Aquaculture Production and Biodiversity Conservation

JAMES S. DIANA

This overview examines the status and trends of seafood production, and the positive and negative impacts of aquaculture on biodiversity conservation. Capture fisheries have been stabilized at about 90 million metric tons since the late 1980s, whereas aquaculture increased from 12 metric tons in 1985 to 45 metric tons by 2004. Aquaculture includes species at any trophic level that are grown for domestic consumption or export. Aquaculture has some positive impacts on biodiversity; for example, cultured seafood can reduce pressure on overexploited wild stocks, stocked organisms may enhance depleted stocks, aquaculture often boosts natural production and species diversity, and employment in aquaculture may replace more destructive resource uses. On the negative side, species that escape from aquaculture can become invasive in areas where they are nonnative, effluents from aquaculture can cause eutrophication, ecologically sensitive land may be converted for aquaculture use, aquaculture species may consume increasingly scarce fish meal, and aquaculture species may transmit diseases to wild fish. Most likely, aquaculture will continue to grow at significant rates through 2025, and will remain the most rapidly increasing food production system.

Keywords: fish meal, invasive species, eutrophication, fishery harvests, food production

The human population is rising dramatically, reaching 6 billion in 2000 and 6.63 billion in 2007. The highest rates of population growth occur in some developing countries, where the standard of living for many people is very low. A major challenge is not only to adequately feed the burgeoning population of the world but also to improve the quality of life for those people living in poverty. To meet that challenge requires improvements in food security and in the economic status of many developing countries. One option for such development is to use and improve current indigenous systems for local food production and export; another is to import technology from industrial countries to drive a new economy. Most industrial countries have achieved their high standard of living by very high consumptive demands on resources, and those demands are probably not sustainable for those countries, let alone for additional countries seeking to achieve a similar standard by the same methods (UN 1992). As a result, the development of indigenous food production systems for local consumption as well as for export should be a priority means for achieving higher living standards in many countries. The purpose of this article is to review aquaculture, including its role as an indigenous food production system and its influences on natural biodiversity. Because there are large discrepancies in methods employed in aquaculture, and in the species farmed throughout the world, I will also focus on local differences in these production systems.

Fishery products are important for local food production in developing countries, as 72.4% of all capture harvest (by mass, including only animals) and 92.3% of all culture harvest occurs in developing countries. Production in capture fisheries has become relatively stable over recent years, whereas aquaculture—the farming of aquatic organisms, including fish, mollusks, crustaceans, and aquatic plants—is the fastest-growing food production system globally, with an increase in production of animal crops of about 9.3% per year since 1985 (Diana 1993, FAO 2005). Both aquaculture and capture fisheries have caused much public concern about their sustainability and influence on the environment (Goldburg and Triplett 1997). In response to such concerns, several systems have been developed to rate the sustainability of wild-caught seafood and aquaculture products; among them are Seafood Watch (Monterey Bay Aquarium 2006), SeaChoice (2008), and *Guide to Ocean Friendly Seafood* (Blue Ocean Institute 2007). These ratings use red, yellow, or green colors to indicate seafood that should be avoided, bought with caution, or freely purchased to promote sustainability. Their ratings list the majority (56% to 70%) of capture types (species, locations, and methods) as green or yellow choices, based mainly on ecological criteria. Different methodologies are used to rate wild and farmed seafood. Each rating system takes into account accepted ideas about environmentally sound practices, but there is no clear way to combine the various metrics objectively or to set breakpoints between farmed and wild seafood,

which makes determining the equivalence of farmed and wild seafood somewhat subjective. Also, farmed seafood is generally a minor component of all rated seafood (< 20% of the types listed), and the ratings often ignore basic social-equity questions, such as the economic impact of farming or fishing on local peoples.

Aquaculture systems mirror agriculture in that some aquaculture operations convert land into ponds to grow aquatic organisms, just as land is converted to grow row crops in agriculture. Aquaculture also uses cages and other sorts of containment systems to grow fish in natural water bodies, a practice that is akin to feedlots or concentrated animal feeding operations. Although total conversion of land would be problematic, far less land has been converted for aquaculture than has been for agriculture. Some aquaculture practices are harmful to biodiversity (e.g., see Goldburg and Triplett 1997), and environmental groups have cited this potential damage as reason to call for reductions or even elimination of some types of aquaculture. Some of these claims arise because it is difficult to compare the impacts of aquaculture with impacts from other land or water uses. It is also difficult to compare the sustainability of seafood (farmed or caught) with traditional agriculture commodities. No food production system now in use is truly sustainable from an energy and biodiversity perspective—all food production systems generate wastes, require energy, use water, and change land cover. Food production systems also promote economic activity. This economic activity is very important in developing countries, where aquaculture may replace more damaging income-generating activities by poor farmers (Rönnbäck et al. 2002).

In the literature, aquaculture is most commonly assessed by examining its impacts on natural ecosystems, rather than by comparing aquaculture's impacts with those of other methods of food production (Flaherty and Karnjanakesorn 1995, Monterey Bay Aquarium 2006). A more comprehensive approach would compare aquaculture with terrestrial agriculture systems; doing so is necessary to understand what constitutes environmentally friendly seafood production and to promote conservation practices while still producing food. Some authors have used life-cycle assessment (LCA) as one quantitative method for such comparisons (Mungkung et al. 2006), but to date such assessments have not included the impacts of species decline caused by a fishery or of nonnative species' escape from aquaculture. LCA methodology, including calculations of costs, greenhouse gas emissions, and eutrophication potential, is nonetheless closer than any other available methodology to being an appropriate quantitative method for comparison of food production systems (Mungkung et al. 2006).

Historical and future trends for fisheries and aquaculture

Aquaculture is the fastest-growing food production system globally, with an 8.8% increase in production of animal crops per year since 1985 (FAO 2007). It fulfills a major role in feeding people today, and its potential for doing so in the future

is large. Since natural fisheries rely on wild stocks, which are often overexploited, aquaculture can either exacerbate this overexploitation through damages to natural ecosystems (Naylor et al. 2000) or reduce it by alleviating pressure on wild fish stocks (Stotz 2000). Aquaculture is a relatively new industry (at least in North America) with significant potential for innovation. Most species that are grown are not much different from their wild counterparts, nor have they been domesticated to a great extent (Hulata 2001). Aquaculture innovation produces a higher capital return to the farmer than traditional farming practices do, and such innovation can also be a natural way of managing aquaculture production to become more sustainable.

The International Food Policy Research Institute (Delgado et al. 2003) forecasts that the annual increase in seafood consumption will be about 1.5 kilograms (kg) per person in 2020, which would make the demand for seafood products considerably higher than it is now—more than 10 million metric tons of additional seafood would be consumed each year (assuming no increase in the human population). Over this same time, harvest from natural fish stocks will probably remain static or decline (Wijkstrom 2003, FAO 2007). In the United States alone, the projected per-person increase in consumption should lead to a total increase of 1.5 million to 2 million metric tons by 2020. To avoid further damage to natural fish stocks, nearly all of this increase must come from aquaculture.

