Murky Waters:

Environmental Effects of Aquaculture in the US

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The Environmental Defense Fund

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The Environmental Defense Fund is a leading national, New York-based, nonprofit research and advocacy organization with over 300,000 members. EDF's scientists, economists, and attorneys seek practical solutions to a wide range of environmental and human health problems.

Cover photo: View from inside a salmon netpen. Photo by Natalie B. Fobes

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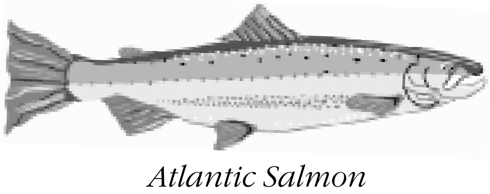
Preface

The international seafood industry is undergoing a major transition. The percentage of seafood from wild fisheries is steadily decreasing, and fish farming is the source of a steadily increasing percentage of seafood in the United States and worldwide. Unfortunately, existing aquaculture operations can be a significant source of chemical and biological pollutants and nutrient wastes. Untreated fish wastes have the potential to add to coastal pollution problems such as recent outbreaks of the toxic microbe *Pfiesteria piscicida*, which some experts believe are linked to wastes from hog and poultry farms.

If the U.S. aquaculture industry is to expand and thrive, its operations must be financially profitable as well as environmentally safe in order to be acceptable to the communities in which they are located. Otherwise the industry may fail because community members will believe that all they receive from aquaculture facilities is their pollution. This report identifies environmental problems caused by aquaculture and recommends approaches to establishing an aquaculture industry that is environmentally and economically sound.



Atlantic Salmon

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Executive Summary

Aquaculture Production

Most Americans would be surprised to discover that their last seafood meal may have been raised on a farm, rather than caught in the ocean. Largely because of declines in wild fisheries and rising demand for seafood, aquaculture has become the source of an increasing percentage of seafood consumed in the United States and throughout the world. Although precise figures are not available from the aquaculture industry or government, most of the catfish and trout, roughly half the shrimp, and approximately one-third the salmon consumed in the United States is raised by aquaculturists, or fish farmers.

World aquaculture production has more than doubled since 1984, and reached a record 20,900,000 metric tons (mt) of fish and shellfish in 1995, the latest year for which statistics are available. This farmed seafood was worth over U.S. $36.2 billion and represented 18.5% of the total world seafood supply. Aquaculture is now the source of 27% of seafood consumed by people worldwide, since more than a quarter of wild fish harvests are used in animal feed.

Similarly, the value of U.S. aquaculture production has grown by roughly 5-10% each year over the past decade, and aquaculture is regarded as the fastest-growing segment of U.S. agriculture. Fish are now farmed in every state and territory in the United States, and U.S. aquaculture production totals more than 400,000 mt of fish and shellfish (shell weight included), worth $729 million.

More than 100 species of aquatic organisms are farmed in the United States. However, only about 10 types of finfish and shellfish (together called "fish" by seafood professionals) dominate U.S. aquaculture production for food, with catfish making up almost half of U.S. production (see Fig. 1). These finfish and shellfish are raised in both freshwater and saltwater using a variety of production systems – primarily ponds, tanks, raceways, netpens, and cages. (Raceways are a series of tanks through which water flows continuously. Netpens and cages are enclosures used to raise fish directly in bodies of water, such as lakes, ponds, and coastal bays.)

Growth in U.S. aquaculture production has resulted largely from three different forces. First, harvests from most U.S. wild fisheries are declining or reaching their limits, creating opportunities in the U.S. seafood market for aquaculture products. Second, greater overall demand for seafood has favored the growth of aquaculture. Third, government promotion of aquaculture - for example, more than $60 million in financial assistance from the federal government in 1994 alone - has helped to spur the industry.

Figure 1. Important Aquaculture Organisms in the United States, 1995

	Quantity (MT)	Percentage of Total Quantity	Value (thousand $)	Percentage of Total Value
Total Production	413,431	—	729,097	—
Catfish	202,706	49.0	350,681	48.1
Oysters*	109,080	26.4	70,646	9.7
Crawfish	26,375	6.4	34,815	7.2
Trout	25,240	6.1	52,752	4.8
Salmon	14,106	3.4	75,504	10.4
Clams*	13,481	3.3	19,221	2.6
Baitfish	9,883	2.4	71,355	9.8
Tilapia	6,838	1.7	22,634	3.1
Hybrid striped bass	3,772	0.9	21,161	2.9
Marine shrimp	1,000	0.2	8,820	1.2
Mussels*	930	0.2	1,218	0.2
Sturgeon	20	0.0	290	0.0

Source: FAO 1997.
*Shell weight included.

U.S. aquaculture production is expected to continue to increase steadily. Some observers believe that there is a natural transition underway to obtaining fish from aquaculture rather than wild fisheries, similar to the transition our society has made to obtaining meat from farming and ranching rather than hunting. However, wild fisheries are unlikely to disappear. Compared to many land animals, fish populations tend to have high reproductive rates and can generally sustain high harvest levels. Seafood demand is steadily growing around the world, along with the growth of populations and affluence. Aquaculture will almost certainly be used to supplement wild fish catches, not to replace them.

Moreover, aquaculture production is not an alternative to fishing unless only fish that are largely herbivorous (such as tilapia, catfish, carp, oysters, and clams) are farmed. In fact, many farmed fish are carnivores and depend on diets of wild fish that are caught to feed them.

The Fishmeal Dilemma

In many aquaculture systems, more protein, in the form of fishmeal, is used to feed farmed fish than is obtained from harvest of the farmed fish. In other words, farming of highly carnivorous species such as salmon, trout, and sea bream can result in a net loss of fish protein, not a net gain. Growing one pond of farmed salmon can require three to five pounds of wild-caught fish.

Huge amounts of small pelagic fishes, such as anchovy, jack mackerel, herring, and sardine, are harvested to make fishmeal and fish oil used in animal feeds. Twenty-seven percent (31,000,000 mt) of the world's total wild fisheries production is now converted to animal feeds. Only 15% of this total is used in fish feeds; however, many aquaculture feeds are 20 to 70% fishmeal, while most feeds for poultry and hogs are only a few percent fishmeal, if any.

The most obvious problem with feeding wild fish to farm fish is that it is inefficient. Feeding fish to fish leads to a net loss of protein in a protein-short world. Less obvious problems of the "fishmeal dilemma" are the ecological effects of massive harvests of small pelagic fishes. Removal by fishing vessels of huge quantities of small fish from marine food webs means that less food may be available for commercially valuable predatory fish and for other marine predators, such as seabirds and seals.

Food for Thought

Since the late 1970's, international development agencies and others have promoted aquaculture as an efficient means to produce protein for domestic consumption by people with protein-poor diets in developing countries. However, in many developing countries, governments have encouraged the production of high-value seafood, such as shrimp, that can be exported to earn foreign exchange, instead production of food for domestic consumption. Many aquaculture products are now relatively expensive and are unlikely to be purchased by poor people in developing countries or in the United States.

Nevertheless, even if it does not for the most part go to feed the poor, increased aquaculture production will have significant health benefits for more affluent consumers. Fish tend to be low in fat, and thus are a healthful alternative to many other meats. Scientific data indicate that people who eat seafood at least once a week have reduced risks of coronary heart disease.

Increased United States aquaculture production can also provide economic benefits for the U.S by creating new sources of economic activity, especially in economically depressed areas. In addition, increased U.S. aquaculture production can help reduce the U.S. seafood trade deficit, which in 1996 was $3.6 billion.

Environmental Effects of Aquaculture

Troubled Waters

Aquaculture is commonly presented as a clean industry. Nevertheless, intensive (densely stocked) aquaculture systems can produce large quantities of polluting wastes, as with other forms of intensive animal production. There is, however, a difference: Wastes from terrestrial farms (such as hog and poultry operations) usually reach natural water bodies only indirectly, for example, in runoff when storms cause waste lagoons to overflow. In contrast, aquaculture wastes are often released directly into natural bodies of water, because fish farms are located in them or because effluent is discharged into them.

Aquaculture wastes consist primarily of uneaten fish feed and fecal and other excretory wastes. They are a source of nutrient pollution - carbon-based organic matter and nitrogen and phosphorous compounds. High nutrient levels can stimulate blooms of phytoplankton, or algae populations. When algae die in large numbers, their subsequent degradation can drastically reduce oxygen levels in water, stressing or killing fish and other organisms.

Oxygen depletion may not be the most harmful effect of nutrient-stimulated phytoplankton growth, however. Blooms of toxic algae species can produce huge fish kills, contaminate shellfish, and potentially even pose a health hazard to humans. Examples of toxic algae blooms include so-called red tides and recent blooms of toxic *Pfiesteria piscicida* on the eastern seaboard. Preliminary evidence suggests that such blooms may be promoted by nutrient pollution from various sources.

The characteristics and impacts of wastes from aquaculture operations vary according to the type and siting of the aquaculture system. In general, cage and netpen systems, such as those typically used to raise salmon, are relatively open to natural waters and have the greatest potential to cause environmental degradation from totally untreated waste discharges. In contrast, pond or tank systems, such as those typically used to raise catfish and tilapia, allow for greater control of waste discharges. Pond and tank systems often discharge pulses of highly concentrated wastes during cleaning and harvesting.

When compared to the largest sources of nutrient pollution, such as municipal sewage systems, U.S. aquaculture operations have a relatively small impact on water quality. This generalization does not mean, however, that pollution from aquaculture is not of concern, especially in areas with large aquaculture industries. The U.S. Environmental Protection Agency is now compelling Idaho trout farms to reduce phosphorous levels in their effluent, which is significantly polluting Idaho's Snake River. Untreated discharges from the many salmon farms along the coast of British Columbia are estimated to be equivalent to raw human sewage from a city of 500,000 people.

One type of aquaculture – mollusk farming - actually reduces nutrient pollution. Mollusk farmers do not use feed. Clams, oysters, mussels, and scallops are filter-feeders that consume phytoplankton already in the water column. Mollusk production actually reduces the nutrients in marine systems, because 35-40% of the total organic matter ingested by a mollusk is used for growth and permanently removed by harvest of the mollusk.

Nutrients are not the only type of pollutants released from aquaculture facilities. Bacteria are an additional pollutant. A primary reason that discharges of raw human sewage to natural bodies of water are hazardous is that they

Eastern oyster

may spread disease-causing microorganisms (pathogens). Untreated fish sewage presents a much smaller threat of disease to humans than human sewage, largely because fish and humans are infected by different pathogens. Nevertheless, some fish pathogens, such as *Streptococcus* bacteria, can infect humans.

A wide range of chemicals are used in many aquaculture operations. These include antibiotics to control disease and pesticides to control weeds, algae, and parasites. Aquaculture chemicals often are put directly into water, where they may be readily dispersed, potentially affecting a large variety of organisms. For example, copper-based algae-killers used in aquaculture can harm or kill shellfish. In addition, residues of aquaculture chemicals in food may harm human consumers, and antibiotics used in aquaculture may contribute to the evolution of drug-resistant diseases.

Compared to many parts of the world, relatively few chemicals are legal to use in U.S. aquaculture. Some aquaculture operations abroad produce fish for export using chemicals that are illegal in the United States, and some seafood imported to the United States may contain residues of these chemicals. The U.S. Food and Drug Administration (FDA) now has only a very limited inspection program for antibiotic residues in imported farm-raised seafood; FDA inspects imported shrimp for residues of the antibiotic chloramphenicol and imported salmon for residues of the antibiotic oxolinic acid .

Figure 2. Water Requirements for Aquaculture and Other Industries

	Water Requirements (m3/mt)
Aquaculture Systems	
Common carp/tilapia in intensive ponds (Israel)	2,250
Channel catfish in intensive ponds (USA)	6,470
Paneid shrimp in intensive ponds (Taiwan)	29,000-43,000
Rainbow trout in raceways (USA)	210,000
Other Industries	
Petroleum	21.6-810/m3
Beef	42
Pork	54
Steel	8-250
Paper	9-450
Cotton	90-450
Alcohol	125-170/m3

Sources: Phillips et al. 1991.

Along with water quality, aquaculture can also affect water quantity. Many aquaculture systems, such the Idaho trout industry's raceways, require huge quantities of freshwater (see Fig. 2). The aquifer that supplies the Idaho trout industry has suffered drawdown in recent years because of drought and overuse, causing declines in stream flow and limiting further expansion of the industry.

Something Fishy

Fish Introductions

Pollutants from aquaculture facilities are not necessarily chemical in nature. Biological pollution from aquaculture, such as the introduction of unwanted non-native species to natural ecosystems, can harm ecosystems by altering species composition or reducing biodiversity. Few aquaculture facilities are escape-proof, and very large numbers of fish sometimes escape from certain types of facilities, particularly netpens. For example, almost 100,000 Atlantic salmon escaped in the summer of 1996 from the relatively small netpen industry in the state of Washington.

Not surprisingly, aquaculture has been the most important cause for introductions of non-native fish species from one country to another. A variety of non-native species are now farmed in the United States, including Atlantic salmon and Japanese oysters raised in the waters of the Pacific Northwest, Pacific white shrimp farmed along the coasts of Texas and South Carolina, and African tilapia species grown in locations throughout the country.

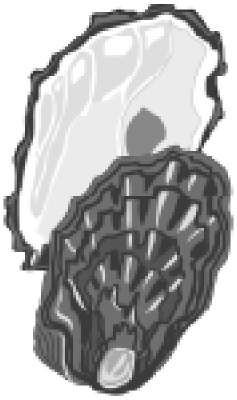
Experience with introduced blue tilapia illustrates the harm that can be caused by species raised in aquaculture facilities. In Florida, blue tilapia that escaped from two aquaculture facilities have become well established in Everglades National Park and elsewhere. Blue tilapia often compete with native species for spawning areas, food, and space. In some Florida streams where these fish have become abundant, almost all vegetation and native fish species have disappeared.

New diseases and parasites can be spread by the introduction of new stocks of non-native and native fish for aquaculture. For example, the Japanese oyster drill and a predatory flatworm were introduced with the Pacific oyster and have contributed to the decline of native West Coast oyster stocks.

Farmed native species of fish can also cause ecological harm if large numbers escape fish farms and interbreed with native wild populations, altering their genetic makeup. The potential genetic impacts from aquaculture introductions are well demonstrated by Atlantic salmon that have escaped from fish farms in Europe and North America. Wild Atlantic salmon are characterized by a large number of genetically distinct populations that are adapted to the specific conditions of the local river systems to which they return to spawn. In contrast, cultured Atlantic salmon are bred to be very uniform genetically and to exhibit favorable production traits, such as rapid growth and low aggressiveness. Interbreeding between wild and farmed Atlantic salmon introduces new combinations of genes to genetically distinct populations of wild salmon, and may break up local genetic adaptations that are critical to the survival of wild salmon in different rivers.

The numbers of Atlantic salmon that escape from netpens are often large in comparison to the small numbers of wild Atlantic salmon that exist today in the Gulf of Maine, exacerbating the genetic impact of farmed Atlantic salmon on genetically differentiated wild populations. Federal officials estimate that only 500 Atlantic salmon with a truly native genetic makeup now remain in Maine and recently proposed listing Maine salmon populations as threatened under the Endangered Species Act. Escapes of farmed salmon are identified as a potential threat to the recovery of these genetically distinct wild populations.

In the future, introductions of genetically engineered fish species, if not done with proper care, could threaten wild populations of aquatic organisms. Genetically engineered fish that exhibit new or greatly altered traits should be considered a special kind of non-native fish. Currently more than 15 species of fish have been genetically engineered, including such common aquaculture species as Atlantic salmon, channel catfish, and rainbow trout. Two U.S. companies are now close to commercializing genetically engineered Atlantic salmon and tilapia that are engineered to grow faster.



Pacific Oyster

Predation by Wild Animals

In contrast to concerns about introduced fish, which center on the impacts of escaped farmed fish on wild animals, concerns about predation center largely on the impacts of wild animals on farmed fish. Many aquaculturists believe that predatory water birds and marine mammals cause significant economic losses by injuring and consuming farmed fish. Their desire to control predators, sometimes by killing them, conflicts with the desire of many members of the public to conserve these birds and mammals as wildlife.

Aquaculture ponds are especially susceptible to predation by wading birds because they often closely resemble natural feeding sites. The growth of the catfish industry in the Mississippi Delta has created a huge increase in the area of artificial water habitats, and these attract large numbers of fish-eating birds. It is difficult to protect catfish ponds from birds by placing netting or other material over the ponds, because of the ponds' large size and typical catfish production procedures.

U.S. aquaculturists are increasingly using "lethal controls" for predatory birds. According to U.S. Fish and Wildlife Service (USFWS) data, between 1989 and 1993 more than 51,553 birds representing 38 species or groups were killed at U.S.(see Fig. 3) aquaculture facilities under legal permits. Some experts speculate that many more birds were killed illegally. Following lobbying by the aquaculture industry, in June 1997 the USFWS proposed to alter its regulations to generally allow aquaculturists to kill a frequent predator, the double-crested cormorant, without a permit. In addition, salmon farmers are increasingly interested in killing predatory seals. These animals are now protected under the Marine Mammal Protection Act, which with a few exceptions prohibits their harassment or killing.

Figure 3. Reported Authorized Kill of Bird Predators at Aquaculture Facilities in the U.S., 1989-1993

Species/Group*	Total
SWIMMING BIRDS	
Double-crested cormorant	25,930
Grebes	708
American coot	475
Common merganser	285
Pelican	225
Mallard	76
Merganser	52
White-winged scoter	48
Western grebe	45
Anhinga	42
Pied-billed grebe	22
American pelican	19
Common eider	14
Goldeneye	10
Old squaw	7
WADERS	
Great blue heron	9,443
Great egret	4,242
Black-crowned night-heron	1,734
Little blue heron	1,379
Snowy egret	1,208
Heron	362
Green-backed heron	19
Egret	5
AERIAL-DIVERS	
Belted kingfisher	1,197
Ring-billed gull	1,050
Herring gull	847
Gull	514
Common grackle	391
California gull	364
Forster's tern	285
Caspian tern	178
Common raven	93
Common tern	38
Great horned owl	18
Franklin's gull	17
Bonaparte's gull	17
American crow	14
TOTAL	**51,373**

Modified from: OTA 1995.

In general, there is little reliable quantitative information on actual fish losses due to predators, making it difficult to estimate their true economic impact. The lack of data concerning the impacts of wild animals on aquaculture facilities makes it difficult to justify killing predators. Based upon a report by a task force set up to study seal predation on Maine salmon farms, the National Marine Fisheries Service recently concluded that there is no compelling reason at this time to allow Maine salmon farmers to intentionally kill seals.

Some experts believe that killing predators is ineffective at stopping predation. Dead predators are rapidly replaced by other individuals, unless the aquaculture facility is made less inviting as a foraging site. A number of nonlethal methods to deter predators are available, and the killing of wild predators of farmed fish is a poor management practice.

Environmentally Friendly Aquaculture

Aquaculture need not be a polluting industry. A wide variety of technologies and practices now are available to make aquaculture facilities environmentally friendly, and many of these are now used on commercial fish farms. As is the case with any industry today, aquaculture has a spectrum of approaches available to it to manage pollutants. The most preferred approach - termed source reduction - is to prevent or reduce the production of pollutants in the first place. Source reduction technologies and practices in aquaculture minimize the production of nutrient, synthetic chemical, or biological pollutants. In decreasing order of preference, other available approaches are to recycle and reuse wastes, treat wastes, and (least preferred) dispose of wastes in the environment.

Reducing Nutrient and Chemical Pollution

A variety of approaches are available to reduce nutrient pollution from aquaculture. One source-reduction approach is to use feeds designed to protect the environment. These include feeds with low fishmeal content, which lessen aquaculture's pressure on wild fisheries, and feeds with nutritional and other characteristics that help aquaculturists minimize feed waste.

Another source-reduction approach is to raise different species together, such as finfish with hydroponic vegetables or with mollusks (for example mussels), in order to make optimum use of water and nutrients and to minimize farm wastes. Aquaculture systems that produce hydroponic vegetables with fish appear to be increasingly common in the United States. These systems grow crop plants with aquatic manure, suspending the roots of crops in aquaculture effluent. These crop plants remove large quantities of nutrients from effluent in order to nourish their growth, thus cleaning the effluent. Sale of these vegetable crops then generates income for aquaculturists. The Inslee Farm, Inc., of Oklahoma, for example, grows chives in greenhouses using the effluent from ponds in which a variety of different fish species are raised, including tilapia, catfish, and grass carp. Currently the farm produces 80 pounds of chives weekly, which are shipped fresh to a wholesaler in Houston.

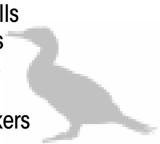
Waste-treatment approaches for aquaculture wastes have been adapted largely from municipal sewage treatment. However, usually only wastes from contained aquaculture systems such as ponds and tanks, can be be treated. Treatment methods include sedimentation ponds, mechanical filters, and constructed wetlands. Sedimentation and mechanical filtration both result in the accumulation of nutrient-rich sludge that requires proper disposal. Sludge from freshwater aquaculture can be applied to agricultural crops as organic fertilizer. This disposal method is environmentally sound as long as sludge is applied in a manner that minimizes field runoff.

Wastes from open aquaculture systems such as netpens and cages cannot be readily collected for treatment. However, siting netpens in areas with strong currents or tides that flush wastes and avoiding overly dense siting of netpens can help limit problems from waste accumulation.

Adoption of preventive tactics that prevent pests and diseases from becoming problems is the key to source reduction of chemicals used in aquaculture. Use of aquaculture drugs can be minimized by practicing preventive medicine, such as stocking fish free of pathogens and parasites, minimizing stresses on fish, and vaccinating fish against disease. Use of chemical pesticides can be minimized by preventing aquaculture pests from becoming a problem in the first place (for example, by constructing ponds deep enough to discourage weed growth) and, if pests become problematic, adopting biological controls.

Eliminating the use of drugs, pesticides, and other chemicals in aquaculture systems potentially gives producers the advantage of marketing organic products that can be sold for higher prices than nonorganic products. Organic standards for seafood are now under development by a major, international organic-certification agency.

Figure 4. Some Non Lethal Methods of Deterring Predators

Method	Avian Predation	Seal Predation
Facility Modification	Increase water depth of culture unit Increase slope of culture unit embankments Remove perches and feeding platforms Remove cover and concealing vegetati Disperse roost/nest site	Increase tension of nets Use rigid nets 
Operational Modification	Modify feed type and delivery method Re-locate young/small stock Remove dead fish promptly	Remove dead fish promptly
Auditory Harassment	Predator distress calls Automatic exploders Pyrotechnic devices Sirens Electronic noisemakers 	Predator vocalizations Explosive underwater devices (seal bombs) Underwater acoustic deterrence devices
Visual Harassment	Lights Scarecrows Reflectors Model airplanes Trained falcons Human presence 	Predator models (killer whale scarecrows) Patrol with boats
Barriers	Perimeter fencing and protective netting Water spray	Perimeter nets around entire site

Sources: OTA 1995; NMFS 1996.

Reducing Biological Pollution

Aquaculturists can reduce aquaculture as a source of biological pollution by carefully choosing the species or strains that they farm. The simplest way to eliminate the possibility of ecological harm from escapes of non-native aquaculture species is not to raise non-native species, unless there is compelling evidence that escaped fish cannot establish wild populations. Instead aquaculturists should raise native species or domesticated strains of non-native species that cannot survive and reproduce outside captivity.

Of course, even escaped fish of native species can cause biological pollution if the fish interbreed in significant numbers with wild fish. Thus, whether native or non-native species are raised, all aquaculture facilities should take measures to minimize escapes of cultivated fish into natural waters. The best method of preventing escapes is to not grow fish in open systems, such as netpens, and instead to use more secure closed systems, such as recirculating systems, discussed below. Nevertheless, even relatively open aquaculture can be altered to reduce the frequency of fish escapes. In addition, growing reproductively sterile organisms can be used to reduce the potential for biological pollution. Methods for inducing sterility in fish are not completely reliable, however. In one 1993 experiment, 20% of supposedly sterile Pacific oysters introduced to Chesapeake Bay reverted back to their sexually fertile state.

A variety of control methods, ranging from siting of ponds to scarecrows, may be used to reduce predation of farmed fish by wild animals, without killing animal predators (see Fig. 4). However, no single method is a panacea for predation problems. The most effective way to deter predators is to develop a predation control program that combines a number of nonlethal control methods, while constantly substituting different methods to avoid habituation by predators.

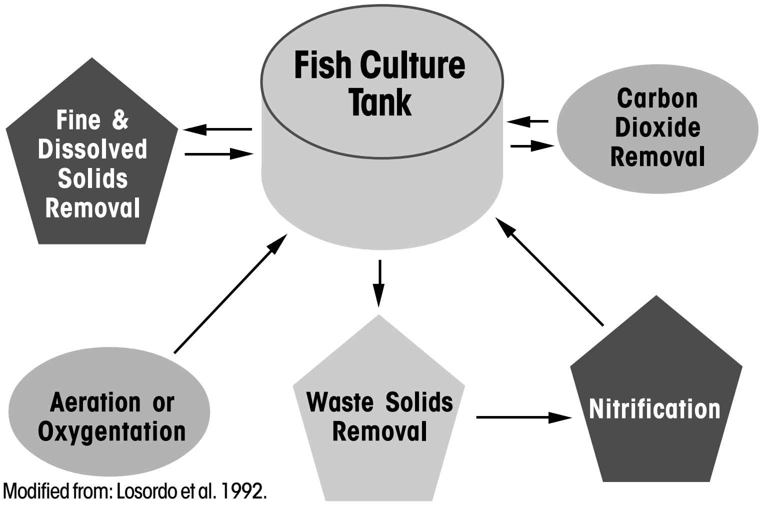
Source Reduction with Recirculating Systems

Aquaculture systems that reuse water more than once before discharging it are called recirculating systems. Most recirculating systems treat their water before it is reused. Because many systems are indoors, they avoid many problems of escaped aquaculture organisms, predator control, and pesticide use. Thus these systems are often regarded as the best approach to preventing environmental damage from aquaculture, since they provide a source-reduction method for water use and nutrient, chemical, and biological pollution.

In comparison to many other types of aquaculture systems, recirculating systems are highly complex, because they must treat and recirculate large volumes of water on a daily basis (see Fig. 5). Thus recirculating systems have relatively high investment and operating costs, and it is unlikely that recirculating systems will be used on a large scale until their average profitability is similar to that of ponds, netcages, and other aquaculture systems.

There are a number of examples of commercial recirculating systems in the United States. Integrated Food Technologies (IFT) in Emmaus, Pennsylvania, raises a total of 500,000 pounds annually of hybrid striped bass, tilapia, steelhead, and yellow perch in tanks in a former factory. IFT recirculates 98% of its water and treats it effluent by several methods. Some wastewater is used to grow hydroponic crops, such as lettuce.

Figure 5. Diagram of a Recirculating System



Modified from: Losordo et al. 1992.

Aquaculture for Economic Development

In the past, environmental goals have often been portrayed as being in direct opposition to economic goals. Such polarized thinking has begun to change, with many opinion leaders now arguing that environmental protection and economic development go hand in hand. Sustainable development not only must be economically viable, but also must conserve natural resources, not degrade the environment, and be socially acceptable. Consideration of socioeconomic goals must be married with consideration of environmental ones.

In recent years, federal and state governments have advanced aquaculture as a promising solution to the socioeconomic problems of some communities, particularly in rural and coastal areas. Many rural communities face serious economic problems from declines in small family farms, and some coastal areas face economic troubles from declining commercial stocks of wild fish.

Efforts to promote aquaculture to achieve economic and social goals in such communities need to be tempered by realistic appraisals of what can be achieved. Aquaculture can be a risky, difficult business; it requires considerable ability, long hours, and in many cases, substantial start-up capital.

