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AQUACULTURE AND OCEAN RESOURCES: Raising Tigers of the Sea

Rosamond Naylor[1] and Marshall Burke[2]
Julie Wrigley Senior Fellow[1] and Research Fellow,[2] Center for Environmental Science and Policy, Stanford University, Stanford, California 94305; email: roz@stanford.edu, mburke@stanford.edu

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■ **Abstract** With continued human pressure on marine fisheries and ocean resources, aquaculture has become one of the most promising avenues for increasing marine fish production in the future. This review presents recent trends and future prospects for the aquaculture industry, with particular attention paid to ocean farming and carnivorous finfish species. The benefits of farming carnivorous fish have been challenged; extensive research on salmon has shown that farming such fish can have negative ecological, social, and health impacts on areas and parties vastly separated in space. Similar research is only beginning for the new carnivorous species farmed or ranched in marine environments, such as cod, halibut, and bluefin tuna. These fish have large market potential and are likely to play a defining role in the future direction of the aquaculture industry. We review the available literature on aquaculture development of carnivorous finfish species and assess its potential to relieve human pressure on marine fisheries, many of which have experienced sharp declines.

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INTRODUCTION

The aquaculture industry has become a major supplier of fish and shellfish in markets worldwide—a trend that will likely persist in the future as wild fish capture pushes the limits of renewable production. Global consumption of fish has doubled since the early 1970s and will continue to grow with population, income, and urban growth in the developing world (1). The demand for fish is also rising in industrialized countries, but the composition of demand differs. Although carp and mollusk species account for a significant share of farm-raised fish for consumers in developing countries, wealthy consumers generally prefer shrimp and carnivorous finfish species such as salmon, cod, halibut, and tuna. Aquaculture production of marine carnivorous finfish has grown by roughly 9% annually, and its value has increased by about 5% per annum since the early 1990s (2). These rates will likely increase as fishing pressure continues to reduce the availability of some of their wild counterparts. How is this trend affecting ocean resources and coastal ecosystems? Given that these marine finfish depend on fish meal and fish oil for feed, will aquaculture growth in this area result in a net gain, or a net drain, to world fish supplies? Unlike terrestrial livestock systems that rely mainly on vegetarian diets, marine aquaculture is centered on raising "tigers of the sea."[1] This process is driven not only by rising demand for fish protein, but also by lucrative business opportunities.

In this review, we examine recent trends in aquaculture, with particular attention paid to the farming of carnivorous finfish species. Our work builds on earlier synthesis studies by a larger team of researchers (3–6) and pursues a forward-looking perspective through the examination of literature on the new species and technologies currently being developed by the aquaculture industry. Although the production of many lower trophic level aquaculture species might be desirable, the wisdom of farming carnivorous fish on a large scale has been called into question. Work on salmon aquaculture, in particular, has shown that farming such fish can have negative environmental and social implications for areas and parties vastly separated in space (7–10). We review the evidence on fish feed requirements, ecological impacts, and socioeconomic implications of widely farmed carnivorous species and new species currently being introduced. We also examine existing studies on offshore aquaculture technologies that are being proposed as a more sustainable alternative to farming marine fish in coastal areas. Finally, we discuss private and public sector options for mitigating environmental damage from marine aquaculture.

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[1] A term coined by Rebecca Goldburg, Environmental Defense.

THE RISING ROLE OF FISH FARMING

Oceans have long been regarded as vast, inexhaustible sources of fish. Even when research began to show that fisheries were being depleted, many people within the fishing industry assumed that more fish were available. Fisheries technology and management policies have continued to be adjusted accordingly, allowing for shifting management baselines and capture of an expanding range of fish populations and species (1, 11–13). In the past two decades, this optimistic view of fisheries has changed. Over 60% of the marine fish stocks for which information is available are either fully exploited or overexploited, and 13 of the world's 15 major oceanic fishing areas are now fished at or beyond capacity (14). Statistics show that annual global fish catches have plateaued at 80–90 million metric tons (14) and may even be declining (15). Small fish at the low end of the food chain compose an increasing share of global catch (16), whereas populations of commercially valuable, large predatory fish—the type many human consumers prefer—continue to decline. By one estimate, commercial fishing has wiped out 90% of large fish such as swordfish, cod, marlin, and sharks (17).

In addition to impacts caused by fishing activities, marine ecosystems and fisheries face serious threats from other sources: run off of land-based pollutants, introductions and invasions of exotic species, coastal development and habitat alteration, and climate change (11, 18, 19). Commercial fishing remains among the most important direct determinants of overall fisheries declines (20) and has lowered the resilience of fish stocks and marine ecosystems to withstand other mounting environmental pressures (21–23). Recreational fishing also has localized impacts, particularly on high-valued and overfished species. In the United States, the recreational fishery accounts for only 4% of total marine fish landed but for almost two thirds of the fish taken from the most threatened nonindustrial fisheries in the Gulf of Mexico (24). The impact of any one of these threats is cause enough for concern and policy action. Taken together, they paint a grim picture for the health of ocean ecosystems and marine fisheries.

The oceans are now poised for yet another transformation: the rapid expansion of fish farming, or aquaculture, resulting from the decline in wild fisheries and lucrative business opportunities. During the past decade, global production of farmed finfish and shellfish almost tripled in weight and nearly doubled in value (2). Roughly 40% of all fish directly consumed by humans worldwide are now farmed. Although most aquaculture production to date has been of freshwater fish, marine aquaculture has been growing dramatically. Global production of farmed salmon, for example, has roughly quadrupled in volume since the early 1990s. This spectacular increase and the resulting decline in salmon prices have helped prompt aquaculturists to begin farming numerous other marine finfish, including a number of species depleted in the wild. New species farmed in marine net pens include Atlantic cod (*Gadus morhua*), Atlantic halibut (*Hippoglossus hippoglossus*), Pacific threadfin (*Polydactylus sexfilis*), mutton snapper (*Lutjanus analis*), and bluefin tuna (*Thunnus* spp.).

Like salmon, many of these new species are farmed in net pens or cages that are anchored to the ocean bottom, often in coastal waters (9). In the United States, where expansion of salmon farms in coastal waters has met local opposition and state-level restrictions, the U.S. National Oceanic and Atmospheric Administration (NOAA) is pursuing the development of large offshore aquaculture operations, primarily in the Exclusive Economic Zone (EEZ), beyond the reach of coastal activities and state laws (25). In some areas, such as the Gulf of Mexico, some offshore oil and gas rigs, which would otherwise have had to be decommissioned, are being pursued as platforms for new aquaculture facilities.

Marine aquaculture development is being promoted in many countries, and parts of the industry are now emerging as major competitors in international markets (8, 26). It has responded to the rising role of large retail chains by supplying homogeneous, made-to-order products on a year-round basis. It has also developed computerized information flows on fish stocks and markets, web-based business-to-business interactions, and in some cases, supply chains that control fish production from hatcheries to sales. The industry has benefited from rapid expansion of seafood trade and overnight transportation of fresh products around the world. In many cases, the aquaculture industry has been able to outcompete the capture fishing industry, partly because subsidies and other policies supporting the fishing industry have impeded adjustments to make it more efficient (26). Given these trends and the limited capacity of oceans to provide more fish for human consumption, it is likely that aquaculture will dominate fish production in the coming decades.

THE CURRENT LANDSCAPE

Salmon aquaculture is a world leader in farmed carnivorous finfish production and value (Table 1) and provides a useful illustration of the types of environmental, resource, and socioeconomic issues that are likely to arise with farmed production of other marine finfish species. Salmon aquaculture has its roots in hatcheries, in which salmon eggs are fertilized and fish are raised to smolts (juvenile fish) before being released into the ocean. The development of hatchery technology began in Europe in the late 1700s with the goal of enhancing wild salmon runs that had been depleted by fisheries (27). It was not until the early 1970s, however, that private salmon-farming companies (which raise smolts from hatcheries to maturity in net pens) began to operate on an international scale. Farmed salmon accounted for only 1% of global salmon output in 1980, but the technology for pen-raised salmon had become well-established in Norway, setting the stage for rapid growth elsewhere. Production expanded during the 1980s in several other high-latitude countries, including Scotland, Japan, Chile, Canada, the United States, Ireland, New Zealand, Australia, and the Faroe Islands, and by the early 1990s, aquaculture accounted for the majority of world trade in salmon (8, 27). Although Norway has dominated the production of farmed salmon for decades, Chile is now becoming the top supplier globally (28).

