Aquaculture:

Three thousand years ago, farmers in China began growing fish in freshwater ponds and a thousand years later began cultivating mollusks along coastlines. For centuries, aquaculture—the farming of fish, shellfish, and aquatic plants—remained mostly a small-scale subsistence activity providing relatively low yields. But during the past few decades, aquatic farming has abruptly undergone a startling transformation. It is now the fastest-growing food production system worldwide. Thirty years from now, experts say, it will provide the largest source of fish and shellfish for human consumption.

The revolution in aquaculture accelerated rapidly during the late 1970s, due primarily to two factors. First, as human populations began to skyrocket, experts worried that many hundreds of millions of people could suffer malnutrition. Thus, international agencies such as the World Bank began encouraging aquaculture in developing countries as a method of providing food for the poor and promoting economic development. Second, around this same time China initiated a series of economic reforms to encourage aquaculture.

Modern fish farming probably arrived just in time. During the last quarter of the twentieth century, the worldwide human population ballooned from 4 billion to 6 billion. Most of this growth occurred in developing countries. Meanwhile, wild fish harvests were unable to keep up with increasing demand. In the 1970s

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Satisfying the Global Appetite

and 1980s, growth of wild harvests faltered, reaching a plateau in the 1990s, according to *The State of World Fisheries and Aquaculture 2000*, a report by the Food and Agriculture Organization (FAO) of the United Nations. Worldwide wild harvests could even decline in future years. The FAO points out that about three-quarters of the earth's important marine stocks may have already reached their maximum potential yields.

People around the globe are demanding more fish and other forms of animal protein. "Until recently, the diets of people in the developing world were very heavily starch," says Christopher Delgado, a senior research fellow at the International Food Policy Research Institute (IFPRI) of Washington, D.C., part of a global agricultural research network. "People are starting to diversify their diets."

In countries where large populations suffer from hunger, animal protein is a crucial means to combat malnutrition. For the world's poor, consuming just a small amount of milk and meat (beef, pork, mutton, goat, or poultry) can provide the same level of nutrients, protein, and calories that a larger amount of vegetables and cereals can offer, according to the 1999 IFPRI discussion paper *Livestock to 2020: The Next Food Revolution*.

Fish similarly provides important nutrition. The protein in seafood is high quality, providing all the amino acids that the human body needs to build its own

proteins. Because seafood has less connective tissue than red meats and poultry, it is easy to chew and digest and thus a good choice for people such as children and the elderly to help them gain their daily protein. Seafood, moreover, is generally a low-calorie food compared to red meat and poultry, so eating seafood allows people to consume fewer calories while meeting their daily protein needs. Lean fish also has much less fat than other animal foods.

Fish is often the cheapest form of animal protein that people can buy in many developing nations, according to Albert Tacon, an aquaculture nutritionist based in Hawaii. Fish offers 25% of the animal protein that people consume in Asia. During the mid-1990s, fish offered more than 50% of animal protein that people consumed in 34 countries, according to the FAO. Several Asian and African nations were included in this group.

From 1984 to 1999, aquaculture production expanded from 7 million to 33 million metric tons. Now, growing more than 220 species, aquatic farmers are providing one-third of the world's total food-fish supply. By the year 2030, more than half of all fish consumed will come from aquaculture, says the FAO.

What Is Aquaculture?

There are many varied categories of aquaculture, but two top the list of importance. The first category generally includes traditional farming of low-value fish, especially carp, that feed low on the ecologic food chain and are grown in ponds for local consumption. This kind of fish farming, primarily focused in Asia, contributes about four-fifths of the world's aquaculture volume. The overwhelming bulk of low-value fish grown in Asia is generally not traded internationally, but instead is consumed locally by large numbers of people in many poorer regions.

The second category includes high-value seafood products such as shrimp and salmon, which are prized for their taste appeal. Shrimp are grown almost exclusively in developing countries in the Southern Hemisphere, primarily Thailand, China, India, and Ecuador, and traded to wealthier countries in the Northern Hemisphere, especially the United States, Japan, and the European Community. Salmon is grown mostly in Norway and Chile and is also sold to the same countries that buy shrimp.

Carnivorous species such as salmon and shrimp are the most valuable fish products on the international market. This kind of aquaculture, which can be very lucrative for farmers, provides economic development and foreign currency for many developing countries. But many experts say that aquatic farming of high-value species for international export markets has caused environmental damage and needs reform.