Aquaculture is sometimes advanced as a means of self-employment for underemployed fishermen and farmers. However, aquaculture is experiencing the same trends toward consolidation that are evident in terrestrial agriculture. Some aquaculture sectors are now dominated by large businesses. The Mississippi Delta catfish industry, salmon farming in Maine and Washington, and trout farming in Idaho are dominated by industrial-scale farms. Although these well-established aquaculture sectors produce large numbers of jobs, most of them are with processing companies and other upstream segments of the industry, such as feed production and equipment manufacturing. Small farmers may find it difficult to succeed in these sectors.

Despite these realities, aquaculture fulfills socioeconomic goals to help sustain communities in some areas of the United States. In Florida and Massachusetts, underemployed commercial fishermen have become operators of small shellfish farms. In western Alabama, some small family farmers now farm catfish and other

fish species as an income-diversification strategy that helps these farmers to maintain their farms. Over the long term, the greatest benefits to rural and coastal communities will come from aquaculture enterprises that are not only economically profitable over the short term, but also environmentally sound and thus sustainable for the foreseeable future.

Recommendations

The phenomenal growth of aquaculture around the world has spurred considerable concern and controversy about resulting environmental degradation. In some countries, evidence of environmental damage has prompted governments to severely restrict or halt the expansion of salmon and shrimp aquaculture. Environmental problems caused by salmon farms have led to moratoria on the expansion of sites for salmon netpens in three of the world's largest producers of farmed salmon – Norway, Ireland, and Chile (where the moratorium is limited to freshwater lakes). Environmental and socioeconomic problems caused by a boom in shrimp farming along India's east coast, including destruction of mangrove forests and displacement of subsistence fishermen, led the Indian Supreme Court to rule in December 1996 that these farms must be removed.

Such disastrous experiences provide cautionary tales for the U.S. aquaculture industry as producers and policy makers set the course for the U.S. industry's continued growth. Not only is environmental degradation undesirable in and of itself, but if the U.S. aquaculture industry is to continue to expand and thrive, fish farms must be acceptable to the communities in which they are located. Otherwise proposals to construct or expand fish farms may be hamstrung because community members will believe that all they will receive from aquaculture facilities is their pollution.

As discussed above, aquaculture can cause a range of environmental problems, but a variety of methods are available to solve or avoid them. These methods provide the basis for this report's principal conclusion**: Aquaculture facilities constructed or operated without environmental protection in mind can cause serious environmental degradation and may ultimately be doomed to financial difficulties or failure. However, aquaculture need not be a polluting industry. A variety of strategies and technologies are now available to make fish farming environmentally sound.** From this conclusion flow a number of recommendations aimed at improving the environmental performance of U.S. aquaculture. Implementation of these recommendations rests on both the private sector (members of the aquaculture industry and consumers of aquaculture products) and the public sector (federal, state, and local governments).

Recommendations for the Private Sector

Recommendation One: Aquaculturists should adopt management strategies and technologies that make aquaculture environmentally sound. Many of these strategies and technologies are mentioned above and further detailed in this report.

Recommendation Two: The aquaculture industry should move away from raising finfish in netpens. Netpens are the type of aquaculture system most likely to cause environmental problems. There are few if any practical methods for collecting fish wastes from most netpens, and netpens are highly vulnerable to fish escapes.

Netpen proponents often argue that water-pollution problems can be avoided by siting netpens in coastal waters with strong currents that sweep away wastes. This strategy is akin to the now-discredited "dilution is the solution" approach to pollution that prevailed earlier this century.

Recommendation Three: Fish farmers should preferentially chose to raise, and consumers should preferentially chose to purchase, fish that require little fishmeal in their diets. A large fraction of farmed fish consumed in the United States, such as shrimp, trout, and especially salmon, are carnivores that are fed diets high in fishmeal. Other types of farmed fish, such as catfish, tilapia, crawfish, clams, oysters, mussels, and scallops, require little or no fishmeal in their diets. Aquaculturists can help to relieve pressure on wild fisheries by electing to farm these and other partially or entirely herbivorous fish, in preference to highly carnivorous species. U.S. consumers can create a strong financial incentive for aquaculturists to farm herbivorous fish by choosing to purchase farmed herbivorous instead of farmed carnivorous species.

Recommendation Four: Organic certification and potentially other "eco-certification" programs should be established that empower consumers to chose aquaculture products grown in an environmentally sound manner and that give aquaculturists incentives to produce products which can bring higher prices. Consumers cannot now generally determine at the seafood counter whether fish was farmed (or wild caught) in an environmentally sound manner. Organic certification of seafood can help consumers use their pocketbooks to encourage environmentally sound production practices.

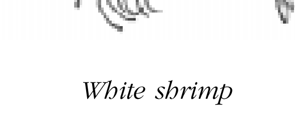
Recommendations for Government

Government regulation of and support for aquaculture is a major force affecting the sustainability of aquaculture. Unfortunately, federal regulations covering several key environmental issues in aquaculture are deficient or nonexistent. Steps are recommended below to remedy inadequate regulatory oversight in three areas and to guide government support for research, small business loans, and other programs that support aquaculture.

Recommendation Five: The U.S. Environmental Protection Agency (EPA) should implement the Clean Water Act for aquaculture by developing effluent limitations. Under the Clean Water Act, EPA is supposed to set effluent limitations for various industries – discharge quality standards for specific pollutants that are found to be achievable using particular technologies. However, EPA has failed to establish effluent limitations for aquaculture, with the result that water-quality standards for aquaculture effluents vary dramatically among states. In many states, untreated fish sewage is discharged directly into waterways.

Recommendation Six: The federal government should develop a comprehensive oversight framework for introduction of potential biological pollutants from aquaculture and other human activities. Federal oversight of introductions of potential biological pollutants is at best piecemeal. A concerted federal effort to develop a coherent framework is essential to limiting future ecological harm by biological pollutants from aquaculture and other sources.

Recommendation Seven: The federal government should develop a regulatory framework for open-ocean aquaculture that includes strong environmental protections. Several netpen or cage facilities are now being planned or built in the open ocean, beyond state-controlled waters where they have historically been located. A coherent regulatory program, perhaps led by the National Marine Fisheries Service, is needed to protect marine ecosystems.



White shrimp

Recommendation Eight: Government research and other support programs for aquaculture should emphasize environmental protection and the development of aquaculture operations that provide long-term social and economic benefits to economically distressed communities. Two "win-win" research topics that will help accomplish source reduction of pollutants and provide financial benefits especially stand out as candidates for government support. These are 1) domestication of farmed fish via selective breeding to improve production traits and simultaneously reduce the ability of escaped farmed fish to survive, and 2) refinement of recirculating aquaculture systems to increase their competitiveness in the marketplace.

Chapter One

Old MacDonald Had a Fish: A Portrait of the Aquaculture Industry

Introduction

Most Americans would be surprised to learn that their last seafood meal may have been raised on a farm rather than caught in the ocean. Largely because of declines in wild fisheries and increasing demand for seafood, aquaculture has become the source of an increasing fraction of the seafood consumed in the United States and throughout the world. Although precise figures are not available, most of the catfish and trout, roughly half the shrimp, and approximately one-third of the salmon consumed in the United States is raised by aquaculturists, or fish farmers. Other aquatic organisms, including hybrid striped bass, tilapia, crawfish, and clams, are being raised in tanks, ponds, and coastal waters.

Aquaculture can be defined "as the propagation and rearing of aquatic organisms in controlled or selected environments."[1] These organisms are usually "fish" — defined as both finfish and shellfish. Production of aquatic plants, such as seaweeds, is also generally defined as aquaculture, as is alligator production. Most aquatic organisms are reared for food, but some are raised for pharmaceutical products, bait, ornamental aquarium fish, and other diverse purposes. Rearing fish for part of their life cycle so that they can be stocked in lakes, estuaries, and other water bodies is sometimes regarded as aquaculture but will not be considered in this publication.

The value of U.S. aquaculture production has grown by roughly 5-10 % each year over the past decade, depending on how it is measured (NMFS 1996a; FAO 1997a). Aquaculture is the sector of U.S. agriculture that experts predict will grow the most in coming years (Gempesaw et al. 1995). The United States currently leads the world in farmed catfish and crawfish production and is a major producer of farmed trout.

Increasing aquaculture production in the United States could provide a welcome alternative to harvesting fish from overexploited wild stocks and may increase the variety and freshness of seafood available to consumers. However, concerns about environmental problems and access to coastal and inland waters are creating tensions between aquaculturists, environmentalists, and others.

The Texas state government, for example, promoted coastal shrimp farming in the mid-1980's as a form of economic development. Environmental protection received little thought, even though shrimp farms have caused serious environmental problems in other countries. Although the Texas shrimp-farming industry is relatively modest in size, environmental degradation caused by Texas shrimp farms has spurred lawsuits by grassroots organizations. A coalition of coastal residents, environmentalists, and recreational fishermen is now working to achieve major changes in the way shrimp farms are operated and regulated in Texas.

If the U.S. aquaculture industry is to continue to expand and thrive, aquaculture operations must be designed not only to be financially profitable, but also to be environmentally benign and to be acceptable to the communities in which they are located. Otherwise the industry may be hamstrung because opponents believe that all they receive from aquaculture facilities is their pollution (Costa-Pierce 1994).

This report identifies elements necessary to produce an aquaculture industry that is both environmentally and economically sound. Such identification should help to prevent conflict between environmental and economic development objectives, while encouraging the development of aquaculture operations that most benefit communities. This handbook can serve as a resource for government decision makers, environmentalists, community activists, potential aquaculturists, local officials, and others who influence the design and success of aquaculture operations.

The report begins with six chapters that review and analyze the environmental and economic status of aquaculture, focusing on the United States. These chapters are followed by three case studies that illustrate some of the problems and successes of aquaculture development in North America:

- Chapter 1 describes the rapid growth and diversity of U.S. and worldwide aquaculture, and highlights issues such as aquaculture's heavy reliance on the capture of wild fish to feed farmed fish.
- Chapter 2 details environmental problems associated with aquaculture, such as nutrient pollution, water demand, and the use of farm chemicals.
- Chapter 3 discusses ecological and genetic harm that may be caused by aquaculture, including problems resulting from escapes of non-native species and genetically altered fish from farms.
- Chapter 4 provides an overview of technologies and management practices, such as water-reuse systems, that can be used to prevent or mitigate environmental problems caused by aquaculture.
- Chapter 5 discusses aquaculture's possible roles in community economic development.
- Chapter 6 provides a summary of aquaculture regulation in the United States and the Environmental Defense Fund's policy recommendations for U.S. aquaculture.
- The first case study describes environmental problems and other conflicts caused by the growth of the coastal shrimp-farming industry in Texas, which until recently was not subject to key environmental regulations.
- The second case study reviews government policies that facilitated the rapid and largely unregulated growth of the large salmon aquaculture industry just north of


Sunset over catfish ponds. Courtesy of Catfish Farmers of America.

Maine in New Brunswick, Canada, despite evidence of environmental degradation.

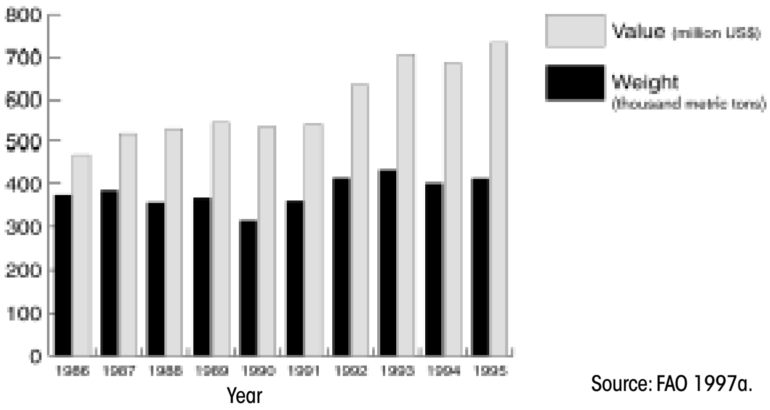
- The third case study argues that, to date, the Maine salmon farming industry has been relatively clean, in part because of effective state regulations.

Growth of Aquaculture

Aquaculture is a relatively new industry in the United States. Oysters have been farmed here since the 1880's and trout since the early 1900's; however, aquaculture did not become a major U.S. industry until the 1950's, when the catfish-farming industry developed in the Southeast (Bush and Anderson 1993; OTA 1995). Since then, aquaculture production has grown immensely. Today fish are farmed in every state and territory, and aquaculture is the fastest-growing segment of U.S. agriculture (Harvey 1991). In 1995 the aquaculture industry produced more than 400,000 metric tons (mt) of finfish and shellfish (shell weight included), worth $729 million, and production has increased 55% by value over the last decade (FAO 1997a). U.S. aquaculture production of finfish and shellfish more than doubled in weight between 1983 and 1994 (sehllfish shell weight not included) (NMFS 1996a). Nevertheless, domestic aquaculture production still makes up only 10-15% of the total U.S. seafood supply, the rest of which comes from domestic capture fisheries and from imports of wild-caught and farmed fish (OTA 1995).

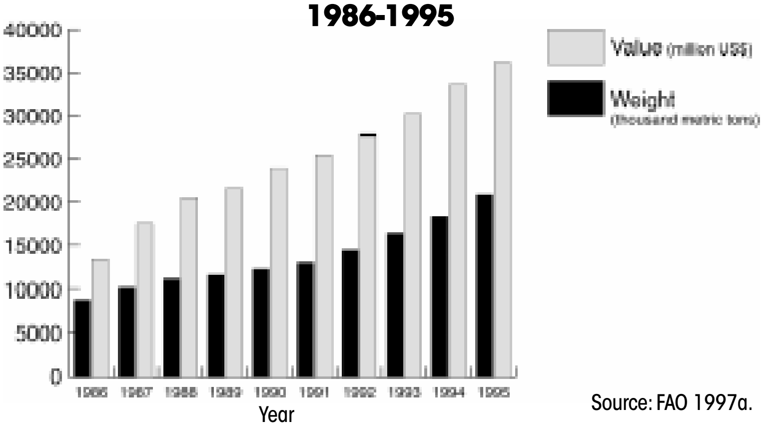
The steady growth of aquaculture in the United States mirrors its phenomenal growth worldwide. (Figs. 1.1a and 1.1b show U.S. and world aquaculture production). Unlike the relatively young U.S. industry, aquaculture has been a form of food production in Asia for 2,000 years. Modern intensive[2] versions of this ancient practice have boomed in recent years, as aquaculture has become a major export industry in many developing countries, especially in Asia. In 1995 world aquaculture production reached a record 20,900,000 mt of fish and shellfish worth more than U.S. $36.2 billion. This production represents 18.5% of the total world seafood supply, more than double the 1984 figure (FAO 1997b, 1997c). Aquaculture is the source of 27% of seafood consumed by humans worldwide, since more than a quarter of wild fish harvests are used in animal feed (FAO 1997b, 1997c).

Figure 1.1a. U.S. Aquaculture Production, 1986-1995



Source: FAO 1997a.

Figure 1.1b. World Aquaculture Production, 1986-1995



Source: FAO 1997a.

Worldwide, China dominates aquaculture, with almost 60% of all production by weight. Chinese production is so much higher than any other country that aquaculture experts sometimes exclude China when they present aquaculture production figures for the rest of the world's countries. Including China, the U.S. aquaculture industry is the world's

Figure 1.2. Principal Aquaculture-producing Countries, 1995

	Percentage of World Aquaculture Production (by weight)	Percentage of World Aquaculture Production, Excluding China (by weight)
China	61.1	—
India	7.7	20.0
Japan	3.9	10.1
Indonesia	2.9	7.5
Thailand	2.2	5.7
USA	2.0	5.1
Korea Rep.	1.8	4.5
Philippines	1.7	4.2

Source: FAO 1997a.

Figure 1.3. Important Aquaculture Organisms in the United States, 1995

	Quantity (MT)	Percentage of Total Quantity	Value (thousand $)	Percentage of Total Value
Total Production	413,431	—	729,097	—
Catfish	202,706	49.0	350,681	48.1
Oysters*	109,080	26.4	70,646	9.7
Crawfish	26,375	6.4	34,815	7.2
Trout	25,240	6.1	52,752	4.8
Salmon	14,106	3.4	75,504	10.4
Clams*	13,481	3.3	19,221	2.6
Baitfish	9,883	2.4	71,355	9.8
Tilapia	6,838	1.7	22,634	3.1
Hybrid striped bass	3,772	0.9	21,161	2.9
Marine shrimp	1,000	0.2	8,820	1.2
Mussels*	930	0.2	1,218	0.2
Sturgeon	20	0.0	290	0.0

Source: FAO 1997a.
*Shell weight included.

sixth largest, with a comparatively small 2.0% of world production; when China is excluded, the United States' share increases to 5.1% (see Fig.1.2).

Species Produced by Aquaculture

More than 100 species of aquatic organisms are farmed, or "cultured," in the United States in a variety of production systems (see Box 1.1) (OTA 1995). However, only about 10 types of finfish and shellfish dominate U.S. aquaculture production for food (see Fig 1.3).[3] Worldwide approximately 250 species are raised (FAO 1997b).

Close to 60 % of U.S. production by weight is of freshwater fish. In particular, catfish culture has long dominated U.S. aquaculture, and now stands at about 50% of U.S. aquaculture production. Although catfish production, as measured by weight, declined in 1994 for the first time in 20 years, production grew in 1996 to 230,000 mt, worth $387 million. Production is expected to increase by 5-7% in 1997 (USDA 1997). Most catfish are farmed in ponds in the Mississippi Delta region. Other freshwater fish cultured in the United States include tilapia and carp species, which are raised throughout the country.

Mollusks are almost one-third of U.S. production by weight (including shells) and are worth $91 million. Two species of oysters, the American oyster and the Pacific oyster (also known as the Japanese oyster), dominate production. Mussels and a variety of clams are also produced. Oysters are grown mainly along the coasts of the Pacific Northwest, the Gulf of Mexico, and the Northeast.

Diadromous fish (fish that spend parts of their lives in saltwater and freshwater) are 3.4 percent of U.S. aquaculture production by weight. However, diadromous fish — salmon, rainbow trout,[4] and sturgeon — sell for relatively high prices. Their percentage of production by value is 10.4%, substantially higher than their percentage by weight (see Fig. 1.4). Rainbow trout production has declined slightly in the last few years. However, it still earns more than $50 million annually for farmers in Idaho, where most rainbow trout is raised in raceways (USDA 1996). Atlantic salmon production has grown from none in 1985 to more than 14,000 mt, worth more than $75 million, although the rate of growth in production has slowed down in the last few years. Atlantic salmon is grown in sea cages along the coasts of Maine and Washington. A very small amount of sturgeon is farmed in California and Idaho.

In contrast to diadromous fish, crustaceans are nearly the same percentage of U.S. production (6 %) by both weight and value. Most crustacean production is of crawfish, most of which is raised in earthen ponds in Louisiana. Imports of inexpensive Chinese crawfish have skyrocketed in recent years, clouding the future of the Louisiana industry (St. George 1997). Freshwater and marine shrimp are a small fraction of crustacean production by weight but are not far below crawfish production in value. Seventy percent of U.S. farmed-shrimp production occurs in ponds in Texas (U.S. Marine Shrimp Farming Program 1995).

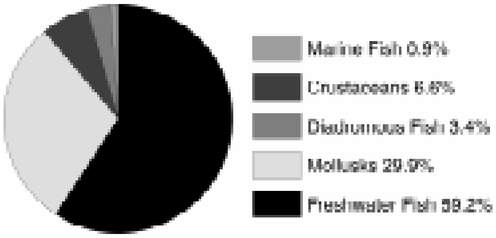
Freshwater fish dominate world, as well as U.S., aquaculture production, measured in weight (see Fig. 1.5). Worldwide, however, carps, rather than catfish, dominate; carps and other closely related freshwater fish make up nearly 46% by weight of total aquaculture production. Four carps (silver, grass, common, and bighead), raised largely in China for domestic consumption, total half of world fish production. In comparison to U.S. production, mollusks make up a much smaller percentage of world production. Diadromous fish and crustaceans, however, make up only a slightly smaller percentage of world production than of U.S. production. The U.S. production of seaweeds is extremely low, while seaweeds are nearly 25% of world aquaculture production when aquaculture is defined to include farming of aquatic plants. Most seaweeds are raised to produce agar, carrageenan and additive used by the food and pharmaceutical industries.

The world production picture looks quite different, however, if production is measured by monetary value rather than weight. In particular, some crustaceans (primarily marine shrimp) and diadromous fish (primarily salmon) are extremely valuable. The giant tiger prawn, for example, ranked eleventh in world

Figure 1.4. U.S. Aquaculture Production by Category, 1995

Percent of Total Production

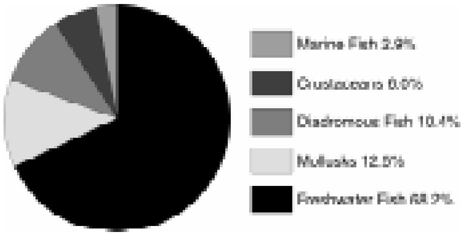
Total Production: 413,431 MT



Source: FAO 1997a.
* Includes tilapia and carps

Percent of Total Value

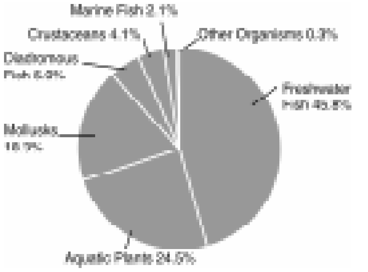
Total Value: $729,097,000



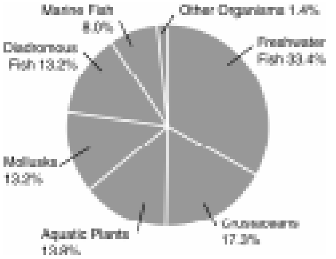
Source: FAO 1997a.

Figure 1.5. World Aquaculture Production by Category, 1995*

Total Production: 27,800,000 MT



Total Value: US$ 42.3 billion



Source: FAO 1997b. * Includes aquatic plants

BOX 1.1. PRODUCTION SYSTEMS IN US AQUACULTURE

Production systems include ponds (top left), raceways (middle), and netpens (bottom). Photos courtesy of Texas Parks and Wildlife Department (top left), American Tilapia Association (middle) and New Brunswick Department of Fisheries and Oceans (bottom).

Earthen ponds are the most widely used production systems in the United States. Ponds are located outdoors and vary greatly in shape, size, and depth. Catfish, shrimp, tilapia, and other fish are raised in ponds containing fresh or brackish water. The majority of pond aquaculture systems are located in the Southeast where the catfish industry is concentrated.

Raceways are a series of tanks through which water (generally freshwater) flows continuously. Raceways may be located indoors or outdoors. In Idaho and other states, the trout industry uses outdoor raceways of rectangular tanks. Other fish, including catfish, tilapia, and yellow perch, are also raised in raceways in some parts of the United States.

Cages, netpens, rafts, and trays are used to raise fish and shellfish within bodies of water, such as lakes, ponds, and coastal bays. Salmon are raised in floating netpens anchored to the bottom of the water column in coastal areas. While salmon netpen production currently occurs only in nearshore areas, there is interest in making use of underwater cages in locations offshore. Shellfish are sometimes grown in bags or on ropes suspended from floating rafts in coastal waters. In the United States, however, most shellfish farming occurs on the sea floor either on trays or on cultch (crushed oyster shells).

Recirculating systems treat and reuse 50-90% of the water they contain — which is usually held in tanks — not unlike giant versions of home aquariums. In comparison to other systems, there are few commercial recirculating systems operating in the United States. Those operating today raise a variety of different fish, including tilapia, hybrid striped bass, and trout. (Stickney 1994, OTA 1995) production by weight (502,701 mt) but first in value (U.S. $3.50 billion) (FAO 1997a). Similarly, while Atlantic salmon ranked 13th in world production by weight (471,813 mt), it ranked fifth in value (U.S. $1.80 billion) (FAO 1997a).

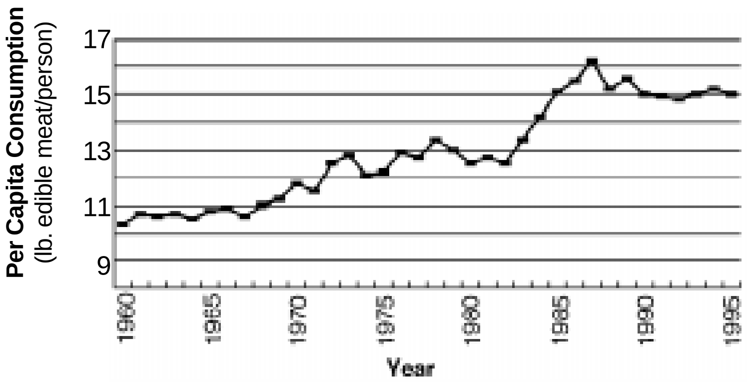
Factors Affecting the Growth of U.S. Aquaculture

Growth in U.S. aquaculture production has resulted largely from three different forces: declines in domestic and world fisheries catches; increases in demand for seafood, in general, and for aquaculture products themselves; and government promotion of aquaculture.

Aquaculture products have steadily increased their share of total US seafood consumption (OTA 1995). Harvests from most U.S. capture fisheries are declining or reaching their limits, creating opportunities in the U.S. seafood market for aquaculture products (National Research Council 1992). Precipitous declines in many fishery stocks around the world have led to skyrocketing prices for many types of wild-caught seafood (Zimmerman 1996). As a result, prices for many aquaculture products are comparatively low.

Consumer demand for seafood products has grown tremendously in the second half of this century (see Fig. 1.6), and this increased demand has stimulated growth in U.S. aquaculture production. The most rapid increases in per capita consumption of seafood occurred during the early to mid-1980's; a peak of 16.2 pounds/year, reached in 1987, represented a 50% increase over 1960 levels. Publicity about the nutritional benefits of seafood helped boost consumption in the 1980's, despite an increase in seafood prices relative to other meats (Hanson et al. 1994). After 1987, however, per capita consumption declined somewhat and seems to have stabilized at about 15.0 pounds/year (Johnson 1996). This decline can be attributed to a delayed consumer response to the high price of seafood relative to other meats, as seafood supply could nor grow as fast as demand (Hanson et al. 1994; G. Lockwood, pers. comm.), and possibly to consumer worries about seafood safety. The total amount of seafood consumed in the United States will continue to grow as a result of U.S. population growth (about 1 % per year), though per capita consumption of seafood is expected to remain at about 15.0 pounds/year in the future (Johnson 1996).

Figure 1.6. U.S. Seafood Consumption, 1960-1995



Source: NMFS 1996a.

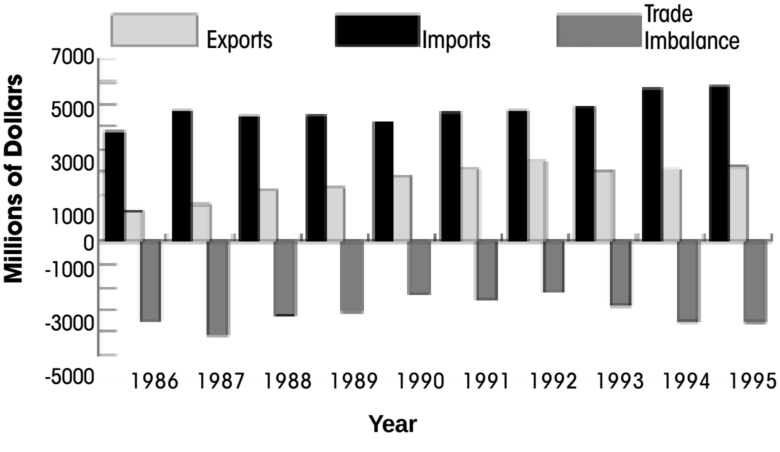
Aquaculture production has grown primarily due to greater overall demand for seafood; however, greater demand for aquaculture products themselves has also been a factor. Year-round demand for seafood products (OTA 1995) and demand for products with consistent quality and appearance have favored aquaculture, particularly the growth of the catfish and trout industries (USDA 1994).