TABLE 1 The top 10 species of marine finfish farmed worldwide and the location of production in 2002 (2)

Species	Total farmed volume, marine and brackish water (tons)	Annual percentage growth in farmed volume, 1992–2002	Percent farmed in marine environment	Value in 2002 (U.S. million dollars)	Top three producers
Atlantic salmon (*Salmo salar*)	1,084,740	15.9	99	2851	Norway, Chile, United Kingdom
Rainbow trout (*Oncorhynchus mykiss*)	220,148	16.6	94	509	Chile, Norway, Faroe Islands
Japanese amberjack (*Seriola quinqueradiata*)	162,718	0.9	100	1383	Japan, Korea
Coho salmon (*Oncorhynchus kisutch*)	112,696	8.8	100	267	Chile, Japan, Canada
Gilthead seabream (*Sparus aurata*)	76,898	23.1	81	257	Greece, Turkey, Spain
Silver seabream (*Pagrus major*)	73,402	1.1	100	443	Japan, Korea, Taiwan
European seabass (*Dicentrarchus labrax*)	42,505	16.4	91	185	Greece, Italy, Spain
Bastard halibut (*Paralichthys olivaceus*)	33,161	12.4	100	343	Korea, Japan
Barramundi (*Lates calcarifer*)	21,976	4.5	10	65	Thailand, Indonesia, Malaysia
Chinook salmon (*Oncorhynchus tshawytscha*)	19,852	2.2	100	46	Canada, New Zealand, Chile

Farmed salmon production reached 1217 thousand metric tons (mt) in 2002, 68% higher than the 722,000 mt of wild capture (2). Over 90% of the farmed product is Atlantic salmon (*Salmo salar*), a species nearly depleted in the wild. Despite rapid growth in salmon aquaculture, capture levels of salmon (Atlantic and Pacific salmon combined), which are supported in most salmon fisheries by hatchery enhancement, remain higher today than in the period leading up to 1990 when salmon farming was insignificant in global markets (9). Salmon aquaculture is thus supplementing, not replacing, wild catch.

With a high degree of consumer substitution among salmon species, prices for all species have fallen as a result of increased market supply. Between 1988 and 2002, the price of farmed Atlantic salmon fell by 61%, and ex-vessel prices for Pacific salmon species that compete most highly with Atlantic salmon (sockeye, coho, and chum) fell by 59% to 64% (8). Competition within aquaculture, capture, and processing industries remains fierce, and the expanding role of fish farming is clearly transforming seafood production, marketing, and consumption. A wide range of fresh fish products is now available to consumers at relatively low prices throughout the year.

Ownership within the salmon aquaculture industry has become highly concentrated, with roughly 30 companies controlling two thirds of the world's farmed salmon and trout production in 2001 (29). Although the salmon fishing industry is made up of many small businesses that operate at arm's length from processing corporations, the farming industry is made up of companies with corporate affiliations. The four largest multinational companies involved in global salmon aquaculture production are Panfish, Fjord Seafood, Cermaq, and Marine Harvest (representing the recently merged companies Stolt-Nielson and Nutreco) (Figure 1). It is typical for an aquaculture multinational to have subsidiaries that include feed, hatchery, grow-out, distribution, and value-added processing companies, and most of the multinationals have operations on at least three continents. Cermaq and Nutreco are the biggest feed producers for salmon aquaculture in the world, and Fjord Seafood, Pan Fish, and Stolt-Nielson have major international processing and sales subsidiaries. The largest Chilean company, AquaChile, is also vertically integrated and controls production and processing of many smaller salmon aquaculture firms within the country.

As a result of both declining margins in the salmon farming business and expanding market opportunites for a diversity of fish products, most large aquaculture companies are now also involved in farmed production of other species, including trout, halibut, cod, turbot, bluefin tuna, sturgeon (for caviar), and sea bream (7, 8). The diversity of activities and production locations provides some buffering during sectoral downturns, and technological innovations for net-pen culture can be shared to varying degrees across species.

Excluding diadromous fish (salmon and trout, raised in a combination of freshwater and marine environments), the output of farmed marine fish grew by 350% from a very low base between 1985 and 2002 (7) and could, by one estimate, double again by 2010 (30). The top 10 species of marine finfish farmed worldwide

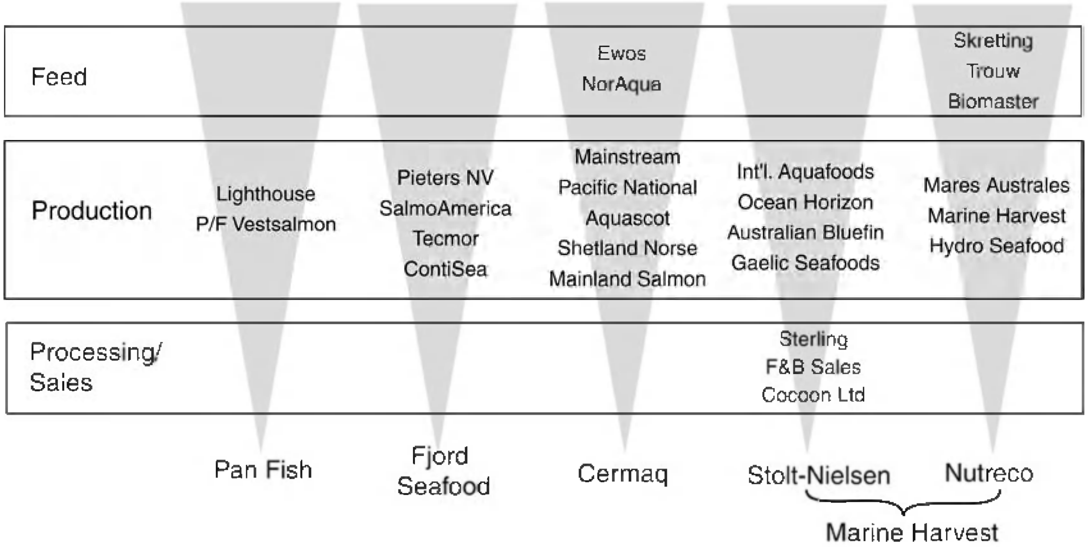

Figure 1 Consolidation in the salmon aquaculture industry. Pan Fish, Fjord, and Cermaq are all also vertically integrated in processing and sales. The Marine Harvest merger is awaiting approval from antitrust regulators in Europe. Taken from company Web sites and industry reports.

and the location of production in 2002 are shown in Table 1. Virtually all of the fish, with the exception of milkfish, are farmed in ocean environments as opposed to brackish water environments. Some of the fastest growing sectors on the list, in addition to Atlantic salmon, include farmed production of rainbow trout in Chile, Norway, and the Faroe Islands, and production of bastard halibut in Korea and Japan. With rapid expansion in marine finfish aquaculture, China is expected to become one of the leading producers in the future; it currently dominates global aquaculture production, but mainly for freshwater species (e.g., carp, tilapia) and shellfish (e.g., shrimp).

EMERGING MARINE FINFISH SPECIES

Several new carnivorous finfish species are beginning to be farmed and are likely to change the composition of the "top ten list" (Table 1) within the next decade. For some of these new species, aquaculture is emerging as a potential replacement for depleted fisheries (e.g., Atlantic cod and Atlantic halibut), and in other cases, aquaculture and capture production are rising simultaneously (e.g., barramundi and cobia).

Like Atlantic salmon, Atlantic cod have been reared in hatcheries and released into marine ecosystems for more than a century to enhance diminishing wild populations (31, 32). It was not until the 1990s, however, that techniques were developed for maintaining captive broodstock and breeding cod in captivity. Cod are generally viewed as a possible direct substitute for salmon in existing net-pen operations because the grow-out stage of cod production is almost identical to that of salmon (32). Some of the major multinational companies shown in Figure 1, particularly Nutreco, are taking a lead in developing this industry. A few technical hurdles exist, such as finding a suitable nutrition regime for larvae (unlike salmon, cod larvae have no yolk sac for nutrition and require zooplankton, brine shrimp, or other live organisms for feed) and establishing a sufficient number of juveniles to make year-round production possible because the natural spawning cycle of cod is short (7, 31–33). Commercial cultivation of Atlantic cod is currently established in Norway, the United Kingdom, Canada, and Iceland (7, 34) with production at about 1500 tons in 2002 (2). Norway is positioned to lead the global cod aquaculture industry, just as it has done with salmon, and some sources predict that Norwegian production could reach 30,000 tons a year by 2008 (35). Canada and Scotland are following its lead (31). At this stage in the development process, commercialization of farmed cod depends on low capture rates of wild cod and high prices to remain economically viable (7).

