 2,167 m^3/t. In arid climates, consumptive water use in ponds may increase by 50% or more (Boyd, 2005).

Total water use is important where water is pumped into aquaculture facilities, for there is an energy cost for doing so. In marine shrimp culture, large amounts of water may be pumped into ponds to effect water exchanges (Table 6). Total water use also is important where water right issues are involved. In Idaho, for example, water for trout culture flows from springs, but producers must have a water right to use it. Competition for water rights among trout producers and other users is increasing, and trout production in Idaho can only be increased by intensifying water use (Randy McMillian, personal communication). Water also may be taken from irrigation systems and used for aquaculture. Water used in flow-through systems usually can be returned to the irrigation system; nevertheless, water rights may be an issue.

Some examples of the consumptive water value index are provided in Table 7. The economic value obtained for water used in pond aquaculture is higher than that obtained for traditional irrigated crops (Boyd, 2005; Boyd and Gross, 2000). The economic value obtained for water use in raceway or cage culture is many times greater than for pond culture. Comparisons also should be made with terrestrial animal production. We found drinking water requirements for swine, chicken, and beef cattle, but we could not find the amount of water used per tonne of production of different species in concentrated animal feed lot operations.

Competition may occur between aquaculture and other water uses (Yoo and Boyd, 1994; Boyd et al., 2005). Withdrawal of groundwater for use in ponds may lower water table levels and lessen the discharge of other wells in the vicinity. Installation of several ponds on a watershed may lessen downstream flow. Some large, flow-through aquaculture facilities may take water from streams, irrigation systems, or other sources and discharge

Table 7
Consumptive water use value index for selected agronomic and aquacultural crops

Crop	Consumptive water use	Consumptive water value index ($/m^3)
Rice	123 cm/ha	0.091
Alfalfa hay	107 cm/ha	0.068
Corn	88 cm/ha	0.081
Cotton	83 cm/ha	0.121
Soybeans	80 cm/ha	0.067
Channel catfish[1]		
(undrained embankment ponds)	1,500 m^3/t	1.15
(watershed ponds)	2,163 m^3/t	0.80
Trout[2] (un-aerated raceways)	35 m^3/t	51.14
Tilapia[3] (cage culture)	0.75 m^3/t	666.70

Source: Boyd (2005), Boyd and Gross (2000), Yoo and Boyd (1994).
[1]$1.72/kg live weight.
[2]$1.79/kg live weight.
[3]$0.50/kg live weight.

into different water courses. Although these aquaculture facilities do not consume large amounts of water, they may alter downstream flow patterns and lessen the amount of water available to other users. Cage and net pen culture consumes little water and coastal ponds for brackish water aquaculture consume none. Nevertheless, these facilities may interfere with the use of water bodies or adjacent land areas by other resource users.

Land Use

Aquaculture uses land in two ways. First, aquaculture facilities occupy a defined area or space on land or in water; however, facility area accounts for only a portion of the total land or water area needed to produce an aquaculture crop. Additional ecosystem area is needed to provide support or service functions. The two most important of those functions are food production and waste treatment (Boyd, 2006; Boyd and Polioudakis, 2006).

Land-based aquaculture converts land surface area to water surface area. Pond production data reflect this land use when reported as biomass harvested per unit water surface area. However, land use for production facilities in not always conveniently reported in areal terms. Production in raceways, tanks, and indoor water reuse systems is reported on a volume (kg/m^3, for example) or water-flow (kg/m^3 per sec, for example) basis because the culture unit surface area usually is small. Cages, net pens, and shellfish plots do not use land in the traditional sense, but they occupy space in water bodies.

When expressed on an areal basis, the land or water area needed per unit production of aquaculture crop varies over more than two orders of magnitude. At one extreme are highly intensive water recirculating systems, which are capable of annually producing 1 to 2 million kg of fish per hectare of culture unit (Timmons et al., 2001). Rainbow trout production in raceways are about 10 times less intensive and therefore require about 10 times the surface area per unit of fish production. Fish and shrimp production in ponds requires several hundred times the land area compared with intensive recirculating systems.

In addition to surface area devoted to culture of aquatic organisms, land surface area must be dedicated to support of production facilities. Pond aquaculture requires embankments, intake and discharge canals, settling basins, and pump stations. Aquaculture facilities have access roads, parking lots, storage areas, staging areas, space for administrative and service buildings, etc. We made some approximate calculations based on maps of Alabama catfish farms with watershed ponds that suggest the land used for support purposes typically is about 25% of pond water surface area. Watersheds normally have other uses, and although necessary for aquaculture, they are not dedicated specifically to aquaculture. Watershed areas probably should not be considered as land use for aquaculture. In marine shrimp culture, canals are used to supply and discharge water at farms. Farms of 25 ha or more in size usually have support areas of about 25% of water surface areas, but the support area may increase to as much as 50% at smaller farms. Embankment catfish pond facilities in Mississippi typically have only 10–15% of the total land area devoted to support, and the support area as a proportion of total land area decreases slightly as farm size increases (Keenum and Waldrop, 1988). For a farm with a total land area of 65 ha, 2% of the area is used for buildings, parking, feed storage, etc., 13% of the area is in embankments, and the water surface comprises 85% of the area. For a farm with a total area of 260 ha, the estimates are 1%, 11%, and 88%, respectively.

In addition to the physical space occupied by the facility, land is required to produce plant meals and oils for aquafeeds. Corn meal, soybean meal, peanut meal, cottonseed meal, wheat middlings, rice flour, and vegetable oils are common plant products used in aquafeeds. Cottonseed meal and wheat middlings are by-products of cotton fiber and wheat flour production. Vegetable oils are extracted from soybeans, peanuts, corn, and other seeds in the process of making meals. Their use in aquafeeds usually does not require land dedicated specifically for production. Land must be dedicated specifically for the production of corn, soybean, peanut, and certain other plant meals used in aquafeeds. Data from the United States Department of Agriculture (2004) allowed estimates of average seed and meal yields per hectare for corn, soybeans, and peanuts (Table 8). Yields of these crops in other nations probably are similar to that achieved in the United States.

Typical feed ingredients and FCRs for some common aquaculture species are reported in Table 2. The only plant ingredients specifically produced for use in these feeds were corn and soybean meals. No attempt will be made to estimate the surface area of the ocean necessary to produce the fish for 1 t of fish meal.

Boyd and Polioudakis (2006) presented the following equation for calculating the land area necessary to provide plant meals for production of 1 t of live aquatic animals:

$$\text{Land requirement, ha/t} = \frac{(\%\ \text{ingredient}/100)\ (\text{FCR})\ (1{,}000\ \text{kg animals})}{\text{Meal yield, kg/ha}} \tag{10}$$

Tilapia feed contains 38.3% soybean meal, 48.8% corn meal, and 6% fish meal, and the typical FCR is 1.8 (Table 2). The land requirements for corn meal and soybean meal

Table 8
Average yield of common plant meals used in aquafeeds

Plant	Seed yield (kg/ha)	Meal yield (kg/ha)
Corn	9,413	9,413
Soybean	2,824	2,231
Peanut	3,440	1,927

Source: United States Department of Agriculture (2004).

Table 9
Land required to produce plant meals and feed fish needed for fish meal in feed to produce 1 t of some common aquaculture species. Data were calculated using methods presented in the text

Species	Land area for plant meals (ha)	Feed fish for fish meal (kg)
Atlantic salmon	0.074	1,350
Trout	0.081	1,350
Shrimp	0.220	1,710
Tilapia	0.402	486
Channel catfish	0.388	198

based on the feed formula (Table 2) and plant meal yield (Table 8) were calculated with Equation 10 to be 0.093 ha/t and 0.309 ha/t, respectively, for a total of 0.402 ha/t. The feed for 1 t of tilapia would contain 108 kg fish meal. About 486 kg of feed fish would be needed to produce 108 kg fish meal.

The dedicated land requirements for plant ingredients and quantities of feed fish for fish meal for the production of five aquaculture species are provided in Table 9. Culture of 1 t of salmon or trout requires less than 0.1 ha of land for plant ingredients, while 1 t of channel catfish or tilapia takes about 0.4 ha of land. Shrimp is intermediate requiring about 0.2 ha/t for plant ingredients. The feed fish requirements for fish meal are much greater in feeds for salmon, trout, and shrimp than in those for channel catfish and tilapia.

It is interesting to compare the land requirements for plant meals used in aquatic animal with those for terrestrial animal production. A typical feed for swine contains 74.4% corn and 23.4% soybean meal, while broiler chicken feed usually is about 67% corn and 23.7% soybean meal. Typical FCRs for broilers and swine are 1.88 and 2.80. The land requirements for plant ingredients in feed for 1 t net production are 0.515 ha and 0.333 ha for swine and broilers, respectively. These land area estimates are similar to the ones for channel catfish and tilapia. Poultry and swine production each use about 20% of global fish meal production, but fish meal is primarily used, if at all, in the early stages of poultry and swine production so overall fish meal use per tonne of animal produced is low.

Studies should be conducted to determine the usual total land area necessary to support 1 ha of pond water surface area or to provide 1 t production. However, it is possible to make approximate calculations for some species. In pond culture of channel catfish in Alabama, production often reaches about 8 t/ha per year. Each hectare of water surface for watershed ponds requires about 0.25 ha of surrounding land for operational purposes. Another 3.1 ha of land must be dedicated to producing plant ingredients for feed to produce 8 t fish. The land requirement to support production of fish in a pond of 1-ha water surface area is 3.35 ha. The total land necessary for producing 8 t channel catfish by pond culture is 4.35 ha (0.54 ha/t).

We reviewed data related to a large pond culture facility for tilapia in Ecuador that produces about 6 t/ha per crop. The total farmland area including ponds is about 1.25 times the surface area—similar to catfish farms in Alabama. Thus, production area is 0.21 ha/t per crop. The land area for feed ingredients is the same as for cage culture of this species as estimated above, so total land use is 0.61 ha/t. Pond culture of channel catfish and tilapia has similar values for total land use per crop. However, 2.5 crops per year of tilapia typically are harvested from the farm in Ecuador. Annual tilapia production for the water surface area is

12 to 15 t/ha per year. In Alabama, channel catfish production usually ranges from 4 to 8 t/ha per year (Boyd et al., 2000).