Import demands by the United States and other industrial nations make seafood exports a major contributor to the economy of many developing countries. In 2001, seafood exports valued at $56 billion (FAO 2005) generated more money for developing countries ($28.1 billion) than did exports of coffee ($5.1 billion), tea ($2.4 billion), bananas ($2.9 billion), rice ($4.5 billion), and meat ($12.9 billion) combined (FAO 2005). By 2004, the value of total seafood exports had grown to $71.5 billion; at least 43% of those exports, by weight, came from aquaculture. Despite the high export value of fish crops, about 75% of all seafood harvested by developing countries was consumed locally rather than exported. All of these factors indicate that aquaculture has a role in future food production. Judging from the current growth of the aquaculture industry, human needs for future growth, local consumers' nutritional health, and the economic benefits that developing nations derive from aquaculture, that role will be a significant one.

Aquaculture, as noted earlier, is the controlled growing of some type of aquatic crop, mainly for food. The crop can vary from aquatic plants to invertebrates, reptiles, or fishes. The level of control over production can vary from managing only a portion of the life cycle to managing the complete life cycle by producing seed (e.g., fish fry) in a hatchery and using the fry to grow adults that can be harvested or used as brood stock. Extensive aquaculture is practiced when aquatic organisms are placed into an appropriate environment in which they can grow and be left unattended for a time before being harvested. In semi-intensive aquaculture, fertilizers may be added

to increase the natural production of a water system, and water quality may also be manipulated by flushing new water into the system or by using aerators to increase the rate of growth for the organism being produced. Intensive aquaculture is practiced using regular aeration and adding new water, full feed, and chemical supplements, in various combinations, to promote the health of organisms grown at very high density. As the level of farming intensity accelerates, the production per unit area increases dramatically, although often the feed-conversion efficiency decreases, costs rise, and more waste is discharged.

Capture production has stabilized at about 90 million metric tons of fish since the late 1980s, while aquaculture has increased from about 12 million metric tons in 1985 to about 45 million metric tons in 2004 (yields do not include aquatic plants and will be tabulated similarly throughout this article) (figure 1; Wijkstrom 2003, FAO 2005). The accuracy of reporting on fish harvests from China, the major fishing and aquaculture country in the world, has been questioned (Watson and Pauly 2001). The capture statistics are most likely overestimates, but for this analysis I will nonetheless use data from the Food and Agriculture Organization. Increasing aquaculture production now results in about one-third of all aquatic harvest by weight. Also, up to one-fourth of seafood harvested from the wild is used in fish meal or other products, not for human consumption (FAO 2007). Predictions are that capture fisheries' production will remain at about the current yield of 90 million metric tons, while aquaculture's production should continue to increase (Delgado et al. 2003), although at a rate lower than 8.8% annually through 2025. Although the total production of capture fisheries has stabilized, the composition of captured species and the trophic level of the catch remain in a state of flux, raising questions about the sustainability of capture fisheries (Delgado et al. 2003, Wijkstrom 2003).
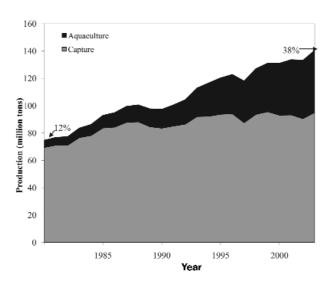
Both capture fisheries and aquaculture generate large yields of certain species. The top 24 species harvested each yield more than 1 million metric tons per year (figure 2). Of these species, 14 are produced mainly by aquaculture, and 10 solely by capture fisheries. The most commonly harvested fish in the world today is anchoveta (*Engraulis ringens*), which has had a dynamic history of overharvest and fluctuating production. The next largest group includes carps, grown in aquaculture throughout Asia. A number of invertebrates, including oysters and clams, are also among the top 24. Four of the top species in capture fisheries today are used for fish meal production: anchoveta, Japanese anchovy (*Engraulis japonicus*), chub mackerel (*Scomber japonicus*), and Chilean jack mackerel (*Trachurus murphyi*), whereas all of the 14 aquaculture species—2 plant species, 9 lower-trophic-level species, and 2 carnivorous species—are used for human consumption.

As figure 2 indicates, production of any species tends to occur through either aquaculture or capture fisheries, and rarely are both important in the overall production of a single species. This may be caused by competition between these two sources, because a caught fish can commonly be sold at a relatively low price, but cannot be cultured at this low price for a profit. As capture fisheries decline because of overharvesting, the prices of target species often increase dramatically. Under these conditions, aquaculture can thrive, thereby further reducing the value of that capture fishery. For some seafood, consumers tend to prefer a particular species, such as beluga sturgeon caviar, blue crabs, and Maine lobster, whereas for other products, larger groups of species are the target for consumption, such as shrimp, oysters, and salmon. If one evaluates these larger groups of organisms (salmon, shrimp, scallops, oysters, and carp for the major cultured groups in figure 2), the replacement picture is less clear. In 1950, all of these groups of animals were common capture fisheries. However,

Figure 1. Production, in millions of metric tons, for aquatic animals from capture fisheries and aquaculture from 1980 to 2004. Source: FAO (2005).
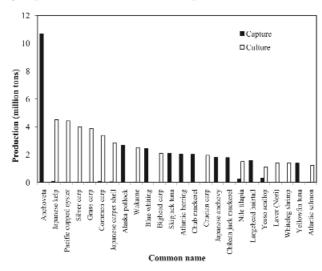

Figure 2. Production, in millions of metric tons, in 2004 for the top 24 aquatic animal species harvested. The source of this harvest is either aquaculture (open bars) or wild capture (closed bars). Production values for mollusks are shell-on weight. Source: FAO (2005).

by 2005, all except shrimp more commonly came from aquaculture, but both types of production continued. Thus, neither species nor group analysis provides a complete picture of seafood market dynamics.

In contrast to the situation with wild fisheries, the trend in aquaculture is toward increasing production. About 62% of all animals grown in aquaculture are finfish, 30% are mollusks, and 8% are crustaceans (FAO 2005). Of the fishes currently grown worldwide, about 40% are carps and about 4% are salmon or tilapia (FAO 2007). Between 1980 and 2000, aquaculture grew on all continents, although the majority of production—over 75% of all aquaculture harvest in 2004—occurred in Asia (figure 3). North America, South America, and Europe have increased production levels, although their absolute yields, in comparison with Asia, indicate that further increases could occur. Yields of Nile tilapia (*Oreochromis niloticus*), Atlantic salmon (*Salmo salar*), and tiger shrimp (*Penaeus monodon*) grew a great deal between 1970 and 2000 (figure 4). Most changes have been exponential, although tiger shrimp production declined in the late 1990s as a result of viral infestation and other diseases (World Bank et al. 2002). As disease outbreaks occurred among tiger shrimp, many countries switched from farming tiger shrimp to white shrimp (*Litopenaeus vannamei*), for which disease-resistant stocks have been developed. Disease outbreaks in shrimp have occurred as a consequence of overintensification, which has repeatedly caused major difficulties in the shrimp farming industry (Boyd and Clay 1998).