Norway is the world leader in farmed production of Atlantic halibut, a high-valued species with good market growth potential (7, 36). Advanced hatchery and research programs for Atlantic halibut are also underway in Scotland, Ireland, Canada, Chile, Iceland, and the United States. By 2000, several hatcheries around the world were providing juvenile halibut for grow out. Similar to Atlantic cod, raising Atlantic halibut is constrained by small and fragile larvae (especially compared with Atlantic salmon) that require feed formulations of live food organisms (plankton, zooplankton, or brine shrimp) (36–38). Juvenile development and long growth cycles can also be constraining factors. Because halibut live near the ocean's floor, they are not naturally suitable for the type of open net pens designed for salmon; however, many farmed halibut are still raised in converted salmon net pens with shallow or multiple bottoms (39, 40). Halibut are not tolerant of high water turbulence and must therefore be raised in sheltered environments, and thus the majority of farmed halibut are currently raised in on-land tanks (39). Wild Atlantic halibut landings have declined precipitously during the last 50 years, and according to the Food and Agriculture Organization of the United Nations (FAO) (2), production of farmed Atlantic halibut reached 300 tons in 2002 or roughly 10% of wild catch. In 2003, Norwegian production alone reached an estimated 700 tons or about 25% of capture production (41). Industry sources report that the price of Norwegian farmed halibut in Europe rose by over 25% in 2004 despite a 40% increase in production (42).

Bluefin tuna is another carnivorous species coming on line as a major aquaculture product in response to serious declines in wild fisheries stocks and large potential profit margins. Unlike cod and halibut, most farmed bluefin tuna are ranched, meaning juvenile tuna are captured at sea and then fattened in cages until they reach marketable size (43–45). This process can take from two months to two years depending on the size of juveniles captured (44, 46). On a given farm site, up to 2000 bluefin tuna may be confined in a single net pen offshore, with eight or more net pens typically grouped together (7). Australia has ranched southern bluefin tuna since the early 1990s with great economic success; the value and volume of its industry grew by an astonishing 40% and 16% per annum, respectively, between 1992 and 2002 (2). Atlantic and Pacific bluefin tuna ranching has emerged more recently in Mediterranean countries, such as Spain and Croatia, as well as in Mexico, and development is beginning in several other countries including the United States (46, 47). In all cases, the market potential is exceptional, with Japan consuming most of the output. Tuna capture quotas exist in all regions and act as a constraint on industry growth; however, these quotas tend to be poorly regulated in regions outside of Australia (45, 46). Breeding tuna in captivity for commercial purposes will likely be critical to the sustainability of both the industry and wild stocks. Attempts to do so have been ongoing since the 1970s (7, 44), and recent work in Japan has succeeded in closing the production cycle by getting artificially reared bluefin to produce eggs (44).

Public research institutions and private companies are developing and marketing many other farmed carnivorous finfish in marine environments, thus contributing to the rising market share of this segment of the aquaculture industry (7). Black cod (sablefish) culture is being developed in British Columbia and Washington state for high-end markets in Japan and North America and is expected to compete in world markets with wild sablefish and Patagonia toothfish (also marketed as Chilean seabass and mero) (48). Farmed haddock is being developed in eastern

Canada, Norway, and northeastern United States (49–52). Cobia is produced in Taiwan and is being developed in experimental offshore facilities in the Gulf of Mexico (7). Pacific threadfin (moi) is raised in offshore netcages in Hawaii (53). Barramundi is raised in coastal net pens and in on-land ponds in Southeast Asia and Australia (54, 55). Turbot is raised mainly in on-land tanks in Europe (39) and is also being developed by Chilean aquaculture companies (56). More than 20 species of grouper are raised commercially; like tuna, most grouper are captured as juveniles and fattened to market size in coastal net pens in East and Southeast Asia, but a small number are also raised in hatcheries (44, 57). Numerous other carnivorous finfish species, including red drum, mutton snapper, flounder, spotted wolffish, yellowfin tuna, yellowtail kingfish, and southern hake, are also being farmed, experimentally or commercially (7).

The rapid expansion of aquaculture into a diverse range of high-valued species reflects government and industry attention toward market opportunities and the hedging of risks. The salmon experience has shown that there are limits to market expansion; with rapid growth in supplies and constant demand, prices will eventually fall. At the same time, the aquaculture industry can be very lucrative, particularly for high-valued species, and this has led many governments to develop policies and programs to support and encourage fish farming. Private companies are keen on securing a market edge with new products, particularly if they can adapt existing infrastructure and cultivation technology to a broader range of species. In addition, the risks of business failure due to diseases and pathogens can often be reduced through a diversification of farmed products.

Although growth and diversification in farmed marine finfish species generate certain benefits to the aquaculture industry, governments (in the form of foreign exchange earnings), and consumers (in terms of a wider selection of seafood products at lower prices), there are also ecological and resource costs. In contrast to the majority of freshwater farming systems, almost all aquaculture production of diadromous and marine finfish species is dependent on capture fisheries for essential inputs. All of these species rely on the use of whole or processed fishery products as feed inputs; many marine finfish depend on the capture of wild broodstock for spawning; and several of the species, such as bluefin tuna and groupers, depend on the collection of "wild seed" for subsequent grow out to market size (58). As this segment of the aquaculture industry continues to expand, more pressure will likely be placed on marine ecosystems.

FEEDING WILD FISH TO FARMED FISH

Carnivorous finfish species require fish or other aquafeeds in their diets to varying degrees. This feed source may come in the form of processed fish meal and fish oil, live pelagic fish, or "trash fish" from trawling capture. Nearly all farm operations for carnivorous diadromous fish and marine finfish are net fishery "reducers" rather than "producers," i.e., the quantity of fish inputs often exceeds outputs in terms of farmed fishery products by a factor or two to three (58). This ratio of wild fish inputs to farmed fish outputs is a function of the efficiency with which the fish utilizes the feed (usually referred to as the feed conversion ratio or FCR), the amount of fish meal and fish oil contained in the feed, and the amount of wild fish it takes to produce a given amount of fish meal or fish oil. Feed conversion ratios for carnivorous finfish species—typically defined as the amount of dry feed it takes to produce a unit of "wet" fish—range from about 1:1 up to 2:1 or higher. Fish meal and fish oil generally constitute 50%–75% by weight of compound aquafeeds for most carnivorous marine finfish species that are commercially farmed (58), e.g., for salmon, a typical diet contains 35%–40% fish meal and 25% fish oil (59), although diets containing less than 20% fish oil are also cited (9).

For widely farmed species that rely on processed feed inputs, the amount of wild fish that it takes to produce a unit of farmed fish has declined over time with technological and management improvements in both FCRs and the percentage of fish meal and fish oil used in feeds. In 1997, an estimated 1.9 kilograms of wild fish were required on average to produce each kilogram of fed farmed fish (4). This ratio fell to 1.31 kilograms of wild fish for each kilogram of fed farmed fish in 2001 (Figure 2). Although this trend is promising for the sustainability of both aquaculture and marine fisheries, it is overshadowed by growth in the aggregate number of farmed carnivorous fish produced. For example, the amount of wild fish required to produce one unit of farmed salmon was reduced by 25% between 1997 and 2001, but total production of farmed salmon grew by 60% (2) during this same period. Several other species with much higher fish feed requirements have come into production and some—such as tuna culture—are expanding rapidly. In the case of ranched tuna, which depend largely on live pelegic fish such as sardines, anchovies, and mackerel, up to 20 kilograms of wild fish input are needed to produce each kilogram of ranched fish output (7, 45, 46).

Feed conversion ratios for the new carnivorous species vary. Atlantic cod require one third of the amount of fish oil in feeds as compared with Atlantic salmon, and the feed conversion ratio is ~1:1 with enriched pelleted feeds (32), compared with roughly 1.2:1 for salmon (61). Halibut grow more slowly than salmon, but the fish are docile, and therefore the FCR is typically low (~1.1:1) in experimental on-land tanks (36). Because halibut are bottom feeders, however, raising them in coastal net pens inevitably leads to food wastage, with a FCR ~ 1.5:1—a significant difference from on-land tanks (36). With careful feeding practices, this ratio can be reduced to 1.3:1 (40). Halibut, a flatfish, requires more protein in its diet than salmon, and typical diets include feed with 48% protein compared with 38%–42% for salmon feeds (40). Turbot, also a flatfish, requires large amounts of protein and has a reported FCR ranging from 1.2:1 to 1.8:1 (7, 39, 50). For some marine carnivores, the feed conversions are much higher; moi, for example, one of the species now farmed in offshore sea cages, has a FCR of 1.8 and requires roughly 4 kilograms of wild fish inputs for every kilogram of harvested fish output (53). Like many new marine species now being farmed, moi are entering into commercial production with a high demand for wild fish inputs in feed, but fish protein