Tilapia production in ponds fertilized with chemical fertilizers or manures typically is about 2 t/ha. Ponds usually are small, and the ratio of land area to water area might be 1.5 or more. Total land use of 0.75 ha/t is greater than for more intensive, feed-based systems.

High-density cages for tilapia culture can yield up to 100 kg fish/m^3 or 500 kg fish/m^2 in 5-m deep cages (Beveridge, 1996; Schmittou, 1993). The water surface area requirement for tilapia cage culture is only 2 or 3 m^2/t; however, the land required for plant ingredients necessary for the feed is 0.402 ha/t. Total land requirement for feed-based tilapia culture in ponds is only 1.5 times greater than for cage culture of this species. This results because the land requirement for plant ingredients in feed per unit of production is greater than the land needed for culture facilities.

Shrimp producers in Central and South America typically operate large ponds at relatively low densities with yields of 1,000 to 1,500 kg/ha per crop. Feed conversion ratio often is about 1.5 because natural food organisms eaten by shrimp in semi-intensive ponds account for a relatively large proportion of production. Assuming a 1.25 water surface:land ratio for production facilities and 0.164 ha/t land for feed plant ingredients, total land use is 1.0 to 1.41 ha/t per crop, respectively. In Thailand, production of shrimp may be 5 to 8 t/ha per crop in small, heavily-aerated ponds. Feed conversion is about 2.0. Assuming a 1.5 water surface:land ratio for farms with smaller ponds and 0.22 ha/t for feed plant ingredients (Table 9), total land use is 0.34 to 0.42 ha/t per crop, respectively. The more intensive systems use considerably less land per unit of production.

In addition to land area for facilities and to produce food, ecosystem area is needed to assimilate wastes produced during aquaculture. In ponds and recirculating systems, significant quantities of waste produced during culture are treated within the facility, and there is relatively little external area needed for waste treatment. On the other hand, much of the waste produced in raceway and net pen culture is discharged directly to the outside environment. The ability of the external ecosystem to assimilate those wastes may limit aquaculture production either by polluting the surrounding water to the point where animal welfare inside the facility is endangered ("self-pollution") or by imposing limits to the amount of waste that can be discharged due to regulatory constraints. In addition to effects on aquaculture production, waste discharge into public waters creates societal externalities such as degraded water quality, water treatment costs, and other downstream impacts.

The ecosystem area needed for waste assimilation, expressed as hectares of waste treatment area per hectare of production facility, varies over at least two orders of magnitude depending on the type of production system (Kautsky et al., 1997; Folke et al., 1998). At one extreme are aquaculture ponds with low to moderate stocking and feeding rates that can, in theory, be operated for many years without intentional water exchange to remove wastes. Natural biological, chemical, and physical processes active inside the pond remove or transform wastes at rates adequate to prevent year-to-year accumulation of potential pollutants. In theory, no outside ecosystem support area is needed to treat wastes produced during culture, and, therefore, the ratio of land area for waste treatment divided by facility area is one. In other words, the pond functions as its own waste treatment facility. In practice, of course, ponds must be occasionally drained, and some overflow is inevitable during periods of heavy precipitation. Nevertheless, for ponds operated with long hydraulic residence times, more than 90% of the waste organic matter, nitrogen and phosphorus produced during culture are assimilated inside the pond before water is discharged (Tucker et al., 1996).

Internalizing waste treatment imposes a relatively high direct land cost to pond aquaculture that is evident in the large size of pond aquaculture facilities. The high land cost is the result of the pond functioning as both a crop confinement area as well as a waste treatment facility. For example, more than 95% of the total area of a catfish pond functionally acts as a high-rate, photosynthetic waste treatment lagoon, and less than 5% of the total area serves as "fish-holding" area (Brune et al., 2003). In effect, more than 95% of the land and construction costs for ponds can be assigned to a waste treatment function, and the relatively large land area occupied by a pond aquaculture facility is a price the farmer pays for treating wastes on site rather than discharging the waste to public water. Engle and Valdarrama (2002) explored other costs (such as aeration, labor, etc.) associated with the internalizing waste treatment in channel catfish ponds and calculated that almost 30% of the total cost of producing channel catfish can be ascribed to internal waste treatment processes. Land area requirements and other costs that result from internalizing waste treatment costs in pond aquaculture limit profitable culture only to areas where land is available at a reasonable price.

Aquaculture production in ponds is limited by the finite capacity of the pond ecosystem to treat wastes produced during culture. Further intensification of production is possible only if wastes are treated external to the culture unit, usually by discharging wastes to public waters. Accordingly, ecosystem area outside the culture facility is used to assimilate wastes, and in most instances the aquaculturist does not bear the cost of that treatment.

Relatively few studies have been conducted to determine the external ecosystem areas needed to treat aquaculture wastes produced during raceway or net pen culture. Furthermore, requirements will vary depending on the hydrology and biology of the water into which wastes are discharged. Based on the few studies conducted, it appears that ecosystem support areas between 100 and 300 times the facility area are needed to treat wastes produced from cage and net pen fish culture (Berg et al., 1996; Kautsky et. al., 1997; Folke, 1998; Brummett, 1999). These values for ecosystem waste assimilation area are somewhat larger, but still within the same approximate order of magnitude as the ratio of "waste treatment area" and "fish-holding" area in the catfish ponds described above. This is not simply a coincidence because the same biological and physicochemical processes are responsible for waste treatment whether the water is inside a pond or in the lake, stream, or brackish-water bay in which cages are suspended. Areal requirements for waste treatment should therefore be of similar magnitude. The difference, of course, is that the ecosystem area needed for waste treatment in ponds is, for the most part, inherent in the system whereas waste treatment for cage and net pen culture is external to the system.

The overall ecosystem area required to support a particular activity is called the "ecological footprint" (Rees and Wackernagel, 1994; Folke et al., 1998). Footprints for aquaculture include areas needed for the facility, food production, and waste treatment. Footprints may also be calculated to include ecosystem requirements for other services, such as forest or ocean area for carbon dioxide sequestering and, for some systems, nursery areas used to produce seedstock or brood animals. The ecological footprint concept has been proposed as a broad sustainability index that can be compared across culture systems, aquaculture species, and even between aquaculture and capture fisheries (Folke et al., 1998). Although it has been argued that the ecological footprint concept is too simplistic and static to serve as a comprehensive decision-making tool (Roth et al., 2000), it is a useful heuristic device that can also provide an additional tool for assessing relative resource use efficiency.

Nutrients

Nitrogen and phosphorus are key nutrients in aquaculture. Primary productivity in aquatic ecosystems increases as concentrations of plant-available nitrogen and phosphorus increase (Wetzel, 2001). Chemical fertilizers, triple superphosphate, diammonium phosphate, urea, and manures and other organic fertilizers are applied to ponds to increase the base of the food web for aquaculture. Nitrogen and phosphorus also are critical components of aquafeeds because these two elements are major components of animal biomass.

Nitrogen and phosphorus are used in traditional agriculture for the same reason that they are used in aquaculture—to promote plant and animal growth. There also are many other uses of the raw materials from which fertilizers and feeds are manufactured. Moreover, unused nutrients are discharged from aquaculture facilities, and nitrogen and phosphorus are the main cause of eutrophication of water bodies. Efficient use of nitrogen, phosphorus, and other nutrients is a defining characteristic of sustainable aquaculture.

Nutrient use in aquaculture could be evaluated by several methods, but a simple technique is to sum the amount of a nutrient added to a production system in fertilizer and feed over a period and divide by production during that time span (Boyd et al., 2006) as illustrated below for nitrogen:

$$\text{Nitrogen use, kg/t} = \frac{\text{Fertilizer N} + \text{feed N, kg}}{\text{Production, t}} \tag{11}$$

The natural contribution of nitrogen, phosphorus, and other nutrients to aquaculture systems is small in comparison to inputs in fertilizer and feed and can be neglected in computing nutrient use indices. An estimate of nutrient recovery in harvested biomass also should be made. This index can be estimated for nitrogen, phosphorus, or other nutrients as follows:

$$\text{\% Nutrient recovery} = \frac{\text{Nutrient in harvest biomass, kg / t}}{\text{Nutrient index, kg/t}} \times 100. \tag{12}$$

Typical application rates of triple superphosphate (20% P) and urea (44% N) in fertilized tilapia ponds are about 20 kg/ha and 40 kg/ha, respectively, at biweekly intervals, and production normally is about 2 t/ha (Boyd and Tucker, 1998). A total of 64 kg phosphorus and 282 kg nitrogen/ha would be applied in fertilizer. The nutrient indices are 32 kg P and 141 kg N/t. Live tilapia contain about 0.72% phosphorus and 2.17% nitrogen (Table 1) or 7.2 kg P and 21.7 kg N/t. Fertilizer nutrient recovery in fish at harvest would be 22.5% and 15.3% for nitrogen and phosphorus, respectively. A typical response to manuring of tilapia ponds was provided by Collis and Smitherman (1978). Application of 28,380 kg fresh cow dung containing 141.9 kg N and 25.5 kg P resulted in 1,646 kg/ha of tilapia. Nutrient indices were 15.5 kg/t and 86.2 kg/t for phosphorus and nitrogen, respectively. The efficiency of nutrient recovery was 46.5% for phosphorus and 25.1% for nitrogen.

Tilapia feed typically contains about 1% phosphorus (10 kg/t) and 4.78% nitrogen (47.8 kg/t). In pond, cage, or net pen culture with feeding (FCR = 1.8), nutrient indices are 18 kg P/t and 86 kg N/t with 40% of phosphorus and 22.5% of nitrogen being recovered at harvest. The efficiency of nutrient use is similar in feed-based and manure-based tilapia culture, and these two production methods are more nutrient efficient than tilapia production in fertilized ponds.