The effects of aquaculture on biodiversity

Unfortunately, the aquatic fauna of the United States is at high risk of extinction; up to 70% of all freshwater mussels, 49% of freshwater fishes, 30% of plants, and 20% of mammals and birds are in an imperiled state (Master et al. 1998). Global rates are similar for those groups (MEA 2005). Many evaluations have demonstrated that exotic species, habitat loss,
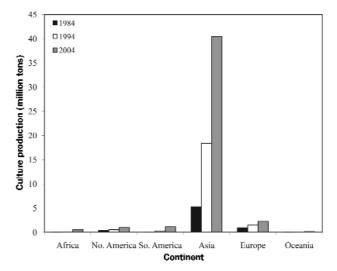
pollution, and exploitation explain most of the animal extinctions that have occurred (Wilcove et al. 1998). Therefore, it is important to evaluate not only species at risk but also the distribution of exotic species to understand future trends in aquatic biodiversity. Rahel (2000) evaluated the change in the number of shared fish species between each US state from the time of presettlement to the present. Local extirpations occurred 196 times throughout the United States, and no states had more than 7 extirpations. In contrast, introductions of exotic species had occurred about 900 times, and in some states, up to 50 new species were introduced. Both introductions and local extinctions have caused the fish fauna of neighboring states to become similar; introductions seem to be more important than extinctions as a cause of homogenization (Rahel 2000). The studies above have focused on US freshwaters because knowledge of the fish population trends is more complete there; however, marine systems everywhere face similar problems with homogenization (Stachowicz et al. 1999), and other countries very likely mirror the United States in biodiversity trends.

Certification of environmentally friendly aquaculture systems has been proposed as a means to enforce safe practices in aquaculture (Clay 1997, New 2003). In a review of aquaculture issues that certification should address, Boyd and colleagues (2005) evaluated a variety of species groups and environmental impacts, focusing on negative influences that certification programs should try to reduce (table 1). The potential environmental impacts of common aquaculture systems for many species were rated medium or high, although not all of the negative influences would affect biodiversity (Boyd et al. 2005). No objective method to quantitatively compare and rank the effects of aquaculture on biodiversity currently exists. Also, most impacts have both positive and negative components or trends as a result of the variety in aquaculture systems and improvements in management. My ranking, based on the literature as well as

Figure 3. Culture production, in millions of metric tons, in 1984, 1994, and 2004 for each continent. Source: FAO (2005).
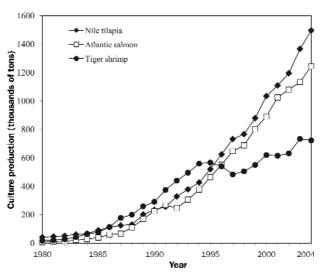

Figure 4. Trends in culture production, in thousands of metric tons, from 1980 to 2004, for Nile tilapia, Atlantic salmon, and giant tiger shrimp. Source: FAO (2005).

Table 1. Certification issues for various aquaculture species and the level of concern expressed about them.

Issue	Tuna	Shrimp	Salmon	Trout	Catfish	Tilapia	Abalone	Scallops	Oysters	Clams	Mussels
					Species or species group						
Antibiotic use	M	H	H	H	M	M	M	–	–	–	–
Benthic biodiversity	H	M	M	M	–	M	–	M	M	M	M
Chemical use	M	H	M	H	H	–	M	–	M	M	–
Disease transfer	H	H	H	–	–	–	M	–	H	–	–
Escapees/invasive	H	M	H	–	–	H	M	–	H	–	–
Genetic alteration	–	–	H	H	H	H	–	M	H	–	M
Land and water use	–	H	–	H	H	H	M	M	M	M	M
Removal of dead fish	–	–	M	M	H	H	–	–	–	–	–
Fish meal/oil use	H	H	H	H	M	M	M	–	–	–	–
Water pollution	H	H	M	H	M	H	–	–	–	–	–
Predator control	–	M	M	H	H	H	H	H	H	H	H
User conflicts	M	H	M	–	–	M	–	M	M	M	M

H, high level of concern; M, medium level of concern.
Note: The level of concern was derived from focus group and published evaluations (from Boyd et al. 2005).

on trends in aquatic biodiversity, would list the following negative effects in order of decreasing importance as threats to biodiversity:

1. Escapement of aquatic crops and their potential hazard as invasive species.

2. The relationships among effluents, eutrophication of water bodies, and changes in the fauna of receiving waters.

3. Conversion of sensitive land areas such as mangroves and wetlands, as well as water use.

4. Other resource use, such as fish meal and its concomitant overexploitation of fish stocks.

5. Disease or parasite transfer from captive to wild stocks.

6. Genetic alteration of existing stocks from escaped hatchery products.

7. Predator mortality caused by, for example, killing birds near aquaculture facilities.

8. Antibiotic and hormone use, which may influence aquatic species near aquaculture facilities.

The first five, which I examine more closely below, have by far the most important effects on biodiversity. Escapement issues include both establishment of invasive species and changes in the genetic diversity of wild fish, so both of these (numbers 1 and 6) will be covered together.

Escapement and genetic alterations of wild stocks. Probably the most important aspect of aquaculture as an influence on biodiversity is the negative impact of introducing new species or modified genotypes. General attributes of successful invasive species include characteristics such as a widely distributed original range, a broad environmental tolerance, high genetic variability, short generation time, rapid growth, and early sexual maturation (Ricciardi and Rasmussen 1998). Virtually all of these characteristics are traits favored for species used in aquaculture, so the potential of many aquaculture species to become invasive is high.

Tilapia is the most-cited example of the negative impacts of aquaculture, because tilapia has invaded all continents, displacing many native species. Although it is difficult to gain objective data on the causes of most introductions, more than half of the documented introductions of tilapia were not the result of commercial aquaculture but of intentional stocking of tilapia in natural waters by governmental entities (Canonico et al. 2005). Introductions of many other species of fish arise from the release of aquarium pets into natural waters; such releases are not the result of aquaculture. Indeed, most introductions of invasive fishes have not been the result of aquaculture, although aquaculture has played a role. Details on exotic species in the Laurentian Great Lakes bear out this conclusion (Mills et al. 1994, Canonico et al. 2005), as only one of the exotic fish species introduced there was the result of aquaculture in the region. Moreover, the highly controversial expansion of grass carp (*Ctenopharyngodon idella*) and other Asian carps to North America started when government laboratories began culturing and using them for biocontrol purposes, not for commercial aquaculture (Mitchell and Kelly 2006).

The negative genetic effects of domesticated species released from aquaculture systems within their native range are constrained somewhat by the nature of aquaculture itself. Most species grown in aquaculture are essentially wild, but some have been selectively bred for earlier maturation, faster growth, or other characteristics (Hulata 2001). Some species have been modified by hybridization or polyploidy to produce infertile individuals to culture (Hulata 2001). While permanent infertility would eliminate genetic issues for escapees, there would still be concerns about competition between native and cultured species (Naylor et al. 2005), although the number of escapees would not expand after escape. There are also concerns about the permanence of infertility caused by hybridization. A few species, such as Atlantic salmon, do have genetically modified types developed for higher growth rates, but to date none of these has been commercially cultured. The genetic composition of most species in aquaculture resembles that of the same species in the wild, although

domestication rates (even unintentional ones) may be quite rapid in fish (Duarte et al. 2007).