Certain aquaculture sectors have been "driven mainly by market forces, short-term profits, and in many developing countries, export earnings," says Meryl Williams, director general of the International Center for Living Aquatic Resources Management (ICLARM), headquartered in Penang, Malaysia. She spoke at a mini-symposium on aquaculture at the American Association for the Advancement of Science annual meeting in San Francisco on 18 February 2001. She noted that the world is adding 80–90 million people a year. "All systems of food production, including especially aquaculture, are going to have to contribute to feeding people," she says. "Governments are asking for an extraordinary expansion of aquaculture production in a very short time, and now we must consider what types of aquaculture we should be focusing on. We need new techniques, new tools, new knowledge. Aquaculture is an industry that the world needs, but we've certainly got to get it right."

In for the long haul. Workers at India's Central Institute of Freshwater Aquaculture at Kausalyagang harvest carp raised in the main stock pond as part of a fisheries research project.

FAO photo

Feeding the Hungry

China is easily the world's greatest aquatic farming success story. Indeed, Chinese farmers produce two-thirds (by volume) of all aquaculture products worldwide. About 90% of Chinese production is finfish, especially Chinese carp species, which include silver carp, grass carp, common carp, Chinese bream, crucian carp, and black carp.

Fish has a very important place in Chinese cuisine, according to Ximing Guo, a native of China and a shellfish geneticist at the Haskin Shellfish Research Laboratory of Rutgers University in Port Norris, New Jersey. He has visited his homeland to study its aquaculture industry as part of a U.S.–Chinese living marine resources exchange sponsored by the National Oceanic and Atmospheric Administration. "If given a choice, most Chinese people prefer to eat fish," he says. "It's always the premium table food, served as the last dish at all the major holidays. Everyone wants to eat fish once a week."

For many centuries, Chinese carp have been grown in earthen ponds. "People would enrich pond water with whatever they had, rice bran or cow dung or whatever, and stimulate growth of natural food such as algae or mollusks, and the fish would harvest the natural food," says Ronald Hardy, a University of Idaho aquaculture nutritionist and vice president of the World Aquaculture Society, a trade group based in Baton Rouge, Louisiana.

Various kinds of carp traditionally have been grown in polyculture—that is, stocked together at particular ratios to consume a pond's food resources, says Guo. Grass carp are herbivores, traditionally fed with grass harvested from nearby fields. Manure added to ponds and grass carp feces both stimulate the growth of algae, which filter-feeding silver and bighead carp consume. Carnivorous black carp feed on worms and snails. Omnivorous common carp eat many small organisms and debris. A farmer can adjust the proportion of these stocks for the highest possible production.

China's aquaculture industry grew steadily from the 1950s through the 1970s. In this period, researchers gained understanding of how to inject fish with hormones to make them spawn, similar to the way hormones are given to cattle and other livestock to make them ovulate. Government hatcheries and nurseries could produce large numbers of fingerlings, or young fish, but the nation needed more farmers to grow them out in ponds.

In the late 1970s, China initiated a series of economic reforms, steadily replacing strict central planning with policies to encourage entrepreneurs. These reforms allowed individual families to start their own fish farming businesses in backyard ponds, selling their harvests to neighbors and nearby cities—and the industry took off. Since the early 1980s, China's production has grown by more than 16% per year.

Meanwhile, freshwater finfish farming has exploded throughout Southeast Asia, with significant contributions to human health. "The growth of low-value pond aquaculture has definitely improved the diets of poor people in Asia," says Delgado. "Aquaculture has been a very valuable weapon against malnutrition," adds Tacon, especially in Asia.

Asian farmers accomplished remarkable growth largely by improving fish nutrition through modern feeds rather than by digging great numbers of new ponds, says Hardy. In a traditional fishpond enriched with manure and grass, a farmer could annually harvest 300–500 kg of fish per hectare. But not long ago, Asian farmers began feeding their freshwater finfish with modern pelleted feeds, comprising mostly agricultural by-products including soybeans and small percentages of fish meal. These modern feeds are formulated to provide the optimum amounts of fat, protein, carbohydrates, fiber, and vitamins for each cultured species of fish. Aided by these new feeds, Asian farmers have gained 10-fold increases in their fish harvests. Now farms can grow much faster and bigger for the booming markets of Asia. "Aquaculture in Asia," says Tacon, "is a freight train."

