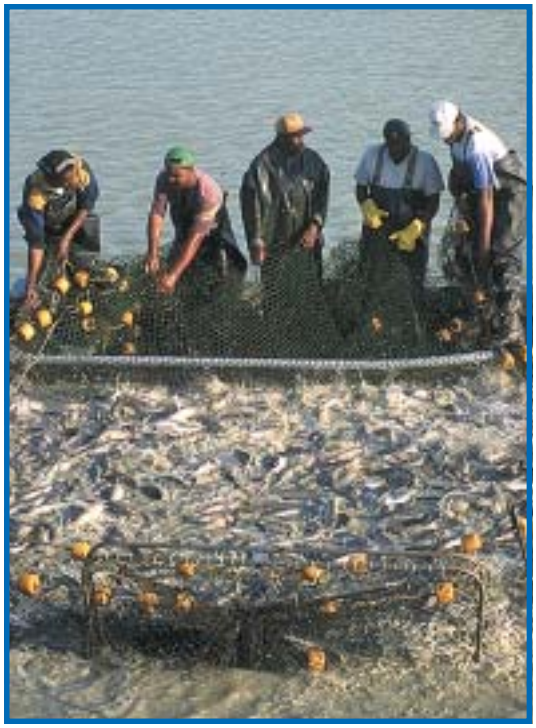
Issues in Ecology

Effects of Aquaculture on World Fish Supplies



Effects of Aquaculture on World Fish Supplies

SUMMARY

Global production of farmed fish, shrimp, clams, and oysters more than doubled in weight and value during the 1990s while landings of wild-caught fish remained level. Many people look to this growth in aquaculture to relieve pressure on ocean fish stocks, most of which are now fished at or beyond capacity, and to allow wild populations to recover. Production of farmed fish and shellfish does increase world fish supplies. Yet by using increasing amounts of wild-caught fish to feed farmed shrimp and salmon, and even to fortify the feed of herbivorous fish such as carp, some sectors of the aquaculture industry are actually increasing the pressure on ocean fish populations.

The available scientific evidence indicates that some types of aquaculture are on a destructive path that poses a threat not only to wild fish stocks but also to the industry's own long-term potential. One of the most disturbing trends is the rapid expansion and intensification of shrimp and salmon farming and culture of other high-value carnivorous marine fish such as cod, seabass, and tuna. Production of a single kilogram of these species typically uses two to five kilograms of wild-caught fish processed into fish meal and fish oil for feed.

Besides this direct impact on wild fish stocks, some aquaculture as currently practiced degrades the marine environment and diminishes the ecological life support services it provides to fish, marine mammals, and seabirds, as well as humans. These impacts include

- Destruction of hundreds of thousands of hectares of mangrove forests and coastal wetlands for construction of aquaculture facilities
- Use of wild-caught rather than hatchery-reared finfish or shellfish fry to stock captive operations, a practice that often leads to a high rate of discarded bycatch of other species
- Heavy fishing pressure on small ocean fish such as anchovies for use as fish meal, which can deplete food for wild fish such as cod, as well as seals and seabirds
- Transport of fish diseases into new waters and escapes of non-native fish that may hybridize or compete with native wild fish

As aquaculture production continues to expand and intensify, both its reliance and its impact on ocean fisheries are likely to increase. The balance between farmed and wild-caught fish, as well as the total supply of fish available for human consumption, will depend on future trends in aquaculture practices. If the goal of aquaculture is to produce more fish for consumers than can be produced naturally, then it will become increasingly counterproductive to farm carnivores that must be fed large amounts of wild-caught fish that form the foundation of the ocean food chain. Indeed, non-carnivorous species such as marine mollusks and carps account for most of the current net gain in world fish supplies from aquaculture.

Without clear recognition of its dependence on natural ecosystems, the aquaculture industry is unlikely to develop to its full potential or continue to supplement ocean fisheries. We recommend the adoption of four priority goals for aquaculture:

- Encourage farming of species lower on the food web – that is, fish with herbivorous or omnivorous diets or filter feeders such as oysters
- Improve feed management and efficiency in industrial aquaculture systems and develop substitutes for fish-derived feed ingredients
- Develop integrated fish farming systems that use multiple species to reduce costs and wastes while increasing productivity
- Promote environmentally sound aquaculture practices and resource management

Governments have a key role to play in developing regulations to protect coastal ecosystems and in reexamining subsidies to unsustainable marine fisheries. Development agencies are strategically placed to help in developing and implementing sustainable production practices and in financing otherwise economically and socially unattainable reforms in developing countries. If public and private interests act jointly to reduce the environmental costs generated by fish farming, present unsustainable trends can be reversed and aquaculture can make an increasingly positive contribution to global fish supplies.

Cover (clockwise from top): shrimp ponds in Honduras (courtesy CODDEFFAGOLF); basket of milkfish (J. Primavera); harvesting catfish in Mississippi (K. Hammond, courtesy USDA).

Effects of Aquaculture on World Fish Supplies

by Rosamond L. Naylor, Rebecca J. Goldburg, Jurgenne Primavera, Nils Kautsky, Malcolm C. M. Beveridge, Jason Clay, Carl Folke, Jane Lubchenco, Harold Mooney, and Max Troell

INTRODUCTION

Global production of farmed fish and shellfish has more than doubled in weight and value during the past 15 years, growing from 10 million metric tons or megatons (Mt) in the late 1980s to 29 Mt in 1997. Meanwhile, harvests of ocean fish have remained at around 85 to 95 Mt, and there is wide acknowledgment that most wild fish stocks are either over-fished or fished at maximum capacity. Today aquaculture — the farming of fish, shrimp, clams, and oysters — supplies more than one-fourth of all fish that humans eat. Many people believe continued growth in aquaculture will relieve pressure on deteriorating wild fish stocks, allowing their populations to recover while supplying an ever-increasing demand for protein to nourish a growing human population.