In semi-intensive culture of marine shrimp, both feeds and fertilizers often are applied. Typical inputs of fertilizer and feed to such systems would be 25 kg/ha triple superphosphate (5 kg P/ha), 150 kg/ha urea (66 kg N/ha), and 2,000 kg feed/ha (32 kg P/ha and 120 kg

N/ha). Shrimp production of 1,500 kg/ha could be expected. The nutrient indices are 25 kg P/t and 80 kg N/t. From Table 1, live shrimp contain about 2.5 kg P/t and 27.5 kg N/t. The nutrient recovery indices are 10% and 34.3% for phosphorus and nitrogen, respectively. Intensive shrimp culture usually does not require fertilizer, and FCR averages about 2.0. The nutrient indices are about 32 kg P/t and 120 kg N/t, and the nutrient recovery indices are 7.8% and 22.9% for phosphorus and nitrogen, respectively. The semi-intensive system is slightly superior in nutrient efficiency compared to the intensive one.

The much greater efficiency of phosphorus use in tilapia culture as compared to shrimp culture illustrated above results because fish have bones made of calcium phosphate and thus contain considerably more phosphorus than shrimp. The percentage nitrogen of shrimp is slightly greater than that of fish (Table 1).

Liming Materials

Agricultural limestone is made by finely crushing limestone. This product is added to pond water or bottom soils to neutralize acidity. Burnt lime is made by burning limestone at a high temperature to drive off carbon dioxide. It consists of a mixture of calcium and magnesium oxides (Boyd and Tucker, 1998). Hydrated lime is made by adding water to burnt lime. Burnt or hydrated lime is applied to pond bottoms to increase the pH and kill unwanted organisms including the vectors of diseases.

Application rates of liming materials are expressed on an equivalent calcium carbonate ($CaCO_3$) basis (Jones, 1979). The calcium carbonate equivalence of liming materials can be obtained by multiplying the decimal percentage of the neutralizing value (NV) by 1,000 kg as was done in Table 10 for some pure sources of common liming materials. The neutralizing value should be determined for commercial sources of liming materials for they are not pure compounds and tend to have slightly lower neutralizing values (Thunjai et al., 2004). The calcium carbonate index for aquacultural production is:

$$\text{CaCO}_3 \text{ index, kg/t} = \frac{\text{Liming material, kg} \times \%\text{NV}/100}{\text{Production, t}} \tag{13}$$

Table 10
Neutralizing values for common liming materials used in aquaculture

Material	Neutralizing value (%)
Agricultural limestone:	
Calcitic	100
Dolomitic	109
Burnt lime:	
Calcitic	179
Dolomitic	208
Hydrated lime:	
Calcitic	135
Dolomitic	151

Source: Boyd and Tucker (1998).

The use of agricultural limestone in freshwater aquaculture usually is restricted to areas where waters and bottom soils are acidic. Typical application rates are 1,000 to 2,000 kg/ha of agricultural limestone (Boyd and Tucker, 1998). Lime may be used regardless of bottom soil pH to treat pond bottoms between crops by elevating pH above 10 to eradicate unwanted wild fish in puddles and to kill disease organisms and their vectors in the pond bottom (Boyd and Tucker, 1998). Application rates for lime for disinfecting pond bottoms normally are 500 to 2,000 kg/ha.

Marine shrimp culturists typically treat all ponds with liming materials (Boyd et al., 2006). Most managers treat bottoms of empty ponds between crops with 500 to 2,000 kg/ha of liming material, and some continue to lime at 25 to 50 kg/ha weekly during the crop. Calculation of the calcium carbonate index will be illustrated for a 1-ha intensive shrimp pond with a production of 4,500 kg/ha where ponds were treated with 1,000 kg/ha of lime (NV = 130%) before filling and with 250 kg/ha of dolomitic agricultural limestone (NV = 105%) during the crop:

$$\text{Calcium carbonate index} = \frac{1{,}000\ \text{kg}\left(\frac{130}{100}\right) + 250\ \text{kg}\left(\frac{105}{100}\right)}{4.5\ \text{t shrimp}} = 347\ \text{kg}\ CaCO_3/\text{t}. \quad (14)$$

Application rates for liming materials are similar between intensive and semi-intensive pond aquaculture. The calcium carbonate index usually will be less for intensive than semi-intensive shrimp culture. For example, the calcium carbonate index for a semi-intensive shrimp pond treated with liming material as above but producing only 1,200 kg/ha would be 1,302 $CaCO_3$/t.

Energy

There are many uses of energy in aquaculture to include energy used for construction of facilities, production of liming materials, fertilizers, and feed, operation of machines and vehicles during culture and harvesting, processing, transportation, etc. However, only two of these energy inputs can be readily estimated at the farm level. These are energy uses for pumping water and for mechanical aeration, and, at the farm level, they are the major, direct energy inputs. This discussion will be limited to pumping and aeration, but studies of total energy use per tonne of aquacultural production should be conducted for a number of species and culture methods.

Mechanical aerators powered by internal combustion engines or electric motors are used to supplement the natural supply of dissolved oxygen in grow-out systems. Aeration allows greater stocking and feeding rates to increase production.

Aeration rates in pond aquaculture often are expressed in horsepower per hectare or horsepower applied per volume (Boyd and Tucker, 1998). In channel catfish farming, aeration usually is applied at 4 to 8 hp/ha, while in intensive marine shrimp culture, rates of 10 to 30 hp/ha may be applied. Use of electricity typically is measured in kilowatt·hours (kW·h), and 1 hp = 0.745 kW. However, there are inefficiencies in the use of electricity by machines, and for aerators, the typical efficiency is about 90% (Boyd, 1998). Thus, electricity use for aeration can be estimated as follows:

$$\text{Aeration energy, kW} = \frac{\text{Aerator power, hp} \times \text{Aeration time, hr} \times 0.745\ \text{kW/hp}}{\text{Production, t} \times 0.9}. \quad (15)$$

Aerators in channel catfish ponds in the southeastern United States normally are operated between May and September for about 10 h/night. Aeration at 6 hp/ha in a catfish pond will use 7,599 kW·h of electricity during a crop year or about 950 kW·h/t for production of 8,000 kg/ha.

Production of marine shrimp in a pond with 15 hp aeration/ha might be 8,000 kg/ha for a 120-day crop. Aeration usually is supplied 24 h per day for at least 100 days, but only half of the aerators may be operated during the day. The total electrical use will be about 27,000 kW·h or 3,375 kW·h/t—over three times the amount of aeration used for channel catfish.

In Asia, paddlewheel aerators often are driven by small, internal combustion engines powered by diesel fuel or gasoline. Energy use can be estimated from fuel consumption; 1 L diesel fuel is equal to 3.27 kW·h while 1 L of gasoline equates to 2.21 kW·h (Yoo and Boyd, 1994).

The energy use for pumping water to supply ponds can be estimated as follows:

$$P = \frac{\gamma QH}{E} \tag{16}$$

where P = power required by pump (kW), γ = specific weight of water (9.81 kN/m^3), Q = discharge (m^3/sec), H = pumping head (m), and E = pump efficiency (decimal fraction). Boyd and Tucker (1995) used this equation and water management data to estimate that about 1,275 kW·h of electricity typically would be used to fill a 1-ha channel catfish ponds. Annual energy use for pumping water to maintain water levels would be less than 500 kW·h in humid climates and up to 2,000 kW·h in arid climates. Assuming total energy use of 1,775 kW·h//ha per year for catfish ponds in a humid climate, the energy use for pumping would be about 296 kW·h/t as compared to 950 kW·h/t for aeration.

In semi-intensive shrimp culture, ponds are about 1.2 m deep and water often is exchanged at 5% of pond volume daily. The average lift for the water is 3 m. The pump discharges 3 m^3/sec at 85% efficiency, and from Equation 16, the pump power is 103.9 kW. Initial filling of ponds for each crop will require 12,000 m^3/ha of water and the water exchange requirement is 600 m^3/day. Assuming a production of 1.2 t/ha during a 120-day crop, the total water requirement would be 84,000 m^3/ha, and the pump would operate for 7.78 h and use 808 kW·h of energy. This would be equal to 673 kW·h/t of shrimp—much less than the energy requirement for aeration of intensive shrimp ponds.

Life cycle assessment, or LCA, is a relatively new discipline that attempts to account for all environmental impacts of providing goods and services to society. Life cycle assessment derives its name from the concept that all products have a "life" starting and ending at pre-defined points that set the boundaries for the assessment. In agriculture, product life may, for example, begin with acquisition of raw materials (fertilizers, feedstuffs, etc.) and include production, processing, transportation, and so on. Assessments can be made on the basis of any impact of interest. For example, the total contribution to greenhouse gases can be estimated for all activities involved in production and retirement of a particular product. Other commonly used impacts in LCA are eutrophication, ozone creation, ecotoxicology, carcinogen production, land use, water use, and energy use. One type of LCA for aquaculture has already been mentioned in this paper—that based on land use or "ecological footprint."

Studies using modified LCA methodology consistently show that the energy used to produce aquafeeds dominates the energetics of aquaculture production. For example, more than 75% of the total energy cost of producing Atlantic salmon in net pens is used in procuring or growing feed ingredients and manufacturing the feed (Folke, 1988; Troell et al., 2004; Tyedmers, 2004; Ellingsen and Aanondsen, 2006). The remaining energy inputs, in order of importance, were fuel and electricity used to operate the facility, embodied energy costs (manufacture, maintenance, etc.) associated with physical infrastructure, and energy used to produce smolts). Feed production dominates the energy budgets of all aquaculture systems relying on aquafeeds, regardless of species (Troell et al., 2004).