Government promotion of U.S. aquaculture has also spurred the industry's growth. Aquaculture received at least $60 million in financial assistance from the federal government in 1994. Although 25 federal agencies contributed funding, most came from the Departments of Agriculture, Commerce, and Interior. Most of this money funded research. Aquaculture support activities — such as loans and training programs and, to a lesser extent, aquaculture regulation — received the remainder of the funding (OTA 1995). Numerous states, including Massachusetts, Maine, Texas, and Florida, also promote aquaculture. Despite these federal and state programs, some aquaculturists argue that much greater government support is necessary to make the U.S. industry competitive in the world market.

Government promotion of aquaculture stems largely from concerns about declines in natural fishery harvests and an increasing annual trade deficit in fish and fish products (National Research Council 1992). The growing U.S. trade deficit in seafood is evidence that U.S. capture fisheries have not kept up with U.S. seafood demand (see Fig. 1.7). In 1996 the U.S. seafood deficit was $3.6 billion (Bureau of the Census, Foreign Trade Division 1997). Currently the United States imports half the seafood it consumes and is the world's second-largest seafood importer (USDA 1996). Much of the growth in seafood consumption in the 1980's was made possible by substantial increases in fishery product imports (Hanson et al. 1994).

U.S. aquaculture production is expected to continue to increase steadily (Johnson 1996). Some observers believe that aquaculture must grow, arguing that obtaining fish from capture fisheries is comparable to obtaining meat from hunting (for example, Avery 1996). Hunting wild animals for meat, as was once common, could not come close to meeting the modern-day demand for meat, which is now produced on farms. Similarly, the argument goes, we must now make a transition to obtaining seafood from aquaculture, rather than from capture fisheries.

Figure 1.7. U.S. Seafood Trade Value, 1986-1995



Source: NMFS 1996a.

The situation is not so straightforward, however, for several reasons. First, fish species tend to have much higher reproductive rates than warm-blooded animals such as deer, and thus wild fish populations can sustain relatively high harvest rates. Second, aquaculture production can grow only so fast. Although some experts predict that the share of world fisheries production from capture fisheries will continue to decline, it will take 50 years or so before aquaculture will make up the majority of production (Williams 1996). Third, production of some aquaculture species actually requires more fish as feed than are ultimately produced for consumers.

The Fishmeal Dilemma: Net Fish-protein Reduction

In many intensive and semi-intensive aquaculture systems, more protein, in the form of fishmeal, is used to feed the farmed species than is supplied by the harvest of the farmed species. Overall, it is estimated that the total amount of fish and fishery resources used as feed in such systems is two to six times greater than the amount of new fish protein produced, depending on the aquaculture system and the fishmeal source (New 1995, Tacon 1996). In short, aquaculture can be a net fish-protein reducer, not a net fish-protein producer.

Not all aquaculture systems act as net fish-protein reducers. Worldwide, the species farmed range from herbivores and omnivores (such as tilapia, milkfish, and carp) to carnivores (such as salmon, trout, and sea bream). Herbivorous and omnivorous species, long farmed in many parts of the world, are generally net protein producers, although in some modern aquaculture systems even these species are fed feeds containing fishmeal (Tacon 1996). Farming carnivorous finfish and marine shrimp in intensive systems is a relatively new practice (Primavera 1993; Landesman 1994; Muluk and Bailey 1996; Tacon 1996). This is the type of aquaculture system that acts as a net fish-protein reducer.

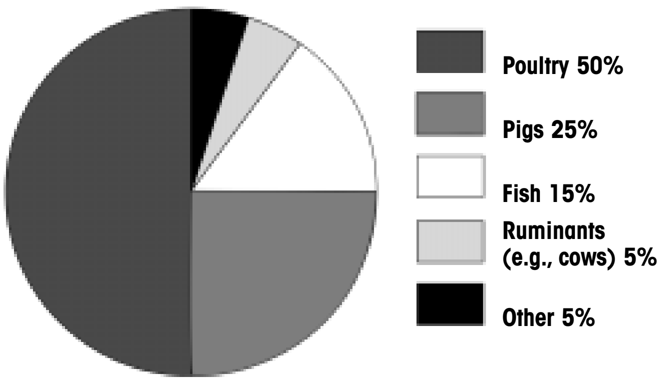
Farming of carnivorous finfish and intensive farming of marine shrimp requires fishmeal and fish oil as the main sources of dietary protein and lipids (Tacon 1996). Fishmeal and fish oil make up 70% by weight of “compound” aquafeeds for most carnivorous finfish species, and up to 50% by weight of compound aquafeeds for marine shrimp (Tacon 1996). The remainder of these feeds consists chiefly of grains and agricultural byproducts (Stickney 1994). Small pelagic fishes,[5] such as anchovy, jack mackerel, pilchard, capelin, menhaden, herring, and sardine, are harvested to make fishmeal and oil (Tacon 1996).

Huge amounts of pelagic fish are used to produce fishmeal. Twenty-seven percent (31,000,000 mt) of total capture fisheries production is reduced to animal feeds (FAO 1997c). A relatively small portion of this fishmeal (15%) is used in aquaculture production compared to terrestrial animal production; however, aquaculture feeds tend to contain much higher percentages of fishmeal than other animal feeds. Figure 1.8 shows the percentage of total fishmeal supplies that go to different livestock, and the percentage of fishmeal in each type of feed.

Figure 1.8. Global Fishmeal Use by Livestock

	Average Percentage Fishmeal in Feed
Poultry	
Broiler starter, grower	0-2.5
Broiler finisher	nil
Layers	0.1
Pigs	
Weaner	5-10
Starter	2.5-5
Grower	0.2
Finisher	nil
Breeders	0-2
Aquaculture	
Salmon	50-70
Trout	30
Marine shrimp	25-50
Common carp, tilapias	20*
Catfish	3-5

Average Percentage of Fishmeal Supply Consumed by Livestock, 1995



Sources: *Terrestrial Livestock, salmon, trout, common carp, tilapias:* New 1995.
Catfish: Boyd and Tucker 1995; New 1995.
Marine shrimp: New 1995; Tacon 1996.
* Particularly in developing countries, these fish are frequently produced without fishmeal-containing feeds (Tacon 1996).

The amount of pelagic fish required to produce certain aquaculture species is enormous. In 1993, some 3,370,000 mt of pelagic fish were used to produce 1,000,000 mt of farmed finfish, and 1,300,000 mt of pelagic fish were used to produce 800,000 mt of farmed marine shrimp (Tacon 1996). The amount of pelagic fish required to produce a certain amount of aquaculture product depends both on the efficiency of the conversion of pelagic fish to fishmeal and the effi-

Feeding salmon. Courtesy of New Brunswick Department of Fisheries and Oceans.

ciency of the conversion of fishmeal to aquaculture product. In general, the yield from “round” (whole) fish to fishmeal is only about 20%, largely because of water loss (Ellis and Associates 1996).

The most obvious problem with using fishmeal in aquaculture is that it is inefficient. “It does not make a great deal of . . . sense to catch a fish, grind it up, feed it to another fish that is then caught and marketed for human consumption when you can first take the fish and make an entirely acceptable human food” (Stickney 1994). Feeding fish to fish leads to a net loss of protein in a protein-short world. The Food and Agriculture Organization of the United Nations (FAO) notes that small pelagic fishes will have to be redirected to human consumption if world per capita seafood consumption is to remain at its current level of 13 kilograms per year as the world’s population increases over the next 15 years (FAO 1995). Although large quantities of small pelagic species are consumed throughout the world (FAO 1995), there are considerable logistical and economic obstacles to distributing to needy people a substantial fraction of the small pelagics now used for animal feed (James 1995). A few pelagic fish species, such as menhaden, do not make palatable human food (G. Lockwood, pers. comm.)

Less obvious problems of the “fishmeal dilemma” are the ecological effects of massive harvests of small pelagic fishes. The role of fishing and other factors in causing declines in populations of small pelagic fishes is not well understood. Nevertheless, removal by fishing vessels of huge quantities of the biomass of small fish from marine food webs means that less food may be available for commercially valuable predatory fish, that is, fish that comprise major food fisheries (Folke and Kautsky 1989; Fischer et al. 1997). In Newfoundland, the development of a major fishery for capelin (the primary prey of cod) is discussed as a possible factor in the decline of cod (Fischer et al. 1997). In Europe, some observers believe that overfishing has been a major factor in crashes of North Sea capelin and herring fisheries, and may have resulted in starvation of seals and seabird chicks (Folke and Kautsky 1989; Vader et al 1990a, 1990b).

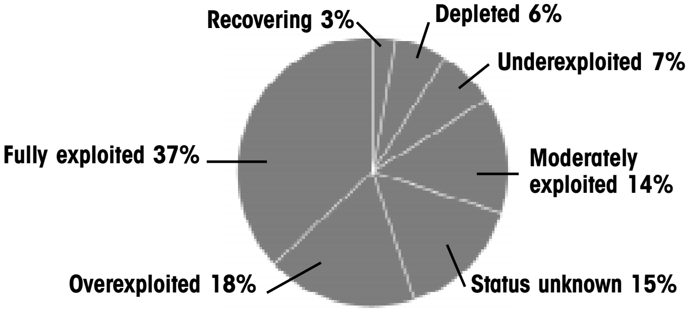
Extrapolation of current production trends indicates that by the year 2000 the aquaculture industry will require substantially larger amounts of fishmeal and fish oil (Chamberlain 1993). However, it is unlikely that aquaculture’s future fishmeal demand will be met, and because fishmeal supplies are limited, aquaculture must compete for fishmeal with livestock production (Rumsey 1993; Stickney 1994). Fishmeal requirements may decrease if researchers are successful in developing new feeds that contain more grains and less fishmeal (Tacon 1994; Williams 1996; also see discussion of reducing feed waste in Chapter 4). Nevertheless, some experts predict that fishmeal shortages will in the near future limit the growth of the farming of carnivorous finfish and shrimp (Csavas 1994).

Figure 1.9. Feed Conversion Ratios for Some Food Animals

	Average Feed Conversion Ratio
Terrestrial livestock	
Cattle	8.0
Pigs	3.0
Poultry	2.0
Aquaculture	
Marine Shrimp	1.7-1.8
Catfish	1.5-2.0
Tilapia	1.2-2.0
Trout	1.2-1.5
Salmon	1.1-1.5

Sources: *Cattle and Poultry:* Stickney 1994.
Pigs: Ohio Pork Information Center, pers. comm.
Shrimp: Chamberlain 1993.
Tilapia: K. Fitzsimmons, pers. comm.
Catfish: Boyd and Tucker 1995.
Trout: G. Fornshell, pers. comm.; Idaho Division of Environmental Quality 1996.
Salmon: Ellis and Associates 1996; Chamberlain 1993.

Figure 1.10. Status of the World's 200 Main Fish Stocks, 1992



Source: FAO 1992.

Food for Thought

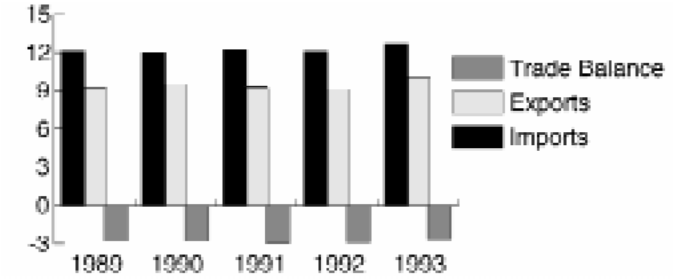
Despite the fact that the farming of carnivorous fish species results in a net loss of fish protein, aquaculture has been promoted as a cure for protein shortages, particularly in developing countries (Kent 1987; Stickney 1994; Bailey 1997). World population is expected to reach close to 7 billion by 2010, with 85% of this growth occurring in developing countries (James 1995). Compared to other meats, fish is a relatively efficient means of supplying protein. Feed conversion ratios (FCR's) describe the efficiency of conversion of feed to livestock product. Fish tend to have lower FCR's than other animals raised for food (see Fig. 1.9). In addition, on average humans can eat approximately 65% of the raw weight of finfish, compared with 50% of the raw weight of chickens and pigs and 40% of the raw weight of sheep (Rogne 1995).

Assuming that the current world per capita consumption of seafood is maintained at or above the current 13 kilograms per year, population and income growth will lead global demand for seafood to increase to more than 100 mmt in 2010 (FAO 1995). Currently, developing countries are more dependent on fish as a source of animal protein than developed countries, with the poor of developing countries more dependent on fish than the wealthier citizens (James 1995). In addition, as economies grow in a number of developing countries, particularly in southeast Asia, demand for seafood from affluent populations is also rising. The potential to meet this demand with increased yields from capture fisheries is, at best, extremely limited over the long term (FAO 1997c). Virtually all of the world's major fisheries are being fished at or above their sustainable yields (National Research Council 1992; FAO 1996c; Williams 1996). (Figure 1.10 shows the status of the world's 200 main fish stocks in 1992).

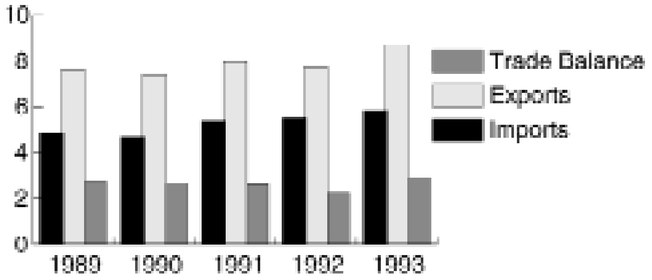
In the late 1970's, international development banks and aid organizations began to promote aquaculture as a means

Figure 1.11. World Trade in Fish and Fisheries Products by Weight, 1989-1993

Developed Countries



Developing Countries



Source: FAO 1996.

to supply protein to developing countries (Stickney 1994). Some development programs have succeeded, especially those promoting production of freshwater herbivorous and omnivorous fish. According to the Food and Agriculture Organization of the United Nations, in areas with favorable farming conditions, the farming of freshwater fish is the fish production tactic with the greatest potential to increase domestic fish supplies (FAO 1995).

China and India lead the world in aquaculture production. Both countries have long histories of inland freshwater fish farming, which is the majority of their fish production. Government promotion of freshwater aquaculture and, especially in China, private sector interest have significantly increased domestic fish production (Sanjeeva Reddy 1995; Tripathi 1995; Rama Rao 1995; C. Bailey, pers. comm.). China's aquaculture production has nearly quadrupled in weight over the last decade. This increase has largely come from freshwater fish production, which accounts for almost 75% of China's aquaculture production by weight. Most of China's increased aquaculture production is consumed domestically (FAO 1995; FAO 1996). China's supply of fish has doubled in the last decade, and fish has continued to make up 20% of China's animal protein intake (FAO 1995). A similar situation exists in India, where freshwater fish production makes up almost 95% of aquaculture production by weight, most of which is consumed domestically (FAO 1996).

Despite some successes, many of the development programs that sought to increase domestic food production and protein consumption in developing countries through aquaculture have failed (Kent 1987; Stickney 1994). In order to earn foreign exchange, the governments of these countries encouraged the production of high-value seafood items for export (Bailey 1997). Particularly in Asian countries, a combination of forces from national governments, international development agencies, and the private commercial sector caused traditional aquaculture systems producing food for local consumption to be replaced by modern aquaculture systems producing high-value species for export (Landesman 1994; Muluk and Bailey 1996). Even in China, production of scallops and shrimp for export has boomed. At the same time as Chinese production of carps quadrupled over the last decade, production of bay scallops increased by a factor of almost 40 (FAO 1997a). Between 1985 and 1991, China's production of shrimp increased by a factor of five, and for a while China led the world in farmed-shrimp production; however, problems with shrimp diseases have reduced production considerably in recent years (Tacon 1996).

An increasing fraction of aquaculture production in many developing countries is now of expensive luxury products, particularly shrimp that are targeted for sale in developed countries (Stickney 1994; Bailey 1997). Unlike many other food commodities, such as grains and other meats, trade in fisheries products favors net export from developing countries and net import by developed countries (see Fig. 1.11). The United States is a major importer of high-value aquaculture products; for example, US imports of shrimp from Ecuador and Thailand grew by 125% to 128,895 mt between 1987 and 1994 (NMFS 1996b). In contrast, the United States exports very little of its own aquaculture production; 1994 exports of farmed catfish, salmon, and trout were 5% or less (NMFS 1996b).

The trend toward intensification of aquaculture production appears likely to continue throughout the world (Tacon 1996). Some observers believe that aquaculture production will become increasingly controlled by large investors (Williams 1996) and that aquaculture products will become increasingly expensive due to rising production costs (Stickney 1994). In general, aquaculture products are too expensive to be purchased by the world's poor (Stickney 1994). With the possible exception of China, the developing world is expected to continue to export much of its aquaculture production (Williams 1996), and the gap in average fish consumption between the developed and developing world is likely to increase (Westlund 1996).

Health Benefits of Fish Consumption

Even if aquaculture is not providing as much food for poor people in developing countries as once was hoped, aquaculture production can have important health benefits for relatively affluent consumers who can afford to purchase seafood. People who eat fish at least once a week have reduced risks of coronary heart disease (Jacobson et al. 1991; Daviglus et al. 1997). Seafood is a low-fat, low-cholesterol source of protein and is rich in B-vitamins, trace elements, and omega-3 fatty acids (Jacobson et al. 1991).

Figure 1.12. Saturated Fat and Cholesterol in a 3-oz. Serving of Meat, Poultry, and Seafood

Type of Meat	Preparation	Saturated fat (g)	Cholesterol (mg)
Beef (bottom round)	roasted	2.2	66
Pork (loin chops, lean only)	broiled	2.3	68
Chicken breast (white meat, w/o skin)	roasted	0.9	73
Trout	dry heat	0.7	62
Salmon (pink)	dry heat	0.6	57
Halibut	dry heat	0.4	35
Shrimp (shells removed)	boiled	0.2	166
Tuna (light)	canned in water	0.1	20
Orange roughy	dry heat	0.0	22

Source: American Heart Association 1995.

High blood cholesterol contributes to cardiovascular disease, the number one cause of death in the United States (American Heart Association 1996a). Most seafood is extremely low in artery-clogging saturated fat, which raises blood cholesterol and fat levels (American Heart Association 1996b). For example, 3 ounces of flounder contains only 0.3 ounce of saturated fat, a third of that contained in 3 ounces of skinless chicken breast (American Heart Association 1995). Figure 1.12 shows the fat levels in various meats and seafoods. Shellfish tends to contain high levels of cholesterol but it is low in saturated fats.

In addition, the oil found in seafood, especially coldwater fish, is rich in omega-3 fatty acids, which can lower blood levels of triglycerides (fats) and reduce frequency of blood clotting (American Heart Association 1996c). Recent studies suggest that diets rich in fish oil can reduce the severity of heart attacks by affecting the heart's electrical mechanisms, and can have beneficial effects in some people suffering from diabetes or inflammatory or allergic diseases (American Heart Association 1996b).

U.S. Aquaculture in Context

The U.S. seafood industry is undergoing what many experts believe is an inevitable transition. The percentage of farm-raised fish is steadily increasing, while the percentage of wild-caught fish is decreasing. This transition will likely have some important societal benefits, although not necessarily the benefits commonly touted in efforts to promote aquaculture.

Growth of U.S. aquaculture production is sometimes suggested as a way to reduce fishing pressure on overexploited wild stocks. This assertion may hold true for particular species where aquaculture production is so large or the quality of farmed fish so high that the availability of farmed fish results in decreased prices for wild-caught fish. However, increases in aquaculture production may not generally translate to decreased fishing pressure. U.S. demand for seafood products is steadily increasing. FAO predicts that worldwide aquaculture production will have to roughly double and conservation practices for capture fisheries significantly improve just to maintain the current global average seafood consumption of 13 kilograms per year (FAO 1995). As a result, there will continue to be strong demand for wild-caught fish. Rather than assert that increased aquaculture production will reduce fishing pressure, it may be more accurate to say that increased aquaculture production will prevent pressure on wild stocks from growing as much as it otherwise might grow.

In addition, the diets of almost all the farmed fish produced in the United States require fishmeal and fish oil, which are made from wild pelagic fish stocks. Although the diets of some farmed fish, such as channel catfish, require little animal protein, many others, such as salmon, require large amounts of fishmeal and fish oil. Only increased production of largely herbivorous fish, such as catfish, really have the potential to reduce pressure on wild fisheries. Production of such fish also represents an efficient way of producing meat for U.S. consumers, in that fish require less feed than other types of farmed animals.

Despite promotion of aquaculture as a means to provide protein to the poor, U.S. aquaculture production is unlikely to feed those most in need of protein, either in the United States or throughout the world. Less than 5% of the U.S. production of farmed catfish, salmon, and trout (the majority of U.S. production) is exported, and what is exported goes mainly to developed countries (NMFS 1996b). Most U.S. aquaculture products, such as trout, salmon, shellfish, and even catfish, are relatively expensive and are unlikely to be purchased by poor people in developing countries (Stickney 1994). Similarly, in the United States seafood is generally more expensive than other meats (Johnson 1996). Increased U.S. aquaculture production will go largely to relatively well-fed and well-off consumers.

Nevertheless, even if it does not go to feed poor people, increased U.S. aquaculture production will still have significant nutritional benefits. Fish tend to be low in fat, and thus are a healthful alternative to many other meats.

Increased U.S. aquaculture production can create economic benefits for the United States by reducing the growing seafood trade deficit and, as will be discussed in Chapter 5, by creating new industries and new jobs in economically depressed areas. For example, as declines in wild fisheries continue to cause economic hardship for U.S. fishermen, aquaculture is being promoted as a solution to resulting underemployment and unemployment in coastal regions.

As discussed in the next three chapters, aquaculture facilities that are designed and operated with little thought to environmental protection can cause significant environmental degradation.

Fully reaping the benefits from the growth of the U.S. aquaculture industry will require that aquaculture operations do not harm the environment.

Recommended Readings

Bailey, C. 1997 (in press). Aquaculture and basic human needs. World Aquaculture 28(3).

Bailey, C., S. Jentoff, and P. Sinclair (eds.) 1996. Aquacultural development: social dimensions of an emerging industry. Boulder, CO: Westview Press, 285 pp.

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Stickney, R.R. 1994. Principles of aquaculture. New York, NY: John Wiley & Sons, Inc., 502 pp.

Tacon, A.G.J. 1996. Feeding tomorrow's fish. World Aquaculture (Sept. 27, 1996):20-32.

Williams, M. 1996. The transition in the contribution of living aquatic resources to food security. Food, Agriculture, and the Environment Discussion Paper 13. Washington, DC: International Food Policy Research Institute, 42 pp.

Chapter One Notes

[1] National Aquaculture Act. 16 U.S.C. 2801 et seq.

[2] Intensive aquaculture systems are generally stocked with high densities of fish, which require high rates of feeding. In contrast, extensive aquaculture systems are stocked with low densities of fish or simply raise wild fish that are naturally found in ponds or other bodies of water. Fish in extensive systems are fed little if any feed.

[3] Baitfish production is included in Figure 1.3 because it is a significant percentage of U.S. aquaculture production. However, baitfish are not used to directly feed humans and are not discussed further in this report.

[4] Rainbow trout are usually raised in freshwater in the US. However, they are usually diadromous in the wild, and FAO classifies rainbow trout as a diadromous species in its aquaculture statistics. Rainbow trout raised in saltwater are called "steelhead."

[5] Pelagic fish species spend most of their life cycle in the water column, rather than on the bottom.

Chapter Two

Troubled Waters: Water Pollution, Water Conflicts, and Chemical Use in Aquaculture

Aquaculture Wastes and Effluents

Background

Aquaculture frequently is presented as a clean industry. Nevertheless, as with other forms of intensive animal production, intensive aquaculture systems can produce large quantities of polluting wastes. There is, however, a difference between aquaculture wastes and wastes from intensive terrestrial farms. Wastes from intensive terrestrial operations (for example, hog and poultry farms) usually reach natural water bodies only indirectly, for example, by run-off and leaching. In contrast, aquaculture wastes are often directly released to natural bodies of water, because fish farms are located in these bodies of water or because effluent is discharged into them.

According to U.S. Environmental Protection Agency (EPA) statistics, 38% of assessed river and stream miles, 44% of assessed lake acres, and 32% of assessed estuary miles in the United States are impaired, that is, too polluted to fully support their designated uses. This degradation largely is the result of "non-point source" pollution from terrestrial farms and urban run-off, and "point source" pollution from municipalities and industrial operations (GAO 1995). Aquaculture wastes contribute to this environmental degradation, although on a smaller scale than the sources above. Potential problems from aquaculture effluents include oxygen depletion in surrounding waters, degradtion of benthic (bottom) ecosystems, and exacerbation of toxic algae blooms.

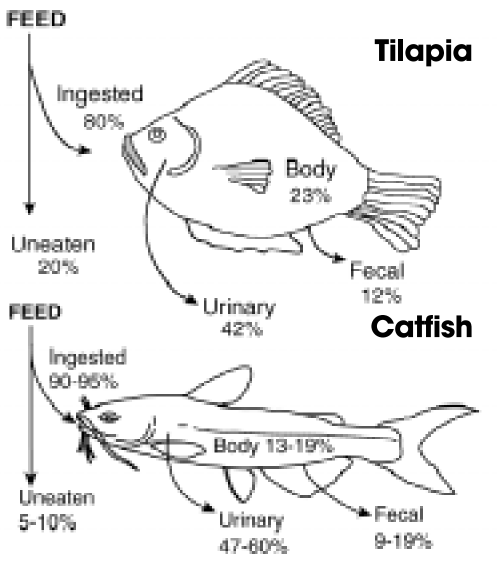
Aquaculture Wastes

Aquaculture wastes consist of uneaten fish feed and fecal and other excretory wastes. The characteristics and impacts of wastes from aquaculture operations vary according to the type and siting of the aquaculture system (Costa-Pierce 1994). In general, intensive cage, floating netpen, and other systems that are relatively open to natural waters have the greatest potential to cause environmental degradation from waste discharges (Costa-Pierce 1994). In contrast, the closed nature of pond or tank systems allows for more control of waste discharge. Pond and tank systems often discharge pulses of highly concentrated waste discharges during cleaning and harvesting (Bergheim et al. 1982; Schwartz and Boyd 1994).

The fraction of fish feed that becomes waste varies considerably. Consider feed wastage in cage systems, for example. One to 15% of dry-pelleted aquaculture feed, the most frequently used type of feed in the United States, typically is not consumed by fish (Beveridge 1996) . However, if "trash fish" (minced low-value fish, fresh or frozen) is used as feed, the percentage of feed not eaten can be as high as 40%, because trash fish feed easily breaks apart in the water (Wu et al. 1993; Beveridge 1996). In addition, a substantial amount of the feed that is eaten is subsequently released to the environment as feces (Beveridge 1996).

These figures vary for each fish species and aquaculture system, as well as with environmental conditions and feed quality (Pillay 1992). Figure 2.1 displays

Figure 2.1. Fate of Feed (by weight) Added to Catfish and Tilapia Ponds



Modified from: Beveridge 1996 (tilapia) and Boyd and Tucker 1995 (catfish).

the fate of feed added to a catfish pond and a tilapia cage farm. In particular, mollusk aquaculture produces far less waste than farming of other types of aquatic animals. Mollusks are not directly fed by aquaculturists. Rather, mollusks are filter feeders and actually clean the water by filtering out particles of food. However, even mollusks release nutrient-rich pseudofeces and feces, which in large enough quantities can produce environmental impacts similar to those from fish wastes (see Box 2.1).