Current trends in the aquaculture industry, however, do not support that belief. As practiced today, aquaculture is a mixed blessing for the sustainability of ocean fisheries. The diversity of production systems leads to an underlying paradox: aquaculture is a possible solution, but also a contributing factor, to the collapse of fisheries stocks worldwide.

The farming of carnivorous species such as salmon and shrimp, for example, requires vast quantities of wild-caught fish to feed confined stocks — indeed, the norm is that two to five kilograms of wild fish biomass are required to produce a single kilogram of these high-market-value species. Confining large numbers of fish in coastal waters, especially in mangroves and wetlands, can also degrade the marine environment and threaten wild species by destroying nursery habitat, generating large quantities of nutrients and other wastes, importing diseases that can spread to wild fish, or allowing exotic species to escape and thus compete or hybridize with wild fish.

In contrast, the farming of species such as carp and tilapia that can eat aquatic plants, or oysters, clams, and mussels that filter plankton from the water, can make a large contribution to global fish supplies and food security. However, the trend toward industrial-scale production of carp and other herbivores — and omnivores such as tilapia, catfish, and some varieties of shrimp — has led to increasing use of manufactured feed that incorporates fish meal and fish oil.

Despite the surge in production of farmed fish, the tonnage of wild fish harvested has not declined. Moreover, as catches of large, valuable carnivorous fish such as cod and haddock have decreased, there has been a gradual shift to harvest of smaller, less valuable species such as anchovy — species destined, in fact, to be ground into fish meal or fish oil for use in manufacturing feed for livestock and farmed fish. Between 1986 and 1997, four of the top five, and eight of the top 20 wild species harvested from the ocean were small fishes used in production of animal feed: anchoveta, Chilean jack mackerel, Atlantic herring, chub mackerel, Japanese anchovy, round sardinella, Atlantic mackerel, and European anchovy.

As aquaculture production continues to increase and intensify, both its reliance and impact on ocean fisheries are likely to expand even further. The future balance between farmed and wild-caught fish, the total supply of fish available for human consumption, and the very health of the marine environment will depend on trends in aquaculture practices.

AQUACULTURE IS A DIVERSE ACTIVITY

Three-fourths of global aquaculture production by weight involves finfish and shellfish; the other fourth is seaweed. Worldwide, more than 220 species of finfish and shellfish are farmed. The range of species includes giant clams that obtain most of their nourishment from symbiotic algae, mussels that filter plankton from the water, carps that largely graze on plants, and salmon that prey on smaller fish (Figure 1). Typically, the farmed species are enclosed in a secure system such as a pond or floating pen in which they can be raised under suitable conditions, sheltered from predators and competitors, and sometimes fed and medicated with antibiotics and other drugs. As the intensity of an aquaculture operation increases, fish are confined at higher densities, supplied with all nutritional requirements, and managed more

Figure 1 — Salmon are farmed in floating ponds where they can be raised under managed conditions. (Photo: G. Daigle, Multi Images, Inc).

heavily. The more intensive the operation, of course, the larger the volume of wastes generated and the greater the possibilities for the spread of disease.

From one aquaculture operation to another, the intensity of culture practices and their impacts on marine ecosystems vary widely (Figure 2). Clams, oysters, and other mollusks are generally farmed along coastlines, with wild-caught or hatchery-reared seed grown on the sea floor or on suspended nets, ropes, or other structures. The animals feed entirely on ambient supplies of plankton and organic particles in the water. Finfish may be farmed in ponds, tanks, or cages. Most marine fish and species such as salmon that migrate between fresh and salt water are reared in floating net cages near shore, and all their nutrition is supplied by formulated feeds. Carp, catfish, and other freshwater finfish are usually grown in ponds, often integrated within agricultural settings. Crustacean farming is dominated by shrimp, which are grown in coastal ponds. Farming of both shrimp and freshwater finfish varies greatly from one operation to another in intensity and in reliance on formulated feeds.

In the past decade, two distinct sectors have emerged within this diverse industry. The first includes commercial farms that rely on intensive and semi-intensive methods to produce commodities for regional or global markets. The second encompasses family and cooperative farms that rely on less intensive practices to produce low-value species for household subsistence or local markets. The line between these sectors is growing more blurred, however. In China and other parts of Asia, for example, many small-scale farming operations are intensifying as land and water resources become increasingly scarce and valuable.

Asia produces roughly 90 percent of global aquaculture output, and China alone contributes more than two-thirds of the total. Although Europe, North America, and Japan together produce just over one-tenth of the global total, these regions consume the bulk of farmed seafood that is traded internationally.

Various species of carp dominate the tonnage of farmed fish produced worldwide, and carp production for local or regional use by relatively low-income households has increased dramatically in Asia (mainly China). In contrast, increased volumes of salmon, shrimp, and other high-value species are marketed mainly in industrialized countries. Farmed output and markets for other lower-value species such as tilapia and milkfish have increased in both developing and industrialized countries. Most farmed mollusks are still consumed locally and regionally in China and in other developing countries. However, production of certain species for global markets has increased in several developed countries. These species include the Pacific cupped oyster, blue mussel, New Zealand mussel, and Yesso scallop.

Figure 2 — Aquaculture is a diverse activity with a range of species such as catfish and tiger prawns. From one aquaculture operation to another, the intensity and impacts vary widely. (Photos: K. Hammond, courtesy USDA (top) and J. Primavera (bottom).

FEEDING FISH TO FISH

Many intensive and semi-intensive aquaculture systems use two to five times more fish protein, in the form of fish meal and fish oil, to feed the farmed animals than is produced in the form of farmed fish. By contrast, so-called extensive or traditional aquaculture systems use little or no fish meal or fish oil, although operators often add nutrient-rich materials such as crop wastes to the water to stimulate growth of algae and other naturally available organisms on which the fish feed.