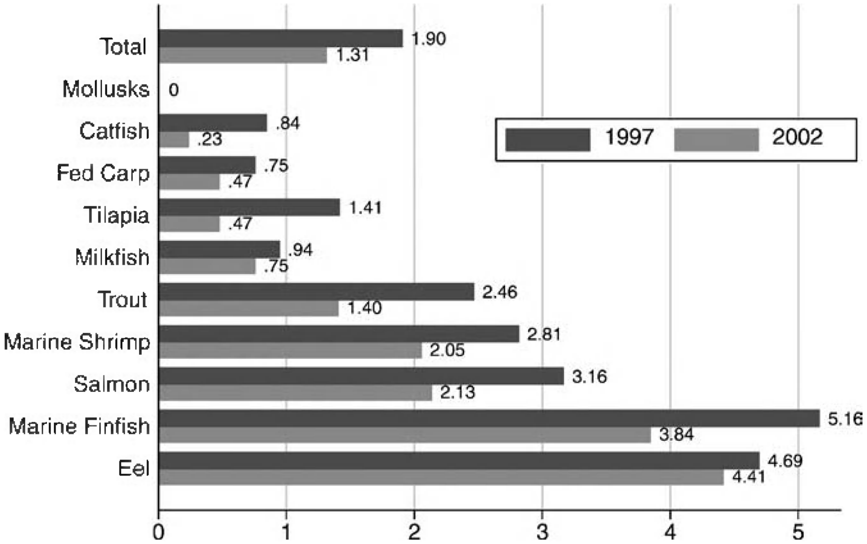

Figure 2 Wild fish inputs used in feed for the 10 types of fish and shellfish most commonly farmed in 1997 and 2002, from Naylor et al. (4) and A. Tacon and R. Goldburg, personal communication. Ratio is wild fish used for fish meal to farmed fish produced using compound feeds. We assume a 5:1 conversion ratio of fish (wet weights) to fish meal and that 1/16 of the fish meal is obtained from processing by-products (60). Marine finfish include cod, halibut, flounder, sole, haddock, redfish, seabass, tuna, congers, bonito, and billfish. Fed carp are those carp species that are sometimes fed compound feeds; filter-feeding carp are silver carp, bighead carp, and catla.

requirements per fish and feed conversion ratios are likely to fall as the industry develops.

Global production of fish meal and fish oil is used principally for livestock (mainly poultry and pig) and aquaculture feeds and has not grown significantly during the past two decades (2, 30). However, aquaculture's share of total fish meal demand has increased markedly since the late 1980s. In 2002 the aquaculture industry used roughly 40% of the world's supply of fish meal (59, 62, 63), compared with 10% in 1988 and 33% in 1997 (4). Aquaculture is expected to consume well over 50% of global fish meal supplies by 2010 (30). The fish oil market has a similar trend; aquaculture feed already consumes over half of the world's fish oil and by 2010 is expected to use 97% of total supply (30). These trends are anticipated despite rapid growth in industrial livestock systems. Unlike livestock systems, which can readily substitute vegetable proteins when fish meal prices rise, carnivorous aquaculture species require a certain amount of fish meal and fish oil for energy, health, and palatability (4). If the farming of carnivorous fish continues to grow at its current rate, the demand for fish oil is expected to outstrip supply within a decade, with a similar result for fish meal by 2050 (35). Such an outcome could jeopardize the industry's economic sustainability (1, 4).

International prices provide a useful gauge for measuring scarcity in the fish feed industry. International fish meal prices typically rise on an interannual basis during and following El Niño events, when upwelling off the Peruvian and Chilean coasts slackens and pelagic fish productivity declines (64). Figure 3*a* plots the ratio of fish meal prices to soy meal prices (a major substitute in livestock feeds) over the past 40 years. Highlighted in this figure are not only the climate-induced changes in relative prices, but also the rising trend in fish meal prices relative to soy meal prices since the late 1990s. The rising trend in the nominal price for fish meal in international markets is shown more closely in Figure 3*b*. In mid-2004, the price of fish meal rose to almost $700/ton, the highest price since the 1997/98 El Niño event and close to the record high (65). This price increase is attributed in large part to diminished anchovy catch in southern Peru and northern Chile and to a strong demand from the aquaculture sector, particularly in China (66). It is possible that the price rise reflects a longer-term trend as opposed to a sudden climatic event. In the short run, the price increase provides a signal to aquaculture producers to substitute with nonfish feeds.

Because feeds account for a large share of variable costs, aquaculturists raising carnivorous species are increasingly substituting plant-based products for fish products in fish feeds (35) but not fast enough to reverse the trend in fish meal use caused by rising aggregate production (67). Several plant-based feed formulations are being developed to lower the use of wild fish inputs, with some studies achieving plant-based substitutions of up to 50% (68). Examples include plant oilseed and grain legume meals, cereal by-product meals, and various protein sources such as single-cell proteins and invertebrate meals (7) (58). Feed formulations based on fish offal (the remains of fish, such as tilapia or catfish, after fillets have been used for human consumption) are also being researched (69, 70). Eventual success of these replacements will depend on improved techniques in feed processing and manufacture (71, 72) and feed formulation (73–75), but the rising price for fish meal will almost certainly accelerate the substitution process (63).

With the rapid expansion of carnivorous species in marine aquaculture, the question posed by Naylor et al. (4) is of continued interest: Does aquaculture provide a net gain or drain on world fish supplies? Tracing the flow of net aquatic primary production that moves through aquaculture (Figure 4) provides a framework for answering this question. The underlying numbers for aquatic primary productivity, fish capture, and fish meal production have not changed significantly since the earlier analysis (4), but the fish meal use numbers and aquaculture production numbers have changed. Using 1997 data, Naylor et al. (4) showed that 10 million metric tons (mmt) of fish caught for feed—just under one third of the total caught for this purpose—was consumed by the aquaculture industry to produce 29 mmt of farmed fish and shellfish. Updating the figure with 2001 data shows that 17 mmt—almost half of the fish caught for feed—is now

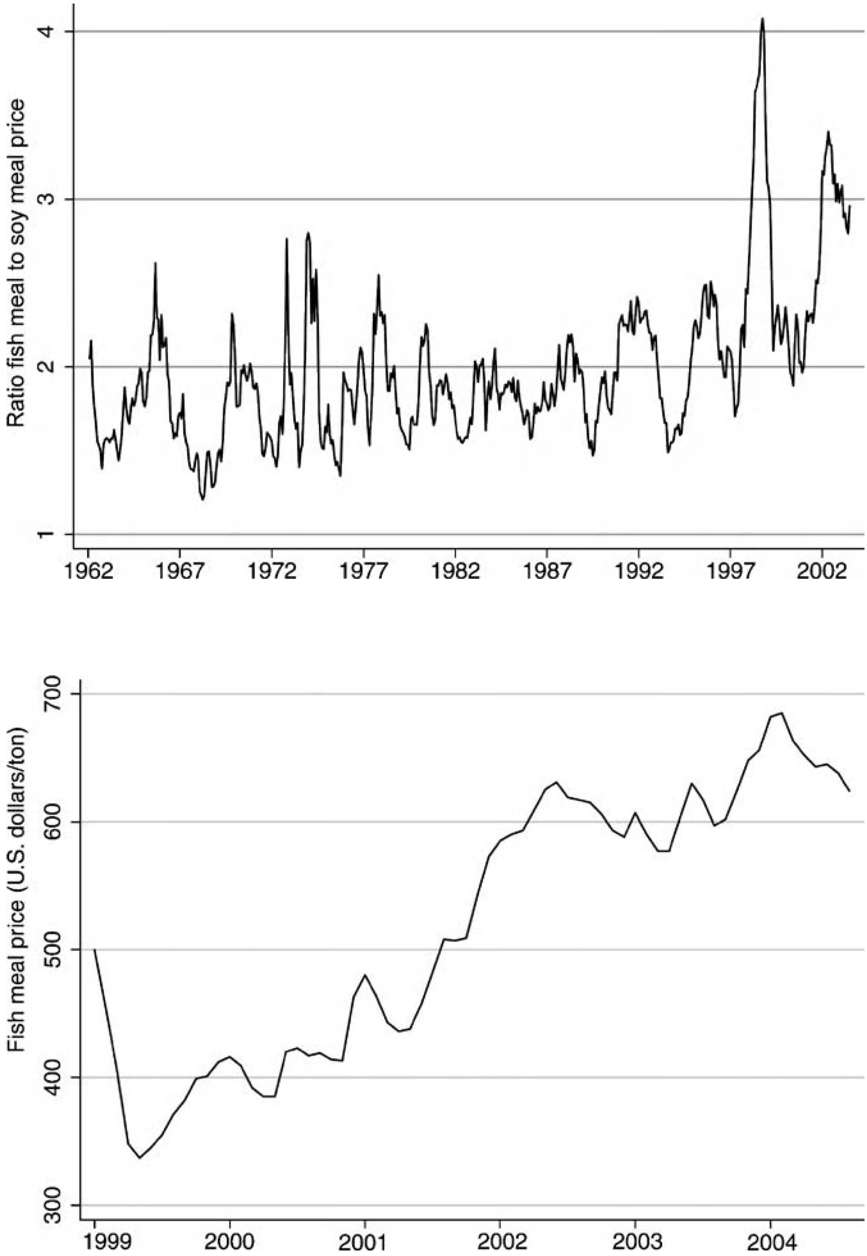

Figure 3 (*a*) Ratio of fish meal to soy meal prices, monthly from 1962–2003, fish meal 64%/65% Hamburg cif (cost, insurance, and freight); soy meal 44%/45% Hamburg fob (free on board) (65). (*b*) Nominal price of fish meal, 1999–2004, 64%/65% Hamburg cif (65).