The feed and fecal wastes produced in aquaculture systems sink to the bottom in the relatively still waters of pond and cage culture systems or are dispersed by the moving waters in raceway and tank systems. Solids from these wastes are almost entirely made of "organic matter," a mixture of carbon-based compounds. "Biological oxygen demand" (BOD) is used as a measure of the concentrations of organic matter available for degradation by microorganisms (Atlas and Bartha 1987). When the BOD is high, microorganisms may use much of the oxygen in the water to degrade organic matter, ultimately stressing or killing fish and other organisms that require oxygen for

Mollusks, such as clams, oysters, mussels, and scallops, are raised in marine waters in suspended nets or on bottom structures. These creatures feed on phytoplankton in the water column and thus recycle nutrients already in the water. Mollusk production actually reduces the nutrients in marine systems, because 35-40% of the total organic matter ingested by a mollusk is used for growth and permanently removed by harvest of the mollusk (Pillay 1992). As a result, mollusk aquaculture can lessen the potential for hypernutrification and eutrophication in marine waters. The remaining nutrients ingested by mollusks are either released back to the water column or deposited in the form of nutrient-rich feces and pseudofeces on the sediments below and around the culture area.

This concentrated deposition of nutrients and organic-matter-enriched sediments causes changes in the physical, chemical, and biological properties of the sediments that are similar to those produced by fish-farming operations. Shifts in benthic (bottom environment) communities toward more pollution-tolerant species can occur (Kaspar et al. 1985; Mattsson and Linden 1983); however, other studies have shown little overall impact on the benthos (Mojica and Nelson 1993; Grant et al. 1995).

Clams with identifying marks for aquaculture research. Courtesy of Sea Grant.

Catfish killed by oxygen depletion. Courtesy of Louisiana Cooperative Extension Service.

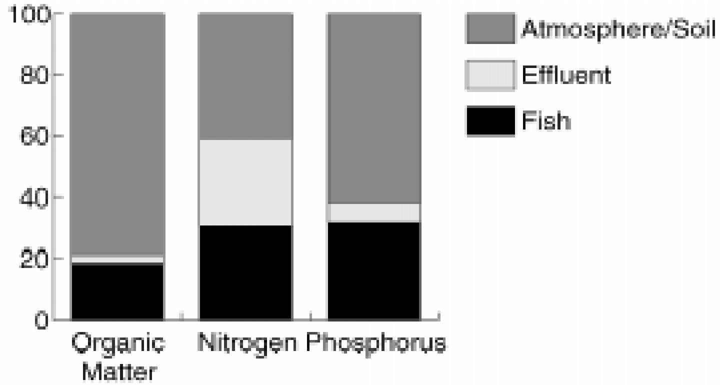
survival.

Some fraction of nitrogen and phosphorus dissolves from feed and fecal wastes and is excreted by fish as urine and via the gills. If this excess nitrogen and phosphorous accumulates, high concentrations of these nutrients can harm fish and aquatic ecosystems (Tucker 1996). High nutrient levels can be a major headache for aquaculturists, especially in the closed environments of tanks and pond systems, where nutrients are not readily diluted (Losordo et al. 1992). Elevated concentrations of nitrogen and phosphorous, termed hypernutrification, can stimulate the growth or blooms of phytoplankton (algae), a process termed eutrophication. Algae blooms can damage aquatic ecosystems. When algae die in large numbers, their subsequent degradation can drastically reduce dissolved oxygen levels, stressing or killing fish and other organisms.

In marine systems, phytoplankton growth generally is limited by the availability of nitrogen, while in freshwater systems phosphorus is usually the limiting nutrient. As a result, excess nitrogen can cause algae blooms in marine systems, while excess phosphorus can cause algae blooms in freshwater systems. The ratio between the total amount of nitrogen and total amount of phosphorus (TN:TP) dissolved in water is used as a relative measure of the potential of pollution sources to cause eutrophication. An analysis of TN:TP ratios shows that intensive cage aquaculture discharges are most similar to urban runoff and human sewage (Costa-Pierce 1994). However, the quality, or specific TN:TP ratio, of aquaculture discharges varies considerably.

The total amount of nutrients released from aquaculture facilities depends upon the scale and intensity of the system, the amount

Figure 2.2. Fate of Organic Matter, Nitrogen, and Phosphorus Added as Feed to a Channel Catfish Pond



Source: Schwartz and Boyd 1994.

Figure 2.3. Pollution Released from Trout Cage Farms and Catfish Pond Farms

	Catfish kg/ton	Trout kg/ton
Total Nitrogen	20.3	83-104
Total Phosporus	0.78	11.0-23

Sources: *Trout:* Costa-Pierce 1994 and sources therein.
Catfish: Schwartz and Boyd 1994.

Figure 2.4. Contribution of Aquaculture and Other Industries to Phosphorus and Nitrogen Loads to Seas Surrounding Sweden

	Phosphorus (metric tons)	Nitrogen (metric tons)
Rivers, excluding agriculture	3,040	87,739
Agriculture	935	41,361
Industries	908	3,465
Municipal Sources	840	14,210
Aquaculture	35	264
Total	5,758	147,039

Source: Ackerfors and Enell 1990.

Box 2.2. Trout Farming

Waste management has recently emerged as one of the most important issues facing the Idaho trout industry. In 1994 EPA identified the middle Snake River as "water-quality limited" due to elevated levels of phosphorus, nitrogen, and suspended sediments. The sources of this pollution, including the trout industry, are now required to reduce their releases of pollutants to the river. Expansion of trout farms has been halted until these reductions are accomplished.

Phosphorous is the first pollutant to be reduced. The trout industry is one of several major sources of phosphorus, along with terrestrial agriculture, municipalities, and food-processing plants, and contributes approximately 25-35% of the total phosphorus load. The trout industry is required to reduce its share of the phosphorus load by 40% over five years, with 20% of these reductions occurring within the first year of the pollution-reduction program.

The effluent released from Idaho trout farms is extremely dilute, containing only 0.1 milligram of phosphorus per liter. However, the tremendous daily combined water flows from industry produce a very large overall discharge of approximately 735 kilograms per day. Because it is difficult to remove very dilute dissolved phosphorus from farm effluent, trout farmers are reducing the amount of phosphorus that enters effluent in the first place, by reducing the amount of phosphorous feed and reducing the amount of feed wasted. The industry may already have achieved a 20% reduction in phosphorous discharges simply by switching from sinking to floating feed pellets, which reduce feed waste because a larger percentage of the pellets are consumed by trout. The trout industry is also adopting best management practices to prevent the release of solids from raceways (G. Fornshell, pers. comm.).

of waste treatment used, and the degree of connection to natural bodies of water (Costa-Pierce 1994). Releases of TN and TP from catfish ponds are relatively low per unit of fish produced, for example. Today most catfish ponds are drained only every 3-10 years (Boyd and Tucker 1995), which allows considerable time for nutrients to be "assimilated" by natural processes such as algae and bacterial growth within the pond. As Figure 2.2 shows, most of the organic matter, nitrogen, and phosphorus added to catfish ponds is released to the atmosphere or stored in the pond sediments. In contrast, there is little time for nutrients to be assimilated in water flowing through trout raceways, and releases of TN and TP are much higher per unit of fish produced (see Fig. 2.3).

In general, releases of nutrients from aquaculture operations are small in relation to some sources (see Fig. 2.4). The impact of current U.S. aquaculture operations on water quality is relatively low and localized when compared to the largest sources of nutrient pollution, such as municipal sewage systems (Ewart et al. 1995).

This general statement does not mean, however, that pollution from aquaculture is not of concern, especially as the aquaculture industry grows. Discharges from the many salmon farms along the coast of British Columbia are a significant pollution source, estimated to be equivalent to raw human sewage from a city of 500,000 people (Ellis and Associates 1996). Although Idaho trout farms produce extremely dilute effluent, they cumulatively discharge enormous amounts of effluent, which is significantly polluting Idaho's Snake River (See Box 2.2). The development of many aquaculture facilities in one area can also harm the farms themselves. In Thailand, Taiwan, and Ecuador, crowding of shrimp ponds has led to the reuse of one farm's effluent as intake water for another, ultimately reducing shrimp farm productivity (Hopkins et al. 1995).

Impacts of Aquaculture Wastes

Eutrophication and Toxic Algae Blooms

Hypernutrification and eutrophication often are apparent around freshwater cage systems located in areas with low currents and limited dilution (Beveridge 1996 and sources therein) (see Box 2.3). Catfish ponds release effluents containing high concentrations of nutrients, often at concentrations exceeding water-quality limits set by EPA and state governments. Figure 2.5 shows recommended effluent limits and pond effluent samples exceeding these limits. As discussed above, catfish ponds "assimilate" large quantities of organic matter and nutrients from wastes; nevertheless, substantial amounts of these pollutants still remain in discharged pond water. Relatively little is known about the quantity, content, and environmental impacts of catfish pond effluent, even though catfish farming has become a major animal-production industry (Tucker 1996).

Dissolved nutrients from aquaculture netpen or cage systems located in marine waters with strong tidal currents are quickly diluted and tend not to cause hypernutrification or eutrophication (Beveridge 1996; Gowen and Bradbury 1987). However, in enclosed, slowly flushed sites and in areas where many farms are crowded together, eutrophication is possible (Wu et al. 1994; Gowen and Bradbury 1987). (Also see case study on salmon farming in New Brunswick.)

Figure 2.5. Recommended Effluent Concentration Limits and Concentrations from Catfish Pond Samples

	Recommended Effluent Limit*	Pond Samples Exceeding Limit (%)**
Total phosphorus	0.17 mg/L	80
Suspended solids	30 mg/L	75
Total ammonia nitrogen	1.77 mg/L	23
Dissolved oxygen	5 mg/L***	13
BOD	30 mg/L	2
pH	6.0-8.5	1
Nitrite-nitrogen	0.83 mg/L	1
Nitrate-nitrogen	16.9 mg/L	0
Settleable solids	3.3 ml/L	0

Source: Schwartz and Boyd 1994.
* Limits taken from U.S. Environmental Protection Agency and from state pollution-control agencies.
** Samples taken from surface and near bottom of 25 commercial ponds over two years.
*** Represents a minimum limit, not a maximum limit.

Eutrophication may not be the most harmful effect of nutrient-stimulated phytoplankton blooms. Some species of phytoplankton, usually dinoflagellates, can produce extremely potent toxins that are deadly to marine organisms and humans alike. Blooms of such algae, termed toxic algae blooms, are responsible for the red tides that often kill huge numbers of fish and contaminate shellfish. Even humans may be harmed: People exposed in 1997 to water from Maryland rivers containing toxic *Pfiesteria piscicida* suffered memory loss and other health problems (Shields

Box 2.3. Minnesota Aquafarms, Inc.

The saga of Minnesota Aquafarms, Inc., illustrates how damaging waste production can be to aquaculture operations. Minnesota Aquafarms planned to raise millions of trout and salmon in netpens in five abandoned mine-pit lakes in northern Minnesota. These lakes rapidly became polluted since they had little water circulation and no outlets to remove food and fish wastes.

State water-quality requirements were violated as oxygen reductions, extensive algae blooms, and smelly black deposits formed in some of the lakes. The Minnesota Pollution Control Agency (PCA) forced Minnesota Aquafarms to remove its operations from two of the lakes. Public outcry over pollution of a third lake, which served as the drinking water supply for a nearby town, caused the company to voluntarily remove its operations from that lake. Eventually Minnesota Aquafarms went bankrupt and all the fish and netpens were removed. According to the Minnesota PCA, lake conditions have slowly returned to normal over the last few years, although water quality in the lakes continues to be monitored (Mary Hayes, pers. comm; Rigert 1993).

and Hsu 1997). Preliminary evidence suggests that high nutrient concentrations may promote toxic algae blooms (Holligan 1985), and some scientists believe that nutrient loads from coastal aquaculture farms may contribute to the growth of these blooms (Folke et al. 1994). Fish-farm wastes can stimulate dinoflagellate growth (Nishimura 1982), and biotin, a vitamin found in fish-farm wastes, has been shown to trigger toxin production in marine dinoflagellates (Graneli et al. 1993).

Harm to Benthic Ecosystems

The buildup of feed and fecal waste below and around aquaculture facilities can enrich sediments, producing a variety of physical, chemical, and biological changes in the benthos. The impacts of aquaculture waste on the sediments below freshwater and marine-cage aquaculture systems are relatively well studied. Overall, aquaculture wastes affect the benthos as severely as other types of organic pollution, but these effects are typically confined to a relatively small area beneath and adjacent to aquaculture facilities (Gowen and Bradbury 1987).

Accumulations of wastes rich in carbon and nutrients can produce anaerobic (oxygen-deficient) sediments. In severe cases, these sediments may release methane and hydrogen sulfide gas, which is toxic to fish (Pillay 1992). In freshwater, the sediments below cage farms and downstream from raceways may sustain low levels of biodiversity and result in communities of largely pollution-tolerant species (Beveridge 1996 and sources therein; Kendra 1991). Similar effects are seen below and around marine-cage systems; the radius of the affected area varies with the speed of the current and other factors. A study of a salmon farm in Maine showed that these farms have little impact on benthic ecosystems, except within 20 meters of the netpen (Findlay and Watling 1995). In contrast, a study of a salmon farm in Puget Sound showed benthic impacts up to 150 meters away from the netpens (Weston 1990). If fish farms are removed, benthic ecosystems appear to recover over a period of several years (Gowen and McLusky 1988; Mattson and Linden 1983; Johannssen et al. 1994).

Figure 2.6. Bacteria Pathogenic to Humans that Have Been Isolated from Fish or Their Immediate Environment

Pathogen	Disease	Infection Route
Salmonella sp.	Food poisoning	via mouth
Vibrio parahaemolyticus	Food poisoning	via mouth
Campylobacter jejuni	Gastroenteritis	via mouth
Aeromonas hydrophila	Diarrhea/septicaemia	via mouth
Plesiomonas shigelloides	Gastroenteritis	via mouth
Edwardsiella tarda	Diarrhea	via mouth
Pseudomonas aeruginosa	Wound infection	via skin
Pseudomonas fluorescens	Wound infection	via skin
Mycobacterium fortuitum	Mycobacteriosis	via skin
Mycobacterium marinum	Mycobacteriosis	via skin
Erysipelothrix rhusiopathiae	Erysipeloid	via skin
Leptospira interrogans	Leptospirosis	via skin

Source: Smith, et al. 1994.

Bacterial Pollution

While human and fish sewage share similar TN:TP ratios, they differ in their bacterial content. A primary reason that discharges of raw human sewage to natural water bodies are hazardous is that they may spread disease-causing microorganisms (pathogens) (Pelczar et al. 1986). Fish sewage presents a much smaller threat of disease to humans than human sewage, largely because fish and humans are infected by different pathogens. Nevertheless, some fish pathogens can infect humans. A recent Canadian study demonstrated that humans can develop invasive infections from handling raw farmed tilapia iinfected with the fish pathogen *Streptococcus iniae* (Weinstein et al. 1997). Fish and fish wastes can contain known or putative human pathogens (Austin and Austin 1989; Midvedt and Lingaas 1992; Smith et al. 1994), although Smith et al. (1994) argue that some of these microbes pose little danger to humans. Figure 2.6 shows pathogenic bacteria found at fish farms that may cause disease in humans.

Should aquaculture wastes be viewed, and thus regulated, similarly to human and other animal wastes? One might argue not, since fish are not terrestrial organizsms, and our waterways are populated by wild fish that defecate regularly. But wastes from humans and terrestrial animals in nature also often wash into waterways. As human and domestic animal populations have increased, our society has chosen to greatly restrict releases of sewage from humans, pigs, chickens, and other animals. Under the federal Clean Water Act, even relatively minor sources such as small commercial fishing vessels and other watercraft may not discharge raw human sewage.[1] Similarly, the Clean Water Act forbids the direct discharge of wastes from virtually all animal feedlots into natural bodies of water, except under rare emergency flood conditions.[2] By analogy, it should not be unacceptable for our society to sanction the discharge of untreated fish wastes from intensive fish farms directly into natural bodies of water.

Water Use in Aquaculture

Background

Many inland aquaculture systems require large quantities of clean freshwater. Water exchange is used to replenish dissolved oxygen, to remove or dilute harmful wastes, to regulate salinity levels in shrimp farming and other brackish-water farming, and to harvest crops by partially or completely draining ponds. In some regions, farmers also regularly add substantial quantities of water to ponds to compensate for evaporation and seepage.

Global freshwater supplies are extremely limited, and water scarcity is expected to be an increasingly pressing issue in the near future (Postel 1996). Groundwater supplies are being depleted in many of the world's most important crop-producing regions, such as California's Central Valley (Postel 1996). As a result, expansion of aquaculture in the United States is expected to be limited by the availability of high-quality freshwater (Randall et al. 1991). The growing aquaculture industry almost certainly will face increasing water-use conflicts with other users, especially with terrestrial agriculture, which uses 65% of all water removed for human uses from rivers, lakes, and aquifers (Postel 1996). The shrimp-farming industry in southeast Asia is already experiencing such conflicts (Primavera 1993; MacQuaid 1996).

Figure 2.7. Water Requirements for Aquaculture and Other Industries

	Water Requirements (m3/mt)
Aquaculture Systems	
Common carp/tilapia in intensive ponds (Israel)	2,250
Channel catfish in intensive ponds (USA)	6,470
Paneid shrimp in intensive ponds (Taiwan)	29,000-43,000
Rainbow trout in raceways (USA)	210,000
Other Industries	
Petroleum	21.6-810/m3
Beef	42
Pork	54
Steel	8-250
Paper	9-450
Cotton	90-450
Alcohol	125-170/m3

Sources: Phillips et al. 1991.

Water use by Aquaculture

To date, shrimp farming in southeast Asia arguably has caused the greatest water-use conflicts of any form of aquaculture. Nearly all shrimp farms use some water exchange (Hopkins et al. 1995), and intensive (high stocking density) shrimp farming has higher water use per kilogram of production than most other forms of pond aquaculture (see Fig. 2.7). Shrimp typically are grown in brackish water. Use of huge quantities of freshwater to reduce the salinity of coastal shrimp ponds has depleted groundwater sources, allowing saltwater to infiltrate aquifers and even causing subsidence (sinking of land) (Primavera 1993). Saltwater infiltration

Figure 2.8. Water-replacement Requirements for Catfish Ponds in Various Regions of the United States

	Water required (cm/year)		Water required (cm/year)
Auburn, AL	63.5	**Jackson, MS**	66.0
Fairhope, AL	33.0	**Stoneville, MS**	83.8
Stuttgart, AR	78.7	**Raleigh, NC**	96.5
Fresno, CA	218.4	**Tulsa, OK**	127.0
Gainesville, FL	94.0	**Charleston, SC**	83.8
Athens, GA	91.4	**Memphis, TN**	88.9
Baton Rouge, LA	78.7	**San Antonio, TX**	172.7

Source: Boyd and Tucker 1995.

Top: Constructing levees for a catfish pond.
Bottom: Harvesting seine for catfish. Courtesy of Louisiana Cooperative Extension Service.

and discharge of salty wastewater from shrimp ponds have together contaminated traditional sources of freshwater, making rise farming impossible and forcing some southeast Asian villagers to import their drinking water (Primavera 1993; MacQuaid 1996).

In the United States, trout farming is an extremely heavy water user (see Fig. 2.7). Most U.S. trout production occurs along a 35- to 40-mile stretch of the Snake River in Idaho. This industry depends on the high-quality, cold spring water of the Eastern Snake River Plain Aquifer, which stretches from Yellowstone to south-central Idaho, to provide water for its raceways (ID DEQ 1996). Large farms, which produce most of Idaho's trout, use tremendous amounts of water; the largest farms, which produce several million of pounds of trout annually, use 64 million gallons of water each day (G. Fornshell, pers. comm.). Overall the aquaculture industry diverts approximately 1.5 million acre-feet of water each year (Idaho Water Resource Board 1997). In recent years, Idaho has suffered a drought, and demand for irrigation water for terrestrial agriculture, which uses close to 13 million acre-feet annually (Idaho Water Resource Board 1997), has increased (G. Fornshell, pers. comm.). Net water loss from the Eastern Snake River Plain Aquifer is causing declines in stream flow, which greatly concern Idaho's trout industry (G. Fornshell, pers. comm.).

In contrast to the trout industry, water use in the U.S. catfish industry has declined dramatically since catfish farming began in the 1950's. At that time the industry was seasonal and ponds were drained annually for harvest. Since then, farmers have found it more profitable to produce a mixed-age crop and to harvest the largest fish by seining ponds one or more times a year (Boyd and Tucker 1995). Most ponds now are drained only every 3-10 years in order to repair levees (Boyd and Tucker 1995).

The catfish industry uses well water and rain water to fill and replace pond water lost to seepage and evaporation (Boyd and Tucker 1995). Water is not exchanged. (Catfish tolerate murky water.) The amount of water that must be added to ponds varies by location within the United States. In the Southeast, where most catfish are raised, the clay soils prevent excessive seepage, while evaporation is low and annual rainfall is high. Consequently most ponds require only an additional 50-100 cm of water per year, assuming an average pond depth of 150 cm (Boyd and Tucker 1995). If ponds are drained annually this figure increases to 200-250 cm per year (Boyd and Tucker 1995). In arid regions, much higher amounts of water are required to keep ponds full (see Fig. 2.8).

Although the water requirements of catfish ponds are low in comparison to other forms of aquaculture, they are nevertheless high per unit of production in comparison to other agricultural and industry uses (see Fig. 2.7). The U.S. catfish industry relies on the groundwater resources of the Mississippi Delta region. These once-abundant resources are beginning to show signs of drawdown, which could limit further expansion of the industry (Tucker 1996; Randall et al.1991).

Chemical Pollution by Aquaculture

Background

A wide variety of chemicals are used in fish farming. These include antibiotics used to control disease; pesticides used to control parasites, algae, and other problematic organisms; and hormones to initiate spawning, anesthetics used during transport and handling of fish, and pigments, vitamins, and minerals used to promote rapid growth of fish with desired qualities.

The large number of chemicals used in aquaculture worldwide triggers concern about the ecological and human health impacts of these chemicals. Aquaculture chemicals often are put directly into water, where they may be readily dispersed, potentially affecting a large variety of organisms. Residues of aquaculture chemicals in food may harm human consumers.

Compared to many parts of the world, relatively few chemicals are legal to use in U.S. aquaculture. Some aquaculture operations abroad may produce fish for export using chemicals that are illegal in the United States, and some imported seafood may even contain residues of these chemcials. The U.S. Food and Drug Administration now has only a very limited inspection program for antibiotic residues in farm-raised seafood; shrimp are inspected for chloramphenicol residues and salmon for oxolinic acid residues (FDA 1996a).

Antibiotics

Antibiotics are probably the most controversial chemicals used in aquaculture. As of 1991, roughly 50 antibacterial drugs were being used in aquaculture worldwide (Bjorkland 1991). In much of the world, antibiotic use is little restricted. In regions such as southeast Asia, huge quantities of antibiotics are used in aquaculture, both prophylactically and to treat disease (Pillay 1992; Primavera et al. 1993; Saitanu et al. 1994; Hopkins et al. 1995).

The U.S. aquaculture industry frequently notes that few antibiotics or other drugs are approved for use in the United States because the process of obtaining formal approval for new drugs is considered to be expensive and time-consuming (National Research Council 1992; OTA 1995). In the United States, only three antibiotics are specifically approved for use in aquaculture: oxytetracycline, sulfamethoxine-ormetoprim, and sulfamerazine. However, new “extra label” drug-use regulations allow antibiotics and other drugs to be used under certain conditions, even if they are not specifically approved for use in fish (FDA 1996b). As a result, the types and amounts of drugs used in U.S. aquaculture may considerably expand in the near future.

Antibiotics are applied to fish using baths, injections, and oral treatments. Oral administration through the incorporation of drugs in feed is the most common method (Smith 1991). Antibiotics enter the environment as a result of leaching from feces and uneaten feed. It has been estimated that a minimum of 75% of most antibiotics applied as feed to aquaculture systems are lost to the environment (Roed 1991a). Antibiotics applied as feed often are far from fully consumed, because medicated feeds taste bad to fish, sick fish have reduced appetites, and absorption of ingested drugs by the intestine is limited (Roed 1991b).

Most antibiotics applied to aquaculture systems end up bound to particles in the sediment (Pillay 1992). Although the persistence of antibiotics in the sediments varies, synthetic antibiotics, such as quinolones, may remain in the environment for long periods of time because they are not easily broken down by microbes (Midvedt 1990). Antibiotics also can accumulate in wild fish and shellfish through direct feeding on waste food and the feces of treated fish, as well as through filtration of particle-bound residues and absorption of dissolved drugs (Samuelson et al. 1992).

Humans potentially can consume residues of antibiotics by eating farmed fish that have received medication (Saitanu et al. 1994). In addition, wild fish and shellfish can accumulate antibiotics from fish farms. For example, residues of oxolinic acid have been found in wild fish 400 meters from culture sites (Samuelson et al. 1992).

Ingestion of low levels of antibiotics is generally not considered to be harmful to humans. Nevertheless. some antibiotics are toxic to humans, and ingestion of even low doses as food residues is undesirable. Chloramphenicol can harm blood cell production by bone marrow and, in newborns, can trigger circulatory collapse, or gray baby syndrome (Berkow and Fletcher 1992). Sulfamethazine has been shown to increase the rate of thyroid tumors in rats and mice (Yndestad 1992). Some antibiotics, especially beta-lactam compounds, can cause allergic reactions in humans that can be fatal in some cases (Berkow and Fletcher 1992; OTA 1995).

Figure 2.9. Herbicides and Algicides Registered by the U.S. Environmental Protection Agency for Use in U.S. Aquaculture and Aquatic Systems

Chemical	Purpose	Tolerance (ppm)	Withdrawal Time and Comments
AQUACULTURE			
Acid blue and acid yellow	Algicide and herbicide	Exempted	None required
Chelated copper	Algicide	Exempted	None established
Elemental copper	Algicide	Exempted	None established
Copper sulfate	Algicide	Exempted	None established
2,4-D	Herbicide	Fish and shellfish: 1.0	None established
Diquat Bromide	Herbicide	Fish and shellfish: 0.1	None established
Fluridone	Herbicide	Fish and crayfish: 0.5	None required
Glyphosate	Herbicide	Fish: 0.25, shellfish: 3.0	None established
Potassium ricinoleate	Algicide	Exempted	Four weeks
Simazine	Herbicide and algicide	Fish: 12	None established
AQUATIC SYSTEMS			
Dichlobenil	Herbicide and algicide	n/a	n/a
Endothall	Herbicide and algicide	n/a	n/a
Xylene	Herbicide	n/a	n/a

Sources: Stickney 1994; Federal Joint Subcommittee on Aquaculture 1994.

Use of antibiotics in aquaculture may contribute to extremely troubling and increasingly common problems with bacteria that cannot be controlled with commonly available antibiotics. Antibiotic use in terrestrial livestock production has been shown to contribute to the development of antibiotic-resistant strains of bacteria pathogenic to humans (Spika et al. 1987; Endtz et al. 1990). The American Society of Microbiology (1995) has singled out the use of antibiotics in aquaculture as potentially one of the most important factors leading to the evolution of antibiotic-resistant bacteria.

Bacteria are known to rapidly evolve resistance to antibiotics (Pillay 1992), and the presence of antibiotic-resistant bacteria in aquatic environments has been demonstrated to be related to continual and intensive use of antibiotics at fish farms (Toranzo et al. 1984; Sandaa et al. 1992; Vaughan et al. 1996). Once resistance evolves, it can be transferred from one strain of bacteria to another via plasmids, pieces of DNA that can be transferred between bacteria. Since some bacteria that are pathogenic to humans are found in fish, resistance could be transferred to human pathogens living in fish, and these pathogens could subsequently be ingested by humans (Nakajima et al. 1983; Sandaa et al. 1992) (see Fig. 2.6). The spread of antibiotic resistance to fish pathogens is causing problems for the aquaculture industry itself. In 1990 and 1991 in Scotland, for example, 54% of the bacteria causing furunculosis (a disease affecting salmonids) were estimated to be resistant to treatment with oxolinic acid (Richards et al. 1992).