Worldwide, about 80 percent of carp and 65 percent of tilapia are farmed without the use of modern compound feeds – that is, feeds formulated from multiple ingredients. In China, however, farmed production of carp and other omnivorous species is intensifying, and new commercial feed mills are being developed to serve this industry. China is also the largest importer of fish meal in the world. Such intensive systems, including U.S. catfish farms, must rely heavily on added feeds because fish are stocked at higher densities than can be supported by natural food sources. Generally these operations use compound feeds that contain high percentages of protein supplements from soybean meal, cottonseed meal, and peanut meal. But compound feeds for herbivorous and omnivorous fish can also contain low to moderate levels of protein obtained from fish and terrestrial animals.

By contrast, fish meal and fish oil are dominant ingredients in compound feeds for carnivorous fish and shrimp. These two ingredients supply essential amino acids (that is, lysine and methionine) that are deficient

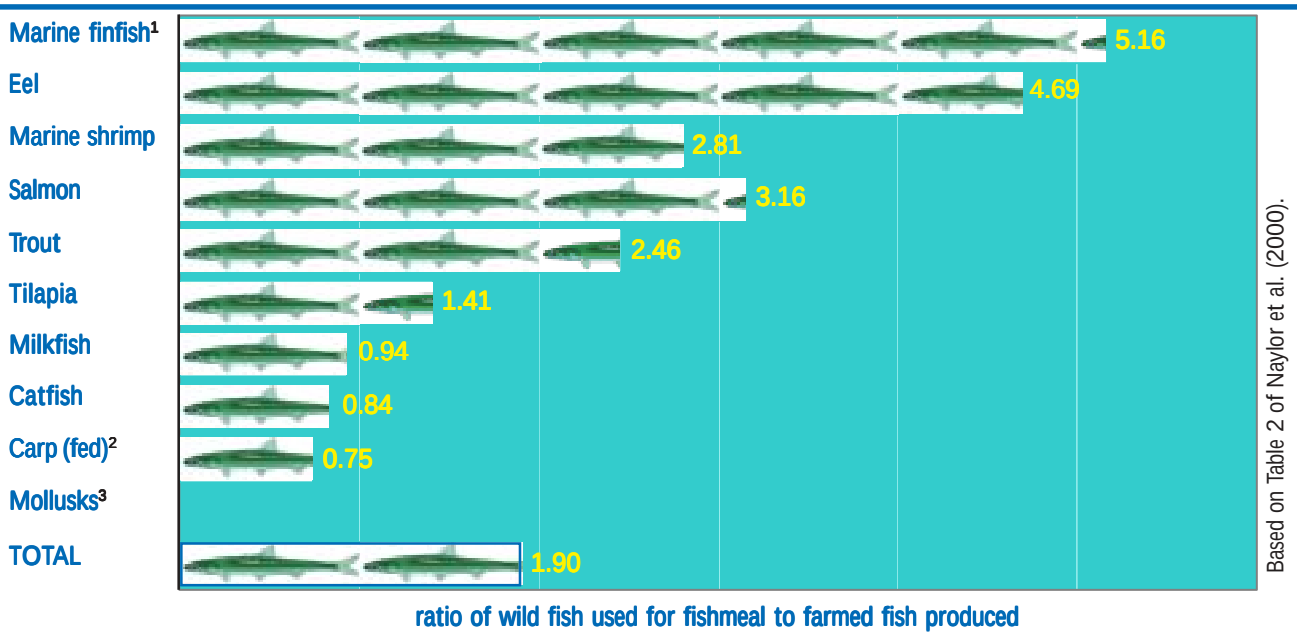


Figure 3 — Wild fish inputs used in feeds for the ten types of fish and shellfish most commonly farmed in 1997 presented as the ratio of wild fish used for fishmeal to farmed fish produced using compound feeds. In calculating the amount of wild fish used in compound feeds, we assumed a 5:1 conversion rate of fish to fishmeal and that one-sixteenth of fishmeal is obtained from processing by-products. [1]Marine finfish (other than salmon, which is listed separately because of its market significance) include flounder, halibut, sole, cod, hake, haddock, redfish, seabass, congers, tuna, bonito, and billfish. [2]Fed carp refers to carp species that are sometimes fed compound feeds. Filterfeeding carp (silver carp, bighead carp, and catla) are not fed compound feeds and are not included here. [3]Mollusks are filter-feeders and are not fed compound feeds.

in plant proteins and fatty acids (eicosapentaenoic acid [EPA] and docosahexaenoic acid [DHA], known as n-3 fatty acids) not present in vegetable oils. The fish oil and protein also provide energy, which is important because fish tend to be poor at using carbohydrates for energy.

All fish, whether omnivorous, herbivorous, or carnivorous, require about the same quantity of dietary protein per kilogram. But freshwater herbivores and omnivores such as carp, tilapia, and catfish are better than carnivores at using plant-based proteins and oils, and consequently, they need only minimal quantities of fish meal to supply essential amino acids. Nevertheless, compound feeds for tilapia and other omnivorous fish often contain about 15 percent fish meal — much more than required. Indeed, manufacturers often over-formulate feeds, in part because information on the dietary requirements for particular fish species is inadequate.

Because of these high levels of fish meal and fish oil in aquaculture feeds, it takes more fish biomass to raise some farmed species than those species produce. For the ten types of fish most commonly farmed, for instance, an average of 1.9 kilograms of wild fish are required for every kilogram of farmed fish produced using compound feeds (Figure 3). The highest inputs of wild-caught fish — more than five kilograms for each kilogram produced — are used in raising marine fish such as flounder, halibut, sole, cod, hake, haddock, redfish, seabass, congers, tuna, bonito, and billfish. Many salmon and shrimp operations use roughly three kilograms of fish biomass for each one produced (Figure 4).

Only three of the ten types of fish most commonly farmed — catfish, milkfish, and carp — use less fish as inputs than is ultimately harvested. (Marine mollusks and many filter-feeding carp are not fed compound feeds at all.)