Escapement from aquaculture is almost inevitable in all but the most biosecure aquaculture systems: fish escape from holes in cages or when ponds are drained for harvesting, and through other cultural practices. The best way to avoid the negative impacts of invasive species is to not culture species outside their native or common range. This last point can be debated, in that current ranges may not be the native range for some species that have become widely distributed, so much so that apprehension about their introduction as an invasive species is past. Adding to the complexity of this issue, in naturalized ranges there may still be negative genetic interactions between naturalized and cultured fishes (Miller et al. 2004).

Effluents' effects on water quality. The second major negative impact of aquaculture on biodiversity has to do with effluents from aquaculture systems and pollution of receiving waters. This has been a common concern, particularly in cage and pen culture for salmon (Goldburg and Naylor 2005). Humans rely on the assimilative capacity of waters as an essential ecosystem service; we treat wastes and discharge them into water with the intent that the water will assimilate them into primary or secondary production. Aquaculture and agriculture are no different in that wastes from both enterprises can be assimilated by natural systems. The magnitude of aquaculture wastes can be quite large, so the potential impact of these wastes is an important consideration.

The waters in which wastes from cage or pond culture are placed have a large influence on the impact of those wastes. Studies have shown that in more oligotrophic marine waters, aquaculture effluents increase local biodiversity. For example, a study of 43 Chilean fish farms found negative effects on benthic invertebrates in the fallout zone (Soto and Norambuena 2004); in contrast, diversity and production of pelagic fishes in the surrounding waters increased. Similarly, Machias and colleagues (2004, 2005) showed an increase in both pelagic and benthic fish diversity and production in areas around Aegean fish farms. However, greater species richness does not always mean improved biodiversity, as globally or locally invasive species could be responsible for the increased richness (Scott and Helfman 2001). These studies (Machias et al. 2004, 2005, Scott and Helfman 2001) concerned waters of relatively low nutrient content, and they incorporated farms at a level below the assimilative capacity of water. Clearly, high densities of cages and high numbers of fish in cages could produce situations in which the assimilative capacity of water is exceeded by the demands of aquaculture (Beveridge et al. 1997).

In contrast with marine cage culture, freshwater systems have had much more difficulty with nutrient loading (Islam 2005). More people have access to these freshwaters, and governments often fail to limit growth in the inexpensive cage systems that can be used there. Also, the smaller size of most freshwater systems limits their ability to assimilate waste. Abery and colleagues (2005) documented a typical example for Indonesian reservoirs. Early cage culture was promoted as an alternative livelihood for rural poor people, but as the venture became successful, more cages were introduced and the freshwater's carrying capacity was exceeded. The resultant decline in water quality and widespread fish kills due to turnover of anoxic water damaged culture yields. Many other examples of such overuse result from the lack of suitable data to provide loading guidelines, as well as from the lack of effective regulations or enforcement (Costa-Pierce 1998, Islam 2005).

A decline in water quality can also result from intensive fish culture in ponds when the crop grows and food is added at high rates. The water then needs to be exchanged to improve the quality of the pond water, and in the exchange the receiving waters gain nutrients and waste products, and the biochemical oxygen demand rises (Jones et al. 2001, Islam 2005). Many current studies are evaluating ways to remediate the nitrogen, phosphorous, and particulate loading of natural waters by aquaculture systems, but many aquaculture systems, especially in developing countries, still discharge untreated water (Boyd 2003). Common treatment options for pond effluents include the use of settling ponds to sequester particulates, oysters to remove suspended materials from water before its discharge, and seaweed or other plants to act as biofilters to remove excess nutrients. This problem of eutrophication is mainly a by-product of intensive fish production, rather than extensive or semi-intensive systems (Beveridge et al. 1997). In most cases, water discharged from ponds is of much lower quality than the receiving waters, although in some cases, its quality is higher as a result of remediation treatments during aquaculture processes.

Pollution of local waters that supply aquaculture systems threatens aquaculture itself as well as biodiversity. Obviously, poor water quality stimulates poor fish growth and production, and discharge waters from one facility often serve as supply waters for downstream culture facilities. When intensive culture was first expanded, pollution problems were common. Early feeding was often ineffective, with feed conversion rates (kg of feed, usually dry, per wet kg of fish produced) of five or higher, indicating high wastage by fish not consuming feeds (Wu 1995). Similarly, the protein level and phosphorous content of feed were often much higher than necessary (Green et al. 2002). More effective feeds and feeding systems have been developed (Cho and Bureau 2001) to address these problems, which cost money as well as cause pollution. It is rare today for a well-developed intensive culture system to have a feed conversion rate exceeding 1.3, and low-protein, low-phosphate feeds are commonly used. Islam (2005) produced a model of effluent loading from freshwater cage culture and showed that a feed conversion rate of 1 to 1.3 resulted in minimal effluent discharge. Nutrient loading still occurs, but its cause is more often too many cages or ponds rather than poor feeding practices (Islam 2005).

Conversion of sensitive land. The third major negative impact on biodiversity is land-use change associated with aqua-

culture. The perceived negative impact of shrimp aquaculture, in particular, has received much attention (Boyd and Clay 1998); some environmental groups have even proposed that cultured shrimp products be boycotted. One of the major objections to shrimp culturing is that mangroves are cleared to make way for pond facilities. Also, land is cleared and saltwater brought inland, resulting in the salinization of soils. As the intensity of shrimp production is stepped up, disease outbreaks and other conditions cause some aquaculture systems to fail. After ponds fail, they may be abandoned, and the altered land cannot be returned to normal productive processes because of soil salinization. This abandonment of shrimp ponds and conversion of mangrove forests into abandoned land is another of the major concerns about shrimp aquaculture (World Bank et al. 2002).

In spite of these concerns, shrimp culture production has burgeoned, from a total of about 72,000 metric tons in 1980 to 2.5 million metric tons today. The growth in production has occurred in many parts of the world, in particular in China, Thailand, Vietnam, Indonesia, and India. Mangrove losses have been substantial—the best estimates are that 33% of all mangroves that once existed are gone today (Alongi 2002). Coastal development, which includes urbanization, agriculture, and pond shrimp aquaculture as well as the pond culture of other species, has caused these large losses. Aquaculture has been responsible for a share of mangrove loss, but aquaculture operations have also been set up in areas where forests have already been cleared (New 2003). Boyd and Clay (1998) estimate that shrimp farming is responsible for less than 10% of the global loss of mangroves because the total area of shrimp ponds globally is small. New, intensive pond systems need to be fully drained to harvest the shrimp, so they are commonly placed above the high-tide elevation, which is also beyond mangrove forest areas (Menasveta 1997).