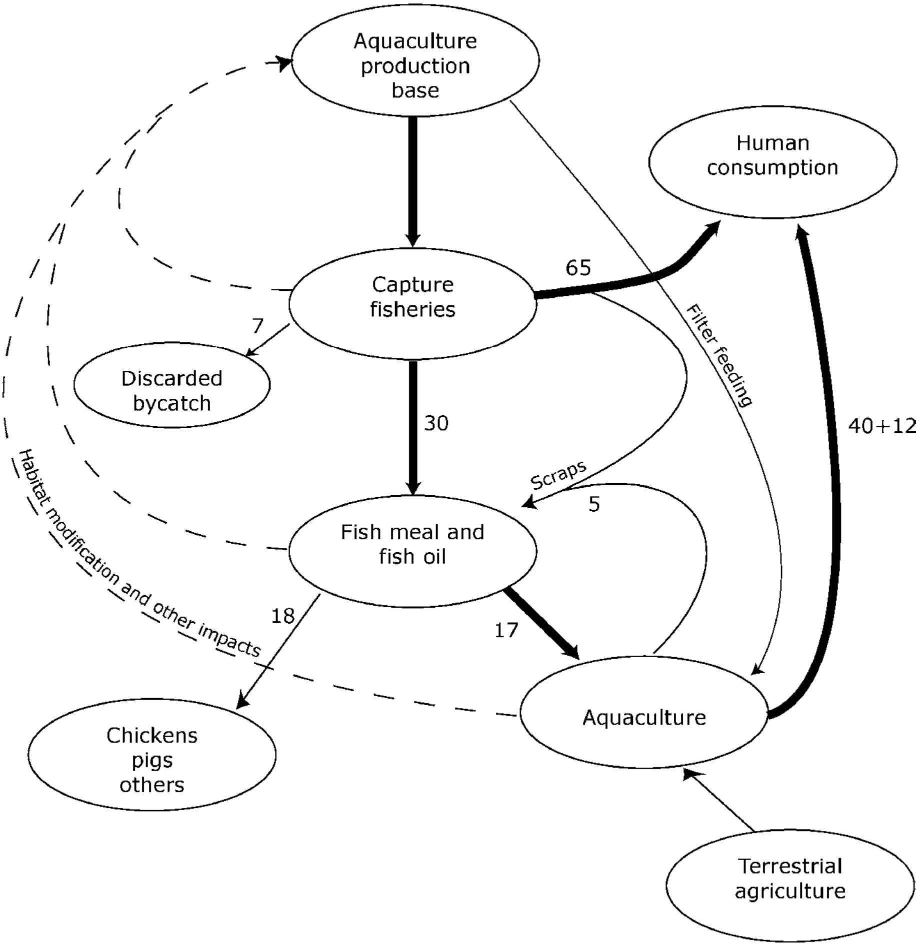

Figure 4 Flow chart of capture and farmed fisheries products from aquatic primary production. Data are the most recent available and are in millions of metric tons. Thicker lines refer to direct flows of aquatic primary production through capture fisheries and aquaculture to humans. Thin lines refer to indirect and minor flows. Dashed lines indicate negative feedbacks on production base.

consumed by aquaculture. Total production of farmed fish and shellfish has risen to 40 mmt, so the net gain in 2001 is 23 mmt of wild fish, compared with 19 mmt in 1997. The fact that the net gain is greater, despite a higher level and share of fish meal use, reflects very rapid growth in the noncarnivorous aquaculture species, such as carps, tilapia, and mollusks. What is masked by the figure, however, is the use of trash fish in feeds.

“Trash fish” are typically a by-product of higher value fish, shellfish, and mollusk but are not always counted in the categories of fish capture, by-catch, or fish meal production. Global use of trash fish is estimated at over 5 mmt, although no hard data for this figure exist (76). Trash fish are sold at a local price depending on the market and may include dozens of species. In Vietnam, for example, there are over 100 species of marine trash fish used in aquaculture feeds (77). The composition of fish is seasonal and depends on the fishing gear used, but most of these fish result from trawling activities. Spoiled fish intended for the commercial market are also used as trash fish. The use of trash fish in Vietnam has been rising with the expansion of marine net cages for grouper and lobster, but it is also used for omnivorous freshwater fish like catfish (77). Data are not available on the use of trash fish in other developing countries, but the rates could be very high, particularly for countries such as China where the aquaculture industry is experiencing explosive growth. If fish meal and fish oil prices remain high or rise further, it is likely that the use of trash fish to feed the new carnivorous species—and even the omnivores—will increase in the future.

Some aquaculturists argue that using trash fish and other pelagic fish low in the food chain to feed large, high trophic level farm fish is desirable because this practice is more efficient than leaving small fish in the ocean to be consumed by larger wild fish in capture fisheries (78). The relative efficiency of fish farming versus capture is difficult to quantify, in part because energy transfer between trophic levels in marine systems is not well documented (4, 9). Nevertheless, fish farming is almost certainly more efficient because farmed fish are protected from mortality sources, such as predators, and they do not have to forage for food. Even if marine finfish aquaculture is comparatively efficient, however, its heavy dependence on wild fish inputs remains economically and ecologically problematic if it is intended to supplement, not replace, capture fisheries (9). Not only is the supply of these low trophic level fish finite, but the small fish used to make fish meal and oil are critical food for wild marine predators, including many commercially valuable fish, marine mammals, and seabirds (4). Managing the oceans for input fish used in feeds, as opposed to output fish such as salmon and cod, is likely to prevail if aquaculture begins to supplant capture fisheries (1, 9). Such an approach might be justified as being economically rational, but it would not be ecologically sound.

ECOLOGICAL IMPACTS OF FARMING MARINE FINFISH

Aquaculture production of marine finfish has potential ecological impacts that go beyond the use of wild fish in feeds (4). The three most widely covered topics in the literature include effluent discharge from farms, which pollutes local marine environments; the escape of farmed fish, which can have detrimental effects on wild fish populations through competition and interbreeding; and the spread of parasites and diseases between wild and farmed fish (6, 9, 79). Other impacts are also important: Tuna and grouper farming, for example, rely on wild juveniles for grow out, and if the scale of production grows without careful regulation of wild fish capture, the breeding stock for these species could be diminished (44). The magnitude of impacts varies considerably among aquaculture systems. Ecological effects of marine finfish aquaculture have been studied most thoroughly for salmon, but research on other carnivorous species is also starting to emerge.

Effluent Discharge

Open net-pen operations release untreated nutrients, and sometimes harmful chemicals and pharmaceuticals, into marine ecosystems, using “dilution as a solution” to water quality problems (6–9). Untreated wastewater laden with uneaten feed and fish feces contributes to nutrient pollution near open net pens (80, 81), particularly in shallow or confined water bodies (82) or in concentrated production areas. In some cases, nitrogen wastes (e.g., ammonia and nitrite) exceed the assimilative capacity of the local marine ecosystem and lead to degenerated water quality that can be toxic to fish and shellfish (83). Moreover, nutrient loading from net pens alters the biogeochemistry of surrounding benthic communities (84); large changes in sediment chemistry and in the benthic community can occur even with relatively low salmon stocking and feeding rates in the early stages of production (8). Although the eutrophication potential of aquaculture remains relatively insignificant on a global scale, nutrient loading by fish farms can be significant on a local scale (6, 9).

Other marine finfish species now being raised in open net pens have similar, if not larger, environmental impacts. Recent published figures by Scotland’s Fisheries Research Services (85) show that farmed cod generates considerably more waste than Atlantic salmon, and waste from farmed turbot is even higher. Farmed salmon discharged on average 48.2 kg of nutrient nitrogen into the surrounding environment per ton of production, compared with 72.3 kg N per ton of farmed cod and 86.9 kg N per ton of farmed turbot. It is estimated that Scotland’s salmon aquaculture industry as a whole produces the same amount of nitrogen waste as would be released from untreated sewage of 3.2 million people (86). As waste from other farming systems, such as cod, are added to these estimates in the future, nitrogen loads are expected to increase.