Aquaculture is not the world's largest consumer of fish meal. That distinction belongs to the poultry and swine industries. Aquaculture, however, has the fastest growing demand for fish meal and fish oil. Its share of fish meal supplies rose from 10 percent in 1988 to 17 percent in 1994 and 33 percent in 1997. Also, the proportion of fish meal in aquaculture feeds is much higher than in poultry and livestock feeds, which contain an average of only 2 to 3 percent fish meal as a protein supplement. The production of a kilogram of pork or poultry typically uses large amounts of plant proteins, but only a few hundred grams of fish, whereas production of a kilogram of carnivorous fish can use up to five kilograms of wild fish.

Some aquaculture proponents argue that even if farmed fish production requires more wild fish biomass than is ultimately harvested, it is still more efficient than the making of big fish from little fish in the wild. In other words, even

if it takes several kilograms of wild-caught fish to grow one kilogram of salmon or cod in captivity, these and other carnivorous fish species would consume at least that amount of smaller fish if they grew to maturity in the wild. Whether natural predation or captive feeding is more energy efficient is an unsettled scientific question that involves calculations of energy flows in wild food webs. It is reasonable to believe that farmed fish operations are somewhat more efficient since captive fish are protected from some types of mortality as they grow. Regardless of the outcome of the efficiency debate, however, it is clear that the growing aquaculture industry cannot continue to rely on finite stocks of wild-caught fish, many of which are already classified as fully exploited, overexploited, or depleted. Taking ever-increasing amounts of small fish from the oceans to expand the total supply of commercially valuable fish would clearly be disastrous for marine ecosystems and, in the long term, for the aquaculture industry itself. If the goal of aquaculture is to produce more fish for consumers than can be produced naturally, then it will become increasingly counterproductive to farm carnivores that must be fed large amounts of wild-caught fish that form the foundation of the ocean food chain.

NET INCREASE IN FISH SUPPLIES FROM AQUACULTURE

Clearly, the feed requirements for some types of aquaculture systems place a strain on wild fish stocks. But does farmed fish production overall represent a net gain to global fish supplies? Our calculations indicate it does, but most of that gain in fish supplies from aquaculture comes from carps, marine mollusks, and other mostly herbivorous species.

Global harvest of wild fish and aquatic plants removes 123 Mt from seas and lakes each year, and 27 Mt of this is directly discarded as bycatch (Figure 5). Without the bycatch, fisheries landings amount to 96 Mt, of which 65 Mt of whole fish and 1 Mt of seaweeds are consumed by humans. The remaining 30 Mt of fish catch plus another 2 Mt of processing scraps from aquaculture and fisheries are used for fish meal production.

(The fish meal industry has proposed that fishing vessels be encouraged to retain the currently discarded bycatch for sale to producers of fish meal and fish oil. Sale of bycatch could prove undesirable, however, if it undermines efforts to reduce bycatch rates or decreases the return of bycatch to the waters from which it was taken.)

One-third of the fish used to make fish meal, about 10 Mt, is currently converted to aquaculture feeds, while the remaining 22 Mt goes into fish meal for chicken, pig, and other livestock feeds. The use of these wild-caught fish for feeds reduces supplies of wild fish that could potentially be consumed directly by people. In Southeast Asia, for example, small open ocean fishes such as mackerel, anchovy, and sardines supply an important protein source for local people. Although some fish utilized for fish meal and fish oil, such as menhaden, are distasteful to humans or are worth more as fish meal and oil than as food for consumers, the demand for small ocean fish for direct human consumption is likely to increase with population growth in the developing world.

Finally, total aquaculture production of finfish, crustaceans, and mollusks amounts to 29 Mt. However, after the 10 Mt of wild-caught fish going into fish feed is subtracted, the net volume of fish provided for human consumption via aquaculture is 19 Mt.

Carps and marine mollusks account for more than three-fourths of current global aquaculture output, and tilapia, milkfish, and catfish contribute another 5 percent. These species, fed mostly herbivorous diets, account for most of the 19 Mt gain in fish supplies from aquaculture.

Figure 4 — Atlantic salmon, the dominant salmon species farmed worldwide, are commonly fed compound feeds rich in fish oils and fish meal from wild fish. Roughly, three kilograms of wild fish are required for each kilogram of salmon produced (Photos courtesy the New Brunswick Department of Fisheries and Oceans).

ECOLOGICAL IMPACTS OF AQUACULTURE

The use of wild fish to feed farmed fish directly impacts ocean fisheries. But aquaculture can also diminish wild fisheries indirectly by habitat modification, collection of wild seedstock, changes in ocean food webs, introduction of non-native fish species and diseases that harm wild fish populations, and nutrient pollution (Figure 6). The magnitude of such impacts varies considerably among different types of aquaculture systems, but it can be severe.

Habitat Modification

Hundreds of thousands of hectares of mangroves and coastal wetlands around the world have been transformed into milkfish and shrimp ponds (Figure 7). This transformation results in direct loss of essential ecological services that mangroves provide, including nursery habitat for juvenile fish and shellfish, protection of the coast from battering storms and typhoons, flood control, trapping of sediments, and filtering and cleansing of nutrients from the water.

Mangrove forests provide food and shelter to many juvenile finfish and shellfish that are later caught as adults in coastal and offshore fisheries. In Southeast Asia, mangrove-dependent species account for roughly one-third of yearly wild fish landings, excluding trash fish. In Indonesia, Malaysia, and the Philippines, catches of finfish and shrimp increase with mangrove forest area. Healthy mangroves are also closely linked to the condition of coral reefs and seagrass beds. As mangrove forests are lost, more sediment runoff is carried onto and can smother downstream coral reefs and seagrass beds. The degradation of these biologically rich systems, in turn, affects fish harvest: fish caught from reefs contribute about 10 percent of fish humans consume globally, and the proportion is much higher in developing countries.