The other common land-use stigma attached to shrimp aquaculture is abandonment of shrimp ponds (Boyd and Clay 1998). Some studies have linked the overproduction cycle mentioned previously with the abandonment of damaged shrimp ponds, the lack of land conversion options, and a net loss of productive land (Naylor et al. 1998). However, in a study of Thai fishponds, Clark (2003) found there was a cycle of pond use. Ponds were used for shrimp culture when the market was good, but when the market became bad, ponds were left fallow or converted to other uses. In some cases, they were used to grow other fish species; in others, they were converted to land crops, left as salt pans, or held fallow and returned to shrimp culture when the market improved. Most of the empty ponds (87%) in the study (Clark 2003) thus were not abandoned but were in use for other purposes or being held for the future.

Inefficient resource use. The fourth negative impact is the use of fish meal and fish oil in prepared feeds. About 28.3 million metric tons of seafood harvested in 2003, including 5.2 million metric tons of fish meal, were used for purposes other than human consumption (Tacon et al. 2006). About 46% of this

fish meal and about 81% of the fish oil produced in 2002 went into aquaculture (Tacon et al. 2006). Given the current rates of aquaculture growth and the rising importance of intensive aquaculture, forecasts are for even higher demands for fish meal (Delgado et al. 2003). For example, salmon aquaculture used 10.3% of fish meal production in 2003, and shrimp aquaculture used 12.1% (Tacon et al. 2006). Fish meal is a limited resource, however, and most fish stocks are already overexploited (Delgado et al. 2003). Because fish meal is composed of many captured species, overexploitation results in declining biodiversity. Fish meal commonly comes from small pelagic species of fish, whose harvest can also reduce food for production for larger predatory fishes at sea. For these reasons, the use of fish meal in aquaculture must be considered a negative impact of the industry (Naylor et al. 2000).

Overall, the use of fish meal in aquaculture is becoming a major impediment to future production in intensive systems because of the expense of the feed and its limited availability for future expansion. Feeds are currently produced using the components of the fish carcass that are not used for human consumption (by-products) to substitute for fish meal, with good success (Bergheim et al. 2003). In Norway alone, the volume of by-products was estimated at 372,000 metric tons in 1999, so this resource may supply considerable material for future aquaculture feeds (Bergheim et al. 2003). Other sources of protein will become important components of fish feed, including plant protein and waste products from other operations, as will the culture of more species at lower trophic levels for human consumption, since these species do not require fish protein in feed. Alternate feed derivations have been a major subject of aquaculture research and development, and efforts are intensifying (Watanabe 2002, Opstvedt et al. 2003). Moreover, aquaculture is not the only user of fish meal; 47% of all fish meal used in 2002 went to intensive livestock feeding, and the pet food industry is also a competitor for fish meal (about 7%; Tacon et al. 2006). Fish meal is well established in the animal feed business, and elimination of fish meal from aquaculture feeds does not remove it from other uses. Reducing the pressure on species used in fish meal production will take a comprehensive effort in all areas of animal feed production.

Disease or parasite transfer from captive to wild stocks. The final negative impact of aquaculture covered in this article is the transmission of diseases or parasites from farmed animals to wild fish stocks. These problems, combined with concerns about antibiotic resistance that could develop from use of antibiotics in culture, have been suspected for a long time but not substantiated. Recently, papers by Krkosek and colleagues (2006a, 2007) have provided modeling and empirical results to support transmission of sea lice from captive to wild salmon, and to predict that the transmission causes major mortality of infected wild fish. These studies have led to further field studies and models predicting collapse of other salmon stocks as well (Ford and Myers 2008). In fact, Krkosek and colleagues (2007) stated: "If outbreaks continue, then

local extinction is certain, and a 99% collapse in pink salmon abundance is expected in four salmon generations." This predication was focused on pink salmon stocks in central British Columbia, and given the obligate two-year life cycle of pink salmon, anticipated local extinction would occur in eight years (by 2015). The dire nature of these predictions has resulted in broad coverage of the sea lice–salmon issue in the popular press.

Predictions of imminent extinction for pink salmon in the Broughton Archipelago of British Columbia conflict greatly with previous modeling and empirical evidence (Brooks and Jones 2008). Strong criticism of these studies has been generated on both sides of the debate. Krkosek and colleagues (2006b) rebutted the previous studies of Brooks (2005) on salmon and lice interactions, and Brooks and Jones (2008) recently published evidence questioning the extinction hypotheses. The issue is far from settled, with well-respected scientists lining up on both sides of the debate.

The heated arguments generated in this debate caused concerns about the validity of general conclusions from these studies. It does appear likely that the incidence of sea lice in pink salmon is growing as a result of the rearing of Atlantic salmon in cages along the migratory route. The magnitude of infestation, as well as the effects on salmon mortality, remains controversial. However, evidence from several sources, as well as adherence to the precautionary principle, indicates that we should remain cautious about the impact of aquaculture on disease and parasite transfer. As more studies are completed, it is likely that other parasitic or disease interactions will also be detected.

Presenting aquaculture as entirely negative is biased, as some effects of aquaculture on biodiversity may be positive. For example:

- Production of fish can reduce pressure on wild stocks, which may already be overexploited.

- Stocking organisms from aquaculture systems may help to enhance depleted stocks with limited reproductive success.

- Effluents and waste from aquaculture can increase local production, abundance, and diversity of species.

- Destructive land-use patterns, such as slash-and-burn agriculture, may be replaced by more sustainable patterns, such as aquaculture in ponds, which also may generate income, reduce poverty, and improve human health.

The substitution of aquaculture fish for harvested fish in the market can reduce pressure on some natural stocks, yielding a benefit to biodiversity. Naylor and colleagues (2000), on the basis of a literature review, indicated that there was no evidence of aquaculture production restoring natural stocks, and limited evidence of market replacement. However, aquaculture production of Atlantic salmon has increased dramatically, from almost none in 1960 to 1.2 million metric tons in 2005. Historically, Atlantic salmon was a capture fishery producing up to 16,000 metric tons per year; the peak harvest occurred

in 1990 (figure 5), but by then many populations had declined dramatically (Fay et al. 2006). Now, cultured salmon have largely replaced captured salmon in the market (figure 5), which has brought down the market price of Atlantic salmon, allowed cultured products to be substituted for captured ones, and apparently contributed to the rebound of some local fish stocks. This rebound has occurred after many interventions, including intentional restocking of natural populations with hatchery-reared fish, breeding by escaped fish from aquaculture systems, reduced demand for wild stocks because of their declining market value, and reductions in harvests due to many management interventions. Still, many stocks of Atlantic salmon remain critically depressed in abundance (Fay et al. 2006). While aquaculture may be helping to reduce pressure on natural Atlantic salmon stocks, the culture of all species of salmon has also increased dramatically in recent years, whereas the harvest of wild salmon has stabilized but not declined as dramatically as that for Atlantic salmon.

Data on market substitution, similar to those shown in figure 5, are available for 10 other species listed in figure 2 that are produced mainly through aquaculture. Of these, 5 species show trends similar to those in figure 5, and 5 species show increases in both capture and culture harvests, indicating that replacement may have occurred in about half of these cases, while in the other half, harvest continues at the same rate. Although replacement of captured with cultured fish in the market indicates market substitution, much more detailed work is necessary to definitively tie this replacement to recovery of wild populations.