The Story of Shrimp: Huge Market for Small Creatures

Thirty years ago, few people in Missouri or Ohio regularly ate shrimp. It was a rare treat, enjoyed in pricey restaurants or during vacations to the beach. But in the 1980s, seafood distributors began marketing frozen shrimp around the United States, and grocery stores opened specialty displays and counters for seafood. Dual-income families had less time for home cooking and ate in restaurants more frequently, particularly in chain restaurants, some of which advertised their shrimp dishes on television. Many Americans, concerned about their health, shifted from eating beef to eating fish and shellfish. The hit Tom Hanks movie *Forrest Gump*, about a slow-witted wise man who became a shrimper, also boosted sales. According to the FAO, the United States has a larger trade deficit in shrimp than in any other product but one: petroleum.

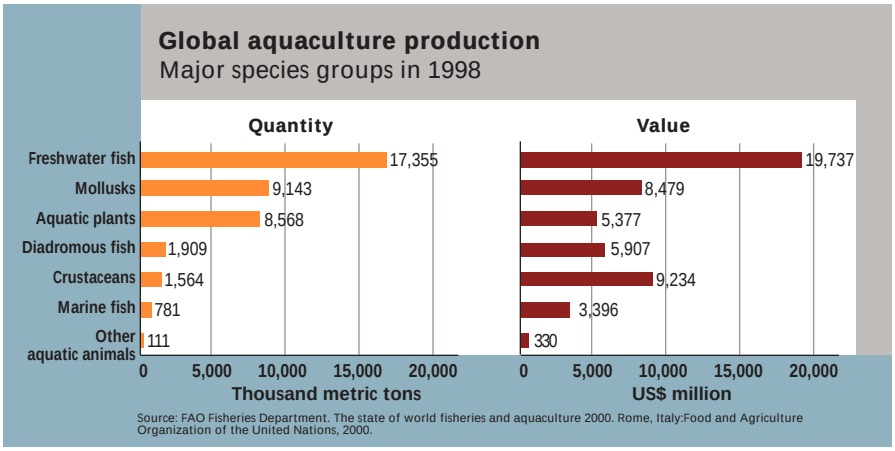
The hugely successful marketing of shrimp in the United States, Japan, and the European Community has helped to transform the international fish trade, a $53 billion industry, says Delgado. In value terms, shrimp is the most important seafood commodity sold around the world. Shrimp sales across national borders are worth one-fifth of the total value of internationally traded fish products, according to the FAO. That is, shrimp accounts for one of every five dollars earned selling fish products on the world market.

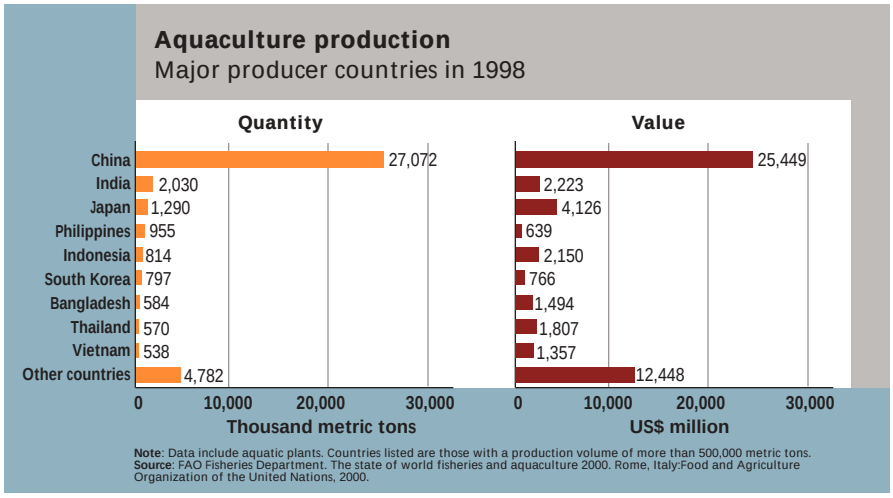
About 15 years ago, Delgado points out, northern countries were the primary producers of globally traded seafood, and southern countries were the consumers. In those days, the Soviet Union was still a major fishing nation, but that country's industry has since fallen on hard times. Until the mid-1980s, U.S. fishermen were still catching massive amounts of cod and other bottom-dwelling fish, which were marketed in poor countries. But Georges Bank, the historically significant fishing ground off New England, has been virtually tapped out of its major fisheries. Now poorer countries in the Southern Hemisphere are the primary producers of internationally traded seafood. They farm and catch seafood to sell to richer nations, says Delgado.