Herbicides, Including Algicides

In comparison to antibiotics, a relatively large number of chemicals are available to control algae and other aquatic plants in U.S. aquaculture facilities (see Fig. 2.9). EPA permits some, but not all, of these herbicides (plant-killers) and algicides (herbicides specifically intended to kill algae) for use in aquaculture systems where fish are raised for food. For herbicides used where food fish are grown, EPA specifies a “tolerance” level — the maximum amount of herbicide residue that may remain in fish sold for consumption. Other types of herbicides are permitted for use only in aquatic systems where fish are not raised as food, such as aquaculture systems where aquarium fish are raised. However, these chemicals may be used in aquaculture sites where food fish are raised if the fish are removed beforehand (A. Bravo, pers. comm.). After a sufficient amount of time has elapsed, fish can be returned to the facility.

In pond aquaculture systems, algae blooms can be desirable because algae produce oxygen as a product of photosynthesis and absorb nutrients from fish wastes (Brunson et al. 1994). Algae may also serve as a food source for herbivorous fish or for invertebrates consumed by fish. However, if algae become too abundant, decomposition of dead algae or respiration (metabolism) by live algae can reduce dissolved oxygen levels, stressing or killing fish. Blooms of blue-green bacteria — which, like algae, photosynthesize — can produce off-flavors in fish (Brunson et al. 1994; Tucker 1996). As a result, freshwater aquaculturists sometimes use algicides to control blooms of blue-green bacteria as well as algae.

Nevertheless, control of algae in pond systems with algicides is usually unsuccessful, because aquaculturists continually add new nutrients to ponds via feed, which stimulates growth of algae (Brunson et al. 1994). Moreover, algicide-caused die-offs can cause dangerous declines in dissolved oxygen levels from decaying algae (Brunson et al. 1994; Stickney 1994). Instead of using algicides, many catfish farmers use mechanical aerators to boost oxygen levels and counter the effects of uncontrolled growth of algae (Brunson et al. 1994; Tucker et al. 1994).

Herbicides are used to control aquatic weeds in some freshwater aquaculture systems (Shelton and Murphy 1989). Weeds can make harvesting ponds difficult (Shelton and Murphy 1989). As with algae, decomposition of large amounts of dead weeds can reduce dissolved oxygen levels in aquaculture systems (Stickney 1994). To avoid these problems, spot treatments are sometimes used, killing only a portion of the weeds at a time (Stickney 1994).

As with other pesticides, herbicides used in aquaculture can harm nontarget animals if they become concentrated in water or soil (Stickney 1994). Copper, an active ingredient in many algicides, is toxic to many aquaculture species (Stickney 1994). Copper-based antifoulants can reduce the growth of and kill scallops (Paul and Davies 1986). Some experts have in the past argued that 2,4-D is the aquaculture herbicide least persistent and harmful to fish and other animals (Ramaprabhu and Ramachandran 1983). However, more recent studies indicate that 2,4-D may cause non-Hodgkin's lymphoma in humans (Zahm et al. 1990; Wigle et al. 1990; Blair 1990; Faustini et al. 1996) and a similar form of lymphatic cancer in dogs (Hayes et al. 1991). Based on 2,4-D's potential to cause cancer, EPA is currently considering whether to inititate a "special review" of this chemical, a step toward determining whether any uses of 2,4-D should be prohibited (A. Bravo, pers. comm.).

Other Pesticides

Antifoulants are pesticides used to prevent fouling organisms, such as barnacles and algae, from accumulating on and damaging aquaculture enclosures, particularly in the marine environment (Stickney 1994). Copper compounds and organic tin compounds, especially tributyltin (TBT), were once commonly applied as dips or paints to aquaculture enclosures to prevent fouling. However, both types of chemicals are now known to accumulate in organisms and the environment around aquaculture systems, where they can harm farmed and wild organisms, especially shellfish (Davies et al. 1986; Davies et al. 1988; Minchin et al. 1987; Paul and Davies 1986). Most uses of TBT paints and dips have been banned in many parts of the world, including Maine (Getchell 1988) and Washington State (Parametrix 1990). Similarly, use of copper compounds is highly restricted in the United States (Stickney 1994). Today members of the U.S. salmon industry use netpens made from PVC material that has antifouling chemicals incorporated in it, thus reducing the release of these chemicals to the environment (J. McGonigle pers. comm., 3-97). Farmed fish still may be harmed by the release of TBT-containing and copper compounds, many of which are still legal for nonaquaculture uses, such as boats, floating docks, and rafts (EPA 1995).

Worldwide a large number of pesticides are used to control parasites and fungi in marine and freshwater aquaculture systems. In many cases, the environmental effects of these chemicals are not well understood, and their use is worrisome, as many are biologically potent even at quantities below chemical detection limits (Pillay 1992). In the United States, relatively few aquatic pesticides are allowed for use. A few of the chemicals commonly used in U.S. and world aquaculture are discussed below.

Formalin, an aqueous solution containing formaldehyde gas, is widely used in the United States. This pesticide is used to control parasites in ponds, tanks, and raceways containing trout, catfish, and marine shrimp, and to control fungi on fish eggs (Federal Joint Subcommittee on Aquaculture 1994). Quaternary ammonium compounds are used in many parts of the world to control bacterial gill infections, but in the United States they are permitted only for disinfection of water, equipment, and culture chambers (Stickney 1994).

In Willapa Bay, where 50% of Washington State's farmed oysters are raised, a carbamate insecticide called Sevin has been used for 35 years to control infestations of burrowing shrimp (Simestad and Fresh 1995; Pitts 1997). The shrimp burrow into the sediments of the intertidal zone, making it impossible for most organisms and structures to remain on the bottom without sinking deep into the sediments (Simestad and Fresh 1995). This use of Sevin is controversial. Opponents point out that, along with burrowing shrimp, Sevin also indiscriminately kills other organisms, including the Dungeness crab, which is fished commercially in Willapa Bay (Simestad and Fresh 1995). Proponents argue that this chemical is applied only every 6 — 8 years, and that by killing burrowing shrimp and stabilizing sediments, applications of Sevin promote greater biological diversity (Pitts 1997). Use of Sevin in Washington State is permitted under an EPA "local needs" permit (Pitts 1997).

In many parts of the world, the salmon industry uses the organophosphate chemicals dichlorvos and trichlorphon to control sea lice, parasites that feed on the mucus of salmonids. This class of chemicals, which interferes with the nervous system, includes nerve gases and many insecticides. While the effects of these chemicals on the marine environment is not well studied, dichlorvos is toxic to a number of crustaceans and mollusks (Edgius and Moster 1987). Neither of these chemicals is permitted for use in the United States. However, the pyrethroid insecticide cypermethrin currently is being used on an experimental basis by the Maine salmon industry to control sea lice (Pitts 1997; see also Maine case study).

Malachite green is used widely to control fungi in aquaculture systems (Pillay 1992; Lightner 1993; Primavera et al. 1993). Malachite green is not permitted for use in U.S. aquaculture because it is considered carcinogenic (Pillay 1992). Malachite green also can be toxic to crustacea, especially when they are molting (Johnson 1974).

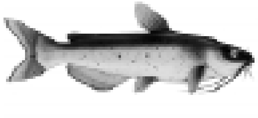
Hormones, Pigments, Vitamins/ Minerals, and Anesthetics

Applications of fish hormones are used to induce maturation, spawning, and sex reversal for brood fish in hatcheries that supply fish farms. There appears to be little potential impact to human health from such practices, since the fingerling (baby) fish sold to farms are generally not the fish that are treated (Pillay 1992). Pigments are fed to farmed salmon and trout to produce a pink/orange flesh consumers apparently prefer over the whitish flesh these fish would otherwise have. These pigments are carotenoids that are also found naturally in many vegetables. Vitamins and minerals often are added to feed to fulfill fish nutrition requirements.

Anesthetics are used in large quantities in the transport and handling of farmed fish. Tricaine methanesulfonate (MS222) and sodium bicarbonate are permitted for use as anesthetics in U.S. aquaculture (Federal Joint Subcommittee on Aquaculture 1994). In the rest of the world, the use of quinaldine and quinaldine-sulfate as anesthetics is common.

Conclusions

Aquaculture can cause significant environmental problems. Fish wastes can pollute water bodies with excess nutrients — although at this time the magnitude of this pollution is smaller than the largest sources of nutrient pollution, such as municipal sewage, terrestrial agriculture, and some industries. Aquaculture also can cause environmental problems by using large amounts of scarce water and by administering chemicals, some of which are harmful to humans and ecosystems. These problems need not be inevitable, however. As will be discussed in Chapter 4, there are a number of farm practices and technologies that, although far from universally adopted, are available to prevent or mitigate these problems.



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Chapter Two Notes

[1] 40 C.F.R. 140.3

[2] 40 C.F.R. 412.

Something Fishy: Biological Pollution from Aquaculture

Background

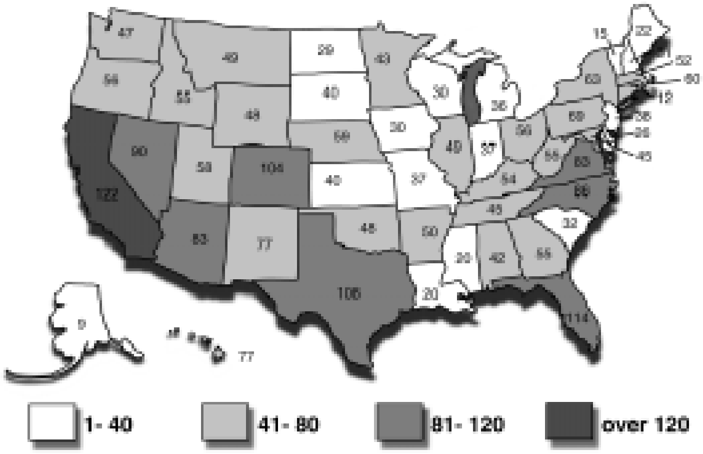
Pollutants from aquaculture facilities are not necessarily chemical in nature. Biological pollution from aquaculture, such as the introduction of unwanted non-native species to natural ecosystems, can cause environmental harm. The disastrous ecological and economic impacts of biological pollutants from aquaculture and from other human activities are well documented in North American waters. One of the best-known examples of a biological pollutant is the Eurasian zebra mussel (*Dreissena polymorpha*), which was accidentally introduced to the Great Lakes region in ballast water from ships, and which has now spread south to the Mississippi River and other bodies of water. Roughly $2-3 billion dollars will have been spent by the year 2000 to remove local zebra mussel infestations, which frequently clog municipal and industrial water intakes (Ruiz et al. 1995).

Biologists typically use the term "introduction" to mean the transfer by humans of an organism into an area outside its native range (Krueger and May 1991). Introductions of non-native species may be accidental, as in the case of the transfer of the Eurasian zebra mussel to North America. They may be intentional, as in the case of rainbow trout, which is native to the western United States but stocked in the eastern United States as a sports fish. Introductions also include the transfer of genetically differentiated populations of a species from one region of its native range to another region inhabited by another genetically distinct population of the same species. Transfers of salmon can be considered introductions, since salmon species is made up of hundreds of genetically differentiated populations. Salmon in each genetically distinct population are adapted to the streams where they hatched and where they will spawn.

Introductions and Aquaculture

Large numbers of non-native fish have been introduced to the United States and other countries for aquaculture and for other purposes. At least 291 species of inland fishes have been transferred outside their native ranges into 148 countries (Welcomme 1992). Within the contiguous United States, at least 170 species of fish have been introduced from other countries, and 357 species and subspecies of fish have been introduced

Figure 3.1. Map of United States Showing Numbers of Exotic Fish Species Per State



Modified from: U.S. Geological Survey 1997, www.nfcrg.gov/images/nss-fish.gif

Figure 3.2. Some Exotic Species Raised in U.S. Aquaculture

Species	Where cultivated	Comments
Pacific oyster	Pacific northwest	
European flat oyster	Maine, Washington, California	Established in Maine
Malaysian prawn	Hawaii, Texas, Florida	
Pacific white shrimp	Hawaii, Texas, South Carolina	
Carps	California and other states	Includes common, bighead, and grass carps; common carp is established in all contiguous states except Maine
Tilapia spp.	Throughout the U.S.	Various species and hybrids; blue tilapia is established in NC, TX, and FL, and possibly OK, PA, and CO; Mozambique tilapia is established in hot springs in Idaho

Sources: Clugston 1990; Courtenay and Williams 1992; Chew and Toba 1993; Fuller et al. (in prep.).

Government carp nursery, Yangshou, Guangxi Province (Southern China). Courtesy of Tracy Triplett.

to areas outside their native ranges within the United States (U.S. Geological Survey 1997). Figure 3.1 is a United States map that shows the number of exotic fish species in each state.

Few aquaculture facilities are escape-proof, and very large numbers of fish sometimes escape from certain types of facilities, particularly netpens. For example, almost 100,000 Atlantic salmon escaped in the summer of 1996 from the relatively small netpen industry in the state of Washington (Mottram 1996). Not surprisingly, aquaculture has been the most important reason for introductions of non-native species from one country to another (Welcomme 1992). In fact, the first documented introductions of fish across international boundaries occurred during the 11th and 12th centuries, when Asian common carp escaped or were released from ponds where they were being grown in Europe (Allan and Flecker 1993; Courtenay and Williams 1992).

In the United States, a minimum of 22 of the 74 non-native fish species to be established (that is, to maintain wild populations) were introduced at least in part because fish escaped from aquaculture facilities (Courtenay and Williams 1992; U.S. Geological Survey 1997). More than half of these escapes were ornamental fish raised for the aquarium trade; such fish are particularly common in the warm waters of Florida and California. A smaller number were fish that escaped farms where they were raised as food.

The U.S. aquaculture industry once largely raised native North American species, such as channel catfish and rainbow trout; however, the aquaculture industry is now increasingly farming non-native species such as African tilapias and Asian carps (Courtenay and Williams 1992). At least some experts believe that, without appropriate regulation, aquaculture has the potential to be the largest source of introductions of non-native fishes into North American waters (Courtenay and Williams 1992; Courtenay 1993). A number of non-native species are currently farmed in the United States (see Fig. 3.2). Prominent among them are the following.

- The Pacific, or Japanese, oyster *(Crassotea gigas)*, a native of Japan, is now the most widely farmed non-native species in the United States. The Pacific oyster is grown in the Pacific Northwest, where it was introduced early this century to supplement declining stocks of the native Olympia oyster. The Pacific oyster is generally thought to reproduce only rarely in the chilly waters of the Pacific Northwest. However, a reproducing population that is displacing native oysters was recently found in the Hood Canal (P. DeFur, pers. comm.). Proposals to introduce Pacific oysters to Chesapeake Bay, where they may readily reproduce and outcompete native stocks, are highly controversial. (Aquaculture News 1996). For similar reasons, it is presently illegal to raise Pacific oysters in New England, where they are "generally reviled" (Chew 1995).

- Atlantic salmon (*Salmo salar*) are raised in Pacific waters off the state of Washington. Escapes of Atlantic salmon from Washington farms have spurred concerns that they may become established, and the Washington State Hearings Board recently ruled that Atlantic salmon that escape netpens should be classified as a "pollutant" (Doughton 1997). To date, however, no Atlantics are known to have reproduced in Washington (Canadian Department of Fisheries and Oceans 1997). Atlantic salmon now dominate U.S. and worldwide salmon production. Salmon farming originated in Norway, where Atlantics are a native species, and salmon-farming technologies are best developed for Atlantic salmon.
- Non-native Pacific white shrimp (*Penaeus vannamei*) are farmed along the Gulf coast of Texas and the Atlantic coast of South Carolina. As in the salmon farming industry, much of the technology for shrimp farming has been developed for this and other non-native species. Free-swimming Pacific white shrimp have been captured off the coast of South Carolina (OTA 1993).

Use of introduced species in aquaculture should be considered in the broader context of agriculture. Terrestrial agriculture in the United States relies heavily on cultivating varieties of non-native species, such as soybeans, wheat, cows, and chickens. Most of these varieties are highly domesticated. Selection for desirable farm traits (such as high yield), rather than the ability to survive and reproduce in natural ecosystems, has debilitated many of these varieties, and they typically require considerable human care to survive and reproduce. In contrast, many organisms used in aquaculture, such as farmed shrimp, are not highly differentiated from their wild ancestors. Upon escape or release, these organisms may easily survive and reproduce inside or outside their native ranges (Courtenay and Williams 1992).

Impacts of Introduced Species

Introduced species harm natural ecosystems by altering species composition or by reducing biodiversity. They may feed on native species, compete with native species for food and for space, modify or destroy habitat for native species, and introduce new diseases and parasites (Krueger and May 1991). These impacts can lead to the displacement or extinction of native species or populations of native species (Krueger and May 1991). Introduction of non-native fish from aquaculture facilities is believed to be a factor in the decline of seven fish species listed as endangered or threatened under

Figure 3.3. Examples of Atlantic Salmon Escapes from Aquaculture Facilities Worldwide

Region	Numbers escaping as a result of storms or other netpen damage	Source
Norway	1992-1996: average annual total escapes of 1.3 million	Fleischman 1997
Scotland	Feb. 1989: 184,000 in Loch Eriboll, northern Scotland	Webb et al. 1991
British Columbia	1994: 70,000 total escapes; 20,000 from a tanker truck spill on Vancouver Island	Ludwig 1996; Slaney et al. 1996
Washington	July 1996: 100,000 smolt and adults from one farm at Cypress Island	Mottram 1996
British Colombia	1997: 50,000 juvenile salmon from a Clayquot Sound farm	Vovscko 1997
Washington	1997: 300,000 juvenile and adult salmon from a Bainbridge Island farm	Dodge 1997

the Federal Endangered Species Act (Lassuy 1995).

Farmed eel. Courtesy of Louisiana Cooperative Extension Service.

Experiences with introduced blue tilapia (*Oreochromis aureus*) and common carp (*Cyprinus carpio*) illustrate the harm that can be caused by species raised in aquaculture facilities. In Florida, blue tilapia that escaped from two aquaculture facilities have become established in Dade County and Palm County canals and in Everglades National Park, where Park Service officials view them as a major management problem (Courtenay and Williams 1992). Blue tilapia often compete with native species for spawning areas, food, and space (Muoneke 1988 and Zale and Gregory 1990). In some Florida streams where these fish have become abundant, almost all vegetation and native fish species have disappeared (Courtenay and Robins 1973). In two Texas reservoirs where blue tilapia were stocked, populations of freshwater mussels have declined, possibly as a result of the tilapia feeding on juvenile mussels (Howells 1995).

Common carp were first introduced in the United States in the 19th century by European immigrants who had raised them in ponds in Europe (Courtenay and Williams 1992). In the United States, immigrants raised common carp in ponds for later stocking in natural bodies of water. Common carp have now spread throughout most of the United States as a result of stocking (Courtenay and Williams 1992), and are now raised in aquaculture ponds, from which they may also escape. Common carp are considered pests; during feeding they dislodge rooted aquatic plants and stir up sediments, a feeding behavior that harms water quality by increasing turbidity and lowering oxygen levels (Courtenay and Williams 1992) and that destroys habitat and food sources for native fish and waterfowl (Courtenay 1979). Common carp also eat the eggs of other fish species (Courtney and Williams 1992) and may have been a factor in the decline of the now federally endangered razorback sucker in Colorado (Taylor et al. 1984).

New diseases and parasites can be spread by the introduction of new stocks of non-native and native fish for aquaculture. A native population with little natural resistance to an introduced disease or parasite can be devastated by infection (Krueger and May 1991). The spread of exotic pathogens to wild fish is considered to be the greatest threat to wild fish from salmon netpen farming (Kent 1994). In Norway, *Aeromonas salmonicida*, a bacterium causing the disease furunculosis has infected wild Atlantic salmon stocks. In 1985, imported Atlantic salmon from Scotland carried a strain of *A. salmonicida* more virulent than strains native to Norway (Munro 1988). As a result of the stocking of infected salmon, the disease spread to salmon farms throughout Norway (Heggberget et al. 1993). Farmers slaughtered stocks from more than 20 farms, for total losses estimated at $100 million (Stewart 1991). Furunculosis also spread to wild salmon streams throughout the country, possibly carried by escaped farmed salmon, and killed large numbers of wild fish (Heggberget et al. 1993).

Diseases and parasites have also been introduced to the United States on farmed shellfish. The Japanese oyster drill (*Ocenebra japonica*) and a predatory flatworm (*Pseudosylochus ostreophagus*) were introduced with the Pacific oyster, and have contributed to the decline of West Coast oyster stocks (Clugston 1990). Some biologists believe that the Asiatic clam (*Corbicula manilensis*), which like the zebra mussel has clogged pipes throughout the United States, was introduced with the Pacific oyster (Clugston 1990).

American eels (*Anguilla rostrata*) may face harm from a parasitic nematode (*Anguillicola crassus*) that entered the United States with eels imported for aquaculture. A Texas aquaculture facility suffered an outbreak of the parasite in 1995. This facility discharged water, which probably contained parasite eggs and larvae, into a nearby river for more than a year before the parasite infestation was discovered. As a result, the parasite now may be established in the wild (Fuller 1995).

Imports of virus-laden frozen farmed shrimp for U.S. consumption may be introducing shrimp viruses to U.S. waters. In recent years, four foreign shrimp viruses have infected U.S. shrimp-culture operations (Joint Subcommittee on Aquaculture Shrimp Virus Working Group 1997 and references therein). Taura Syndrome Virus, which is endemic in Central and South America, caused devastating losses to the Texas shrimp-farming industry in 1995. Farms lost more than 95% of their stocks of *Penaeus vannemai,* the main shrimp species farmed in Texas. Researchers have now demonstrated that imported frozen shrimp carry exotic viruses, and experts hypothesize that infectious waste from shrimp-processing plants may spread these diseases to wild shrimp in the United States. Preliminary evidence suggests that Asian white spot syndrome virus may have spread to wild shrimp in South Carolina (Joint Subcommittee on Aquaculture Shrimp Virus Working Group 1977).

Genetic Impacts of Aquaculture Introductions

Farmed native species of fish can cause ecological harm if large numbers escape fish farms and interbreed with native wild populations, altering their genetic makeup. The potential genetic impacts from aquaculture introductions are well demonstrated by Atlantic salmon that escaped from fish farms in Europe and North America. Wild Atlantic salmon are characterized by a large number of genetically distinct populations[1] that are adapted to the specific conditions of the local river systems to which they return to spawn (Gausen and Moen 1991). In contrast, cultured Atlantic salmon are bred to be very uniform genetically and to exhibit favorable production traits, such as rapid growth, low aggressiveness, and resistance to disease (Gausen and Moen 1991). Interbreeding between wild and farmed Atlantic salmon introduces new

Box 3.1. Impacts of Stocking

Along with their concern about escaped farmed salmon, geneticists are also troubled by the possible genetic impacts of the stocking of hatchery-raised salmon for commercial and recreational fishermen. Huge numbers of salmon are released yearly to natural waters with the intent that the mature fish will be harvested on their return to freshwater for spawning. Nearly 8 million hatchery-raised Atlantic salmon are released yearly into North Atlantic and Baltic Sea drainages, and 4 billion such salmon of various Pacific species are released yearly into North Pacific drainages (Ikasson 1988). As with farmed salmon, these hatchery-raised salmon may be more genetically uniform than wild salmon. Interbreeding between wild and hatchery-raised salmon may lead to significant genetic pollution (Hindar et al. 1991; Committee on Protection and Management of Pacific Northwest Salmonids 1996).

combinations of genes to genetically distinct populations of wild salmon, and may break up local genetic adaptations that are critical to the survival of wild salmon in different rivers (Gausen and Moen 1991; Hindar et al. 1991; Skaala 1995).

Large numbers of Atlantic salmon escape from netpens throughout the world each year. Substantial numbers are lost both from large releases when netpens are wrecked during storms and as a result of everyday "leakage" from the netpens — for example, from poor maintenance, from accidents during fish transfers, and from boat and seal damage to nets. Escapes are best documented in Norway; in North America, large numbers of farmed Atlantic salmon have been found in Puget Sound, off the coast of Alaska, and in the rivers of Maine, Washington, New Brunswick, and British Columbia. For example, as many as 80% of the salmon in one New Brunswick river (the Magaduavic) are from farms (see New Brunswick case study). Figure 3.3 provides other examples of escapes of farmed Atlantics. Stocking of streams and rivers with hatchery-raised salmon also may similarly cause genetic pollution (see Box 3.1).

Wild-caught common carp. Courtesy of Minnesota Sea Grant Program.

The numbers of Atlantic salmon that escape from netpens are often large in comparison to the small numbers of wild Atlantic salmon that exist today, exacerbating the genetic impact of farmed Atlantic salmon on genetically differentiated wild populations. Only 100,000 wild Atlantic salmon spawn in Norway each year (Gausen and Moen 1991). Federal officials estimate that only 500 Atlantic salmon with a truly native genetic makeup now remain in Maine (Fleischman 1997). Because native populations are dwindling, the federal government recently proposed listing stocks of salmon from seven rivers as threatened under the Endangered Species Act (NMFS 1996). The escape of farmed salmon is identified as a potential threat to the recovery of these genetically distinct wild populations.

In northern Europe, interbreeding between wild and farmed Atlantic salmon and spawning of escaped farmed Atlantic salmon is well documented (Lura and Saegrov 1991; Webb et al. 1991; Webb et al. 1993; Gibbs 1996). Such interbreeding and spawning are less well documented in North America. Nevertheless, the Atlantic Salmon Federation has demonstrated that farmed and wild Atlantic salmon have interbred in New Brunswick by comparing DNA from wild Atlantic salmon that lived in the 1970's with DNA from today's populations (Gibbs 1996). In the fall of 1996, sexually mature farmed salmon were found for the first time in the Dennys and Narraguagas rivers of Maine (Fleischman 1997). There are no confirmed observations of Atlantic salmon spawning on the West Coast of North America (Canadian Department of Fisheries and Oceans 1997); however, sexually mature Atlantic salmon have been caught in Washington State's Elwha River (Fleischman 1997).

In Norway, geneticists now warn that large-scale interbreeding over a number of years could easily destroy what is left of genetically differentiated wild Atlantic salmon populations (Gausen and Moen 1991; Gibbs 1996). Wild salmon stocks on the East Coast of North America could potentially suffer a similar fate (Gibbs 1996).

Far less scientific research and public concern has been focused on interbreeding between wild fish and farmed fish other than Atlantic salmon. In part this is because of the distinctive genetic structure of Atlantic salmon: Populations are specific to the rivers where they spawn. Nevertheless, wild and farmed fish populations of other species may also be genetically distinct, and interbreeding wild and farmed fish of other species could also cause genetic pollution.

Transgenic and Genetically Engineered Species in Aquaculture

The introduction of genetically engineered species, if not done with proper care, could in the future threaten wild populations of aquatic organisms. Growth of the aquaculture industry has stimulated considerable interest in genetically modifying fish for economically important traits, such as faster growth. Researchers are modifying fish via traditional selective breeding and with modern genetic engineering techniques involving insertion of novel genes, making the fish "transgenic" (Kapuscinski and Hallerman 1990). Transgenic fish may acquire genes copied from related or unrelated species ranging from other fish to viruses to cows. Foreign genes are inserted with the intention of altering the performance of the fish — for example, through faster growth, increased tolerance to freezing temperatures, increased disease resistance, and altered flesh quality (Hallerman and Kapuscinski 1993; OTA 1995; Entis 1997).