The energy efficiencies of various aquaculture systems span perhaps the widest range of any agricultural sector (Troell et al., 2004; Tyedmers, 2004). Traditional carp polyculture in ponds fertilized with agricultural byproducts lies at one end of the spectrum as one of the most energy efficient food production systems ever devised. When energy efficiency is expressed on the basis of industrial energy input per unit of edible protein energy produced, tradition carp polyculture even rivals vegetable crops for energy efficiency, with energy ratios approaching 1. Most agricultural activities have energy input/output ratios much greater than 1, meaning that energy inputs during production far exceed food protein energy output. Relative to traditional pond culture of carp, aquaculture systems that rely heavily on aquafeeds and other ecosystem support functions lie at the other end of the spectrum, with energy input/energy output values exceeding 50. Nonetheless, most modern aquaculture systems are generally comparable to terrestrial animal production systems with respect to energy efficiency. For example, input/output energy ratios for pond-grown tilapia and channel catfish are similar to those for several common animal production activities, such as eggs, poultry (broiler), and swine production (Troell et al., 2004; Tyedmers, 2004). Likewise, energy ratios for marine shrimp aquaculture, which are among the highest of the major aquaculture systems, are in the same general range as that for shrimp trawling.

Comparing energy use in aquaculture and other forms of agriculture is difficult—and sometimes misleading—because few energy analyses of aquaculture have been conducted. Further, studies may not include adequate information on the “boundaries” of the analysis, which will bias comparisons among systems. Depending on the intent of the analysis, an almost endless number of input functions can be included in an LCA for an agricultural activity. Most studies of energy use include only the most easily quantified inputs, such as direct electrical and fuel inputs for the most obvious production functions (such as feed manufacture, water pumping, aeration, and so on).

Life-cycle assessment of energy use can include post-harvest functions such as processing, freezing, refrigeration, storage, transportation, marketing, waste treatment, and even household activities such as refrigeration, freezing, and cooking. Energy use in these activities apparently has not been assessed for aquaculture but may be an important part of the overall energy costs of delivering aquaculture products to a consumer’s plate. For example, energy used in on-farm production of the United States food supply accounts for only about 20% of the energy used to deliver food to the consumer’s plate (Heller and Keoleian, 2000). Post-harvest processing and transportation each consume about 15% and household preparation accounts for more than 30% of the total energy consumed. Ultimately, it will be economically and socially imperative to improve the energy efficiency of all aspects of the food-supply chain. However, it is possible that greater overall gains in energy savings can be made by improving the efficiencies of processing, transport, retailing, and even household storage and preparation than can be made by improving energy efficiency in the production sector. This may have particular relevancy in aquaculture, where important products are produced only in certain regions (marine shrimp in the tropics; salmon in the north-temperate) and are stored and shipped long distances for ultimate consumption.

Waste Production

Nutrients, organic matter, and suspended solids in aquaculture effluents can cause eutrophication and sedimentation in receiving water bodies. The pollution potential of feed-based aquaculture systems usually is much greater than that of fertilized ponds (Boyd and Tucker, 1998). The fate of feed applied to aquaculture ponds is depicted in Figure 1. Fish usually consume 90 to 95% of feed (Boyd and Tucker, 1995), but shrimp nibble their food, and only 60 to 80% is eaten (Ruttanagosrigit, 1997). About 80 to 90% of feed consumed is absorbed across the intestine while the rest is excreted as feces. Usually about 10 to 20% of nutrients absorbed across the gut become biomass. The remainder is excreted primarily as carbon dioxide and ammonia. Most of the uneaten feed and feces are decomposed to carbon dioxide, ammonia, phosphate, and other inorganic substances by bacteria. A portion settles to the bottom to accumulate as organic matter. Inorganic nutrients from fish and microbial metabolism stimulate phytoplankton growth, and phytoplankton abundance in ponds increases as feeding rates increase. Phytoplankton has a short life span, and dead phytoplankton is decomposed within aquaculture systems or becomes organic sediment.

Some production systems are a much greater pollution threat than others (Beveridge et al., 1991; Boyd and Queiroz, 2001). The hydraulic retention time (HRT) of static ponds usually is weeks or even months, and in ponds with water exchange, HRT usually is a week or more. Natural physical, chemical, and biological processes in ponds assimilate wastes and lessen the proportion of feed wastes discharged into natural waters. Suspended solids tend to settle to the pond bottom. Phytoplankton remove nutrients from the water, and bacteria decompose organic matter. Ammonia from animal excretions and bacteria degradation is lost from ponds by diffusion, converted to organic nitrogen in microbial biomass, and transformed to nitrate by nitrifying bacteria. Nitrate is converted to nitrogen gas through denitrification and lost to the air. Phosphorus is removed from water by microorganisms. It also is sequestered in sediment as relatively insoluble iron, aluminum, or calcium phosphates

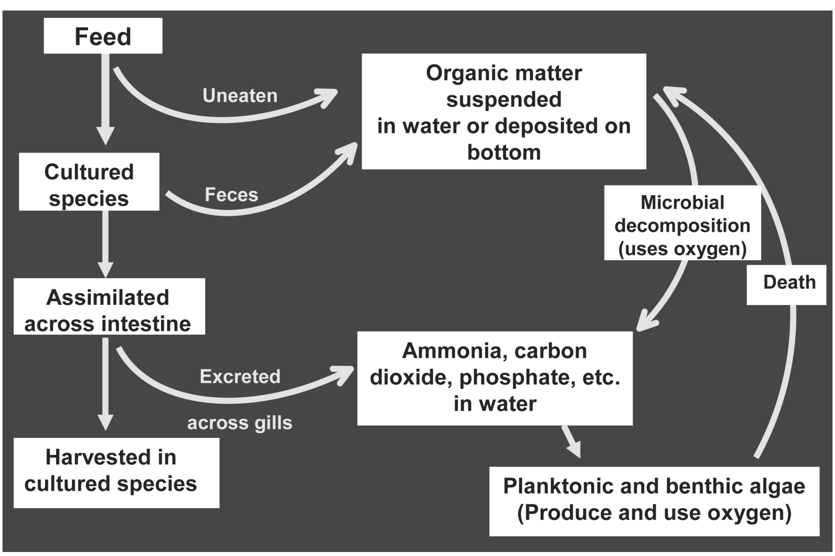

Figure 1. Fate of feed applied to an aquaculture pond (modified from Boyd and Tucker, 1995).

Table 11
A budget for nitrogen and phosphorus in feeds applied to channel catfish ponds

	% feed input	
Pathway	Nitrogen	Phosphorus
Harvest in fish	31.5	31.0
Ammonia volatilization	12.5	—
Denitrification	17.4	—
Sediment accumulation	22.6	57.6
Effluent	16.0	11.4

Source: Gross et al. (1998, 2000).

and as a component of dead organic matter. A budget for feed nitrogen and phosphorus (Gross et al., 1998, 2000) is provided in Table 11 for a channel catfish pond.

Water reuse systems are similar to ponds in that most wastes produced during culture are treated within the facility rather than discharged directly to other water bodies. Whereas waste removal in pond systems relies on natural processes inherent in the pond ecosystem, wastes are removed from water reuse systems by mechanical treatment or by chemical and biological processes that operate within discrete waste treatment units, such as biological filters that convert ammonia to nitrate.

Raceways, cages, and net pens have very short hydraulic residence times, and culture units have direct hydrological connections to effluent-receiving water bodies. As such, the potential for pollution is greater from these systems than for most pond systems. Raceways offer opportunities for effluent management through improved feeds, more efficient feeding practices, and incorporation of solids-removal technologies (Cripps and Bergheim, 2000). Screens are often used to prevent fish from entering the discharge ends of raceways. This creates a “quiescent zone” that allows solid wastes to settle, and they are removed via a drain or collected with a suction device for disposal on land. Solids may also be removed from raceways in off-line settling basins. Effluent treatment is almost impossible in cage and net pen culture, so pollution management relies almost entirely on developing improved feeds and feeding practices. Nutrients and organic matter from feed that are not converted to fish biomass pass directly from cages into surrounding waters. Thus, considering all types of aquaculture, cage culture has the greatest potential for causing pollution. An example of the amounts of wastes from tilapia cage culture is given in Table 12.

The most important variables in consideration of effluent quality are pH, dissolved oxygen, temperature, nitrogen, phosphorus, total suspended solids, 5-day biochemical oxygen demand, and salinity. Various surrogate analyses for salinity may be used to include total dissolved solids, specific conductance, or chloride. Most authorities recommend that the pH of effluents should not be below 6 or above 8.5, and effluents should not differ in temperature by more than 3 to 5°C from the receiving water, dissolved oxygen concentration should not be less than 5 mg/L, and brackish water should not be discharged into freshwater (Boyd, 2000). Freshwater can be defined as water containing no more than 1 ppt salinity—about 1,000 mg/L total dissolved solids, 500 mg/L chloride, and 1,500 μmhos/cm (Boyd, 2002). Limits for concentrations of other potential pollutants typically are 2 to 5 mg/L total

Table 12
Carbon, nitrogen, and phosphorus budget for tilapia cage culture

	Feed		Fish		
Variable	(%)	(kg)	(%)	(kg)	Waste load (kg)
Amount	—	1, 800	—	1, 000	—
Carbon	45.0	769.5	11.7	117	652.5
Nitrogen	5.12	87.6	2.25	22.5	65.1
Phosphorus	1.0	17.1	0.80	8.0	9.1

Source: Boyd (unpublished data).

nitrogen, 0.2 to 0.3 mg/L total phosphorus, and 20 to 30 mg/L total suspended solids and 5-day biochemical oxygen demand (Boyd, 2000; Schwartz and Boyd, 1994a).

There are several disadvantages to the use of effluent water quality limits in an effort to lessen negative impacts of effluents, particularly for aquaculture effluents. Compliance with water quality criteria can be achieved by increasing inflow and flushing rate of culture units to dilute concentrations of potential pollutants in effluent. The effect of effluents on receiving water bodies usually is related to the total amount of pollutants added over time and not to the concentration of the pollutants, except in situations where concentrations of pollutants are high enough to have localized impacts. Dilution of effluent may allow compliance with water quality criteria, but this practice does not reduce the quantities of pollutants discharged. A small daily volume of highly concentrated effluent might not be as harmful to a water body as a large daily volume of a much more dilute effluent.