In the late 1970s, Taiwan and Ecuador were the first nations to grow hugely profitable crops of shrimp for international markets. In the 1980s, China, Thailand, Indonesia, and the Philippines became leaders in cultured shrimp production. Today, Asian countries overwhelmingly dominate the shrimp aquaculture industry, producing 70–80% of the worldwide volume. Shrimp production has energized coastal economies in some developing nations, providing foreign currency and jobs. Indonesia's shrimp farming industry, for example, provides 150,000 jobs in production, processing, transportation, marketing, and related service activities; Ecuador's farms generate 160,000 direct and indirect jobs.

But the effects of the fast growth of shrimp farming on the environment are evident. Seeing an opportunity for a hugely successful new industry, many governments did not establish or enforce coastal environmental protections. Until the early 1990s, shrimp farmers often cut down coastal mangrove forests to build their ponds. Mangroves are crucial nursery areas for wild fish and shellfish, and the forests provide coastal buffers against tropical storms.

"Many farms were built in places they shouldn't have been," says Jason W. Clay, an aquaculture expert with the World Wildlife





Fund in Washington, D.C. Some nations that allowed destruction of mangroves later experienced massive erosion along their coastlines during tropical cyclones. "In countries where shrimp aquaculture occurs, at least up through the early 1990s, shrimp farming was one of the single greatest contributors to mangrove destruction," says Clay. Today, conversion of mangrove areas is better regulated, and some nations have outlawed mangrove destruction for construction of farms.

Damage to mangroves is not the only effect, however. Large numbers of shrimp farms built along a single stretch of coastline can damage water quality and foster the spread of animal diseases. In country after country, farmers have mistakenly clustered their operations tightly together, using the same water resources. "Too many farms were built in the same places," says Clay.

When shrimp farmers take large numbers of seed stock (or young shrimp) from the wild and grow them out in ponds, some of these crustaceans can be infected with viruses. In the ocean or estuary, these viruses—which do not affect human health—are probably not a serious problem. But crowded in farm ponds, shrimp can be stressed and fall sick. As ill shrimp die, they are eaten by healthy ones, passing the viruses along.

To reduce stress on their aquaculture stock, many farmers release large amounts of wastewater from ponds into estuaries. A decade ago, many farmers would routinely discharge 20% of each pond's water each day. Tiny sick shrimp or infected tissue would escape with wastewater into the estuary, and neighboring farmers would unwittingly pump this same wastewater back into their own ponds. As a result, viruses swept rapidly from farm to farm. Birds also consumed sick shrimp floating on pond surfaces and later defecated viruses into ponds many kilometers away. Thus, diseases raced along coastlines.

Lacking effective quarantine methods, the aquaculture industry for years allowed epidemics to travel rapidly around the world, experts say. Virtually every country with a major shrimp industry in the late 1970s through the early 1990s suffered viral epidemics, which caused production crashes.

Surprisingly, shrimp farmers paid scant attention to potential diseases until the viral catastrophes of the early 1990s, says George Chamberlain, president of the Global Aquaculture Alliance (GAA), an international industry group based in St. Louis, Missouri. In fact, there were few management techniques and quarantine measures in place before the early 1990s to prevent the spread of shrimp viruses, he says.

But it's not just shrimp farmers who face this dilemma. "As aquaculture enterprises intensify and farmers try to produce more of the existing resource, one of the first major problems to arise is fish disease," says Williams. "We'll continue to see enormous problems with fish disease in the future."

Still, "this is not just about disease," says Clay. "You also have to look at the management techniques to deal with disease." Many farmers have attempted to flush diseases out of their ponds by releasing nutrient-rich wastewater into neighboring estuaries. Nutrient enrichment is a serious problem in many estuaries around the world, causing an increase in algal blooms, some forms of which produce toxins. In addition to aquaculture facilities, primary sources of excess nitrogen in coastal waters include fertilizers from agriculture, nitrogen oxides discharged by cars and factories, sewage treatment plants, and urban runoff.