Stocking of fish and other aquatic species to supplement declining natural populations is a common management practice. Atlantic salmon introduced through both intentional stocking and aquaculture escapement have influenced the genetic structure of salmon stocks (Fleming et al. 2000).
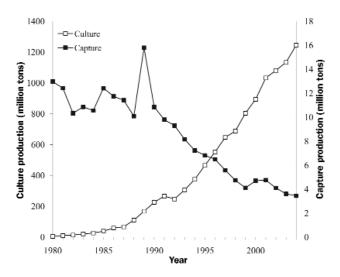

Figure 5. The capture and culture production, in millions of metric tons, from 1980 to 2004 for Atlantic salmon. Source: FAO (2005); data on wild stock are from Romak-kaniemi and colleagues (2003).

A different example of replenishing natural stocks is the Crab Bank in Thailand (Soontornwong 2006), a voluntary program through which culturists release 10% of crab fry produced to reseed the natural population depleted by overfishing and by the 2004 tsunami. This program is too young to evaluate for success. Similar restocking efforts from aquaculture production have been aimed at replenishing giant clam stocks (*Tridacna gigas*; Bell 1999), although in general they have not resulted in large increases in clam populations because clam farming has not been widely adopted.

Special note should be made of aquaculture's role in providing an improved quality of life in developing countries, which cascades to a reduction of the need for other, more environmentally damaging means of employment. When aquaculture displaces more damaging employment, it can benefit biodiversity as well as the economy, as in Peru, where integrated fish farming is being promoted to replace slash-and-burn agriculture (Horizon International 2003). Many nongovernmental organizations (for example, Caritas in Bangladesh) promote small-scale aquaculture as a way to reduce local poverty and improve food security. One major shift in many countries is a move from the countryside to large cities, and providing jobs in rural settings can counter this trend, helping to diversify the local economy (Primavera 1997). Quality of life in rural settings is important in maintaining a viable workforce, since agriculture and aquaculture are both needed to feed the expanding human population, and these rural trades generally require many workers (Primavera 1997). In addition, aquaculture jobs vary from basic labor to highly skilled technical jobs, so they allow lifetime advancement and the possibility of even higher incomes.

Local people may derive economic benefits even from intensive shrimp culture, if the culture is done in a way that is sensitive to local social and economic systems. For example, again in Thailand, after shrimp culture was introduced, most local people perceived that they had a better life as a result of economic change (Clark 2003). Shrimp culture provided a reasonable level of local employment and meant that people did not need to move into urban settings to take up less desirable employment. Asia's situation is somewhat unique, in that many of the culture ponds are owned and managed by small-scale farmers rather than by large corporations. In this regard, shrimp farming in Latin America and the Philippines is perceived to have more negative effects because of ownership patterns and the lack of effective management (Primavera 1997, Tobey et al. 1998).

Poorly executed shrimp culture has also incurred economic losses, particularly in places such as Taiwan, where the introduction of disease and pond abandonment has been a major problem, and where shrimp culture has declined dramatically (Kautsky et al. 2000). Also, aquaculture can displace traditional users of the coastline, such as artisanal fishers or rice farmers, and thus may result in further economic losses (Primavera 1997). Aquaculture development must focus on the value that local people can realize, if aquaculture is to provide local economic benefits.

The future

Many original aquaculture systems were sustainable on a small scale, but increasing numbers of farms and the growing intensity of culture caused environmental damage. These environmentally damaging systems initially used wild-caught fry, inefficient feeding methods, and nutritionally unbalanced feeds; with experience, managers adjusted their practices and the systems became more sustainable (Delgado et al. 2003). Innovation in aquaculture is rapid because of the small margin between cost and market value, and it is important to use up-to-date management practices to evaluate current environmental effects. A 10% more efficient growth rate boosts yield, lowers feed costs, and strongly affects profit, so more efficient practices are quickly adopted, more often because of market issues rather than regulations. Higher market values for fish grown in an environmentally sensitive manner, or inability to export fish grown with damaging practices, will provide strong incentives for greener aquaculture practices (Clay 1997, Boyd et al. 2005). However, government regulations may also be needed, particularly in restricting land and water use to reasonable levels and to locations that can handle the impacts of aquaculture.

Several attempts have been made to quantify the environmental costs of aquaculture or capture fisheries. Naylor and colleagues (1998) reviewed the environmental impacts of shrimp and salmon culture and estimated that the inputs in fish feed exceeded the volume of fish or shrimp production two- to fourfold. However, they offered no methodology for quantifying this natural subsidy among different agriculture crops, and methods for other crops, such as feedlot cattle, also may also require more energy for consumption than they produce. Kautsky and colleagues (1997) estimated the ecological footprint of shrimp and tilapia farming, with more intensive systems requiring 35 to 190 times the aquafarm area to support the food production and waste assimilation of the system. However, integrated systems using waste products (bycatch as feed, waste crops as compost) had a very small footprint, as these wastes would be present regardless of aquaculture production. Later, Paratryphon and colleagues (2004) and Mungkung and colleagues (2006) produced LCAs of salmon feed and shrimp farms, respectively. Neither analysis provided a complete quantitative evaluation of an aquaculture system. However, they did evaluate inputs and outflows of energy and materials, including eutrophication potential, as well as greenhouse gas emissions. Other elements that are not typical of life-cycle methodologies also need to be included in risk analysis, such as indicators for impacts of invasive species or disease introduction. However, a number of complete or ongoing studies are attempting to include these atypical metrics into an LCA framework (Pelletier et al. 2007), indicating that an expanded LCA methodology holds much promise of providing quantitative sustainability comparisons among aquaculture, capture fisheries, and agriculture systems.

Every aquaculture system has positive and negative aspects that influence a more sustainable future. In 2004,

56.6% of all culture harvest of animals came from freshwater, 7.4% from brackish water, and 36% from marine sources (FAO 2005). Freshwater culture takes place mainly in ponds, with cages and more intensive indoor facilities producing a much smaller fraction of the harvest. Semi-intensive aquaculture is more energy efficient than intensive culture because it uses fertilization rather than feeding. However, yield in ponds for intensively fed systems can easily reach 20 metric tons of fish per hectare each year—and for some species it may be as high as 100 metric tons—whereas systems in which fertilizer is used or fish are fed with materials from low trophic levels (such as waste vegetables) produce 5 to 10 metric tons per hectare each year. This means that more land would have to be cleared to accommodate increased aquaculture production with lower trophic level species. Which practice is more sustainable, to use less feed but more land, or vice versa? We need answers to such questions to guide future aquaculture development.

Marine finfish systems, which are based mainly on cage culture, require intensive feeding and create effluent and escapement issues, but they necessitate only limited land conversion (mainly roads, utilities, and other such infrastructure) or freshwater use. The vast oceans present an immense area for expanding culture, but the energy and material costs would be very high. Culture of mollusks and seaweeds is done with less-intensive systems, using ropes or other attachment media as well as cages. Brackish-water culture combines practices from freshwater and marine systems evenly and does so on very valuable coastal lands. Obviously, future expansion of any of these major systems would produce very different environmental scenarios that would be difficult or impossible to compare directly.