Limits on daily loads of variables in an effluent sometimes are required in discharge permits. The load is calculated as follows:

$$\text{Load X, kg/day} = (\text{Effluent volume, m}^3/\text{day})(\text{X, g/m}^3) \times 10^{-3} \qquad (17)$$

where X = the pollutant of interest. An aquaculture farm discharging 100,000 m^3/day of effluent with 6 mg/L BOD_5 would release 600 kg BOD_5/day. A farm discharging 1,000 m^3/day with a BOD_5 of 40 mg/L, a BOD_5 greater than allowed in most concentration-based permits, would have a daily BOD_5 load of only 40 kg/day.

Load-based regulations do not resolve all problems. The load is important because an ecosystem has the capacity to assimilate a certain amount of waste and still maintain adequate water quality. The acceptable waste load varies among water bodies, but unfortunately it is seldom if ever known (Beveridge, 1984). A small, highly-concentrated effluent might not exceed acceptable daily loads for pollutants, but it might cause water quality deterioration in the mixing zone. For example, a small daily input of an effluent high in nutrients and BOD_5 might cause dissolved oxygen depletion in the mixing zone but not lead to eutrophication of a water body. Load-based water quality criteria in discharge permits may be supplemented with concentration limits for variables that could cause oxygen depletion, toxicity, or other adverse impacts in the mixing zone.

The source water for aquaculture facilities contains substances of interest in pollution abatement. In marine shrimp farming and some other types of aquaculture, the same water body serves as source water and effluent recipient. The increase in concentrations or loads of potential pollutants between inflow and outflow represent the contributions of aquaculture to the concentrations and loads. Some aquaculture facilities use groundwater or take surface water from one watershed and discharge it into another. The entire concentrations or loads of potential pollutants in discharge from such facilities can be considered to originate from aquaculture. Some environmentalists have suggested that farms should be required to prove that outflow has no greater concentrations of pollutants than inflow. Others have suggested that the effluent from aquaculture facilities should not be of lower quality than the receiving water body. Neither of these requirements appears realistic, because experience suggests that outflow from semi-intensive and intensive aquaculture farms usually have higher concentrations of nutrients, organic matter, and suspended solids than inflow or receiving water bodies.

It is often suggested that aquaculture effluents should pass through settling basins before final discharge. Sedimentation will remove coarse suspended solids from water released when facilities are cleaned or drained for harvest. It will not remove phytoplankton, dissolved substances or finely suspended organic and mineral particles from effluent (Ozbay and Boyd, 2003; Boyd and Queiroz, 2001), and treatment methods capable of doing so are too expensive for application to aquaculture. It appears necessary to allow an increase in concentrations of potential pollutants between farm influent and effluent, and to allow effluents to be somewhat more concentrated in certain water quality variables than receiving waters.

Monitoring of receiving water bodies to demonstrate whether or not an aquaculture facility causes pollution is often suggested. There are two major flaws in most monitoring programs. Data on water quality seldom are available for the pre-aquaculture period, and aquaculture seldom is the only polluter of a given body of water.

Water re-use to reduce or prevent effluent has advantages. Water use is reduced, dissolved nutrients are conserved, and pollution loads are diminished. However, water use technology applicable to most types of aquaculture is not presently available.

There is much variation in waste loads among aquaculture systems. Frequent monitoring of effluent volume and quality would be necessary to assess these loads. A more feasible way of evaluating the waste load from aquaculture would be to estimate waste loads per tonne of production. With this information, it would be possible to estimate waste loads that would be imposed upon receiving water bodies without resorting to effluent monitoring. The procedure for estimating waste load indices would vary with system:

Watershed ponds and water reuse systems:

$$\text{Load X, kg/t} = \frac{Q_E CX_E 10^{-3}}{\text{Annual production, t}} \tag{18}$$

where load X = load of variable X (kg/t), Q_E = effluent volume (m^3/yr), CX_E = concentration of variable X in effluent (g/m^3), and 10^{-3}= kg/g.

Raceways, embankment ponds, and ponds with water exchange:

$$\text{Load X, kg/t} = \frac{Q_E CX_E 10^{-3} - Q_i CX_i 10^{-3}}{\text{Annual production, t}} \tag{19}$$

where Q_i = influent volume (m^3/yr) and CX_i = concentration of variable X in influent.

Cage and net pens:

$$\text{Load X, kg/t} = \frac{FCX_F - BCX_B}{\text{Annual production, t}} \tag{20}$$

where F = feed used (kg/yr), CX_F = concentration nutrient X in feed (decimal fraction), B = biomass (t), and CX_B = concentration of nutrient X in biomass (decimal fraction).

Loads of potential pollutants for aquacultural production are provided for several species and culture systems (Table 13). Annually drained channel catfish ponds have much greater loads of total suspended solids, 5-day biochemical oxygen demand, nitrogen, and

Table 13
Loads of potential pollutants for some different aquaculture species and production systems

Species and culture method	Load in discharge (kg/t)				Source
	TSS	BOD_5	TN	TP	
Channel catfish:					
Watershed pond					
Drained annually	2,302	39.3	19.6	0.78	Schwartz and Boyd, 1994b
Drained every 6–8 yrs	190	13.1	7.3	0.69	Boyd et al., 2000
Embankment pond					
Drained every 6–8 yrs	68.6	5.5	5.2	0.22	Boyd et al., 2000
Shrimp ponds:					
Intensive	—	—	26–117	13–38	Lin et al., 1993
Intensive	1,500	96	36	3.4	Dierberg and Kiat-tisimkul, 2006
Semi-intensive	—	—	—	7.84	Boyd et al., 2006
Semi-intensive	—	414	36.2	—	Boyd, unpublished data
Rainbow trout:					
Raceway culture	150–200	—	40	7.0	Bergheim and Brinker, 2004
Raceway culture	289–839	—	47–87	4.8–18.7	Axler et al., 1997
Salmon: Cage culture	—	—	20.5–30	6.7	Johnsen and Wandsvik, 1991; Johnsen et al., 1993
	—	—	32.8	3.3	Hardy, 2001
Tilapia: Cage culture	—	—	65.1	9.1	Boyd, unpublished data

phosphorus than ponds drained annually for harvest. When watershed ponds for channel catfish production are drained for harvest, the final 20 to 25% of discharge usually contains 75 to 80% of the loads of potential pollutants (Schwartz and Boyd, 1994b). This pattern is not as pronounced during draining of embankment ponds, but there is a modest increase in the proportion of pollutants discharged during the final stage of draining (Hargreaves et al., 2005). Pollution loads for watershed ponds were greater than for embankment ponds.

A wide range in nitrogen and phosphorus loads for intensive shrimp farms was reported by Lin et al. (1993), and the higher values were for farms with large water exchange rates (Table 13). Lower nitrogen and phosphorus loads for intensive shrimp ponds were estimated from data of Dierberg and Kiattisimkul (1996). Semi-intensive shrimp farms had much greater BOD_5 loads than intensive ones (Table 13). This probably results because the BOD_5 of pond water results mainly from phytoplankton (Boyd and Gross, 1999). Semi-intensive ponds often have phytoplankton blooms nearly as dense as those in intensive ponds, but much lower shrimp production per unit of water volume. Moreover, there were not great differences in nitrogen and phosphorus loads between intensive and semi-intensive ponds.

Although nitrogen and phosphorus loads from raceway and cage culture tend to be greater than for pond aquaculture, impressive reductions in waste production by salmonids have been made through diet modifications. One of the most significant improvements was the development of high-energy diets with increased fat content, reduced carbohydrates, and improved digestibility (Sugiura and Hardy, 2000; Gatlin and Hardy, 2002). Since the 1980s, the lipid content of salmon feeds has increased from less than 20% to 30% or more. Increasing the energy density of diets enhances fish growth and spares dietary protein from use in energy production, thereby increasing protein retention. Protein retention, which was 20–25% before the advent of modern, high-energy diets, has increased to more than 40%. Concomitant with improved protein retention, waste nitrogen production has been reduced by more than 25% (Hardy, 1999). Some diets, especially those for trout raised in freshwater, are also formulated to reduce total phosphorus and improve phosphorus retention (Gatlin and Hardy, 2002). Reducing total dietary phosphorus and using feedstuffs and supplements with high phosphorus availability can reduce urinary losses of phosphorus by more than 70% and reduce fecal losses by more than 50% (Gatlin and Hardy, 2002).

The effects of effluents on receiving waters vary from no impact to severe degradation of one or more aspects of water quality. These effects can be insidious, because pollution loads tend to increase gradually, and negative effects are not observed until loads finally exceed the assimilative capacity causing water quality to deteriorate. Nutrient inputs to lakes may increase over many years, but the onset of dense phytoplankton blooms and other symptoms of eutrophication can be sudden as illustrated in Figure 2 for a lake in a rural area where the human inhabitants of the watershed have steadily increased for years (Boyd, 2006). The lake traditionally had clear water as evident from the high Secchi disk visibility. Nutrient inputs increased until phytoplankton blooms occurred causing the Secchi disk visibility to decline, signaling that the lake had become eutrophic.

It often is difficult to have a meaningful dialogue about the effects of aquaculture effluents on a given water body because stakeholders do not understand how to relate information on sources and amounts of pollutants to possible environmental outcomes. The concentrations and quantities of nutrients, organic matter, and suspended solids in aquaculture effluents entering a water body may be known. However, the information needed to compare the pollution loads from aquaculture with other sources of pollution usually is lacking, and the assimilative capacity of the water body is seldom known. Unless changes in water quality are obvious, some stakeholders assume that pollution is not occurring.