Recently, scientists have refined methods for keeping water almost exclusively within farms, with no discharges and little water pumped in. This is called closing the system. Although it is expensive, many Asian farmers constantly run aerating paddle wheels in their ponds. This technique helps maintain higher oxygen concentrations in pond water and thus reduces animal stress. Aquaculturists have also learned how to control disease outbreaks by significantly reducing how much water they pump in and out of their ponds, according to Chamberlain. Some farmers have installed finer mesh screen in wastewater pipes, reducing the likelihood of tiny farm shrimp escaping into the ocean. And farmers are increasingly buying virus-free young shrimp exclusively from hatcheries that undergo rigorous testing for such diseases.

Most observers agree that when properly located and managed, shrimp farming causes little or no harm to marine and coastal ecology. Sophisticated (and well-capitalized) farmers are taking a number of measures to control environmental impacts and disease threats. These include conducting comprehensive evaluations of sites for new ponds to determine the availability and quality of water, tidal patterns and salinity, soil characteristics, and climatic conditions; avoiding putting too many shrimp into a pond, which stresses the animals; isolating and disinfecting ponds where infection is found without discharging water; disposing of dead shrimp in a sanitary manner; and using special brood stock that have been tested for pathogens. Sophisticated farmers also belong to aquaculture associations through which they receive technical assistance for complying with environmentally friendly codes of conduct.

Undercapitalized small farmers often do not follow best management practices. Shrimp farming is a very risky enterprise, says Clay, and "when people are faced with losing their entire business, they will cut corners." However, he says, although many of the poorer farmers do the most damage to the environment, they have the least information available to improve their practices.

In response to international criticism, the GAA is encouraging voluntary reforms of shrimp farming practices through a code of best practices. Aquaculture associations in some major shrimp farming nations, including Thailand and Ecuador, are adopting environmentally friendly codes of conduct. One of the most important factors in controlling a shrimp farm's impact is to site the operation correctly, says Clay. For example, farmers must not destroy mangrove forests and other sensitive coastal habitats, and they should ensure that their waste discharges do not flow near intake pipes of nearby farms.

Nursery for little ones. In Rangong Province of Thailand, villagers feed prawns raised in floating cages on the river.

FAO photo

Fish Food Debate

The food that farmed fish eat has become a major environmental controversy. To grow fish quickly and to enhance feed flavor so fish will want to eat it, farmers use processed fish meal and fish oil. These products are produced from small pelagic (open sea) fish species including Peruvian anchoveta, Icelandic herring, menhaden from the Gulf of Mexico, Norwegian capelin, and sand eels from the North Sea.

The growing demand for farm-raised shrimp, salmon, and other carnivorous species could affect these wild fish stocks, according to an article published in the 29 June 2000 issue of *Nature* by a team of academic and public interest scientists and economists (including Clay). The rapid rise in aquaculture production "is a mixed blessing . . . for the sustainability of ocean fisheries," argue the paper's authors. Overall, aquaculture production still adds to world fish supplies, they say. But farm operations that raise carnivorous species, which rely on fish meal and fish oil, are indirectly threatening biologically important wild fish populations.

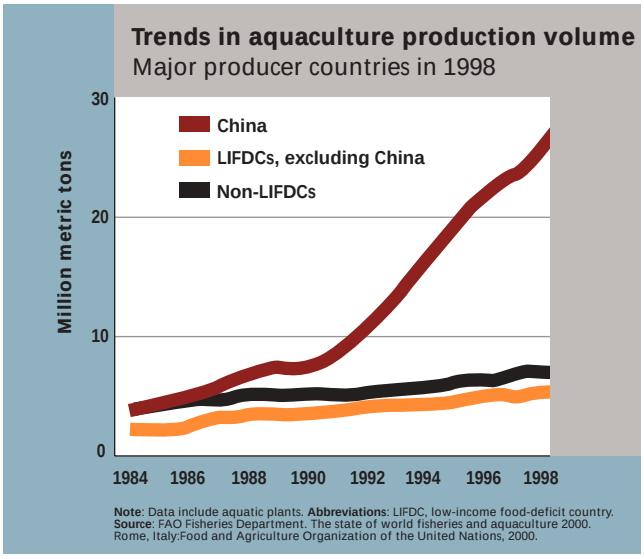
The vast majority of animals grown on fish farms—carp, catfish, tilapia, and milkfish—live on diets consisting primarily of plant food and minimal percentages of fish meal. Some omnivorous carp, for example, consume processed feed that is about 3–10% fish meal. Filter feeders, such as clams, scallops, oysters, and some carp species, do not consume any fish meal in their diets. Farmed salmon, by contrast, consume a diet of 35–45% fish meal and 15–25% fish oil.