Today, in aquaculture production is increasing and management systems are improving, yet aquaculture still has a fairly poor environmental image. It will most likely remain the most rapidly growing food production system, especially in developing countries (Delgado et al. 2003, FAO 2007). Within developing countries, growth in freshwater aquaculture will most likely take place in both semi-intensive systems, which will produce food for local consumption, and intensive systems, which will be designed to accommodate local and export sales. Within developed countries, freshwater aquaculture will probably remain intensive. Clearly, all of the complexities of intensive aquaculture systems must continue to be scrutinized in order to protect biodiversity as well as to promote food production.

Acknowledgments

References cited

Abery NW, Sukadi F, Budhiman AA, Kartamihardja KS, Koeshendrajana S, Buddhiman, De Silva SS. 2005. Fisheries and cage culture of three reservoirs in west Java, Indonesia; a case study of ambitious development and resulting interactions. Fisheries Management and Ecology 12: 315–330.

Alongi DM. 2002. Present state and future of the world's mangrove forests. Environmental Conservation 29: 331–349.

Bell JD. 1999. Restocking of giant clams: Progress, problems and potential. Pages 437–452 in Leber KM, ed. Stock Enhancement and Sea Ranching. Oxford (United Kingdom): Fishing News Books.

Bergheim A, Bekkevold S, Bergslien H. 2003. Use of byproducts from Norwegian aquaculture and fisheries. American Fisheries Society Symposium 38: 613–619.

Beveridge MCM, Phillips MJ, Macintosh DJ. 1997. Aquaculture and the environment: The supply of and demand for environmental goods and services by Asian aquaculture and the implications for sustainability. Aquaculture Research 28: 797–807.

Blue Ocean Institute. 2007. Guide to Ocean Friendly Seafood. (29 October 2008; *www.blueocean.org/seafood*)

Boyd CE. 2003. Guidelines for aquaculture effluent management at the farm-level. Aquaculture 226: 101–112.

Boyd CE, Clay JW. 1998. Shrimp aquaculture and the environment. Scientific American (June): 58–65.

Boyd CE, McNevin AA, Clay JW, Johnson HM. 2005. Certification issues for some common aquaculture species. Reviews in Fisheries Science 13: 231–279.

Brooks KM. 2005. The effects of water temperature, salinity, and currents on the survival and distribution of the infective copepodid stage of sea lice (*Lepeophtheirus salmonis*) originating on Atlantic salmon farms in the Broughton Archipelago of British Columbia, Canada. Reviews in Fisheries Science 13: 177–204.

Brooks KM, Jones SRM. 2008. Perspectives on pink salmon and sea lice: Scientific evidence fails to support the extinction hypothesis. Reviews in Fisheries Science 16: 403–412.

Canonico GC, Arthington A, McCrary JK, Thieme ML. 2005. The effects of introduced tilapias on native biodiversity. Aquatic Conservation: Marine and Freshwater Ecosystems 15: 463–483.

Cho CY, Bureau DP. 2001. A review of diet formulation strategies and feeding systems to reduce excretory and feed wastes in aquaculture. Aquaculture Research 32 (suppl. 1): 349–360.

Clark MM. 2003. Shrimp aquaculture brownfields: Social, environmental, and economic issues determining rehabilitation options. Master's thesis. University of Michigan, Ann Arbor.

Clay JW. 1997. Toward sustainable shrimp aquaculture. World Aquaculture 28: 32–37.

Costa-Pierce BA. 1998. Constraints to the sustainability of cage aquaculture for resettlement from hydropower dams in Asia: An Indonesian case study. Journal of Environment and Development 7: 333–363.

Delgado CL, Wada N, Rosegrant MW, Meijer S, Ahmed M. 2003. Fish to 2020: Supply and Demand in Changing Global Markets. Penang (Malaysia): World Fish Center.

Diana JS. 1993. Conservation and utilization of fish genetic resources in capture and culture fisheries. Pages 89–103 in Cohen JI, Potter CS, eds. Case Studies of Genetic Resource Conservation in Natural Habitats. Washington (DC): American Association for the Advancement of Science.

Duarte CM, Marbá N, Holmer M. 2007. Rapid domestication of marine species. Science 316: 382–383.

[FAO] Food and Agriculture Organization of the United Nations. 2005. Yearbook of Fishery Statistics. Rome: FAO.

———. 2007. The State of World Fisheries and Aquaculture. Rome: FAO.

Fay C, Barton M, Craig S, Hecht A, Pruden J, Saunders R, Sheehan T, Trial J. 2006. Status Review for Anadromous Atlantic Salmon (*Salmo salar*) in the United States. Washington (DC): US Fish and Wildlife Service.

Flaherty M, Karnjanakesorn C. 1995. Marine shrimp aquaculture and natural resources degradation in Thailand. Environmental Management 19: 27–37.

Fleming IA, Hindar K, Mjolnerod, IB, Jonsson B, Balstad T, Lamberg A. 2000. Lifetime success and interactions of farm salmon invading a native population. Proceedings of the Royal Society of London B 267: 1517–1523.

Ford JS, Myers RA. 2008. A global assessment of salmon aquaculture impacts on wild salmonids. PLoS Biology 6: 1–7.

Goldburg R, Naylor R. 2005. Future seascapes, fishing, and fish farming. Frontiers in Ecology and Environment 31: 21–28.

Goldburg R, Triplett T. 1997. Murky Waters: Environmental Effects of Aquaculture in the United States. Washington (DC): Environmental Defense Fund.

Green JA, Hardy RW, Brannon EL. 2002. Effects of dietary phosphorus and lipid levels on utilization and excretion of phosphorus and nitrogen by rainbow trout (*Oncorhynchus mykiss*), 1: Laboratory-scale study. Aquaculture Nutrition 8: 279–290.

Horizon International. 2003. Integrated Aquaculture Provides a Viable Alternative to Slash-and-Burn Agriculture, Reducing Destruction of Tropical Forests. (29 October 2008; *www.solutions-site.org*)

Hulata G. 2001. Genetic manipulations in aquaculture: A review of stock improvement by classical and modern technologies. Genetics 111: 155–173.

Islam MS. 2005. Nitrogen and phosphorus budget in coastal and marine cage aquaculture and impacts of effluent loading on ecosystem: Review and analysis towards model development. Marine Pollution Bulletin 50: 48–61.

Jones AB, O'Donohue MJ, Udy J, Dennison WC. 2001. Assessing ecological impacts of shrimp and sewage effluent: Biological indicators with standard water quality analyses. Estuarine, Coastal and Shelf Science 52: 91–109.

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

Kautsky N, Ronnback P, Tedengren M, Troell M. 2000. Ecosystem perspectives on management of disease in shrimp pond farming. Aquaculture 191: 145–161.

Krkosek M, Lewis MA, Morton A, Frazer LN, Volpe JP. 2006a. Epizootics of wild fish induced by farm fish. Proceedings of the National Academy of Sciences 133: 15506–15510.

Krkosek M, Lewis MA, Volpe JP, Morton A. 2006b. Fish farms and sea lice infestations of wild juvenile salmon in the Broughton Archipelago—a rebuttal to Brooks (2005). Fisheries Science 14: 1–11.