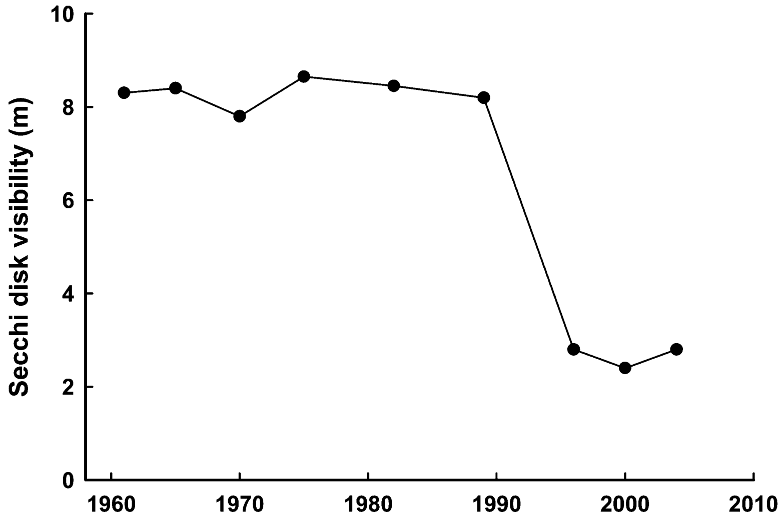

Figure 2. Sudden onset of eutrophication in a tropical lake as indicated by decreasing Secchi disk visibility (Boyd, 2006).

Domestic wastewater is a common source of pollution that increases in direct proportion to the number of humans who comprise the source. Aquaculturists are aware of this because they express concern about the possible effects of pollution from towns and villages near fish and shrimp farms. Most other stakeholders also are aware of the relationship between human population and pollution or could be easily convinced of it. Folke et al. (1992) suggested discharges from aquaculture farms could be converted to a human population equivalent basis to provide perspective on the amount of waste generated by aquaculture facilities.

Folke et al. (1992) estimated that the production of 100 t salmon in cages in Sweden was equivalent to the phosphorus and nitrogen loads imposed by 2,800 and 3,200 people, respectively, in 1974. Estimates for production methods used in 1992 (Folke et al., 1992) indicated that improvements in practices had lowered the estimates to 850 people for phosphorus and 3,200 people for nitrogen. Hardy (2001) made calculations suggesting that current human population equivalents for a 100 t salmon farm might be as low as 180 for phosphorus and 1,250 for nitrogen.

The use of human population equivalents seems like a reasonable way to visualize aquaculture wastes despite criticisms of this approach by Black et al. (1997). A standard source should be used for the waste contribution of humans. We suggest using data from Tchobanaglous et al. (2003) who provided the typical per capita contribution of selected pollutants to sewage by humans in both developed and developing nations (Table 14).

In closed-system shrimp production, effluents are released only when ponds are drained for harvest. A 1-ha pond with a depth of 1.5 m might produce 4 t of shrimp/crop twice a year. The total volume of wastewater would be about 30,000 m^3/year. Concentrations of water quality variables in intensive shrimp ponds averaged about 10 mg/L BOD_5, 80 mg/L TSS, 4 mg/L total nitrogen, and 0.4 mg/L total phosphorus (Boyd and Gautier, 2000). The annual amounts of pollutants per tonne of shrimp are about 37.5 kg of BOD_5, 300 kg of total suspended solids, 15 kg of total nitrogen, and 1.5 kg of phosphorus. The human population equivalents per tonne of shrimp for the farm effluent in a developing nation would be 2.03 for

Table 14
Average daily per capita contribution of selected water pollution variables to domestic sewage

	Quantity (g/capita/day)			
	Developed nation (n = 7)		Developing nations (n = 6)	
Variable	Range	Mean	Range	Mean
5-day biochemical oxygen demand	49–120	62.5	27–68	50.6
Total suspended solids	55–96	88.2	41–72	44.8
Total nitrogen	1–22	11.5	4–14	9.9
Total phosphorus	0.15–4.5	2.48	0.4–2.0	0.55

Source: Tchobanoglous et al. (2003).

BOD_5, 18.3 for total suspended solids, 4.2 for total nitrogen, and 7.5 for total phosphorus. A farm producing 500 t shrimp/year would have wastes with human population equivalents of 1,015 for BOD_5, 9,150 for total suspended solids, 2,100 for total nitrogen, and 3,750 for total phosphorus. The water pollution load of shrimp farming in a country producing 100,000 t of shrimp annually using closed systems would be equal to that of 203,000 to 1,830,000 inhabitants, depending upon the variable selected for the comparison.

The population equivalent of the effluent from shrimp farming would be greater for farms using water exchange, because flushing would remove organic matter, suspended solids, and nutrients and lessen the amounts of these substances assimilated within ponds. Studies have shown that semi-intensive shrimp culture ponds with 10 to 20% daily water exchange can release 7 or 8 kg phosphorus/t of shrimp (Boyd et al., 2005) as compared to 1.12 kg/t in the example of closed-system shrimp production given above.

Production of 1 t of tilapia in cage culture would release about 65 kg of total nitrogen and 9 kg of total phosphorus to the water (Table 12). A tilapia cage culture operation located in a lake in a developing nation and producing 5,000 t/year would discharge nitrogen equivalent to 89,917 humans and total phosphorus equal to 227,500 people. The farm would deliver a pollution load to the lake equal to that imposed by a small city. However, if the lake can assimilate the wastes, water quality would not deteriorate.

Trout production is conducted most frequently in developed nations. Typical waste production in raceways for trout has been reported to be 1,156 kg of total suspended solids, 315 kg of BOD_5, 50 kg of nitrogen, and 13.9 kg of phosphorus/t of fish (Boyd et al., 2005). The human population equivalents per tonne of trout are 35.9, 13.8, 11.9, and 15.2, respectively.

Expressing the water pollution potential of aquaculture facilities in terms of equivalent human population clearly demonstrates that aquaculture can be a significant source of pollution. Aquaculture facilities should not be singled out as pollution sources, because pig farms, chicken houses, cattle feed lots, and other agricultural facilities also generate wastes.

The water released from aquaculture facilities usually has rather low concentrations of pollutants as compared to municipal sewage or industrial effluents. For example, pond effluents usually contain less than 20 mg/L BOD_5 (Boyd and Gross, 1999), while raw human sewage typically has a BOD_5 of 250 to 500 mg/L, and effluents from food processing operations have BOD_5 of 1,000 to 2,000 mg/L. In spite of low pollutant concentrations,

Table 15
Percentages of watershed land use and loadings of total suspended solids, total phosphorus, and total nitrogen to Wolf Lake, Mississippi

		Pollutant loadings (% of total loading)		
Land use	Area (%)	Solids	Phosphorus	Nitrogen
Row crops	44	81.8	79.6	64.1
Hardwood forest	28	6.1	7.8	5.9
Pasture/fallow cropland	23	11.6	10.8	18.8
Catfish ponds	5	0.4	1.5	10.8
Residential	1	0.2	0.3	0.4

aquaculture facilities often have large volumes of effluents that can lead to significant pollution loads. Fortunately, the negative environmental impacts of aquaculture can be avoided or lessened through selection of good sites, limits on production, and use of good management practices (Boyd et al., 2005).

A good example of the relative contributions of aquaculture and other land uses to watershed-level pollutant loading comes from a study of Wolf Lake, an oxbow lake in the Yazoo-Mississippi River floodplain of northwest Mississippi (Mississippi Department of Environmental Quality (MDEQ), 2003). The floodplain is a vast expanse of flat land developed predominantly into various agricultural activities, including a high concentration of channel catfish ponds.

Pollutant loadings to Wolf Lake were modeled as part of a federal regulatory activity to establish total maximum daily loads (TMDLs) for waters on the USEPA list of impaired water bodies. Five land uses were identified in the watershed and annual loadings of solids, phosphorus, and nitrogen were determined for each land use category (Table 15). Although catfish ponds accounted for 5% of the total land use in the watershed, they contributed only 0.4% of the solids load to the lake and 1.5% of the phosphorus load. Per unit of land, catfish ponds contributed the lowest proportion of solids and phosphorus to the watershed than any other land use, including undisturbed hardwood forest. Row crop agriculture (principally soybeans and cotton) contributed the highest loadings of all land uses, both in absolute terms and per unit of land. For example, row crops accounted for 44% of the land use, yet generated 82% of the solids in the watershed. Catfish ponds did, however, generate nitrogen loadings that were disproportionately high relative to land use. Ponds (5% of land use) contributed almost 11% of the nitrogen loading to the lake.

The Wolf Lake study illustrates two important points. Overall, pond aquaculture appears to be a relatively benign land use when assessed on the basis of potential problems with waste discharge. The Wolf Lake watershed is considered to be highly developed into aquaculture by United States standards, yet ponds represented only 5% of the total watershed area. Overall loadings and, for solids and phosphorus, loadings per unit of land were low relative to other activities and land uses. However, the study also illustrates that potential impacts of aquaculture effluents vary depending on the variable of interest. Ponds, for example, are good at trapping solids and sequestering phosphorus, but the use of high-quality aquafeeds in catfish farming results in a relatively nitrogen-rich effluent. Accordingly, catfish farming is an excellent land use with respect to production of solids and phosphorus, but high densities of ponds could cause problem with excessive discharge of nitrogen.