Figure 3.4. Fish Species That Have Been Genetically Engineered*

FINFISH	***SHELLFISH***
Bluntnose bream	Abalone
Common carp	Giant prawn
Channel catfish	
Gilthead bream	
Goldfish	
Killifish	
Largemouth bass	
Loach	
Northern pike	
Medaka	
Mud carp	
Atlantic salmon	
Coho salmon	
Striped bass	
Sea bream	
Tilapia	
Rainbow trout	
Walleye	
Zebrafish	

Sources: Hallerman 1996; Songer 1996; Hileman 1995; Kapuscinski and Hallerman 1990.
* Some species not genetically engineered for aquaculture.

Currently more than 15 species of fish have been genetically engineered by researchers, including such common aquaculture species as Atlantic salmon, channel catfish, common carp, and rainbow trout (see Fig. 3.4). Two U.S. companies are now close to commercializing transgenic fish engineered to grow faster. One company, AquaBounty Farms, has engineered Atlantic salmon to contain a growth hormone gene from chinook salmon (Entis 1997). Connecticut Aquaculture has produced a similar fast-growing transgenic tilapia, with genetic material from rainbow trout, striped bass, and carp (Datz 1997).

Transgenic fish that exhibit new or greatly altered traits should be considered a special kind of non-native fish (Kapuscinski and Phillip 1990; OTA 1993).

Salmon killed by a seal. Courtesy of Greg Stone.

Transgenic fish that escape from aquaculture facilities could potentially harm populations of wild fish, in ways similar to the effects of non-native species. For example, fish engineered with a growth hormone gene might outcompete wild fish for food or spawning sites, since the transgenic fish would be larger than wild fish at a given age. Fish engineered to tolerate freezing waters might expand their range and, as a result, compete with new, more northerly or southerly species. Escaped transgenic fish may breed with wild fish, transferring their acquired genetic material to wild populations and potentially causing problems from genetic pollution.

Figure 3.5. Common Avian Predators in Southern Aquaculture

Species	Potential Fish Consumption Rate (lbs/day)*
American white pelican	1.0
Great blue heron	0.75
Double-crested cormorant	0.5-1.0
Great egret	0.3
White ibis	0.3
Snowy egret	0.2
Little blue heron	0.2
Gulls, herring, ring-billed, laughing and Bonaparte's	0.15-0.3
Green-backed heron	0.15
Belted kingfisher	0.15
Tern, common; Forster's	0.1

* Estimated from species body weight; actual consumption rates of farmed fish by these birds are not known.
Source: Stickley 1990.

The introduction of foreign genes to fish raised for food also raises food safety issues. Genes are used as blueprints for proteins. Thus transgenic fish will almost always contain an introduced protein from another species. These new proteins may cause allergic reactions in susceptible individuals (OTA 1993). This phenomenon has already been documented in soybeans engineered to contain a gene from Brazil nuts; the transgenic soybeans caused allergic responses in individuals with Brazil nut allergies (Nordlee et al. 1996).

Predator Control in Aquaculture

In contrast to concerns about introduced fish, which center on the impacts of escaped farmed fish on wild animals, concerns about predation center largely on the impacts of wild animals on farmed fish. Many aquaculturists believe that predatory water birds and marine mammals cause significant economic losses by injuring and consuming farmed fish. Their desire to control predators, sometimes by killing them, conflicts with the desire of many members of the public to conserve these birds and mammals as wildlife.

Wild animals are attracted to aquaculture facilities as sources of food. Aquaculture facilities are often fairly accessible to wild animals and often contain high densities of exposed fish, making them an "optimal foraging situation" (Parkhurst 1994). Moreover, aquaculture facilities are often located within or adjacent to habitats of fish-eating animals. Aquaculture ponds, for example, are often built in marshes and other areas that serve as flyways or nesting and overwintering grounds for many species of birds (Pillay 1992).

U.S. aquaculturists are increasingly using "lethal controls" for predatory birds (OTA 1995). According to U.S. Fish and Wildlife Service data, between 1989 and 1993 more than 25,000 double-crested cormorants were killed legally by aquaculturists (OTA 1995). Some experts speculate that many more were killed illegally (Williams 1992; OTA 1995). In addition, salmon farmers are increasingly interested in killing predatory seals (NMFS 1996).

Predation by wild animals is not a new problem for aquaculture. Nevertheless, as the U.S. aquaculture industry grows, the numbers of mammals and birds preying on farmed fish will likely increase. Members of the aquaculture industry, wildlife organizations, and others now hold widely differing opinions about the appropriateness of killing mammalian and avian predators (OTA 1995), and predator control will likely emerge as one of the most controversial issues facing the U.S. aquaculture industry.

The Impact of Wild Animal Predation on Aquaculture

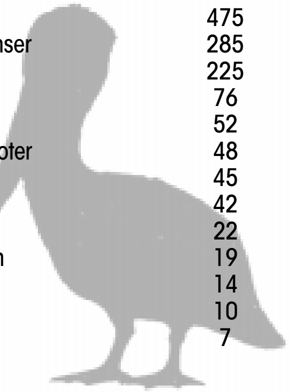
A wide variety of animals — more than 62 species of birds and 13 species of mammals — are thought to be potential predators of farmed fish, although there is no good scientific data demonstrating predation by many of these species (Parkhurst 1994). Avian predators include waterfowl, such as mallards, double-crested cormorants, and great blue herons, as well as raptors, such as ospreys (Stickley 1990). Figure 3.5 shows bird species commonly found in aquaculture facilities in the Southeast and their fish consumption rates. However, not all birds that are perceived to be predators necessarily prey on farmed fish. Cattle egrets, for example, are often found near aquaculture facilities, but these birds feed on terrestrial invertebrates, not aquatic organisms (Stickley 1990). Similarly, in at least some cases, double-crested cormorants and great blue herons feed primarily on wild noncommercial fish that have colonized catfish ponds, rather than the catfish themselves (Littauer 1990b; USFWS 1997).

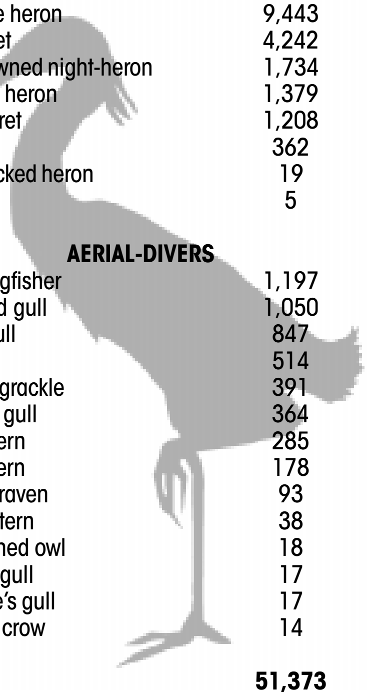
In general, there is less information available on the impact of mammals than on the impact of birds on freshwater and marine aquaculture facilities. A variety of wetland mammals, including muskrats, minks, river otters, feral cats, bears, and raccoons, prey on fish in freshwater aquaculture facilities, especially fish hatcheries (Parkhurst 1994). Seals and other marine mammals are predators on fish in marine cage and netpen operations. Gray seals and harbor seals are predators on Maine salmon farms (NMFS 1996). California sea lions are predators on salmon farms in Washington (P. Granger, pers. comm.).

Predators can feed on fish in almost any type of aquaculture facility, with the exception of those contained indoors or in sealed holding structures. Some aquaculture facilities are hit harder, however, as a result of their design.

Predacious insect with tiny catfish — even insects can prey on very young fish. Courtesy of Louisiana Cooperative Extension Service.

Figure 3.6. Reported Authorized Kill of Bird Predators at Aquaculture Facilities in the U.S., 1989-1993





Species/Group*	Total
SWIMMING BIRDS	
Double-crested cormorant	25,930
Grebes	708
American coot	475
Common merganser	285
Pelican	225
Mallard	76
Merganser	52
White-winged scoter	48
Western grebe	45
Anhinga	42
Pied-billed grebe	22
American pelican	19
Common eider	14
Goldeneye	10
Old squaw	7
WADERS	
Great blue heron	9,443
Great egret	4,242
Black-crowned night-heron	1,734
Little blue heron	1,379
Snowy egret	1,208
Heron	362
Green-backed heron	19
Egret	5
AERIAL-DIVERS	
Belted kingfisher	1,197
Ring-billed gull	1,050
Herring gull	847
Gull	514
Common grackle	391
California gull	364
Forster's tern	285
Caspian tern	178
Common raven	93
Common tern	38
Great horned owl	18
Franklin's gull	17
Bonaparte's gull	17
American crow	14
TOTAL	**51,373**

Modified from: OTA 1995.

Aquaculture ponds are especially susceptible to predation by wading birds because they often closely resemble natural feeding sites (Pillay 1992). The growth of the catfish industry in the Mississippi Delta has created a huge increase in the area of artificial water habitats, which is thought to attract large numbers of fish-eating birds and mammals (Stickley and Andrews 1989). It is difficult to protect catfish ponds from birds by placing netting or other material over the ponds, because of their large size and typical production procedures (Littauer 1990b; Pillay 1992). Birds may also become trapped in nets (OTA 1995)

Unlike ponds, raceways and outdoor tanks are generally relatively small, making it possible to enclose their surfaces with netting or wire. Marine and freshwater netpens can usually be covered, with some inconvenience to normal farming activity (Pillay 1992). Shellfish farms are accessible to waterfowl and aquatic mammals; however, invertebrates, such as starfish and drills, are the predators that often cause losses to shellfish farmers (Stickney 1994).

Predators clearly cause economic losses to aquaculturists by killing or injuring fish and, in the case of marine netpens, by damaging aquaculture facilities. Injured fish are prone to disease and often draw low prices (NMFS 1996). Predators may cause other types of losses, although there are few studies that substantiate them. The presence of predators may stress farmed fish, making them more susceptible to disease (NMFS 1996). Avian predators and other birds may spread disease to farmed fish. Many birds are important hosts in the life cycles of parasites that infect fishes, and some birds carry viruses that infect fish (Pillay 1992).

In general, there is little reliable quantitative information on actual losses due to predators, making it difficult to estimate their true economic impact (OTA 1995; NMFS 1996). Estimated annual losses from birds vary from 8% to 75% of total fish production in U.S. aquaculture systems (Draulans 1988). One study of catfish farms in the Mississippi Delta estimates that losses from catfish farms due to double-crested cormorants are approximately $3.3 million per year, with an additional $2.1 million per year spent to harass birds and protect catfish (Stickley and Andrews 1989). Together these losses represent less than 3 percent of the industry's 1988 production value.

The Maine salmon industry estimates that 10% of its $50 million annual farmgate value[2] is lost to seal predation (NMFS 1996). There are no independent data confirming this estimate, however, and the salmon-farming industry has yet to make a concerted effort to quantify predation problems (NMFS 1996).

Impact of Aquaculture on Mammalian and Avian Predators

A variety of preventive and nonlethal methods are available to deter predators, including measures involving facility siting, design, and management (these methods are discussed further in Chapter 4). Many aquaculturists favor harassment methods, which scare predators with loud noises, scarecrows, and the like. However, harassment measures typically do not deter predators indefinitely, because predators grow accustomed to these stimuli and lose their normal fright response (OTA 1995). As a result, many aquaculturists feel that killing predators is necessary, especially in cases of "problem" individuals that do not respond to deterrents (Littauer 1990a; OTA 1995; NMFS 1996). Shooting is the most common and specific method for killing both bird and marine mammal predators (OTA 1995). Other lethal control methods include trapping and poisons.

In order to kill most predatory birds, a bird depredation permit must be obtained from the appropriate Regional Office of the U.S. Fish and Wildlife Service (USFWS) Division of Law Enforcement (OTA 1995). In June 1997, however, the U.S. Fish and Wildlife Service proposed that aquaculturists be allowed to kill double-crested cormorants without depredation permits in states where double-crested cormorants cause significant losses to fish farmers (USFWS 1997). According to USFWS Division of Law Enforcement data, between 1989 and 1993 a total of 51,553 birds representing 38 species or groups of species were legally killed at U.S. aquaculture facilities by permitees (see Fig. 3.6) (OTA 1995). Double-crested cormorants, the most frequently killed birds, represented 50% of the total, while great blue herons made up almost 20% and great egrets 8% of the total take. Numerous illegal killings likely also occur each year (OTA 1995; Williams 1992).

The number of permits issued and the number of takings has increased throughout the United States since 1980. By far the largest increase (500%) in reported killings has occurred in the Southeast, largely in Mississippi and Arkansas, where the U.S. catfish and baitfish industries are centered. Sixty-seven percent of legal killings are now in the Southeast region.

Marine mammals are protected under the Marine Mammal Protection Act (MMPA) and in some cases the Endangered Species Act, which generally

Pelican with catfish silhouetted in its bill. Courtesy of Louisiana Cooperative Extension Service.

prohibit their harassment or killing (OTA 1995). In 1994, the MMPA was amended to prohibit the intentional killing of seals except in self-defense or to save a human life (NMFS 1996). Between 1988 and 1995, however, the Marine Mammal Exemption Program allowed salmon aquaculturists to kill seals that failed to respond to nonlethal methods and that were thought to cause repeated damage to netpens (NMFS 1996). Only three killings of seals were officially reported to the program; however, NMFS officials believe that many more were likely killed.

In western Canada and parts of Europe, restrictions on marine mammal killings are less stringent than those in the United States (NMFS 1996). In British Columbia, 80 seals were killed under permits in 1994 (NMFS 1996), and an estimated 500 seals were killed annually between 1990 and 1994 (Hatfield 1996).

Little information is available on the numbers of terrestrial mammals killed by aquaculturists. Most terrestrial mammalian predators are classified by state wildlife agencies as game or fur-bearing species. State agencies regulate their killing through hunting seasons, bag limits, and permit systems (OTA 1995).

Controversy Over Killing Aquaculture Predators

Killing aquaculture predators raises both ethical and ecological issues. Many people value avian and mammalian predators as wildlife, and feel that it is unethical to kill these animals for following their natural instincts to feed. Killing of avian and mammalian predators reduces populations of these creatures, which may be ecologically harmful in areas where predator populations have declined. According to the breeding-bird survey sponsored by the USFWS and the Canadian Wildlife Service, bird populations are stable or increasing in most regions where birds are killed in large numbers by aquaculturists (OTA 1995). However, some populations of targeted birds, such as cormorants in Maine and great blue herons in areas of the Midwest and West, have declined in recent decades (OTA 1995). Under the strong protection of the Marine Mammal Protection Act, populations of harbor seals and gray seals have increased considerably in recent years along the Maine coast (NMFS 1996).

Some experts believe that killing predators is ineffective in stopping predation (OTA 1995; NMFS 1996). Dead predators are rapidly replaced by other individuals, unless the aquaculture facility is made less inviting as a foraging site (Draulans 1987). Some experts argue that there is little evidence that removal of avian or marine predators has any long-term effect on predator abundance or fish loss at aquaculture facilities (Draulans 1987).

The lack of data concerning the impacts of wild animals on aquaculture facilities makes it difficult to justify killing predators. Based upon a report by a task force set up to study seal predation on Maine salmon farms, the National Marine Fisheries Service (NMFS) recently concluded that there is no compelling reason at this time to allow Maine salmon farmers to intentionally kill seals (NMFS 1997). Neither the extent of the seal damage to farms nor aquaculturists' claims that only a few rogue seals are responsible for most predation are well documented. Moreover, many salmon farmers are not properly installing predator nets.

Proponents of lethal control methods argue that killing a few predators scares other predators and increases the effectiveness of nonlethal control methods (Littauer 1990a). Particularly in the case of marine mammals, many aquaculturists feel that only a few individuals are problem predators and eliminating these few individuals is sufficient (NMFS 1996). However, this strategy requires aquaculturists to distinguish individual predators when it comes time to kill them (OTA 1995). Some salmon farmers also argue that it is unfair that they cannot kill seals when farmers and ranchers in the western United States can have government agents kill wolves that harm their livestock, even though wolves are listed under the Federal Endangered Species Act as threatened in Minnesota and endangered in other states (D. Morris, pers. comm.).

Some frustrated aquaculturists may be tempted to kill aquaculture predators as a visible means of control that provides immediate gratification (Kevan 1992). Some aquaculturists may also regard lethal predator control methods as easier to implement than nonlethal methods. A survey of aquaculturists in the north-central states found that many respondents felt they should be able to kill birds on their property without permits and that respondents were unwilling to invest money in preventative measures (Floyd et al. 1991).

In general, the killing of wild predators of farmed fish is a poor management practice. There is little scientific evidence that killing predators is effective either in controlling predation or in producing an economic gain for aquaculturists. Moreover, by killing wildlife, the aquaculture industry paints an unflattering picture of itself as insensitive to the environment. Aquaculturists should employ a variety of the existing management and other techniques to deter predators, keeping in mind that it is probably impossible and economically unnecessary to eliminate all predators (Littauer 1990a; OTA 1995; NMFS 1996).

Conclusion

Aquaculture can cause significant biological as well as chemical pollution problems. Farmed fish commonly escape fish farms, sometimes in very large numbers. Escaped fish of non-native species may displace native fish species or otherwise disrupt natural ecosystems. Escaped fish of native species can cause genetic pollution, if farmed fish interbreed with wild fish, making the wild fish less well adapted genetically for life in natural ecosystems. Escaped genetically engineered fish may in the future cause ecological harm by outcompeting wild fish or by interbreeding and transferring their acquired traits to wild fish populations. The shipment to farms of new stocks of both non-native and native fish species from other geographic areas can spread injurious new diseases and parasites to wild as well as farmed fish.

Fish-eating birds and marine mammals feed on fish at aquaculture facilities. U.S. aquaculturists kill large numbers of birds and smaller numbers of marine mammals in an attempt to control losses of fish to predators. Nevertheless, there is little scientific evidence that killing wildlife helps aquaculturists significantly lower predation rates or increase profits.

As will be discussed in Chapter 4, there are a number of farm practices and technologies available to prevent or reduce biological and genetic pollution from aquaculture. There are also a number of nonlethal methods to prevent or reduce predation at aquaculture facilities.

Recommended Readings

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Chapter 3 Notes

[1] These genetically differentiated populations are sometimes referred to as stocks, although there is no widely agreed upon scientific definition for the term “stock” (A.R. Kapuscinski, pers. comm.).

Chapter Four

Off the Hook: Environmentally Friendly Aquaculture

Introduction

Over the past several decades, the strategic foundation for pollution control has evolved so that there is now a recognized spectrum of approaches to managing pollutants. The most preferred of these approaches is to prevent or reduce the production of pollutants in the first place. In decreasing order of preference, other approaches are to recycle and reuse wastes, waste treatment, and disposal of wastes in the environment. This ranking was formalized by the U.S. Congress in 1990 under the Federal Pollution Prevention Act.[1]

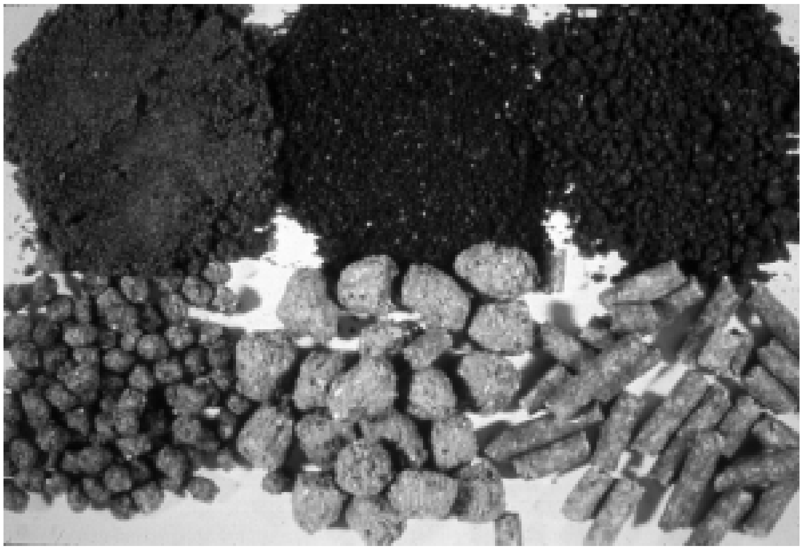
Although this spectrum of approaches is applied most often to manufacturing industries, it is also applicable to terrestrial agriculture (Hoppin et al, 1997) and should be applicable to aquaculture. As detailed below, a variety of approaches are now available to prevent or mitigate environmental problems caused by aquaculture. Source reduction approaches minimize the production of nutrient, synthetic chemical, and biological pollutants. These approaches are generally preferable to other approaches to pollution control, such as waste treatment or preventing the escape of farmed fish into natural ecosystems. Source reduction approaches are particularly appropriate for new aquaculture facilities that can incorporate them into their design. Other approaches, such as waste recycling and waste treatment, may sometimes (but not always) prove easier to implement than source reduction for facilities already in operation.

Reducing Nutrient Pollution from Aquaculture

Source-reduction approaches to nutrient pollution involve reducing the quantity of nutrients present in the water in aquaculture facilities. These approaches include making efficient use of feed and using excess nutrients to grow another crop, such as shellfish or hydroponic plants. Pollution-treatment approaches involve treating aquaculture effluents to remove the nutrients that cannot be used by fish. These approaches include traditional wastewater treatment methods, such as settling ponds, and relatively new, innovative methods borrowed from modern municipal wastewater treatment. Recirculating systems, discussed at the end of this chapter, use such innovative methods to treat their water, which is then reused to grow more fish. Careful selection of sites for facilities, also discussed later in this chapter, can help assure that fish farms are located only in areas that can assimilate wastes that are discharged.

Reducing Feed Waste in Aquaculture Systems

Reducing the amount of feed wasted in aquaculture systems can substantially reduce the waste generated by aquaculture systems. Virtually all nutrients not naturally present in aquaculture systems are derived from the addition of feed; they are either dissolved from uneaten feed or are excreted by fish as feces and other excretory products. Improved feed utilization increases the proportion of feed



Above: Assorted types of catfish feed. Courtesy of Louisiana Cooperative Extension Service.

Figure 4.1. Some Possible Protein Substitutes for Fishmeal in Carnivorous Fish Feeds

Animal by-Products	Blood meal Liver meal Meat and bone meal Poultry by-product meal Poultry feather meal
Plant by-Products	Sunflower seed meal Rapeseed meal Cottonseed meal Soybean meal Faba/broad bean meal Pea seed meal Corn gluten meal Potato protein concentrate
Single-cell proteins	Algal, fungal, or bacterial single-cell proteins

Source: Tacon 1994.

that fish consume and then retain in their bodies — and it can dramatically reduce the quantity of nutrients released in aquaculture effluent. Over the last two decades, the feed conversion ratio (FCR - see Chapter 1) for Norwegian salmon feeds has been reduced by about 50%, resulting in an 80% reduction in the discharge of solids from salmon farms (Lopez Alvarado 1997). Moreover, improving feed utilization can save aquaculturists money, as feed is the most expensive input in many types of aquaculture.

Pollution from aquaculture feeds can be reduced both off the farm, by altering the production of aquaculture feeds, and on the farm, through good feed management practices. The first step in feeding fish — the selection and processing of raw materials for feed — is a significant determinant of the environmental impact of aquaculture feed. Fish require more protein in their diets than most farmed terrestrial animals (Lovell 1991). Fishmeal is now used extensively in aquaculture feeds because it is high in protein, easily digested, and palatable to fish (Tacon 1993). As discussed in Chapter 1, this practice causes a number of problems including a net loss of fish protein, as more pounds of fish are required to feed farmed fish than are ultimately harvested.

Researchers are now evaluating an array of potential substitutes for fishmeal protein, although feeds with greatly reduced amounts of fishmeal are not yet widely commercially available; Figure 4.1 displays some potential substitutes. The relatively high prices of many potential substitutes currently limit their use; however, the substitutes could become competitive if fishmeal prices rise or if new restrictions are placed on nutrient pollution from aquaculture facilities (Hardy 1997).

The poultry industry provides a precedent for reducing fishmeal use. After intensive research on substitutes, the poultry industry decreased its use of fishmeal from 80% of world supply in 1972 to less than 40% in 1992, despite a doubling of poultry feed volume (Rumsey 1993).

There are a variety of potential high-protein substitutes for fishmeal in aquaculture feeds. Plant products such as oilseed cakes and meals (for example, from soybeans and canola) and plant protein concentrates (for example, wheat and corn gluten) are high in protein. Many oilseeds and legumes contain naturally occurring “antinutrients,” which makes them toxic to fish and has to date limited their use as fishmeal substitutes (Tacon 1997). Nevertheless, many of these antinutrients can be inactivated by processing, and plant products hold considerable promise as fishmeal substitutes in the diets of herbivorous, omnivorous, and carnivorous fish species (Tacon 1997; Hardy 1997).

Soybeans are a particularly promising substitute. Proteins are made of amino acids, and fish, like other animals, require a balanced mixture of amino acids in their diet (Lim and Dominy 1991). Among protein-rich plant feedstuffs, the amino acid composition of soybean protein is among the best at meeting the amino acid requirements of fish (Lovell 1991). Researchers are also evaluating the use of feeds containing single-cell proteins from algae, fungi, and bacteria as substitutes for fishmeal (Tacon 1993).

Increasing the content of plant proteins in fish feed has the potential to reduce phosphorous pollution. Fishmeal contains more phosphorous than fish can assimilate, resulting in the release of unused phosphorous to the environment (Rumsey 1993). For example, us of high-phosphorous feed for Atlantic salmon can lead to the release of roughly 80% of the phosphorous in fecal solids and soluble fish wastes (Ketola and Harland 1993). As discussed in Chapter 2, attempts to reduce nutrient pollution from trout farms along Idaho's Snake River are focusing in part on reducing the amount of phosphorous in feed (ID DEQ 1996). Optimizing the phosphorous content of feed ultimately may reduce phosphorous concentrations in effluent by 30%-80% (ID DEQ 1996).

Plant proteins contain less phosphorous than fishmeal (Rumsey 1993). Unfortunately the majority of this phosphorous is in a form called phytin-phosphorous, which fish cannot digest and release as wastes. However, treatment of soybean meal or formulated feed with an enzyme called phytase breaks down phytin-phosphorous and greatly reduces the amount of phosphorous that fish release to the environment (Cain and Garling 1995).

Bags of fish feed. Courtesy of Louisiana Cooperative Extension Service.

Good feed formulation is also a key factor in reducing nitrogen pollution from fish feed. Nitrogen in feed comes primarily from the amino acids that are the building blocks of proteins. Fish use these proteins both as a source of amino acids to build fish proteins and as a source of energy. When fish use dietary protein as an energy source they also excrete nitrogen, in the form of ammonia, as a waste product (Lopez Alvarado 1997). Excretion of nitrogen by fish can be reduced by optimizing the amino acid composition of proteins in feed to meet fish nutritional requirements. When feeds are deficient in a particular amino acid, fish use the other amino acids as an energy source, resulting in the release of nitrogen as waste (Lopez Alvarado 1997).

Nitrogen pollution can also be reduced by formulating feeds that are high in lipids (fats) relative to proteins. Fish then use lipids, rather than proteins, as an energy source, which reduces the excretion of nitrogen by fish (Autin 1997).

Production of less-polluting feeds is facilitated by manufacturing feeds using

Figure 4.2. Pollution Loading from Catfish Ponds Under Varying Feed Conversion Ratios (FCR)

Pollution Load	FCR=2.0	FCR=1.75	FCR=1.5
	(kg/1000 kg live catfish)		
Nitrogen	83.6	70.9	58.1
Phosphorus	12.7	10.7	8.7

Source: Boyd and Tucker 1995.

an extrusion process, in which raw feeds are exposed to high pressure and heat, followed by rapid lowering of pressure (Autin 1997). The extrusion process facilitates the production of feeds with a number of desirable characteristics, including improved digestability, high lipid levels, and inactivation of antinutrients from plant proteins (Autin 1997; Lopez Alvarado 1997). In addition, feed pellets produced by extrusion tend to float briefly in the water before sinking slowly, reducing feed wastage by allowing considerable time for fish to consume them (Botting 1991).