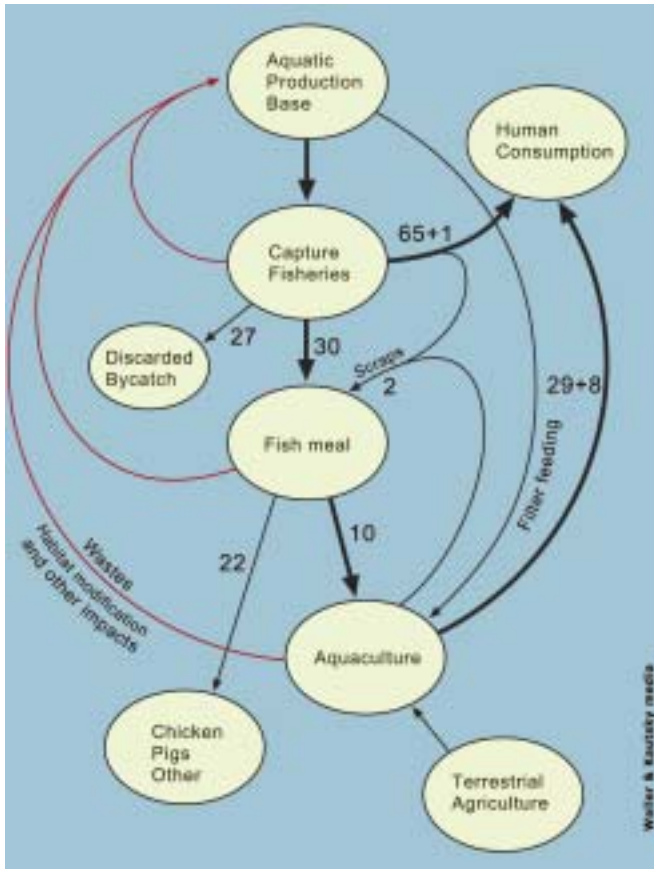


Figure 5 — Flow chart of capture (wild) and farmed fisheries products from aquatic primary production. Numbers refer to 1997 data and are in megatons (million metric tons) of fish. Thicker lines refer to direct flows of aquatic primary production through capture fisheries and aquaculture to humans. Thin lines refer to indirect and minor flows. Red lines indicate negative feedbacks on the aquatic production base. (Modified from Naylor et al. 2000)

Conversion of coastal habitats into shrimp farms can lead to large losses in wild fisheries stocks. In Thailand, where shrimp farms have been carved out of mangrove forests, we estimate that a total of 400 grams of wild fish and shrimp are lost from nearshore catches for every kilogram of shrimp farmed. In addition, if other fish and shellfish species caught from waterways adjoining mangrove areas are considered, the total reduction increases to 447 grams of wild fish biomass per kilogram of shrimp raised. If the full range of ecological effects associated with mangrove conversion is taken into account, including reduced mollusk productivity in mangroves and losses to seagrass beds and coral reefs, the net yield from these shrimp farms is low — even without considering the use of fish meal in aquaculture feeds for shrimp. Moreover, building aquaculture ponds in mangrove areas transforms fisheries from a common property resource available for use by numerous local people — including subsistence fishermen — into a privatized farm resource that benefits a small number of investors.

Use of Wild-Caught Seedstock

Many aquaculture operations, especially extensive ponds, stock wild-caught rather than hatchery-reared finfish or shellfish fry. Examples include farming of milkfish in the Philippines and Indonesia, tuna in South Australia, shrimp in South Asia and parts of Latin America, and eels in Europe and Japan. In these systems, aquaculture is not a true alternative to wild harvests, but rather a means to raise wild fish to marketable size in captivity by reducing the high mortality rates characteristic of wild populations.

Collection of seed-stock for aquaculture operations can have very large consequences for wild fisheries if it results in high bycatch rates. For example, milkfish constitute only 15 percent of total finfish fry collected inshore by seine net — the remaining 85 percent of fry are discarded and left

to die on the beach. Thus the capture of the 1.7 billion wild fry stocked annually in Philippine milkfish ponds results in destruction of more than 10 billion fry of other finfish species. In India and Bangladesh, up to 160 fish and shrimp fry are discarded for every fry of giant tiger shrimp collected to stock shrimp ponds. The magnitude of annual fry bycatch has been estimated at somewhere between 62 million and 2.6 billion in three collecting centers in West Bengal, India.

Changes in Ocean Food Webs

Stocks of some small ocean fish exploited for fish meal are over-fished, and their populations fluctuate sharply during the climate shifts brought on by El Nino-Southern Oscillation events. In seasons when these stocks are depleted, available food supplies for commercially valuable marine predators such as cod and also marine mammals and seabirds decline. In the North Sea, for example, over-exploitation of many capelin, sandeel, and Norway pout stocks, largely for production of fishmeal, has been linked to declines of other wild fish such as cod and also changes in the distribution, populations sizes, and reproductive success of various seal and seabird colonies. Similarly, off the coast of Peru, scientists have documented a strong interaction between anchoveta stocks and the size of sea bird and mammal populations.

Introduction of Non-Native Fish and Pathogens

Aquaculture can also affect stocks of wild fish by allowing escapes of non-native species and by spreading diseases among both farmed and wild fish. Scientists call these introductions of non-native organisms "biological pollution."

Atlantic salmon — the dominant salmon species farmed worldwide — frequently escape from net pens. In some areas of the North Atlantic Ocean, as much as 40 percent of Atlantic salmon caught by fishermen is of farmed origin. In the North Pacific Ocean, more than a quarter million Atlantic salmon have reportedly escaped since the early 1980s, and Atlantic salmon are regularly caught by fishing vessels from Washington to Alaska. Increasing evidence suggests that farm escapees may hybridize with and alter the genetic makeup of wild populations of Atlantic salmon, which are genetically adapted to their natal spawning grounds. This type of genetic pollution could exacerbate the decline in many locally endangered populations of wild Atlantic salmon. In the Pacific Northwest, there is evidence that escaped Atlantic salmon now breed in some streams, perhaps competing for spawning sites with beleaguered wild Pacific salmon.