Effluent from halibut raised in marine environments also tends to have a relatively high impact. Because sea cages for farmed halibut need to be wide, shallow, and in sheltered areas for optimal growth, they can result in heavy loading of solid waste on the sea floor beneath the cage. Models of waste production from farmed halibut indicate an average loss of 66 kg N per ton of fish output (40). Although nutrient waste from farmed halibut and turbot are significantly higher than that of farmed salmon, they are typically raised in land-based tanks where effluents can be treated (39, 87, 88).

The extent of nutrient waste from aquaculture net pens is mainly a function of feed ingredients and uptake efficiency, fish density in net pens, and location and design of pen facilities. A life-cycle assessment of rainbow trout (*Oncorhynchus mykiss*) farming in France showed that nutrient discharge from net pens is significantly lower when plant-based feed ingredients are substituted for fish meal–based feeds, even when "energy/nutrient dense and low polluting feeds" are use for the fish meal feeds (89). The addition of microbial phytase in plant-based aquafeeds can further improve the bioavailability of phosphorous in fish—and hence reduce P waste from farms—although the action of dietary phytase varies among fish species (90).

In salmon aquaculture, improved feeding efficiency—achieved by distributing the feed more directly to the fish and increasing feed uptake and digestion by the fish—has helped to reduce nutrient loading from individual pens during the past decade. Between 15% to 20% of feed used at salmon farms typically enters the surrounding environment uneaten, although this loss has been reduced to 5% in the best-run farms (7). Although improved husbandry practices and FCRs have helped to improve water quality around individual salmon net pens, the growing number and size of farms have contributed to increased pollution in many areas.

Where there is little flushing by tides and currents, net-pen wastes can create a dead zone on the ocean floor that can extend from 100 to 500 feet in diameter (91). Fish farms sited in well-flushed areas often have minimal water quality problems and benthic impacts (92). Dilution of nutrients is often used as a strong argument for moving marine aquaculture out of coastal waters and into offshore cage systems in the open ocean (93). Closed system containment technologies, such as land-based systems or closed-wall sea pens, can also be used to minimize effluent discharge from farms (8, 39). Such technologies may be profitable for farmed halibut at current high prices, but they are currently not profitable for farmed salmon.

Farmed Fish Escapes

A more insidious ecological risk comes from the escape of farmed fish because the real damage—the establishment and invasion of exotic fish—is not usually appreciated until it is too late to reverse. Escapes of farmed fish from pens, both in episodic events and through chronic leakage, are well documented, particularly for salmon (79, 94). Numerous studies show ecological harm from these escapes (79). Depending on the location and species, harms include increased competition for mates, space, and prey (95–98) as well as reduced fitness of wild fish resulting from interbreeding with escaped farmed fish of the same species (96). Wild stock enhancement with hatchery fish that are genetically distinct from their wild cousins can cause similar problems (99–101).

Most literature on the harmful effects of interbreeding between introduced and wild fish focuses on salmon, mainly because salmon have subpopulations adapted genetically to local conditions in river drainages and are prone to reduced fitness from interbreeding with genetically distinct farmed and hatchery fish. Other fish species targeted for marine aquaculture are less differentiated genetically, which may lessen the genetic impact of interbreeding between wild and farmed or hatchery fish. Some marine fish such as Atlantic cod do have distinct subpopulations, however, with little gene flow among them (31, 102). There are also concerns that barramundi and cobia escaping from marine net pens will interbreed with wild populations (7, 54).

Competition between escaped farm fish and wild fish—either of the same or different species—can be significant (79). New species of farmed fish are often grown in areas where they are not indigenous; for example, production of Atlantic salmon now dominates salmon farming in the Pacific as well as the Atlantic, largely because production techniques are well developed for the species and they grow well in captivity. Similarly, Atlantic cod and Atlantic halibut are being targeted for aquaculture growth in the Pacific, even though wild Pacific cod (*Gadus macrocephalus*) and Pacific halibut (*Hippoglossus stenolepis*) are important commercial species and share ecological attributes with their Atlantic congeners, such as overlapping habitat and prey preferences. Naylor et al. (79) show that farmed Atlantic salmon introduced into their native range are more likely to hybridize and exhibit greater competition with wild salmon than would be the case for escaped Atlantic salmon in the Pacific. The verdict is not yet in, however, on how aggressive escaped farmed Atlantic salmon will be in the Pacific. Incipient feral Atlantic salmon populations have been found in at least three British Columbia rivers (103), and Atlantic salmon may establish in Chile, where the industry is growing rapidly. Several feral populations of Pacific salmon have already become established in Chile (104). In both the Atlantic and Pacific regions, biological risks to wild populations rise with the number of farm escapes and are highest when farm escapees outnumber wild salmon in a given location (79).

Potential ecological impacts from farmed fish escapes will gain even more significance if transgenic fish—whose genetic coding is very different from that of wild fish—are introduced for commercial production into open net-pen culture (105–107). Patented, transgenic Atlantic salmon are currently proposed for commercial aquaculture production in the United States and are under premarket review by the U.S. Food and Drug Administration. Model results have demonstrated three possible outcomes for wild populations following the introduction of transgenic fish: elimination of the transgene, successful invasion, and extinction of the recipient wild population (108–110). The uncertainties and risks associated with raising transgenic salmon and other marine finfish in open net pens are therefore large.

Transmission of Parasites and Diseases

Many diseases and parasites are capable of spreading between farmed fish and wild stocks and can alter community structures within ecosystems (6). Dense cultures of fish can lead to disease epidemics, a shedding of pathogens into the environment, and hence to a higher prevalence of disease overall (79, 111). Transmission of pathogens and diseases from aquaculture to vulnerable wild fish can occur through infections at the hatchery source, contact with wild hosts of the disease, infected escapees, and wild fish migrating or moving within plumes of an infected pen or disease outbreak (79). In many cases, pathogens originate from wild populations but reach epidemic proportions in intensively cultivated net pens.

One of the largest parasite threats associated with salmon aquaculture in the Northern Hemisphere is sea (or salmon) lice (*Lepeophtheirus salmonis*, *Caligus* spp.), which can kill fish by essentially eating their flesh (6, 8). Sea lice have a low natural abundance and minimal host damage in the wild, and there is only one pre-aquaculture report of an epizootic spread of sea lice in the wild (112). Recent epidemiological patterns in Ireland, Scotland, Norway, and Canada suggest that outbreaks of sea lice in wild fish are connected with the increased concentration of aquaculture (8). Once sea lice reach a farm, the extent of infection can be substantial. Krkosek et al. (113) demonstrate that the shedding of sea lice from a single farm in British Columbia can lead to infection pressure near the farm that is up to 73 times greater than ambient levels and exceeds ambient levels for 30 kilometers along two wild salmon migration corridors in the vicinity of the farm. Salmon lice can also transfer highly virulent infectious salmon anemia (ISA) between fish (114). ISA has been detected in fish farms in Norway, Canada, Scotland, and the United States, as well as other countries. Chemicals can be used to control sea lice and other pathogens, but there are some risks of harm to surrounding marine organisms (6).

In addition to problems of sea lice, various bacterial and viral diseases affecting fish health are prevalent in salmon aquaculture (8). Bacterial diseases include bacterial kidney disease, vibriosis, and furunculosis. Fish are commonly vaccinated in hatcheries for these diseases, and when outbreaks occur, antibiotics can be administered in the feed pellets. Infectious hematopoietic necrosis (IHN) is a serious viral disease in the Pacific Northwest, where it has attacked Atlantic salmon and Pacific sockeye salmon populations (8). The disease appears to be transmitted in both directions between wild and farm salmon. Pathogens are also a problem in other culture systems; for example, farmed cod are susceptible to vibriosis and sea lice (32). Veterinary certification of aquaculture stock is important in minimizing the spread of fish disease (115) but not fail-safe. Reducing fish stress in net pens and filtering effluent from recirculating tank systems can also help minimize disease transmission (6).

Other evidence suggests that the movement of aquaculture feeds around the world can be an important vector for disease transmission between stocks vastly separated in space (47, 116). Shipments of sardines and pilchards to Australia in the mid- to late 1990s for ranched tuna feed are thought to have carried diseases that nearly decimated local sardine and pilchard fisheries and caused seabirds to starve (47).

The use of antibiotics for disease control has declined in highly developed salmon farming regions such as Norway because vaccines have been developed (7). Antibiotics are typically administered in feeds and can enter the water through uneaten food or feces. Depending on the treatment, they can accumulate beneath net pens where fish have been treated and persist from one day to one and a half years (7). Antibiotics to control disease, antibiotic resistant bacteria, and parasiticide drugs to control sea lice have been shown to accumulate in and may impact nontarget species (6, 117). Although the treatment of farmed salmon has become more sophisticated over time, the impacts of disease, parasite outbreaks, and treatment for new finfish species farmed in open net pens remains uncertain.