On the farm, aquaculturists can readily control many causes of poor feed utilization by fish. Common causes include: poor-quality feed (see above); feed containing a high percentage of fines (tiny, inedible pieces of feed); feed that is an inappropriate pellet size or nutritionally unbalanced for the fish being farmed; and poor feeding techniques, such as overfeeding, that make some feed unavailable to fish (Tetzlaff 1991). In catfish farming, for example, researchers easily obtain feed conversion ratios (FCR's) of 1.3-1.5. Commercial farms in Mississippi, however, often obtain substantially higher FCR's of 2.0-2.4, in part because of overfeeding (Boyd and Tucker 1995). These higher FCR's indicate that some catfish farms are producing higher than necessary pollution loads. Figure 4.2 displays pollution loading under different FCR's for the catfish industry.

To avoid pollution from poor feed utilization, aquaculturists should buy high-quality, nutritionally balanced feed with few fines. They should not use mechanical feeders that produce fines, such as various feeders that use blowers to distribute feed (Tetzlaff 1991). Overfeeding can be avoided by feeding small amounts of feed relatively often and by adjusting the amount of feed according to relationships between maximum feed consumption and temperature, fish size, and other conditions (Tetzlaff 1991).

A number of high-tech solutions are also available. The Freshwater Institute, in West Virginia, and the University of Mississippi recently developed an ultrasonic waste feed controller, which is being commercialized by a company called Aquadyne (R. Kriss, pers. comm.). This system uses a computer to add feed until an ultrasonic controller detects feed reaching the bottom, signifying that the fish are satiated. Another technology uses an air-lift pipe system to collect uneaten feed and dead fish from nets with fine mesh that form the bottom of netpens anc cages (Lopez Alvarado 1997).

Maximizing the Utilization of Nutrients in Aquaculture Systems: Incorporating the Principles of Integrated Farming Systems

Nutrient pollution from aquaculture systems can also be reduced by using the solid and dissolved nutrients found in the effluent to grow other crops. "Integrated farming systems," incorporating aquaculture and terrestrial agriculture, are an extremely efficient means of using the nutrients produced in aquaculture systems. In Asia, where integrated farming systems have existed for thousands of years, fish ponds are often part of a complex farming system that includes production of poultry, livestock, and crop plants, and uses manure, grass, and other crops as feeds and fertilizers (Network of Aquaculture Centres in Asia and the Pacific 1989). In China, for example, carps are raised in combination with sugar cane, mulberry-silkworms, vegetables, and other terrestrial crops. The energy and materials left or produced by one species are used as feed and fertilizer for other species (Ruddle and Zhong 1988).

Integrated farming systems have a number of advantages. They efficiently use on-farm resources and reduce economic risk to farmers through farm diversification (Skladany 1996). Moreover, the need for solid waste disposal is eliminated because wastes are used within the system (Chan 1993).

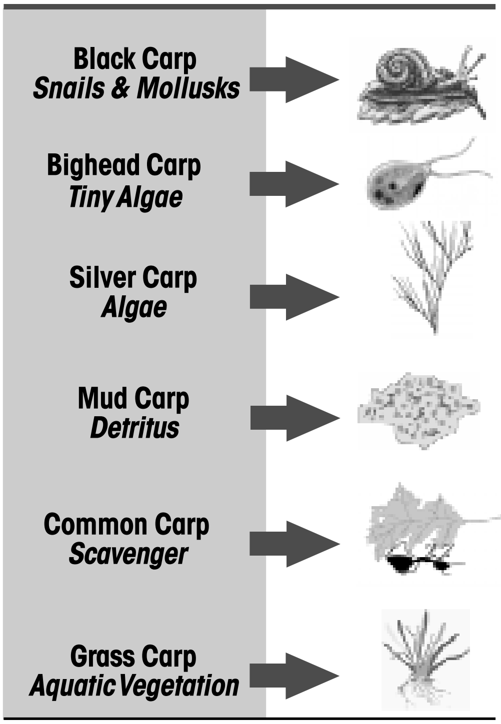
The industrial character of modern U.S. agriculture hinders the adoption of Asian-style integrated farming. U.S. farms typically raise crop plants or animals in large monocultures, while Asian integrated farms simultaneously produce smaller quantities of a variety of crop plants and animals. Nevertheless, some of the principles and components of integrated farming can be applied in the United States. In particular, some U.S. aquaculturists integrate fish and vegetable production and reuse aquaculture wastes on terrestrial crops.

Polyculture and Hydroponics

Polyculture means raising more than one species in a single rearing structure or other location, such as a farm field. Polyculture is essentially a form of integrated farming. By raising species together that require different types of food or nutrients, polyculture allows aquaculturists to make optimum use of water and food resources and to maximize fish production per unit of area or volume (Pillay 1994).

Polyculture has long been used in Chinese and Indian aquaculture (Pillay 1994). In China, the traditional polyculture combination is six carp species, each of which has different feeding preferences (see Fig. 4.3). Similar combinations of the so-called “Indian major carps” have been traditionally used in India (Pillay 1994). More recently a variety of other species have been added to polyculture systems. In Israel, for example, systems using the common carp, silver carp, tilapia, and gray mullet are common (Pillay 1994). However, combinations of three Chinese carps (grass, silver, and bighead) are still the most common in polyculture today (Bocek 1996).

Figure 4.3. Carp Species and Preferred Food Source in Traditional Chinese Polyculture



Source: Pillay 1994.

Carp for sale at market in Yangshou, Guangxi Province, Southern China. Courtesy of Tracy Triplett.

There are some obstacles and disadvantages to polyculture systems (Pillay 1994). Operating a polyculture system can require special skills and additional labor in order to determine the numbers and species to stock and to provide the correct feedings. Markets may not be developed and prices may be low for some fish commonly grown in polyculture systems, such as silver carp. Finally, in some cases, modern intensive monoculture systems that stock extremely high densities of fish may have higher production rates than traditional polyculture systems.

Polyculture involving fish, bivalves, or plants has been used to a limited extent in the U.S. aquaculture industry. Some catfish farms, largely in Arkansas, grow catfish with Chinese carps, including bighead and grass carp (K. Veverica, pers. comm.). Both these carp species are non-native, but they are already established in at least some waters in the southeastern United States (Fuller et al., in prep). Thus their use in polyculture may present less ecological risk (as discussed in Chapter 3) than use of newly introduced species. These herbivorous carps help control algae blooms and weed growth that result from the long residence time of water in catfish ponds.

Grass carp is the species most commonly grown, because it is particularly effective in controlling aquatic weeds. However, this fish is generally stocked in very low numbers, fewer than 5 carp per acre, and is not a valuable crop (K.Veverica, pers. comm.). Many farmers express interest in raising bighead carp with catfish, but few now do so because the market for bighead carp is largely limited to shipping live fish to Asian markets in big cities (Stone 1994). A more secure outlet for bighead carp, such as a processing plant or cannery, would likely encourage many more catfish farmers to practice polyculture (Stone 1994).

Polyculture with plants and finfish is more common in U.S. freshwater aquaculture systems than polyculture systems involving multiple species of finfish. Plants can effectively remove large quantities of nutrients from aquaculture effluent. A number of U.S. aquaculture operations now produce vegetables, fruits, and herbs as hydroponic crops using aquatic manure. The roots of crop plants are suspended in aquaculture effluent, either right above the finfish rearing structures or in raceways or tanks that the effluent flows into from the rearing structures. In the latter case, effluent is "treated" by the plants and then either returned to the rearing structures or discharged. Depending on the climate, these systems may be outdoors or entirely in greenhouses.

Hydroponic systems have two main advantages for aquaculturists (Rakocy et al. 1992). First, hydroponics can reduce nutrient concentrations in aquaculture effluent, allowing aquaculturists to inexpensively meet discharge regulations or reuse their water to grow more fish. Recent research shows that hydroponic systems can be as effective at removing phosphorous as the most current and expensive high-tech processes used in municipal wastewater treatment (Adler et al. 1996). Second, hydroponic systems produce additional crops that can help increase the profitability of aquaculture operation. However, there are some constraints on hydroponics production (Rakocy et al. 1992). Large areas can be

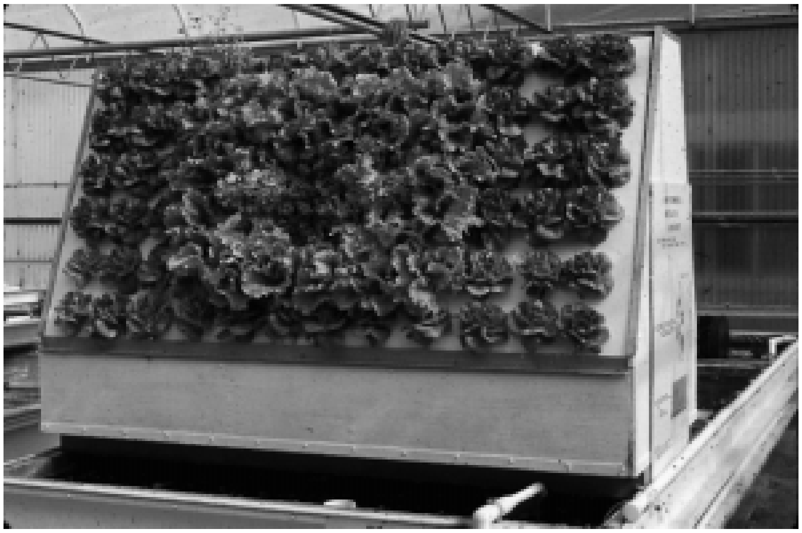
Right: Chinese carps used for polyculture in the U.S. Courtesy of Louisiana Cooperative Extension Service.

required to thoroughly treat large volumes of effluent. Farmers may need additional labor and skills. Hydroponic systems have an environmental advantage that may appear a constraint to some farmers; few pesticides can be used on the hydroponic plants, since these chemicals may harm fish as well as produce illegal food residues in fish.

The number of hydroponic systems in the United States appears to be growing (T. and P. Speraneo, pers. comm.; F. Takeda, pers. comm.). For example:

- The owners of S & S Aqua Farm in Missouri have developed a simple, low-cost aquaculture system that produces tilapia in tanks and a variety of fresh vegetables and herbs in gravel-filled beds into which effluent is released. Treated water is reused, and little additional water must be added. S & S Aqua Farm has sold the technology for their system to a number of other producers across the United States (S & S Aqua Farm 1996).
- Bioshelters, in western Massachusetts, grows hydroponics of basil, broccoli, and tomatoes with tilapia. Bioshelters grows plants directly in the indoor tanks where the tilapia are raised, making little water exchange necessary. Basil and tilapia are shipped fresh to Boston markets, and basil production provides 50% of Bioshelter's revenue (Spencer 1990).
- The Inslee Farm, Inc., of Oklahoma, grows chives in greenhouses using the effluent from ponds in which a variety of fish species are raised, including tilapia, catfish, and grass carp. Currently the farm produces 80 pounds of chives weekly, which are shipped fresh to a wholesaler in Houston (Inslee, pers. comm.).

Aquaculture effluent can also be used as fertilizer for terrestrial crops. Some farmers who grow both fish and terrestrial crops use the effluent from their aquaculture operations to simultaneously irrigate and fertilize their crop plants. In Arkansas, approximately 20% of fish farmers apply their aquaculture wastewater to terrestrial crops as a less costly alternative to installation of irrigation pumps (K.Veverica, pers. comm.).



Top: Hydroponic lettuce raised in conjunction with tilapia.
Left: Farmed tilapia displayed with hydroponic vegetables.Courtesy of American Tilapia Association.

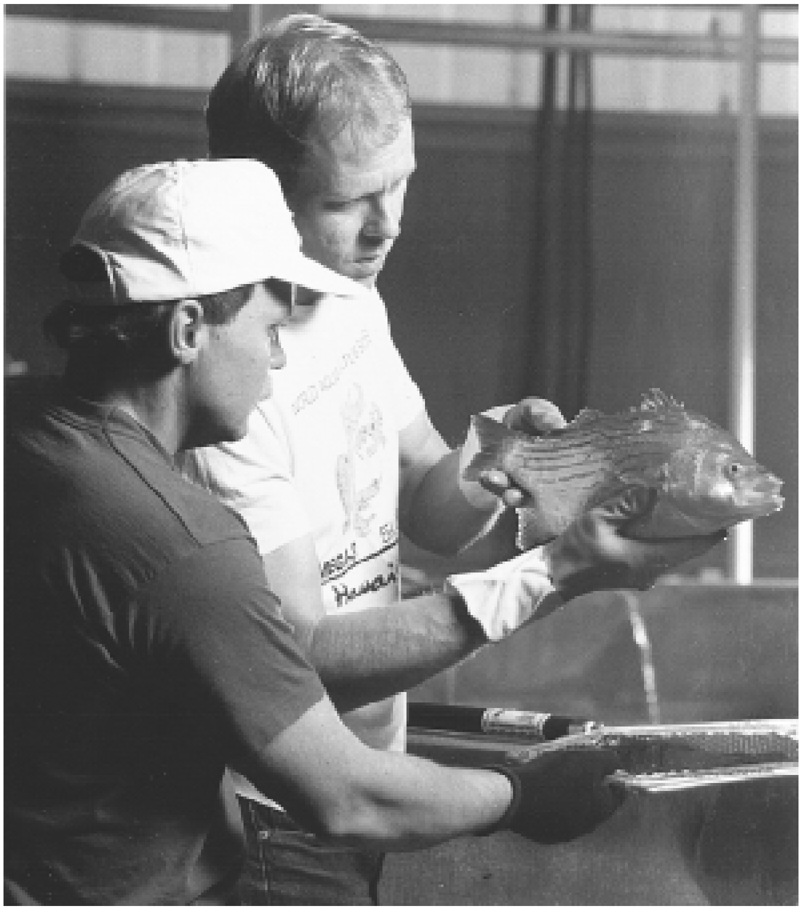
Polyculture in marine waters combines bivalve, seaweed, and marine finfish production. The excess nutrients from finfish production are absorbed by seaweed, while phytoplankton growth stimulated by the nutrients is removed by filter-feeding bivalves. Bivalve-seaweed-fish systems have been well studied in Israel (Shpigel et al. 1993; Neori et al. 1996), but U.S. farms are just beginning to experiment with this kind of polyculture. Maine-based Coastal Plantations, a commercial producer of nori seaweed, observes increased growth rates of nori alongside salmon netpens. This company is now planning to expand their use of this type of polyculture (I. Levine, pers. comm.). The New England Fisheries Development Association, Inc., is studying sea scallops-salmon polyculture in Maine, with the hope of increasing the economic viability of Maine salmon farms in the face of declining profit margins (New England Fisheries Development Association 1996).

Waste-treatment methods for Aquaculture

Conventional Methods of Treating Aquaculture Effluent

Aquaculture effluent not used to grow other crops can be treated with any of a number of methods. These methods are generally applicable only to land-based aquaculture systems and not to cage or netpen systems. Although attempts have been made to use funnel-shaped containers to collect the wastes that accumulate below cage and netpen farms, such devices restrict water flow and are difficult to maintain, especially in exposed marine sites (Pillay 1992). As a result, the primary way to reduce the environmental impacts of wastes released from cages and netpens is to select sites that are well flushed, so that tides and currents disperse wastes. Fallowing — forgoing production at a site for months or years — can be used to allow time for the breakdown and dispersal of accumulated nutrients (Pillay 1992).

Hybrid striped bass at AquaFuture. Courtesy of AquaFuture, Inc.



Waste-treatment methods for aquaculture are adapted largely from municipal wastewater (sewage) treatment. Sedimentation is one of the simplest methods to reduce nutrient pollution from aquaculture effluent. Sedimentation allows solid wastes, mainly uneaten feed and feces, to settle out of the effluent prior to discharge. Effluent flows into a "settling basin," where water velocity is slowed and gravity gradually pulls solids out of suspension before the effluent is discharged (Pillay 1992). Although the effectiveness of settling basins varies, they can remove (as discussed in Chapter 2), up to 90% of suspended solids, 60% of biological oxygen demand, and 50% of total phosphorus loads (University of Stirling 1990). The principle of sedimentation can be adapted to suit different aquaculture operations. For example, most trout farms in the United States use a quiescent zone — a wide raceway at the end of a series of raceways — to reduce water velocity and allow for settling (ID DEQ 1996).

A disadvantage of settling basins is that they typically require large areas of land (Pillay 1992). Sedimentation is also not very effective at removing very small particles or dissolved nutrients. Increased use of settling basins by the Idaho trout industry, for example, can help reduce the release of nutrients from solid wastes by collecting these solids. However, settling cannot be used to remove the extremely dilute concentrations of nutrients already dissolved in the huge volumes of effluent released daily by trout farms. As mentioned above, the trout industry is therefore also reducing the amount of phosporous in feed and reducing the amount of wasted feed (ID DEQ 1996).

Mechanical filtration can remove solids from aquaculture effluent, and provides an alternative method of waste treatment when land is not available for settling basins. A device called a low-head-swirl concentrator removes suspended solids using centrifugal force (Pillay 1992). Effluent is continuously added to a rapidly rotating cylindrical chamber that forces solid particles against the cylinder walls, where they concentrate and are removed. Fine-mesh filters are another method for removing solids; however, the mesh must be cleaned frequently (Pillay 1992). Other types of filters, such as sand and gravel filters, are also available (Stickney 1994b).

Sedimentation and mechanical filtration both result in the accumulation of nutrient-rich sludge that requires proper disposal. Application of aquaculture sludge to agricultural crops as organic fertilizer is an efficient disposal method, since the nutrients in the sludge are reused (Pillay 1992; Chen et al. 1991). AquaFuture, Inc., a company that produces hybrid striped bass in western Massachusetts, gives its sludge to local farmers (Herring 1994). Sludge from small aquaculture operations that are part of terrestrial farms is often used as a crop fertilizer. One West Virginia trout farmer, for example, uses a hog-manure spreader to apply aquaculture wastes collected in a low-head-swirl concentrator to his crops (Jenkins et al. 1995).

Sludge must, of course, be applied in appropriate amounts, in an appropriate manner, and at appropriate times. Otherwise sludge applied to farm fields can end up causing nutrient pollution by washing away as field run-off and by volatilization (conversion to a gas form) and atmospheric transport of nitrogen in the form of ammonium, which is later deposited. Both phenomena are now major problems with hog and chicken wastes applied to farm fields (Thu 1995; Rader and Rudek 1996; Rudek, in press).

Sludge from saltwater aquaculture ponds (for example, shrimp ponds) cannot be directly applied to crops, since salt is toxic to plants. However, sludge from brackish (moderately salty) ponds can be rinsed with freshwater to reduce salinity before being used as fertilizer (Hopkins and Holloway 1997). Other disposal methods for aquaculture sludge include composting, sanitary landfills, treatment at municipal sewage-treatment facilities, and discharge to a constructed wetland (Summerfelt et al. 1996; Tetzlaff 1991; Chen et al. 1991).

Plants can be used to treat aquaculture effluent, even if the plants are not grown as a harvestable crop (as in hydroponic vegetable production systems). Many municipal wastewater treatment facilities use aquatic plants, such as various reeds and duckweed, to reduce biological oxygen demand and to remove suspended solids and nutrients (Bird 1993). These plants take up dissolved nutrients from wastewater, while their roots filter and trap suspended solids that then are broken down by root bacteria (Bird 1993). Large numbers of aquatic plants can be planted in an area to form a constructed wetland. Constructed wetlands are relatively inexpensive to build and operate, and can be used to treat aquaculture effluent as well as municipal wastewater (Jenkins et al. 1995; Bird 1993).

Integrated Food Technologies located outside of Allentown, Pennsylvania uses a constructed wetland of reeds to treat effluent from tanks of various fish species before returning water to its indoor tanks (S. Van Gorder, pers. comm.). The catfish industry has experimented with constructed wetlands, but does not view them as feasible, because they require considerable land (Seok et al. 1995). The area of land required can be reduced, however, by treating only the last 20% of effluent (the portion that contains the greatest concentrations of pollutants) as ponds are drained or by draining a single pond over several weeks or a month (Seok et al. 1995).

The Use of Aquaculture Systems in Municipal Wastewater Treatment

While municipal wastewater technologies can be used to treat aquaculture wastewater, aquaculture can also be used to treat municipal wastewater. These treatment systems can increase food production in developing countries and provide cheaper, simpler alternatives to conventional secondary treatment in developed countries (Edwards 1992). Systems to reuse human sewage in aquaculture have long existed in Asia (Edwards 1992). Such systems may pose health risks, however, since bacteria and other pathogens in sewage could potentially contaminate fish. However, new treatment technologies now make it possible to separate or sterilize pathogens in sewage (Rheault 1997). As a result, in parts of Europe fish ponds are now used to treat agricultural run-off and human sewage (Rheault 1997).

In the United States, there have been only a few experimental projects cultivating fish in municipal wastewater (Edwards 1992), in part because many U.S. consumers may find such fish unacceptable. However, production of nonfood fish, such as baitfish, could be economically feasible for small municipalities (Metcalfe 1995).

Injecting a fish. Courtesy of Louisiana Cooperative Extension Service.

Reducing Chemical Use in Aquaculture Systems

The pollution-control spectrum discussed at the beginning of this chapter can be applied to chemical use in aquaculture, as well as to nutrient pollution. Adoption of tactics that prevent pests and diseases from becoming problems is the key to source reduction of chemical use in agriculture (Hoppin et al. 1997), including aquaculture. A variety of nonchemical pest-control measures are available if pests become a problem. Less-preferred pollution-control tactics, such as efficient use of pesticides and drugs in a manner that minimizes environmental contamination, will not, for the most part, be discussed here.

Preventative Medicine in Treating Disease

The use of drugs in aquaculture can be reduced by increasing the resistance of aquaculture organisms to disease with preventative medicine. Management practices can help minimize exposure of fish to pathogens and reduce stress, which tends to make fish susceptible to disease (Hastein 1995). Vaccinations can immunize fish against some diseases. As discussed later in this chapter, aquaculturists should do their best to stock only disease-free fish (including eggs and other life stages).

The majority of fish health problems in aquaculture are related to stress (Rottmann et al. 1992), and reducing stresses on fish is a key component of preventative medicine in aquaculture. Farmed fish are stressed by poor water quality, high stocking rates, human handling of fish, and unnatural physical conditions. Poor water quality is a common and damaging stress for farmed fish, especially in recirculating and other confined systems (Thune and Schwedler 1991). Water-quality parameters, such as levels of ammonia and dissolved oxygen, must be maintained within limits easily tolerated by particular fish species. Densities of fish must not be so high as to cause behavioral or other density-induced problems. Physical stresses on fish can be minimized by limiting or avoiding handling of fish, startling noises, rapid temperature changes, high rates of water flow, and artificial light sources with inappropriate spectrums and day lengths (Thune and Schwedler 1991; Hallerman, pers. comm.). Figure 4.4 displays a number of other “on the farm” management practices, including siting, sanitation, and health monitoring, that can be used to prevent disease outbreaks in aquaculture facilities.

Vaccination can be a highly effective method for preventing certain infectious diseases in aquaculture systems (Hastein 1995). In Norway, for example, coldwater vibriosis was once a serious problem for salmon farmers but now is largely controlled through the use of a vaccine (Norwegian Fish Farmers Association 1990). Vaccines can be administered orally or by injection or absorption through the skin after immersion or spraying (Avault 1997).

Vaccines currently are available against many important fish diseases, including furunculosis, coldwater vibriosis, vibriosis, yersiniosis, and edwardsiellosis (Hastein 1995). In the United States 15 vaccines are licensed for use by the U.S. Department of Agriculture; however, all but three of these are restricted to use in salmonids (salmon and trout) (OTA 1995) (see Fig. 4.5). In general, vaccines are not widely used in the United States because they are expensive, require skill to administer, and are available for only a narrow range of aquaculture species (Meyer 1994).

Alternatives to Pesticides

As with strategies to reduce drug use in aquaculture, a variety of management practices can reduce pesticide use in aquaculture systems by preventing aquaculture pests from becoming a problem. When pest control is needed, biological controls can serve as alternatives to the use of a number of chemical pesticides.

A number of management practices can help control fouling organisms on

Figure 4.4. On-farm Practices to Reduce Disease

Farm siting	•Maintain separation between farms to reduce risk of pathogen spread from other farms
Use of disease-free stock	•Select eggs, embryos, juveniles, or broodstock certified as disease free
Health monitoring	•Quarantine and inspect incoming stock •Routinely inspect established stock and any mortalities
Establishment of strict hygiene and sanitation procedures	•Regularly disinfect all tanks, cages, and equipment •Disinfect personnel (footgear, etc.) when move between tanks or other growing units

Source: OTA 1995; Hastein 1995.

Figure 4.5. Vaccines for Use in U.S. Aquaculture

Disease(s)	Species	Trade Name
Bacterial diseases-general	Fish	Autogenous Bacterin
Enteric septicemia	Catfish	Escogen
Furunculosis	Salmonids	Biojec 1500 Furogen
Furunculosis and vibriosis	Salmonids	Biojec 1900
Vibriosis	Salmonids	Biovax 1200 Biovax 1300 Vibrogen Vibrogen-2 Biovax 1600
Vibriosis and yersiniosis	Salmonids	Biovax 1700
Yersiniosis	Salmonids	Ermogen Biovax 1100 Biovax 1150

Source: Federal Joint Subcommittee on Aquaculture 1994.

aquaculture structures. As mentioned in Chapter 2, many Maine salmon farms now use netpens constructed from plastic materials that contain antifouling chemicals. According to salmon industry representatives, these cages leach less antifoulant into the environment than if antifoulants were applied by salmon farmers (J. McGonigle, pers. comm.). Each year salmon netpens are brought onto land, and barnacles and other fouling organisms are hosed off with high-pressure jets of water; cages are then dried in sunlight (J. McGonigle, pers. comm.).

Preventing weed growth in pond aquaculture is usually easier and less expensive than controlling weeds once they have become established (Shelton and Murphy 1989), particularly since herbicides may injure fish as well as weeds. Recommended preventative practices include siting and constructing ponds to reduce the size of shallow areas where weeds easily grow. Periodic pond drainage to reduce water levels can expose shallow areas to drying and freezing, which can limit the spread of some weeds (Shelton and Murphy 1989). If weeds become established, grass carp can provide extremely effective and economical control (Shelton and Murphy 1989; C. Tucker pers. comm.). However, escaped grass carp can degrade native fish and waterfowl habitat by consuming large quantities of vegetation, and use of these fish is restricted or banned in a number of states (OTA 1993; U.S. Geological Survey 1997), particularly if sterile, "triploid" fish (discussed later in this chapter) are not used to prevent grass carp from establishing self-sustaining populations.

Aerators increase oxygen levels in pond water. Courtesy of Louisiana Cooperative Extension Service.

Rather than fighting an often losing battle to control algae with algicides, aquaculturists would do better to simply use mechanical aeration to maintain oxygen levels as algae die and decay (Brunson et al. 1994; Tucker 1996). Polycultures with filter-feeding fish, such as silver carp and a native species called paddlefish, can help control algae in pond systems, although their effectiveness varies.

Salmon netpen farms can reduce the level of sea lice parasites and the need for chemical treatments in salmon farms by using preventive management practices, such as selecting sites with strong water currents and fallowing sites between salmon crops (Johnson et al. 1997). A small cleaner fish called wrasse, which literally eats lice off salmon, can be used as a biological control for sea lice and an alternative to the insecticides typically used to control sea lice (OTA 1995; Jonson et al. 1997). According to one study, only 600 wrasse are needed to keep 26,000 salmon smolt clean from lice (Pain 1989). In the same study, netpens without wrasse required several treatments with chemicals. Wrasse are increasingly used on salmon farms in Europe, where they not only reduce the need for chemical treatments, but also reduce stress and allow for increased growth rates in comparison to chemically treated salmon (Johnson et al. 1997). Unfortunately, wrasse are expensive to purchase and often die during the winter.