Movement of captive fish stocks for aquaculture purposes can also increase the risk of spreading pathogens. The relationships between farmed and wild fish and disease

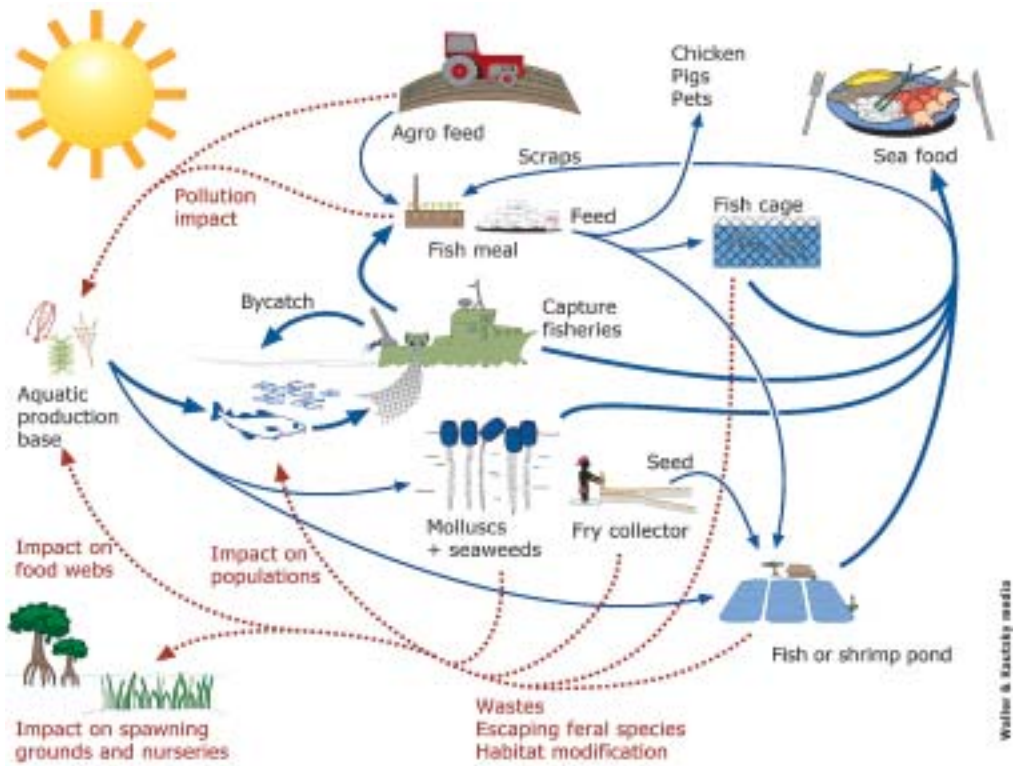


Figure 6 — Ecological links between intensive fish and shrimp aquaculture and capture fisheries. Thick blue lines refer to main flows from aquatic production base through fisheries and aquaculture to human consumption of seafood. Thin blue lines refer to other inputs needed for production (e.g., agro feed, fish meal, seedstock, etc.). Hatched red lines indicate negative feedbacks. (Modified from Naylor et al. 2000)

R. Naylor

J.P. McVey, courtesy NOAA Sea Grant Program

Figure 7 — The conversion of mangrove forests (above) to aquaculture ponds for shrimp and milkfish (right) results in the loss of nursery habitat for juvenile fish and shellfish and other ecosystem services such as coastal protection, flood control, sediment trapping and water treatment.

transfer are complex and often difficult to disentangle. In Europe, however, serious epidemics of furunculosis and *Gyrodactylus salaris* in stocks of Atlantic salmon have been linked to movements of fish for aquaculture and re-stocking.

Since the early 1990s, the Whitespot and Yellowhead viruses of shrimp have caused catastrophic, multimillion-dollar crop losses in shrimp farms across Asia. Both pathogens have recently appeared in farmed and wild shrimp populations in the United States, and the Whitespot virus has been reported in several countries in Central and South America. In Texas shrimp farms, the Whitespot virus has caused high mortalities, and the disease may also kill wild crustaceans. This virus is thought to have been introduced into a Texas shrimp farm by release into nearby coastal waters of untreated wastes from plants processing imported Asian tiger shrimp, and also by shipping of contaminated white shrimp larvae throughout the Americas.

Nutrient Pollution from Aquaculture Wastes

Untreated wastewater laden with uneaten feed and fish feces may contribute to nutrient pollution near coastal fish ponds and cages, especially when these are situated in or near shallow or confined water bodies. Such pollution also can be severe in regions where intensive aquaculture systems are concentrated. In many such areas, buildup of food particles and fecal pellets under and around fish pens and cages interferes with nutrient cycling in seabed communities. And when quantities of nitrogen wastes such as ammonia and nitrite are greater than coastal waters can assimilate, water quality can deteriorate to a level that is toxic to fish and shrimp.

Aquaculture managers clearly have a stake in regulating nutrient pollution since poor water quality and high stocking densities often promote outbreaks of disease and lead to declines in farmed fish production. While waste problems have been widely discussed, however, current management solutions are largely limited to controlling the intensity of fish production by reducing stocking and feeding levels rather than treating wastes.

TOWARD SUSTAINABLE AQUACULTURE

Production of farmed fish and shellfish currently adds to net global fish supplies, although many types of aquaculture result in a net loss of fish. Rapid growth in this net-loss sector is severely limiting the potential contribution of aquaculture to future world food supplies. The benefits of aquaculture, and indeed the potential growth of the industry itself, are diminished by escalating production of species fed carnivorous diets and by aquaculture practices that lead to coastal habitat destruction, biological pollution, and discharge of untreated fish wastes into some of the world's most diverse and productive marine habitats. Continued expansion of aquaculture will require healthy coastal and freshwater ecosystems. Without clear recognition by the industry of its dependence on natural ecosystems, aquaculture is unlikely to develop to its full potential or continue to supplement ocean fisheries. We therefore suggest that governments and development agencies, as well as the aquaculture industry and its

trade organizations, adopt four major priorities: 1) expansion of the farming of non-carnivorous fish; 2) reduction of fish meal and fish oil inputs in feed; 3) development of integrated farming systems that use multiple species to reduce costs and wastes and increase productivity; and 4) promotion of environmentally sound aquaculture practices and resource management.