OFFSHORE AQUACULTURE

Ecological considerations have been one motivation for governments and the aquaculture industry to look further offshore for farming opportunities. Offshore aquaculture (also known as open-ocean aquaculture) generally refers to marine farming systems located in areas with large currents and rough waters, often several miles from shore. There has been some international experience with offshore aquaculture to date, and the United States recently has positioned itself as a key player in the development of the practice (118). In the United States, offshore aquaculture often refers specifically to marine farming systems outside of the 3-mile state jurisdiction and within the 200-mile EEZ under federal jurisdiction (19). Some exceptions exist, such as commercial moi farming in ocean cages a few miles offshore but within Hawaii state waters, and proposed offshore cages tied to decommissioned oil rigs for halibut, tuna, and striped bass off the California coast (47).

Benefits and Constraints

Offshore aquaculture has several perceived benefits, particularly in the United States. Many of the best aquaculture sites near shore are already developed, and near shore farming operations often conflict with local fisheries, recreational activity, and coastal aesthetics (19, 118, 119). In addition, moving aquaculture facilities to less polluted marine environments offshore can improve the quality of the product (119, 120). With high flushing rates in the open ocean, the impact of effluents from aquaculture production on benthic communities can also be reduced (121). Finally, offshore aquaculture facilities can be sited beyond the reach of constraining state laws and within the control of federal authorities. The Department of Commerce has articulated the need to reverse the large $7 billion U.S. seafood deficit (19, 25), and under the leadership of its subagency, NOAA, has a stated goal of increasing the value of the U.S. aquaculture industry from less than $1 billion currently to $5 billion by 2025 (122).

Despite the move beyond state boundaries, the regulatory environment for offshore aquaculture in the United States remains stifling. New firms applying for federal leases are currently required to apply for permits under at least four federal agencies, and there is no existing regulatory infrastructure that can assure secure tenure and exclusive use of space (19, 123). Proposed legislation would streamline the permitting process for offshore aquaculture leases, and the U.S. Oceans Commission (19) has also recommended that NOAA be designated as the lead agency for managing aquaculture in the EEZ. Some critics argue that this would create an undesirable conflict of interest, as NOAA would become both the chief promoter and regulator of aquaculture activities (124).

Moreover, offshore operations can be expensive. They require sturdier infrastructure than nearshore systems, they are more difficult to access, and the labor costs are typically higher than for coastal systems (119, 123, 125). Economic constraints suggest that firms are likely to target lucrative species for large-scale operations or niche markets (125).

Development and Use of Offshore Technology

The model of lucrative species in large-scale systems has been used for offshore ranching of bluefin tuna in Australia, Mexico, and the Mediterranean (47). Unlike the current tuna systems, however, which contain open net pens at the ocean's surface (similar to current salmon farming operations), the new technology for most offshore aquaculture uses submersible cages. These cages are anchored to the ocean floor but can be moved within the water column, they are tethered to buoys that contain an equipment room and feeding mechanism, and they can be large enough to hold hundreds of thousands of fish in a single cage (126). Robotics are often used for cage maintenance, inspection, cleaning, and monitoring. Submersible cages have the advantage of avoiding rough water at the surface and reducing interference with navigation.

In North America, three commercial operations (two in the United States and one in the Bahamas) using submersible cages are in operation, all raising high-valued carnivorous finfish species (e.g., moi, cobia, mutton snapper). Submersible cages are also being used in experimental systems for halibut, haddock, cod, and summer flounder in New Hampshire waters, and for amberjack, red drum, snapper, pompano, and cobia in the Gulf of Mexico. Ireland has been experimenting with submersible offshore technology for salmon since the late 1990s with apparent success (118). The technology is also being developed in waters near China, the Philippines, Portugal, and Spain for a variety of high-valued finfish species (126).

Offshore technology design is progressing quickly with the goals of lowering costs and risks of infrastructure damage (126). Plans are underway to build a 20-ton buoy for submersible systems that will contain equipment for automatically feeding and monitoring fish for weeks at a time. The next generation technology also includes a gigantic cage that will travel hundreds of miles offshore and roam the seas instead of remaining fixed to a buoy. Juvenile tuna placed in roaming cages in Mexico could conceivably arrive in Japan ready for market sales several months later. Roaming cage technology is still in the conceptual stage and will likely meet difficult legal and regulatory constraints as it develops for commercial use (126). The United States currently plays a leading role in offshore technology research and design, as does Spain where both submerged and roaming technologies are being developed (127).

Ecological Effects of Offshore Aquaculture

Because offshore aquaculture is largely in the experimental phase of development, its ecological impacts have not been well documented. One of the touted benefits for offshore aquaculture is the reduction of pollution and benthic stress. In an ongoing demonstration project off the coast of New Hampshire, benthic conditions underneath the facilities have remained unharmed (128), although stocking levels are lower than they would be in a commercial operation (e.g., about 3000 fish as opposed to 200,000 fish on a salmon farm). Commercial offshore cages for moi in Hawaii have also not significantly altered the benthic environment, even with stocking levels at about 130,000 fish (129). The potential for nutrient pollution and benthic damage further offshore will depend on flushing rates, the depth of cage submersion, the scale of the farming operation, and feed efficiency for the species being raised.

Submersible offshore cages are designed to avoid storm damage and are thus less likely to result in massive escape events caused by weather like nearshore systems (120). To date, the moi operation in Hawaii and the cobia operation in the Bahamas have survived major storms without any damage or known escapes. A submersible cage in the Gulf of Mexico managed to break away from its mooring, however, and drifted for some time before recovery (120); no escapes were mentioned in this episode. Although the cost of offshore systems places a large premium on avoiding escape events, escapes are nonetheless likely to occur as the offshore industry develops commercially. The impacts of such events on native species could be large, regardless of whether the farmed fish are within or outside of their native range. At least two of the candidate species in the Gulf of Mexico (red drum and red snapper), as well as cod in the North Atlantic, have distinct subpopulations (102, 123, 130) and could therefore cause ecological harm if farmed fish escape from cages. Furthermore, cod are known to produce fertilized eggs in ocean enclosures (131), and even though ocean cages used for offshore farming are more secure than typical salmon net pens, neither pens nor cages will contain fish eggs. Thus farming certain species might lead to "escapes" on a much larger scale than with salmon farming.

Another risk is posed by the transmission of fish diseases, but there is currently no evidence for disease problems in submerged cages. Nonetheless, new species—for which minimal ecological and epidemiological knowledge exists on their potential diseases—are now being farmed in offshore cages. In general, large-scale aquaculture provides opportunities for the emergence of an expanding array of diseases: It removes fish from their natural environment; exposes them to pathogens, which they may not naturally encounter; imposes stresses that compromise their ability to contain infection; and provides ideal conditions for the rapid transmission of infectious agents and diseases (116). Carnivorous aquaculture production also leads to trade in live aquatic animals for bait, broodstock, milt, and other breeding and production purposes, which inevitably results in transboundary spread of disease (116). The implications of open-ocean farming for pathogen transmission between farmed and wild organisms remain a large and unanswered question (116). Moreover, pathogen transmission in the oceans is likely to shift in unpredictable ways in response to other anthropogenic stressors, particularly climate change (132).

The most obvious ecological effect of offshore aquaculture results from its use of wild fish in feeds. Most of the species being raised in offshore systems are carnivorous and are at or above the trophic level for salmon (133). If offshore aquaculture continues to grow in this direction—a likely scenario to offset large investment costs—the food web effects on ecosystems vastly separated in space could be significant.

IMPLICATIONS FOR SOCIAL WELFARE

Increasing production of farmed carnivorous fish in coastal and open-ocean ecosystems has important implications for human health, employment, incomes, and public use of the marine environment. These issues remain controversial and warrant further scientific, economic, and policy research.

Health Effects

The health benefits of eating fish such as salmon have been well documented, but the health risks are just beginning to be quantified (7, 134). Because salmon are relatively fatty carnivorous fish that feed high on the food web, they bioaccumulate organic contaminants, including PCBs (polychlorinated biphenyls) and dioxins. Recent research by Hites et al. (134) shows that farmed salmon feeding on pelagic fish caught in polluted waters, such as the North Sea, have higher contaminant loads than farmed salmon feeding on fish from more pristine waters, such as the Southern and North American coasts. In both cases, contaminant loads in farmed salmon are generally higher than in wild salmon. Although contaminant loads for any given organic compound are below the tolerance levels approved by the U.S. Food and Drug Administration, they exceed levels considered safe by the Environmental Protection Agency for frequent consumption. Moreover, the combined effects of several contaminants concentrated in a single product may still pose significant risks to human health, particularly if farmed salmon is consumed on a regular basis (134, 135).