Krkosek M, Ford JS, Morton A, Lele S, Myers RA, Lewis M. 2007. Declining wild salmon populations in relation to parasites from farm salmon. Science 318: 1772–1775.

Machias A, Karakassis I, Labropoulou M, Somarakis S, Papadopoulou KN, Papaconstantinou C. 2004. Changes in wild fish assemblages after the establishment of a fish farming zone in an oligotrophic marine ecosystem. Estuarine, Coastal and Shelf Science 60: 771–779.

Machias A, Karakassis I, Giannoulaki M, Papadopoulou KN, Smith CJ, Somarakis S. 2005. Response of demersal fish communities to the presence of fish farms. Marine Ecology Progress Series 288: 241–250.

Master LL, Flack SR, Stein BA, eds. 1998. Rivers of Life: Critical Watersheds for Protecting Freshwater Biodiversity. Arlington (VA): Nature Conservancy.

[MEA] Millennium Ecosystem Assessment. 2005. Ecosystems and Human Well-Being: Biodiversity Synthesis. Washington (DC): World Resources Institute.

Menasveta P. 1997. Mangrove destruction and shrimp culture systems. World Aquaculture 28: 36–42.

Miller LM, Close T, Kapuscinski AR. 2004. Lower fitness of hatchery and hybrid rainbow trout compared to naturalized populations in Lake Superior tributaries. Molecular Ecology 13: 3379–3388.

Mills EL, Leach JH, Carlton JT, Secor CL. 1994. Exotic species and the integrity of the Great Lakes. BioScience 44: 666–676.

Mitchell AJ, Kelly AM. 2006. The public sector role in the establishment of grass carp in the United States. Fisheries 31: 113–121.

Monterey Bay Aquarium. 2006. Seafood Watch. (29 October 2008; *www.mbayaq.org/cr/seafoodwatch.asp*)

Mungkung RT, Udo de Haes HA, Clift R. 2006. Potentials and limitations of life cycle assessment in setting ecolabelling criteria: A case study of Thai shrimp aquaculture product. International Journal of Life-Cycle Assessment 11: 55–59.

Naylor R, et al. 1998. Nature's subsidies to shrimp and salmon farming. Science 282: 883–884.

Naylor R, et al. 2000. Effect of aquaculture on world fish supplies. Nature 405: 1017–1024.

Naylor R, et al. 2005. Fugitive salmon: Assessing the risks of escaped fish from net-pen aquaculture. BioScience 55: 427–437.

New MB. 2003. Responsible aquaculture: Is this a special challenge for developing countries? World Aquaculture 34: 26–31.

Opstvedt J, Aksnes A, Hope B, Pike IH. 2003. Efficiency of feed utilization in Atlantic salmon (*Salmo salar* L.) fed diets with increasing substitution of fish meal with vegetable proteins. Aquaculture 221: 365–379.

Papatryphon E, Petit J, Kaushik SJ, Hayo MG, van der Werf HMG. 2004. Environmental Impact Assessment of Salmonid Feeds Using Life Cycle Assessment (LCA). Ambio 33: 316–323.

Pelletier NL, Ayer NW, Tyedmers PH, Kruse SA, Flysjo A, Robillard G, Ziegler F, Scholz AJ, Sonesson U. 2007. Impact categories for life cycle assessment research of seafood production systems: Review and prospectus. International Journal of Life Cycle Assessment 12: 414–421.

Primavera JH. 1997. Socio-economic impacts of shrimp culture. Aquaculture Research 28: 815–827.

Rahel FJ. 2000. Homogenization of fish faunas across the United States. Science 288: 854–856.

Ricciardi A, Rasmussen JB. 1998. Predicting the identity and impact of future biological invaders: A priority for aquatic resource management. Canadian Journal of Fisheries and Aquatic Sciences 55: 1759–1765.

Romakkaniemi A, Pera I, Karlsson L, Jutila E, Carlsson V, Pakarinen T. 2003. Development of wild Atlantic salmon stocks in the rivers of the northern Baltic Sea in response to management measures. ICES Journal of Marine Science 60: 329–342.

Rönnbäck P, Bryceson I, Kautsky N. 2002. Coastal aquaculture development in eastern Africa and the western Indian Ocean: Prospects and problems for food security and local economies. Ambio 31: 537–542.

Scott MC, Helfman GS. 2001. Native invasions, homogenization, and the mismeasure of integrity of fish assemblages. Fisheries 26: 6–15.

SeaChoice. 2008. Canada's Seafood Guide. (29 October 2008; *www.seachoice.org*)

Soontornwong S. 2006. Improving rural livelihood through CBNRM: A case of self-organization in community mangrove management in Thailand. Pages 182–199 in Mahanty S, Fox J, Nurse M, Stephen P, McLees L, eds. Hanging in the Balance: Equity in Community-based Natural Resource Management in Asia. Honolulu (HI): East-West Center.

Soto D, Norambuena F. 2004. Evaluation of salmon farming effects on marine systems in the inner seas of southern Chile: A large-scale mensurative experiment. Journal of Applied Ichthyology 20: 493–501.

Stachowicz, JJ, Whitlatch RB, Osman RW. 1999. Species diversity and invasion resistance in a marine ecosystem. Science 286: 1577–1579.

Stotz W. 2000. When aquaculture restores and replaces an overfished stock: Is the conservation of the species assured? The case of the scallop *Argopecten purpuratus* in northern Chile. Aquaculture International 8: 237–247.

Tacon AGJ, Hasan MR, Subasinghe RP. 2006. Use of Fishery Resources as Feed Inputs for Aquaculture Development: Trends and Policy Implications. Rome: Food and Agriculture Organization of the United Nations. FAO Fisheries Circular No. 1018.

Tobey J, Clay J, Vergne P. 1998. Maintaining a Balance: The Economic, Environmental, and Social Impacts of Shrimp Farming in Latin America. Narragansett (RI): Coastal Resources Center, University of Rhode Island.

[UN] United Nations. 1992. Report of the United Nations Conference on Environment and Development. (29 October 2008; *www.un.org/documents/ga/conf151/aconf15126-1annex1.htm*)

Watanabe T. 2002. Strategies for further development of aquatic feeds. Fisheries Science 68: 242–252.

Watson R, Pauly D. 2001 Systematic distortion in world fisheries catch trends. Nature 424: 534–536.

Wijkstrom UN. 2003. Short and long-term prospects for consumption of fish. Veterinary Research Communications 27 (suppl. 1): 461–468.

Wilcove DS, Rothstein D, Dubow J, Phillips A, Losos E. 1998. Quantifying threats to imperiled species in the United States. BioScience 48: 607–615.

[World Bank et al.] World Bank, Network of Aquaculture Centres in Asia, World Wildlife Fund, FAO. 2002. Shrimp farming and the environment. Washington (DC): World Bank.

Wu RSS. 1995. The environmental impact of marine fish culture: Towards a sustainable future. Marine Pollution Bulletin 31: 159–166.

James S. Diana (e-mail: jimd@umich.edu) is an ecologist with the School of Natural Resources and Environment at the University of Michigan in Ann Arbor. He studies fish ecology and aquaculture.