Farming Lower on the Food Web

Farmed fish species fed mainly on herbivorous diets account for most of the 19 Mt gain in fish supplies that aquaculture now provides to the world. Carps and marine mollusks make up 75 percent of current global aquaculture output, and tilapia, milkfish, and catfish contribute another 5 percent. But market forces and government policies in many countries favor rapid expansion in production of high-value, carnivorous species, such as salmon and shrimp. Globally, these species represent only 5 percent of farmed fish by weight, but almost 20 percent by value.

In addition, fish meal and fish oil are increasingly being added to carp and tilapia feeds to boost weight gain, especially in Asia where farming systems are intensifying as a result of the increased scarcity and value of land and freshwater resources. Given the huge volume of farmed carp and tilapia in Asia, significant increases in the fish meal and fish oil content of feed would place even more pressure on open ocean fisheries, resulting in higher feed prices as well as harm to marine ecosystems.

We believe new initiatives by governments and international donor agencies are needed to further encourage farming of species lower on the food web — that is, fish with herbivorous diets. At the same time, we believe more scientific research on the feed requirements of herbivores and omnivores is required to lessen the drive to add fish meal and fish oil to their feeds.

Reducing Fish Meal and Fish Oil in Fish Feed

The cost of purchasing feed is the largest production expense for commercial aquaculture, including most farming of salmon, other marine finfish, and shrimp. Moreover, the price of fish meal relative to other protein substitutes has risen in real terms in the past few decades and is likely to continue to escalate as demand grows. Increases in the prices of fish meal and fish oil could undermine the profitability of many aquaculture enterprises. For these reasons, research to improve feed efficiency in industrial systems is already a priority in the aquaculture industry.

Efforts to develop substitutes for fish-derived feed ingredients are now focused on commodities such as oilseeds (especially soybeans), meat byproducts (such as blood meal and bone meal), and microbial proteins. Already the fish meal content of some feeds — for example, feed for salmon — has been reduced considerably, albeit largely by substituting cheaper fish oil for fish meal. Nevertheless, severe barriers exist to complete replacement of fish meal and fish oil in aquaculture feeds, especially for carnivorous fishes, because vegetable proteins have inappropriate amino acid balance and poor protein digestibility.

We believe more scientific research is also needed on the feed requirements of herbivores and omnivores in order to reverse the trend toward adding fish meal and fish oil to their feeds. Substituting vegetable oils for fish oils in freshwater fish diets is technically possible since the n-3 fatty acids found in fish oil are not essential in the diets of these species. However, some herbivorous fish appear to have more robust immune systems when fish oil is included in their diet.

In addition, substitution of fish oil with cheaper vegetable oil in aquaculture feeds may also affect the fatty acid profile and thus flavor and marketability of the fish to consumers. Evidence suggests that the ratio of n-6 to n-3 fatty acids in human diets is already too high. There are, however, alternatives to finfish as sources of n-3 fatty acids for humans, including mollusks and other types of seafood, and research is underway to increase the n-3 fatty acid content in poultry products and in oilseeds used for feed.

A move toward partial substitution of plant and terrestrial animal proteins for fish proteins now used in feed is widely accepted as necessary within the aquaculture industry, yet there is disagreement over the urgency of such a move. Because over-exploitation of ocean fisheries has negative ecological and social consequences, developing a strategy to replace fish meal and fish oil in feeds should be a priority for governments and development organizations as well as industry.

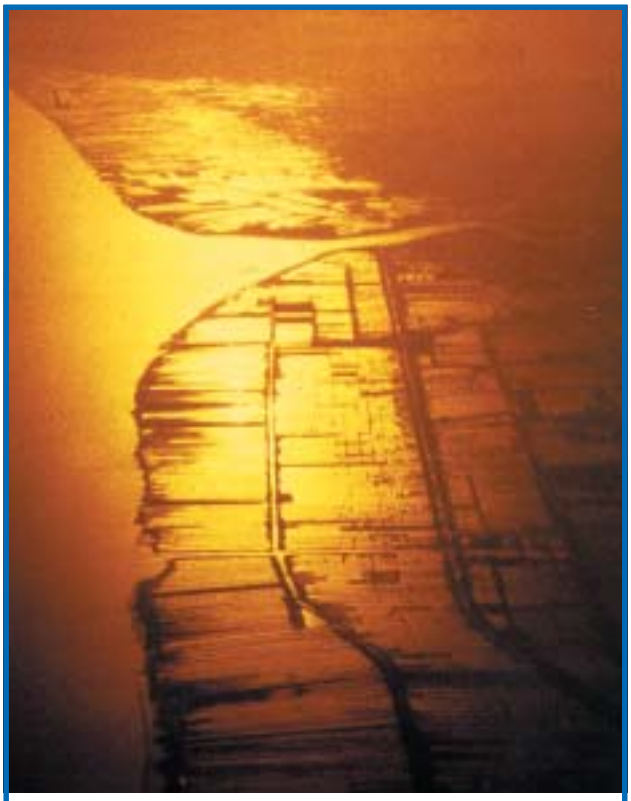
Integrating Production Systems

The farming of multiple species in a single pond — polyculture — was practiced for centuries before the advent of industrial-scale aquaculture. Even today, four of the most widely cultivated fish species are sometimes produced together in the same ponds in China: silver carp (a phytoplankton filter feeder), grass carp (a herbivore that grazes aquatic plants), common carp (an omnivorous bottom feeder that eats detritus), and bighead carp (a zooplankton filter feeder). This type of system efficiently uses food and water resources from all levels of the pond ecosystem, thereby reducing costs and wastes while increasing productivity.