The health benefits of consuming omega-3 polyunsaturated fatty acids also need to be considered (135, 136). Moving toward a vegetarian diet for marine finfish could reduce these health benefits, although studies are underway to retain omega-3 fatty acids with a reduction in the amount of fish meal and fish oil inputs in feeds (4, 35, 63, 137–139).

The potential health effects from added chemicals are also a concern for consumers. Shipments of frozen salmon from Chile were found in Europe in 2003 with unsafe quantities of malachite green, a carcinogenic fungicide prohibited for salmon farm use in Chile since 1995 and widely prohibited around the world (28). Japan also suspended imports of some Chilean salmon in 2003 owing to antibiotic loads higher than are permitted under Japan's health code (28). The main worry with excessive antibiotic use in aquaculture is that over time it promotes the spread of resistance in both human and fish pathogens (6). Antibiotic use is said to have declined on farms, especially in advanced regions such as Norway, but the full extent of antibiotic use in the industry is unclear (28).

Finally, consumer-related concerns over the use of colorants in salmon feeds to produce desired flesh tones are also widely debated (140, 141). The health effects of colorants are not thought to be too severe; the only proven side effects of moderate overdosage of the natural dye, canthaxanthin, by humans is reversible deposition of crystals in the eye (8). Although the colorant issue will not likely arise in the production of most other farmed carnivorous finfish whose natural flesh colors in the wild are not bright like that of salmon, the contaminant issue is expected to remain controversial, particularly for the more fatty farmed fish.

Employment and Income Effects

The net employment gains from growth in marine aquaculture are also controversial. Governments have often promoted aquaculture for the purpose of employment and income generation, particularly in cases where wild fish stocks have been depleted or market conditions for fisheries are weak. In Canada, salmon farming has been promoted for these reasons (8), and the same rationale is now being used for the promotion of black cod and halibut (36). The European Union announced plans in 2003 to create 10,000 more jobs, mainly in areas where commercial fishing is in decline, through a projected 4% annual growth in aquaculture production of cod, haddock, and other marine finfish. In some coastal regions of Scotland and Norway, the salmon farming industry is the largest private-sector employer. In Maine, communities that once relied on incomes from (now-collapsed) wild fisheries also benefit from employment in the salmon aquaculture industry.

At a broader scale, the salmon farming experience has shown that employment and income loss in the fish capture industry may be as large, if not larger, than employment and income generation for coastal residents in aquaculture (8, 79, 142). There are no guarantees that fishermen who lose their jobs because of overfishing or as a direct or indirect result of aquaculture growth will move into the aquaculture industry. In Canada, most of the aggregate gains in aquaculture-related employment have been concentrated in areas where the hatcheries and processing facilities are located, and large multinational companies that control ownership of the salmon farming industry have captured a sizeable share of the sector's income gains (8).

Aquaculture systems that only encompass grow-out operations do not necessarily benefit coastal communities (143). Intensive aquaculture production that lacks community roots and that depends on supplies of feeds, larvae, supplies, equipment, and human experience imported from areas distant from the production site rarely have substantial income multiplier effects and may thus be opposed by local communities (144). With the expected expansion of offshore aquaculture, jobs will more likely be concentrated in the processing industries than at the grow-out facilities, and it is unlikely that employment and income gains will be distributed widely among coastal communities that have lost incomes from a declining fisheries sector.

Rights to Marine Resources

In addition to concerns over health and rural incomes, there are some important ethical issues affecting society that result from the growth in marine finfish aquaculture, particularly offshore aquaculture. One such issue concerns the way in which the U.S. federal government is charged with the management of national resources. Under the public trust doctrine, the nation's land, water, and resources are to be managed by the federal government in a way that benefits all, and the government is to be properly compensated for any private use of public resources (145). Some fear that the U.S. Department of Commerce's aggressive promotion of aquaculture in federal waters will encourage aquaculture practices that benefit only a narrow constituency and that the government (and thus the public) will not be appropriately compensated for the private use of, or harm to, ocean resources (118, 124).

On a global scale, expanding the production of farmed fish high on the food chain for markets directed toward wealthy consumers has implications for some of the world's poorest consumers, who consume pelagic fish directly for protein or who consume fish that directly depend on pelagic species (4). Although some fish used for fish meal and fish oil, such as menhaden, are distasteful to humans, the demand for small pelagic fish for direct human consumption is likely to increase with population growth in the developing world (1).

A FUTURE VISION FOR MARINE AQUACULTURE

Ocean resources are in jeopardy given current trends in fish production. Many capture fisheries are in decline, and marine finfish aquaculture—often considered to be the solution to problems of overfishing and other human stresses on the marine environment—poses additional risks to wild fish stocks. Marine finfish aquaculture is heavily dependent on wild capture for fish meal and fish oil inputs; it pollutes marine waters through nutrient, and sometimes chemical and pharmaceutical discharges; and it potentially threatens native fish populations via disease and parasite transmission and the escape of farmed fish from net pens into the wild. At the same time, aquaculture is essentially the only avenue to produce more fish from the oceans, and the industry appears to be responsive to new technologies and management practices that reduce stress on the oceans. The current process of diversification into new finfish species and the prospect of moving operations into the open ocean provide an opportune time to rethink the present approach toward marine finfish aquaculture.

As marine finfish aquaculture grows in response to market opportunities, improved science and technology, and public sector encouragement, there is a need to marry an ecosystem-based management approach with a sound business approach. A private-sector business approach to marine aquaculture without ecological management principles is not sustainable in the long run. Likewise, an ecosystem-based management approach implemented without proper attention to business incentives is not feasible. Governments have an important role to play in integrating business and ecosystem ideals, lest they face collapse both in wild fisheries and marine aquaculture, as well as further damage to marine ecosystems. At the same time, an international agreement among aquaculture-producing countries could help to "level the playing field" and promote environmentally sound practices (8). Establishment of universal, certifiable best practices for marine finfish farming is in the long-term interest of both the aquaculture industry and the conservation community.

What is required to embody an ecologically sound system for marine finfish farming? Costa-Pierce (143) characterizes "ecological aquaculture" by the following six criteria: preservation of natural ecosystem form and function; trophic level efficiency; nutrient management and the absence of harmful chemicals and antibiotics; avoidance of farmed fish escapes; community participation in production system; and contribution to social welfare globally without proprietary control over resources. Several firms within the aquaculture industry are attempting to integrate at least some of these ecological and social principles into their business plans. Attention toward these goals is driven by the need to cut costs, settle local social or environmental controversies, meet regulatory requirements, or capture a greater market share through an improved social and environmental reputation. Labeling systems are beginning to be developed to help consumers identify sustainable and healthy aquaculture products, but at present there are no widely known or accepted labeling programs akin to the U.S. Department of Agriculture organic standards for agricultural products or the Marine Stewardship Council label for captured fish products (8).

Three key steps could help promote sustainability of marine finfish aquaculture: the identification of lower trophic level marine finfish with strong market potential and suitability for farming, the continued move toward vegetable-based feeds, and farming fish apart from the environment where their wild counterparts live (e.g., through more widespread use of land-based tanks or enclosed bag net pens) (9). In addition, promoting integrated aquaculture, in which mussels, seaweeds, and other species are grown in close proximity with finfish for waste recycling, could help to reduce nutrient pollution (4, 146). Several ecologically integrated marine aquaculture systems currently exist (143), but the commercial viability of such systems depends on larger scale experimentation and further investigation of the interactions and processes among jointly cultured species (9, 147).

Despite the numerous environmental and social impacts of marine finfish aquaculture reviewed in this paper, governments in most countries participating in this segment of the market have yet to implement and enforce comprehensive measures to protect coastal ecosystems and communities (8, 79). The Pew Oceans Commission (18) has called for a moratorium on the expansion of marine finfish farms in the United States until national standards and permitting authority are established for siting, design, and operation of ecologically sustainable marine aquaculture facilities. The establishment of ecologically based standards is particularly important before NOAA's policies concerning offshore aquaculture development are implemented (9). Mandatory—as opposed to voluntary—adherence to standards is needed where irreversible environmental damages are at stake, for instance when the escape and invasion of exotic farmed fish threaten marine ecosystems (8). Meanwhile, nongovernmental organizations (NGOs) have an important role to play in monitoring local conditions and informing the public. The main challenge for all parties—the public, private, and NGO communities—is to entwine principles of economics and ecology within the field of marine aquaculture before the toll on ocean resources becomes too great.

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