Applications

Assessing environmental performance of aquaculture is difficult because activities and potential impacts are extremely diverse. In contrast to this complex situation, there seems to be a desire to answer one simple question, "What are the environmental consequences of aquaculture?" Accordingly there is increased emphasis on using holistic analyses to compare overall impacts of different agricultural production systems and to assess impacts and resource use within a production process to identify opportunities for increasing resource use efficiency. Life Cycle Assessment, which was described previously, is the most common comprehensive analytical tool currently used to quantify environmental impacts of a production process. The LCA concept has been formalized into an analytical methodology under ISO 14000 standards and has been proposed as a measure of environmental performance and sustainability by numerous agencies and environmental groups

The LCA approach is appealing because the impacts of all activities involved in production, use, and retirement of a product are expressed in a single "common currency"—energy use, for example—thereby making it easy to compare impacts among various products, processes, or activities. The LCA methodology is, however, limited in practical application because it may or may not define or predict actual impacts. Further, it is difficult to define a truly meaningful common basis on which to assess theoretical impacts. Many aspects of environment are affected during a product's life and impact assessment can be biased by choices of which components of the environment are most valued and how those values may change over time. Life cycle assessment must also have clearly defined boundaries because impacts can, in theory, flow almost endlessly upstream and downstream of the actual production process. For example, an energy LCA for aquaculture may include energy costs to procure pelagic fish for reduction to fish meal that will be used in aquafeeds. The energy cost of fishing is primarily embodied in the fuel used by the fishing vessel, but can also include the energy used to manufacture the fishing vessel, to produce the steel and fiberglass used to fabricate the vessel, to produce the nylon used in nets, and so on. One of the greatest challenges of LCA is to set meaningful and consistent boundaries on the analysis.

Perhaps the greatest limitation of LCA is also its greatest strength: LCAs are most useful in describing broad-scale impacts of a collective activity, whereas there is often a need to assess location-specific impacts or environmental performance of a specific facility or set of facilities. One goal of our paper is to present a series of environmental performance indicators that can be applied at any scale. Combining the power of LCA with individual indicators based on specific impacts provides a comprehensive set of tools for assessing environmental performance.

Different species or different production systems for a given species ranked well with respect to some indicators but poorly for others. For example, trout and salmon have a lower FCR and greater efficiency of converting feed protein to fish protein than catfish and tilapia. These beneficial attributes must be weighed against the greater amount of fish meal needed in trout and salmon feed than in catfish and tilapia feed. Cage culture consumes very little water and the water surface area devoted to production is miniscule in comparison to pond aquaculture. The pollution load from cage culture is, however, much greater than for ponds, and the resources for assimilating wastes from cage are outside the culture unit (usually in public water), rather than inherent in the culture system as it is in ponds.

There is little agreement among environmentalists or aquaculture scientists on the importance levels of negative impacts caused by aquaculture. Many may think that the main negative impact is water pollution, others may be concerned over excessive use of fish meal, and a few may be worried more about land use. Furthermore, decisions on resource use do not necessarily have to favor one use over another. For example, large expanses of land are used for catfish aquaculture in the southeastern United States but the soils on which ponds are built are poorly suited for most row crops and their use in aquaculture does not therefore compete directly with other agricultural uses. Thus, we decided not to suggest a method for obtaining an "overall" index of resource use efficiency and waste production by individual species, production methods, or facilities. Those interested in using the indicators can devise an overall index according to the priority that they choose to give to the different possible impacts.

It is possible, as we have done here, to make estimates of resource use and waste production under typical conditions for culture of particular species by different methods. Most of the assumptions were based on findings from research in which culture conditions were controlled as much as possible. Although commercial producers seldom control production conditions to the extent that researchers do, some producers are much more efficient than others. Data should be collected from many facilities in order to document the range of each indicator and to ascertain a "normal" value for each. This information would allow producers voluntarily adopting BMPs to use indicators to evaluate improvements resulting from better practices. Buyers seeking products from sustainable farms could apply the indicators to select farms that use resources efficiently and minimize wastes. The indicators also could be an important feature of aquaculture certification programs. Certified farms could be required to perform above normal with respect to the indicators. However, much of the information required for these indices must be obtained from farms, and producers will likely be hesitant to share this information. Therefore, efforts to initiate a dialogue among producers and other stakeholders related to the importance of these indicators will be necessary.

References

Ammerman, G. R. Processing. **In**: *Channel Catfish Culture*, pp. 569–620 (C. S. Tucker, Ed.). Amsterdam, The Netherlands: Elsevier Science Publishers (1985).

Axler, R. P., C. Tikkanen, J. Henneck, J. Schuldt, and M. E. McDonald. Characteristics of effluent and sludge from two commercial rainbow trout farms in Minnesota. *Prog. Fish-Cult.*, **59**: 161–172 (1997).

Berg, H., P. Michelson, C. Folke, N. Kautsky, and M. Troell. Managing aquaculture for sustainability in tropical Lake Kariba, Zimbabwe. *Ecol. Econ.*, **18**: 141–159 (1996).

Bergheim, A., and A. Brinker. Effluent treatment for flow-through systems and European environmental regulations. *Aquacult. Eng.* **27**: 61–77 (2004).

Beveridge, M. C. M. Cage and pen fish farming, carrying capacity models and environment impact. FAO Fisheries Technical Paper 225, Food and Agriculture Organization of the United Nations, Rome, Italy (1984).

Beveridge, Malcom C. M. *Cage Culture*, 2nd Ed. Oxford: Fishing News Books (1996).

Beveridge, M. C. M., M. J. Phillips, and R. M. Clark. A quantitative and qualitative assessment of wastes from aquatic animal production. **In**: *Water Quality in Aquaculture, Advances in World Aquaculture*, pp. 506–533 (D. E. Brune and J. R. Tomasso, Eds.). Baton Rouge, LA: World Aquaculture Society (1991).

Black, E., R. Gowen, H. Rosenthal, E. Roth, D. Stechy, and F. J. R. Taylor. The costs of eutrophication from salmon farming: implications for policy—A comment. *J Envir. Man.*, **50**: 105–109 (1997).

Boyd, C. E. Hydrology of small experimental fish ponds at Auburn, Alabama. *Trans. Amer. Fish. Soc.*, **111**: 638–644 (1982).

Boyd, C. E. Pond water aeration systems. *Aquacult. Eng.*, **18**: 9–40 (1998).

Boyd, C. E. *Water Quality, an Introduction*. Boston, MA: Kluwer Academic Publishers (2000).

Boyd, C. E. Standardize terminology for low-salinity shrimp culture. *Global Aquacult. Advocate*, **5**(5): 58–59 (2002)

Boyd, C. E. The status of codes of practice in aquaculture. *World Aquacult.*, **34**(2): 63–66 (2003).

Boyd, C. E. Water use in aquaculture. *World Aquacult.*, **36**(3): 12–15 and 70 (2005).

Boyd, C. E. Effluent effects. *Global Aquacult. Advocate*, **9**(3): 62–63 (2006).

Boyd, C. E., and D. Gautier. Effluent composition and water quality standards. *Global Aquacult. Advocate* **3**(5): 61–66 (2000).

Boyd, C. E., and B. Green. Dry matter, ash, and elemental composition of pond-cultured tilapia (*Oreochromis aureus and O.* niloticus). *J. World Aquacult. Soc.*, **29**: 125–128 (1998).

Boyd, C. E., and A. Gross. Biochemical oxygen demand in channel catfish *Ictalurus punctatus* pond waters. *J. World Aquacult. Soc.*, **30**: 349–356 (1999).

Boyd, C. E., and A. Gross. Water use and conservation for inland aquaculture ponds. *Fish. Mgt. Ecol.*, **7**: 55–63 (2000).

Boyd, C. E., and M. Polioudakis. Land use for aquaculture production. *Global Aquacult. Advocate* **9**(2): 64–65 (2006).

Boyd, C. E., and J. Queiroz. Nitrogen and phosphorus loads by system, USEPA should consider system variables in setting new effluent rules. *Global Aquacult. Advocate*, **4**(6): 84–86 (2001).

Boyd, C. E., and D. Teichert-Coddington. Dry matter, ash, and elemental composition of pond-cultured *Penaeus vannamei* and *P. stylirostis*. *J. World Aquacult. Soc.,* **26**: 88–92 (1995).

Boyd, C. E., and C. S. Tucker. Sustainability of channel catfish farming. *World Aquacult.*, **26**: 45–53 (1995).

Boyd, C. E., and C. S. Tucker. *Pond Aquaculture Water Quality Management*. Boston, MA: Kluwer Academic Publishers (1998).

Boyd, C. E., D. E. Jory, and G. W. Chamberlain (Eds.) *Operating Procedures for Shrimp Farming*. St. Louis, MO: Global Aquaculture Alliance (2006).

Boyd, C. E., K. Corpron, E. Bernard, and P. Pensang. Estimates of bottom soil and effluent load of phosphorus at a semi-intensive marine shrimp farm. *J. World Aquacult. Soc.*, **37**: 41–47 (2006).

Boyd, C. E., A. A. McNevin, J. Clay, and H. M. Johnson. Certification issues for some common aquaculture species. *Rev. Fish. Sci.*, **13**: 231–279 (2005).

Boyd, C. E., J. Queiroz, J. Lee, M. Rowan, G. N. Whitis, and A. Gross. Environmental assessment of channel catfish, *Ictalurus punctatus*, farming in Alabama. *J. World Aquacult. Soc.*, **31**(4): 511–544 (2000).

Brummett, R. E. Integrated aquaculture in sub-Saharan Africa. *Environ. Dev. Sustain.*, **1**: 315–321 (1999).

Brune, D. E., G. Schwartz, A. G. Eversole, J. A. Collier, and T. E. Schwedler. Intensification of pond aquaculture and high rate photosynthetic systems. *Aquacult. Eng.*, **28**: 65–86 (2003).

Chamberlain, G. W. Consumers speak, aquaculture responds. *Global Aquacult. Advocate*, **8**(6): 2 (2005).

Chamberlain, G. W. Controversial to inevitable. *Global Aquacult. Advocate*, **9**(2): 2 (2006).

Clay, J. W. Towards sustainable shrimp aquaculture. *World Aquacult.,* **28**(3): 32–37 (1997).

Clay, J. *World Agriculture and the Environment*. Washington, D.C.: Island Press (2004).

Collis, W. J., and R. O. Smitherman. Production of tilapia hybrids with cattle manure or a commercial diet. **In**: *Symposium on the Culture of Exotic Fish*, pp. 43–54 (R. O. Smitherman, W. L. Shelton, and J. H. Grover, Eds.). Bethesda, Maryland: American Fisheries Society (1978).