Integrated systems can also be used for high-value fish, such as salmon and shrimp, in order to reduce waste outputs, diversify products, and increase productivity. Some studies show that seaweed and mussels grow well in wastewater from intensive and semi-intensive aquaculture systems, and as a result, reduce nutrient and particulate loads to the envi-

ronment. In Chile, for example, salmon can be farmed along with a type of red alga that removes large amounts of dissolved nitrogen and phosphorous wastes from salmon cages. The effluent output from salmon farming is thus used to nourish a seaweed crop, and the added revenue from the sale of the seaweed more than pays for the extra infrastructure needed for the integrated system.

If government policies required fish farms to internalize the environmental costs of waste discharges — that is, by making sewage treatment mandatory — then integrated systems that reduce the waste stream would be even more profitable. Some caveats apply: Human health considerations now limit the marketability of mollusks raised in the waste stream from intensive fish farming areas, and such concerns must be addressed in order to make these types of integrated systems economically viable.



Shrimp ponds along the southern coast of Thailand (Photo: N. Kautsky).

Promoting Sustainable Aquaculture

Long-term growth of the aquaculture industry depends on both ecologically sound practices and sustainable resource management. Governments can encourage such practices by stringently regulating the creation of new farming facilities in mangroves and other coastal wetlands, establishing fines to minimize escapes of fish from aquaculture pens, enforcing strict disease control measures for the movement of stock, and mandating effluent treatment and in-pond recirculation of wastewater. Many aquaculture operations have adopted such practices even in the absence of strict government policies, especially with the heightening of environmental concerns in recent years. In poor countries, however, such policies are often neither politically enforceable nor economically and socially feasible.

Despite significant improvements in the industry, many ecologically sound technologies remain on the shelf and underused in the field. This is an arena where external funding agencies such as development banks can play a strategic role by encouraging the development and financing the implementation of sustainable aquaculture technologies, the rehabilitation of ecosystems degraded by aquaculture, and the protection of coastal ecosystems.

Whether aquaculture depletes or enhances net fish supplies in the future will depend to a large extent on how markets for resources are managed. The absence of regulations or price disincentives on coastal pollution by fish farms, for example, limits mollusk farming and slows the adoption of non-polluting technologies by other marine aquaculture systems. Furthermore, government subsidies to the ocean fisheries sector often prevent farmed fish from undercutting the market for wild-caught fish, at least until ocean fisheries are fully depleted. Whether farmed fish can replace or provide market alternatives for ocean catches will depend significantly on the economics and policies of fisheries in various nations. High fixed costs of fishing fleets, labor considerations, and continued subsidies to the ocean fisheries sector — subsidies that currently approach 20 to 25 percent of gross fisheries revenue globally — may prevent increased aquaculture production from lowering catches of wild fish in the short term. In the case of salmon, for instance, increased farm production did not result in reduced capture levels despite 30 to 50 percent declines in the international prices for four of the five main species of wild salmon (chinook, coho, pink, and chum) during the 1990s. Salmon catches worldwide actually rose by 27 percent between 1988 and 1997. Similarly, despite rapid growth in alternative farmed fish such as tilapia, wild capture of hake and haddock has remained relatively stable during the past decade.

Finally, perhaps the largest unknown for both the private and public sectors is the future availability of freshwater sites for aquaculture production. Increasing scarcity of freshwater resources could severely limit the farming of herbivorous fish such as carps and tilapia. This constraint on the future growth of freshwater systems makes it even more urgent to develop marine aquaculture systems that are both ecologically and socially sound.

Mandate for the Future

Aquaculture is an industry in transition, and we will continue to evaluate trends as the field develops. Already it is clear, however, that if aquaculture is to fulfill its long-term

potential to enhance global fish supplies and provide food for the world's growing population, both public and private sectors must embrace a shared vision of a sustainable industry. On the public side, governments can support research and development on environmentally benign aquaculture systems, eliminate implicit subsidies for ecologically unsound practices, and establish and enforce regulations to protect coastal ecosystems. At the same time, the private sector must alter its course and recognize that current practices that lead to further pressures on ocean fish stocks, destruction of coastal habitats, water pollution, and introductions of pathogens and non-native fish run counter to the industry's long-term health. If public and private interests act jointly to reduce the environmental costs generated by fish farming, present unsustainable trends can be reversed and aquaculture can make an increasingly positive contribution to global fish supplies. Without this shared vision, however, an expanded aquaculture industry poses a threat, not only to ocean fisheries, but also to itself.

ACKNOWLEDGMENTS

The authors thank the David and Lucile Packard Foundation for funding and M. Williams, W. Falcon, V. Spruill, M. Drew, N. Wada, R. Kautsky, K. Jauncey, C. Tirado, R. Hoguet, R. Tatum, and R. Mitchell for helpful comments and assistance.

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ABOUT THE PANEL OF SCIENTISTS

Dr. Rosamond L. Naylor, Panel Chair, Institute for International Studies, Stanford University, Stanford, CA, 94305

Dr. Rebecca J. Goldburg, Environmental Defense, 257 Park Avenue South, New York, NY, 10010

Dr. Jurgenne Primavera, Aquaculture Department, Southeast Asian Fisheries Development Center, Tigbauan, Iloilo, 5021, Philippines

Dr. Nils Kautsky, Department of Systems Ecology, Stockholm University and the Beijer Institute, Stockholm, Sweden

Dr. Malcolm C. M. Beveridge, Institute of Aquaculture, University of Stirling, Stirling, FK9 4LA, UK

Dr. Jason Clay, World Wildlife Fund, 1250 24th Street NW, Washington, DC 20037

Dr. Carl Folke, Department of Systems Ecology, Stockholm University and the Beijer Institute, Stockholm, Sweden

Dr. Jane Lubchenco, Department of Zoology, Oregon State University, Corvalles, OR, 97331

Dr. Harold Mooney, Department of Biological Sciences, Stanford University, Stanford University, Stanford, CA, 94305

Dr. Max Troell, Department of Systems Ecology, Stockholm University and the Beijer Institute, Stockholm, Sweden

About the Science Writer

Yvonne Baskin, a science writer, edited the report of the panel of scientists to allow it to more effectively communicate its findings with non-scientists.

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