But some aquaculture experts say that the fish feed controversy is greatly exaggerated. For instance, Hardy says the *Nature* study used out-of-date feed conversion ratios, which led the authors to mistaken conclusions about the amount of wild fish needed to make fish meal. Also, people won't consume many of the small, oily fish processed into fish meal, says Hardy; for aesthetic and taste reasons, these fish are undesirable. "No one wants to eat a menhaden," he says. "You're taking something that people don't want to eat very much, and through aquaculture you're utilizing that resource and creating something that people do want to eat."

Four countries produce most of the fish used in fish meal and fish oil worldwide: Peru, Chile, Iceland, and Denmark. These fish stocks can rise and fall significantly from year to year. Over the past two decades there have been fluctuations in harvests during El Niño years, which disrupt fish populations offshore of Peru and northern Chile, but overall international supplies of pelagic fish—and fish meal and fish oil—have essentially remained stable, says Hardy. In fact, the world's poultry producers use the largest proportion of fish meal, though over the past decade they have used less fish meal because of its high cost relative to other poultry feeds. Meanwhile, aquaculture producers have increased their usage of fish meal. Hardy points out that if aquaculture producers didn't purchase fish meal, then poultry producers would perhaps purchase more of it.

Even so, it must be recognized that fish meal is made from a limited wild resource, Tacon points out. There are about 6.5 million metric tons of fish meal available every year, and "it's always going to be at that level," he predicts. Therefore, he says, researchers must continue seeking substitutes for fish meal.

But fish meal will be economically difficult to replace in the aquaculture trade. "Fish meal is competitively priced," says Tacon. "For every unit of fish meal you put into [the system], you get really good growth of fish. Yet if you want this sector [of carnivorous fish] to keep growing, you have to base that growth on ingredients that can keep pace," which include meals made from nonfish sources such as vegetables and grains.



Environmentalists believe that international donor agencies and governments should encourage farming of herbivorous fish and shellfish, which do not rely on fish meal and fish oil. Moreover, they add, aquaculturists should make a concerted effort to reduce the amount of fish meal and fish oil in feed for farmed species. Researchers are searching for substitutes for high-quality fish protein in vegetable and grain products, particularly soybean meal, corn gluten meal, wheat gluten meal, and other by-products of grains and oilseeds.

A continuing problem, environmentalists argue, is that market forces and government policies in many countries encourage rapid expansion of farms that raise valuable carnivorous species. Salmon and shrimp farms "are not producing food for the world's poor," says Clay. "The big question is, do we need [the salmon and shrimp aquaculture] industries? Because they are producing luxury goods, do we accept their learning curve, or do they have to get their act cleaned up?"

Williams responds to the issue of so-called luxury fish with the contention that not all luxury fish and seafood are carnivores, and that some can simultaneously supply luxury markets while lifting the poor out of poverty. For example, she says, pearl oysters are filter feeders and thus feed low on the food chain, but they produce a luxury product: pearls. Increasingly, she says, especially in the Pacific Islands, coastal populations are taking part in the production of pearls, from setting up farms in their own traditional territorial waters to working for larger pearl operations. While costing little to the environment, these productions greatly benefit local and national economies. As another example, farming of giant clams, though not so well developed, is environmentally friendly and provides for luxury markets including the nonfood aquarium trade.

According to Williams, ICLARM chose such types of aquaculture to research and develop new options for island peoples. "Since we knew they would not have the opportunity to grow much of whatever [product they chose to produce]," she says, "producing the highest value at the lowest environmental cost was the best way to go."

Most observers agree that aquaculture is desperately needed to address malnutrition in the developing world. But there is little consensus about luxury seafood products grown primarily in developing nations and sold to wealthier regions. Environmentalists say that farming high-value shrimp and salmon often does more environmental harm than economic good.

Industry defenders, however, point out that many farmers are working hard to restore their reputation as responsible environmental stewards. Some aquaculture experts complain that the industry is being singled out for criticism and that every form of economic development causes ecologic impacts to some degree. The fact is that the economic benefits of high-value cultured seafood are enormous, providing a major source of jobs and foreign currency in many developing nations. A growing global population is clamoring for more animal protein, and aquaculture, when managed correctly, is one of the best methods of providing it to both the world's rich and poor.

John Tibbetts

Tan/EHP; Reuther/EHP