Cripps, S. J. and A. Bergheim. Solids management and removal for intensive land-based aquaculture production systems. *Aquacult. Eng.*, **22**: 33–56 (2000).

Dierberg, F. E., and W. Kiattisimkul. Issues, impacts, and implications of shrimp aquaculture in Thailand. *Environ. Mgt.*, **20**: 649–666 (1996).

Ellingsen, H., and S. A. Aanondsen. Environmental impacts of wild-caught cod and farmed salmon—A comparison with chicken. *Int. J. Life Cycle Assess.,***1**: 60–65 (2006).

Engle, C. R. and D. Valdarrama. The economics of environmental impacts in the United States. **In:** *Aquaculture and the Environment in the United States*, pp. 240–270 (J. R. Tomasso, Ed.). Baton Rouge, LA: United States Aquaculture Association/World Aquaculture Society (2002).

Federal Register. Effluent limitation guidelines and new source performance standards for the concentrated aquatic animal production point source category: Final rule. Federal Register: August 23, 2004, Volume 69, Number 162, pp. 51892–51930. Office of the Federal Register, National Archives and Records Administration, Washington, D.C. (2004).

Folke, C. Energy economy of salmon aquaculture in the Baltic Sea. *Environ. Manage.*, **12**: 525–537 (1988).

Folke, C., N. Kautsky, and M. Troell. Internalizing environmental costs of salmon farming. Beijer Discussion Paper Series No. 21, Beijer International Institute of Ecological Economics, The Royal Swedish Academy of Sciences, Stockholm, Sweden (1992).

Folke, C., N. Kautsky, H. Berg, A. Jansson, and M. Troell. The ecological footprint concept for sustainable seafood production: A review. *Ecol. Appl.*, **8(1)**: 63–71 (1998).

Gatlin, D. M., III, and R. W. Hardy. Manipulations of diets and feeding to reduce losses of nutrients in intensive aquaculture. **In**: *Aquaculture and the Environment in the United States*, pp. 155–165 (J. R. Tomasso, Ed.). Baton Rouge, LA: United States Aquaculture Association/World Aquaculture Society (2002).

Gomes, F., and C. E. Boyd. Dry matter, ash, and elemental composition of farm-cultured, black tiger prawn *Penaeus monodon*. *World Aquacult.*, **34**(4): 61–63 (2003).

Gross, A., C. E. Boyd, and R. T. Lovell. Phosphorus budgets for channel catfish ponds receiving diets with different phosphorus concentrations. *J. World Aquacult. Soc.*, **29**: 31–39 (1998).

Gross, A., C. E. Boyd, and C. W. Wood. Nitrogen transformations and balance in channel catfish ponds. *Aquacult. Eng.*, **24**: 1–14 (2000).

Hardy, R. W. Problems and opportunities in feed formulation. *Aquacult. Mag.*, **25**(4): 56–60 (1999).

Hardy, R. W. Urban legend: Are we one? *Aquacult. Mag.*, **27**(7): 52–56 (2001).

Hargreaves, J. A., C. S. Tucker, and S. K. Kingsbury. Pattern of discharge and mass loading during drainage of excavated ponds used for foodfish production of channel catfish. *North Amer. J. Aquacult.*, **67**: 79–85 (2005).

Heller, M. C., and G.A. Keoleian. *Life Cycle-Based Sustainability Indicators for Assessment of the U.S. Food System*. Ann Arbor, MI: University of Michigan Center for Sustainable Systems (2000).

Johnsen, F., and A. Wandsvik. The impact of high energy diets on pollution control in the fish farming industry. In: *Nutritional Strategies and Aquaculture Waste, Proceedings of the First International symposium on Nutritional Strategies in Management of Aquaculture Waste*, pp. 51–62 (C. B. Cowey and C. Y. Cho, Eds.). Ontario: University of Guelph (1991).

Johnsen, R. I., O. Grahl-Nelson, and B. T. Lunestad. Environmental distribution of organic waste from a marine fish farm. *Aquacult.* **118**: 229–244 (1993).

Jones, U. S. *Fertilizers and Soil Fertility*. Reston, VA: Reston Publishing Company (1979).

Kautsky, N., H. Berg, C. Folke, J. Larsson, and M. Troell. Ecological footprint for assessment of resource use and development limitations in shrimp and tilapia aquaculture. *Aquacult. Res.*, **28**: 753–766 (1997).

Keenum, M. E., and J. A. Waldrop. Economic analysis of farm-raised catfish production in Mississippi. Mississippi Agricultural and Forestry Experiment Station Technical Bulletin 155, Mississippi State University, MS (1988).

Lin, C. K., P. Ruamthaveesub, and P. Wanuchsoontorn. Integrated culture of the green mussel (*Perna viridis*) in wastewater from an intensive shrimp pond: Concept and practice. *World Aquacult.*, **24**(2): 68–72 (1993).

Liu, K. K. M., F. T. Barrows, R. W. Hardy, and F. M. Dong. Body composition, growth performance, and product quality of rainbow trout (*Oncorhynchus mykiss*) fed diets containing poultry fat, soybean/corn lecithin, and menhaden oil. *Aquacult.*, **238**: 309–328 (2004).

MDEQ (Mississippi Department of Environmental Quality). *Total Maximum Daily Load for Sediment/Siltation and Organic Enrichment/Low Dissolved Oxygen, Wolf Lake, Humphries and Yazoo Counties*. Jackson MS: Office of Pollution Control, Mississippi Department of Environmental Quality (2003).

Naylor, R. L., R. J. Goldburg, H. Mooney, M. Beveridge, J. Clay, C. Folke, N. Kautsky, J. Lubchenco, J. Primavera, and M. Williams. Nature's subsidies to shrimp and salmon farming. *Science*, **282**: 883–884 (1998).

Naylor, R. L., R. J. Goldburg, J. H. Primavera, N. Kautsky, M. C. M. Beveridge, J. Clay, C. Folks, J. Lubchenco, H. Mooney, and M. Troell. Effect of aquaculture on world fish supplies. *Nature*, **405**: 1017–1024 (2000).

Ozbay, G., and C. E. Boyd. Particle size fractions in pond effluents. *World Aquacult.*, **34**(4): 56–59 (2003).

Rees, W. E., and M. Wackernagel. Ecological footprints and appropriated carrying capacity. **In**: *Investing in Natural Capital: The Ecological Economics Approach to Sustainability*, pp. 362–390 (A. M. Jansson, M. Hammer, C. Folke, and R. Costanza, Eds.). Washington, D.C.: Inland Press (1994).

Roth, E., H. Rosenthal, and P. Burbridge. A discussion of the use of the sustainability index: 'Ecological footprint' for aquaculture production. *Aquat. Living Resour.*, **13**: 461–469 (2000).

Ruttanagosrigit, W. Organic matter dynamics in a closed, intensive culture system for black tiger prawn (*Penaeus monodon*). Doctor of Technical Science Dissertation, Asian Institute of Technology, Bangkok, Thailand (1997).

Schmittou, H. R. High density fish culture in low volume cages. American Soybean Association, Singapore Office, Singapore (1993).

Schwartz, M. F., and C. E. Boyd. Channel catfish pond effluents. *Prog. Fish-Cult.*, **56**: 273–281 (1994a).

Schwartz, M., and C. E. Boyd. Effluent quality during harvest of channel catfish from watershed ponds. *Prog. Fish-Cult.*, 56: 25–32 (1994b).

Seafood Choices Alliance. Growing appetites and shrinking seas. Washington, D.C.: Seafood Choices Alliance (2003).

Shearer, K. D., T. Asgard, G. Andorsdottir, and G. H. Aas. Whole body elemental and proximate composition of Atlantic salmon (*Salmo salar*) during the life cycle. *J. Fish Bio.*, **44**: 785–797 (1994).

Sugiura, S. H., and R. W. Hardy. Environmentally friendly feeds. **In**: *Encyclopedia of Aquaculture*, pp. 299–310 (R. R. Stickney, Ed.). New York: John Wiley and Sons (2000).

Tacon, A. G. J., M. R. Hasan, and R. P. Subasinghe. Use of fishery resources as feed inputs for aquaculture development: trends and policy implications. FAO Fisheries Circular. No. 1018 Rome: FAO (2006).

Tchobanoglous, G., F. L. Burton, and H. D. Stensel. *Wastewater Engineering*, 4th ed. New York: McGraw Hill (2003).

Thunjai, T., C. E. Boyd, and M. Boonyaratpalin. Quality of liming materials used in aquaculture in Thailand. *Aquacult. Int.*, **12**: 161–168 (2004).

Timmons, M. B., J. M. Ebeling, F. W. Wheaton, S. T. Summerfelt, and B. J. Vinci. *Recirculating Aquaculture Systems*. Ithaca, NY: Cayuga Aquaculture Ventures (2001).

Tookwinas, S. Environmental impact assessment for intensive marine shrimp farming in Thailand. *Thai Fish. Gazette*, **48**: 119–133 (1996).

Troell, M., P. Tyedmers, N. Kautsky, and P. Rönnbäck. Aquaculture and energy use. **In:** *Encyclopedia of Energy*, pp. 97–108 (C. Cleveland, Ed.). Amsterdam: Elsevier (2004).

Tucker, C. S., S. W. Kingsbury, J. W. Pote, and C. W. Wax. Effects of water management practices on discharge of nutrients and organic matter from channel catfish ponds. *Aquaculture*, **147**: 57–69 (1996).

Tyedmers, P. Fisheries and energy use. **In:** *Encyclopedia of Energy*, pp. 683–693 (C. Cleveland, Ed.). Amsterdam: Elsevier (2004).

United States Department of Agriculture. Agricultural Statistics. Washington, D.C.: U.S. Government Printing Office (2004).

Wetzel, R. G. *Limnology*, 3rd ed. San Diego, CA: Academic Press (2001).

Yoo, K. H., and C. E. Boyd. *Hydrology and Water Supply for Aquaculture*. New York: Chapman and Hall (1994).