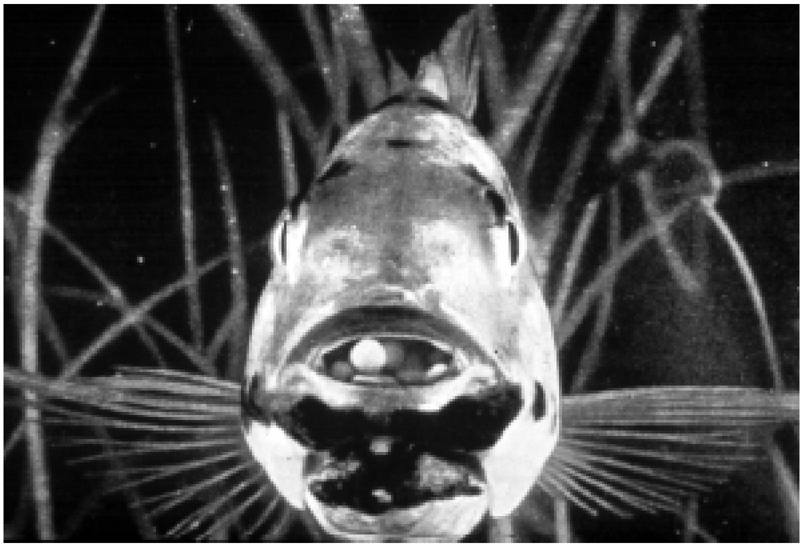
In general, it is probably wise for

aquaculturists to limit their use of pesticides, as well as drugs and other chemicals. Some consumers may now prefer aquaculture products because they perceive them as wholesome and safe. Consumers will likely become more reluctant to purchase aquaculture products if they feel that pesticides and drugs are widely used in their production (OTA 1995).

Advantages of Organic Aquaculture

Eliminating the use of drugs, pesticides, and other chemicals in aquaculture systems potentially gives producers the advantage of marketing organic products that can be sold for higher prices than nonorganic products. The organic food industry has experienced phenomenal growth in recent years. Sales increased from $631 million in 1989 to $3 billion in 1996 (Landay 1996), demonstrating the popularity of organic foods with consumers.

A number fish farms now produce fish without chemicals. Bioshelters, Inc., of western Massachusetts, raises tilapia, as well as basil and other plants, in a recirculating system using no antibiotics, pesticides, or fertilizers (Spencer 1990). AquaMar located in the Delmarva region of Maryland does not use chemotherapeutants and other drugs in their production of tilapia in recirculating systems (G. Redden, pers. comm.). Both these producers are aided by their decision to farm tilapia, a fish that in the United States is rarely infected by disease (Thune and Schwedler 1991). More disease-prone species also can be produced without drugs, however. Yellow Island Aquaculture, Ltd., in British Columbia, produces native chinook salmon in netcages without medication (except vaccines) or antifoulants (Ellis and Associates 1996; D. Ellis, pers. comm.). Yellow Island's production costs are higher than on other salmon farms, as fish are stocked at lower densities to prevent disease. However, the higher prices that Yellow Island salmon receive at specialty markets more than compensate.



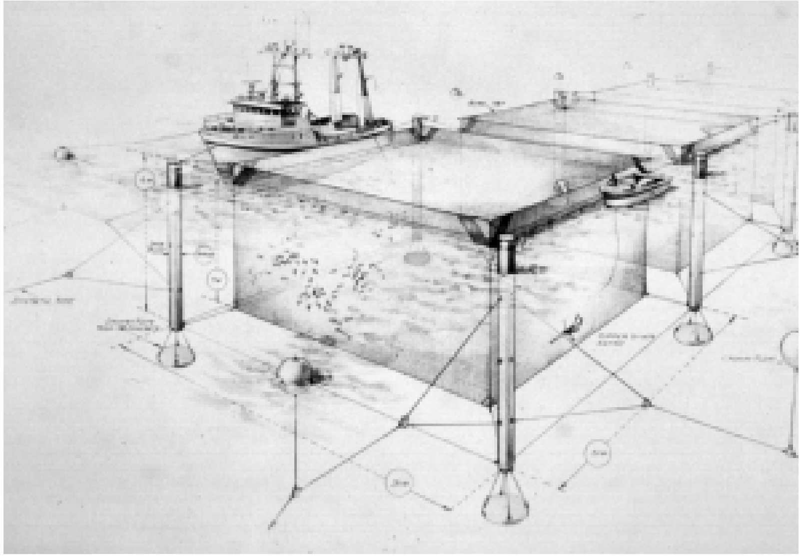
Tilapia with eggs in its mouth. Courtesy of Louisiana Cooperative Extension Service.

The growth of organic aquaculture is currently limited by the lack of widely accepted organic certification standards for fish production. Most organic foods sold in the United States now are certified as being grown under organic standards that specify how crop plants and terrestrial animals should be grown. Criteria include, but are not limited to, a general ban on the use of synthetic pesticides, drugs, and other chemicals. Organic standards for fish have yet to be developed by a major organic certification agency, although the International Federation of Organic Agriculture Movements, based in Germany, has begun to draft fish standards. The U.S. Department of Agriculture intends to propose federal standards for organic foods in the near future, but these standards will not specifically discuss fish production (M. Sligh, pers. comm.).

Reducing the Biological Impacts of Aquaculture

Biological Pollution from Aquaculture Facilities

Biological pollution can be reduced



Cages and netpens are generally the least secure aquaculture systems.
Photos: Top: Diagram of an ocean net pen. Below: Cage culture of fish. Courtesy of Louisiana Cooperative Extension Service.

at the source if aquaculturists carefully choose the species or strains they will farm. The simplest way to eliminate the possibility of ecological harm from escapes of non-native aquaculture species is not to raise non-native species, unless there is compelling evidence that escaped fish cannot establish wild populations. Instead aquaculturists should raise native species or domesticated strains of non-native species that cannot survive and reproduce outside captivity. Nevertheless, consumer willingness to purchase non-native fish species, such as tilapia and Pacific white shrimp, provides a strong economic incentive for U.S. aquaculturists to continue to farm these species. Moreover, as a young industry, modern aquaculture has not yet domesticated most farmed species to the point that they do not survive and reproduce outside of captivity.

Of course, even escaped fish of native species can cause biological pollution if the fish interbreed in significant numbers with wild fish. Thus, whether native or non-native species are raised, all aquaculture facilities should take measures to minimize escapes of cultivated fish into natural waters. The best method of preventing escapes is to not grow fish in open systems, such as netpens, and instead use more secure closed systems, such as recirculating systems, which will be discussed later in this chapter. However, even aquaculture systems that are relatively open to the environment, such as netpens, can be altered to reduce the frequency of fish escapes.

Cages and netpens are generally the least secure aquaculture systems; fish escapes from these systems are considered inevitable (Webb et al. 1991). Large-scale escapes can be reduced by anchoring cages or netpens with heavy moorings, that help prevent storm damage (Gausen and Moen 1991; Windsor and Hutchinson 1995). Other security measures include installation of antipredator nets that prevent damage by seals to marine netpens and cages (see next section) and careful operation of the facilities to minimize “trickle losses,” especially when fish are moved to and from holding structures (Windsor and Hutchinson 1995). In Norway, inspection of salmon-farming facilities has helped to significantly reduce the numbers of escapes from netpens (Windsor and Hutchinson 1995). One U.S. company, SargoTM FinFarms, now sells large floating tanks that can be used as a more secure alternative to netpens and cages (Fish Farming International 1997a).

Fish may escape from pond and raceway systems during overflows, damage to levees, or harvest (if facilities are drained). Similar problems may occur in outdoor tanks. Possible solutions to these problems include placing ponds above 100-year flood zones (OTA 1993), constructing containment dikes, careful inspection and maintenance of levees, harvesting fish with seines or dipnets, as is now done in the catfish industry, and filtration of effluent through sand or gravel in order to prevent the release of eggs or larvae (Courtenay and Williams 1992).

Growing reproductively sterile organisms can be used to augment physical containment of fish, especially since it is often impossible to completely eliminate fish escapes from aquaculture facilities. Escaped sterile fish cannot establish wild populations or interbreed with wild fish, although they can still cause ecological harm by competing with wild fish for food, by spreading disease, and by disturbing wild nest sites. The use of sterile salmon in aquaculture is recommended by the International Council for Exploration of the Sea Study Group on Genetic Risks to Atlantic Salmon Stocks (Anonymous 1991).

Fish and shellfish can be rendered sterile by manipulating their chromosomes so that they are "triploid," which means they have three sets of chromosomes instead of the usual two. Although triploidy is the primary technique now used, there are other techniques under development for inducing sterility in fish (Devlin and Donaldson 1992).

Induction of triploidy does not always produce perfect sterility. Some organisms in a batch of triploids may remain normal "diploids" (with two sets of chromosomes) that readily reproduce (OTA 1995). Some male triploid finfish have substantial gonad development and produce small amounts of genetically abnormal sperm (Lincoln and Scott 1984; Benfey et al. 1986). These fish may try to mate, but produce only inviable progeny and disrupt spawning by wild fish (Thorgaard and Allen 1992). Male triploid shellfish sometimes produce normal "haploid" (with one set of chromosomes) sperm (Allen 1987). Moreover, in one experiment in 1993, 20% of the supposedly sterile triploid Pacific oysters introduced to Chesapeake Bay reverted back to their diploid state (Blankenship 1994). Fortunately, cold water temperatures kept the diploid Pacific oysters from reproducing before these non-native individuals were removed from the Bay.

The U.S. Fish and Wildlife Service operates an inspection service, based in Georgia, that certifies grass carp as triploid (OTA 1993). Many states also offer triploid verification services (E. Hallerman, pers. comm.).

Besides the farmed fish themselves, parasites and diseases may also escape from fish farms and spread to wild populations. Stocking farms with certified "specific pathogen-free" stock is essential to minimizing this problem, as well as to minimizing economic losses of farmed fish to disease. Obtaining disease-free aquaculture organisms is not always straightforward, however. In Texas, shrimp farmers are required by law to stock only "high health" shrimp from populations designated as specific pathogen-free (see case study on Texas shrimp farming). Texas hatcheries produce only a limited supply of high-health shrimp, however. Many Texas shrimp farmers import shrimp from outside the country that experience suggests are not reliably disease-free.

Interactions Between Wild Predators and Aquaculture Organisms

A variety of control methods, ranging from siting of ponds to shooting birds, may be used to reduce predation of farmed fish by wild animals. However, no single solution to predation problems has been found to be effective in most aquaculture facilities, and such a solution is unlikely to be discovered in the near future (OTA 1995). The most effective way to deter avian predators is to combine a number of nonlethal control methods (see Fig. 4.6), while constantly substituting different methods to avoid habituation by predators (Littauer 1990; OTA 1995; NMFS 1996).

Propane cannon for scaring birds. Courtesy of Louisiana Cooperative Extension Service.

Figure 4.6. Some Non Lethal Methods of Deterring Predators

Method	Avian Predation	Seal Predation
Facility Modification	Increase water depth of culture unit Increase slope of culture unit embankments Remove perches and feeding platforms Remove cover and concealing vegetation Disperse roost/nest site	Increase tension of nets Use rigid nets 
Operational Modification	Modify feed type and delivery method Re-locate young/small stock Remove dead fish promptly	Remove dead fish promptly
Auditory Harassment	Predator distress calls Automatic exploders Pyrotechnic devices Sirens Electronic noisemak 	Predator vocalizations Explosive underwater devices (seal bombs) Underwater acoustic deterrence devices
Visual Harassment	Lights Scarecrows Reflectors Model airplanes Trained falcons Human presence 	Predator models (killer whale scarecrows) Patrol with boats
Barriers	Perimeter fencing and protective netting Water spray	Perimeter nets around entire site

Sources: OTA 1995; NMFS 1996.

Predation-control programs are essential to control bird predators (OTA 1995). These programs ideally should be developed prior to constructing a facility. Aquaculture facilities should not be constructed on known bird-migration routes, near rookeries, or near other areas where fish-eating birds congregate. Facilities also also be designed to be unattractive to predators. Ponds with relatively deep water, for example, can prevent wading birds from easily feeding.

After an aquaculture facility has been constructed, various devices and management practices can reduce the attractiveness of aquaculture facilities to birds (OTA 1995). Erection of barriers such as netting, water-spray devices, and overhead wire grids can deter predators, although such methods are not practical for large areas. The removal of any potential perches and feeding platforms and the cutting of tall vegetation can decrease the attractiveness of facilities to birds. Facilities can avoid tempting birds with food by not overfeeding fish and by quickly disposing of spilled feed and dead or dying fish.

Aquaculturists can harass, or drive away birds, with a number of different methods, ranging from loud, explosive noises to scarecrows and radio-controlled toy aircraft. Ideally aquaculturists should begin using such methods as soon as avian predators show up in order to discourage the establishment of a feeding pattern (OTA 1995). Other nonlethal bird-control methods include the trapping and removal of predators and the addition of chemical deterrents to ponds. An extensive listing and description of such techniques can be found in OTA (1995).

Somewhat fewer nonlethal methods are available to deter marine mammals from preying on fish in coastal netpens and cages (see Fig. 4.6). Exclusion devices, such as top nets that extend over the top of netpens or cages, and curtain nets that extend below the netpen or cage bottom, are effective predator deterrents

(Beveridge 1996). The Maine salmon industry has found that in addition to using top and curtain nets, allowing netpens to become greatly fouled with algae and other organisms during the winter season deters seals (NMFS 1996).

A range of harassment measures also are available. Visual harassment measures include the presence of humans, dogs, and flashing lights (Beveridge 1996). One Scottish salmon farmer is marketing a giant killer whale as a "scarecrow" for seals (Greenwire 1995). Acoustic deterrent devices (ADD's) for seals emit distress calls or make loud noises that scare seals. However, seals become habituated to these noises, limiting their effectiveness (NMFS 1996). Moreover, ADD's may drive away other marine mammals from habitat near fish farms; in British Columbia, use of ADD's is correlated with a decline in harbor porpoise populations within 3.5 km of these devices (Olesuik et al. 1994). Whales also appear to avoid regions where there are salmon farms using acoustic harassment devices (A. Morton, pers. comm.).

Appropriate Siting of Aquaculture Operations

Siting aquaculture facilities in appropriate locations can mitigate or prevent many of the environmental impacts of aquaculture. Siting is crucial in cage and netpen farming, which rely on natural tides or currents to flush wastes that settle below farms (Pillay 1992). High rates of erosion of bottom sediments as well as high water flow are most desirable. Farms must be well spaced to reduce the potential for the spread of disease between farms, as well as to reduce any cumulative effects of waste production. Netpens and most other types of aquaculture facilities should not be established in environmentally sensitive areas, such as wetlands, important wildlife habitat, and areas that are particularly susceptible to nutrient pollution from any discharges of wastes from aquaculture operations (Pillay 1992).

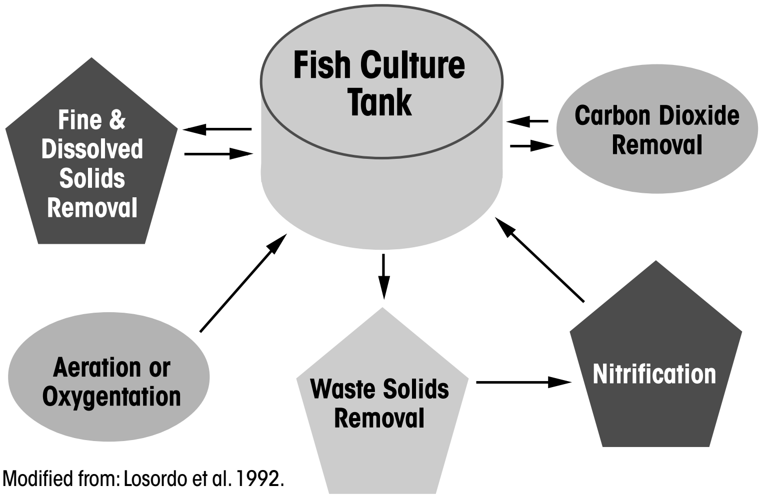
Mathematical modeling can be used to help determine the capacity of an area to assimilate nutrients from aquaculture wastes, and therefore to estimate the relative impacts of an aquaculture operation on surrounding waters. However, a lack of basic information, such as estimates of other nutrient inputs to bodies of water, can make the development of accurate models difficult (Pillay 1992).

Poor siting of aquaculture facilities, especially coastal operations, can prompt conflicts with commercial and recreational fishermen, nearby homeowners, beachgoers, and others who may have economic, aesthetic, and environmental concerns (Pillay 1992). Careful siting of facilities is therefore essential to their acceptance by local communities as well as government regulatory authorities (Beveridge 1996).

Some aquaculturists now want to site marine aquaculture netpens and cages in the open ocean. These facilities would be more than 3 miles offshore and therefore in federal waters. (With a couple of exceptions, states have jurisdiction only over waters within 3 miles of their shores.) Establishing facilities far offshore would prevent conflicts with most users of coastal resources, such as nearshore fishermen and property owners (Stickney 1994a). Proponents of offshore aquaculture also argue that offshore netpens and cages would be better for the environment, since strong ocean currents would quickly disperse wastes (Stickney 1994a).

There may be clear exceptions to this last assertion, however (Hopkins et al., 1997). Wastes from aquaculture netpens and cages located in offshore areas that are relatively shallow or have relatively weak currents, such as the Gulf of Mexico, have obvious potential to cause serious environmental damage. Moreover, biological pollution from offshore facilities could be just as bad as or even more severe than from nearshore facilities, since offshore facilities may be especially vulnerable to storm damage that results in large releases of farmed fish. Federal permits have now been issued for two offshore aquaculture facilities: a finfish farm in the Gulf of Mexico (Hopkins et al, 1997), which has yet to be built, and a sea scallop farm off the coast of Martha's Vineyard, Massachusetts, which will begin as a pilot project in 1997 (Fish Farming International 1997b).

Figure 4.7.Diagram of a Recirculating System



Modified from: Losordo et al. 1992.

Box 4.1: Anatomy of a Recirculating System

In comparison to many other types of aquaculture systems, recirculating systems are highly complex, because they must treat and recirculate large volumes of water on a daily basis. (Losordo and Timmons 1994). Most recirculating systems raise fish in large "growout" tanks. Levels of dissolved oxygen sufficient to support fish are maintained with mechanical aerators or injection of pure oxygen. Carbon dioxide produced by fish and bacteria living in the water are often removed with a mechanical "packed column aerator." Depending on the requirements of the fish species being raised, heating and insulation may be necessary to maintain appropriate temperatures. Automated or demand feeding systems are often used to supply a stable and continuous feed supply. Pumps are used to recirculate water between the growout tanks and water-treatment devices.

Water from growout tanks may be treated in a number of ways to remove solids and dissolved nutrients. Solids (feces, feed, and bacteria) are removed using one or more of three general methods: sedimentation in settling systems, centrifugal systems, or mechanical filtration (see earlier section on waste-treatment methods). Very fine solids are removed through a process called foam fractionation, in which air bubbles are used to concentrate the solids. Alternatively, ozonation, which facilitates the aggregation and settling of particles, may be used (E. Hallerman, pers. comm.) Biofilters are used to remove dissolved nitrogen compounds — ammonia and nitrite. Biofilters are made of materials with large surface areas, such as sand, rocks, or glass balls, on which large numbers of nitrogen-consuming bacteria grow. Some systems also grow hydroponic crops or employ constructed wetlands to remove solids and dissolved nutrients.

Most recirculating systems have emergency electrical systems in case of power outage. Some systems also use computer monitoring systems, which continuously monitor critical water-quality parameters and alert operators to system problems (Tetzlaff 1991; Losordo et al. 1992).

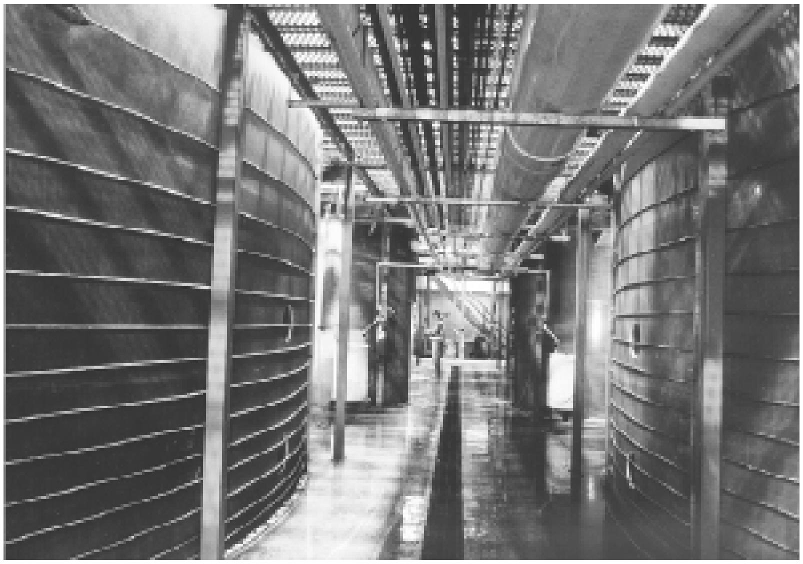
Recirculating Systems in Aquaculture: Comprehensive Source Reduction

One way to both reduce water use and reduce nutrient and biological pollution problems in aquaculture systems is to reuse the water in the systems, instead of discharging it after one period of use. Aquaculture systems that reuse water more than once before discharging it are called recirculating systems. Recirculating systems have a number of advantages over other commercial aquaculture systems (O'Rourke 1991). Their location is less limited by the availability of water, and because recirculating systems are often indoor systems, their location is less limited by climate, soils, and other site-related factors. Greater environmental control means that recirculating systems offer better control of contaminants, product quality, predators, and introductions of diseases and parasites. Waste-management problems are decreased because less water is used. Escapes of aquaculture organisms, as well as poaching and vandalism, are less frequent because facilities are better contained. In addition, aquaculturists can time production to market conditions rather than the seasons of the year.

Recirculating systems also have a number of disadvantages in comparison to other aquaculture systems. Because recirculating systems must treat and circulate large volumes of water, they typically require larger capital investments and have higher operating costs, including labor and energy costs, than other types of systems. Aquaculturists typically stock high densities of fish in order to make recirculating systems cost-effective, which increases costs for supplying supplemental oxygen and for addressing other water-quality problems. High densities of fish can also stress fish and, along with water recirculation, facilitate the rapid spread of any diseases introduced to recirculating systems.

Two difference types of aquaculture systems may be labeled recirculating systems, and their water use can differ dramatically (Van Gorder 1991). "Closed" recirculating systems are what many people commonly refer to as recirculating systems, and are the focus of this report. These systems treat their water. The percentage of recirculation in these systems typically describes the average percentage of total water volume that is reused on a daily basis. For example, a 50,000 gallon, 90% closed recirculation system would require only an additional 5,000 gallons of water each day (Van Gorder 1991). In contrast, "semi-closed" recirculating systems use water exchange, rather than water treatment, to control for water quality. The percentage of recirculation in these systems simply means the amount of water reused in a single pass through the system. Since these systems typically employ raceways or flow-through tanks, they may use large volumes of water, because raceways and tanks are refilled many times a day. For example, a flow-through system using 90% recirculation and 1,000 gallons per minute flow would still require an additional 100 gallons per minute, or 144,000 gallons per day, of new water (Van Gorder 1991).

Recirculating systems are often much more complex than other commercial aquaculture systems because water must be continuously treated and returned to the rearing structure. Recirculating systems must remove both particulate matter and dissolved nutrients from the effluent, while at the same time ensuring that sufficient oxygen levels are maintained to support high fish densities. See Box 4.1, Anatomy of a Recirculating System, and Figure 4.7 which diagrams such a system.



Recirculating system at AquaFuture. Courtesy of AquaFuture, Inc.

Many of the environmental problems associated with aquaculture, including excessive water use, nutrient pollution, pesticide use, escaped aquaculture organisms, and attacks by predators, can be reduced or even eliminated by recirculating systems. Nevertheless, recirculating systems can produce considerable quantities of concentrated, nutrient-rich sludge as a result of wastewater treatment. This sludge must be disposed of properly, using the same sludge-disposal methods as other aquaculture systems (discussed earlier in this chapter).

The Potential for Recirculating Systems in U.S. Aquaculture

To date, the high investment and production costs of recirculating systems have discouraged widespread adoption of recirculating technology. Although both individuals and large corporations have invested in commercial-scale recirculating systems, there are relatively few reported commercial successes (Losordo and Timmons 1994; Libey and Timmons 1996). Recirculating systems tend to be financially riskier than other systems. The investment costs for commercial-scale recirculating systems are approximately $4.00-8.00 per kilogram of annual production capacity, while those for commercial pond or raceway systems are closer to $2.20-3.30 per kilogram of annual production capacity (Losordo and Timmons 1994).

It is unlikely that closed recirculating systems will be used on a large scale until their profitability is similar to that of other aquaculture systems (Losordo and Timmons 1994). However, considerable work is being done toward this goal (Stickney 1994b). Expansion of the U.S. aquaculture industry currently is limited by the availability of land and water, and some aquaculture experts believe that the next great expansion of the U.S. industry will come with the development of more economical recirculating systems (Stickney 1994b).

For the moment, appropriate marketing strategies are key to the economic success of recirculating systems. "In the early years raising catfish in ponds was probably more expensive than dropping a hook and line in the river; however, the catfish raised in ponds were a different product. Fish raised in recirculating systems will similarly be a different product than wild caught or pond raised fish." (O'Rourke 1991). Aquaculturists using recirculating systems have the advantage of being able to produce an extremely fresh product throughout the year (Van Gorder 1991) and can site their facilities near densely populated areas that provide large markets. Moreover, fish raised in recirculating systems may be virtually free of pollutants that are present in wild-caught fish or fish raised in aquaculture systems that use untreated water (Van Gorder 1991). Currently producers using recirculating technology cannot easily compete in the same mass markets with producers using less-costly traditional aquaculture methods. However, there are a number of relatively small, sole-proprietor operations that "niche-market" fresh fish at relatively high prices to local or regional markets (Losordo et al. 1991; Losordo and Timmons 1994).

Figure 4.8. Some Commercial Recirculating Systems in the United States

Company	Product
AquaFuture, Inc., Turners Falls, MA	Hybrid striped bass
AquaMar, Pocomoke City, MD	Tilapia
Bioshelters, Amherst, MA	Tilapia, hydroponic basil, tomatoes
Eastern Fish Farms, Tiverton, RI	Hybrid striped bass, hydroponic vegetables
Freshwater Farms of Ohio, Urbana, OH	Trout and yellow perch
Inslee Fish Farm, Inc., Connerville, OK	Tilapia, channel catfish, grass carp, large mouth bass, hydroponic chives
Inter'l Food Technologies., Emmaus, PA	Hybrid striped bass, tilapia, steelhead, yellow perch, lettuce
S&S Aquafarm, West Plains, MO	Tilapia, variety of hydroponic herbs and vegetables

Producers using recirculating technology are likely to also have an advantage in certain other situations. Production of some fish may be acceptable only in recirculating systems, because these systems minimize the chances for escape of fish. For example, the one U.S. company now interested in commercializing genetically engineered fish says that it intends to grow its fish in recirculating systems (Datz 1997). If taxes or other penalties were placed on discharge of polluted effluent, or high charges placed on water use, recirculating systems would become more cost-effective in comparison to other production systems.

Commercial Recirculating Systems in the United States

Recirculating technology has been tried with almost every major fish species produced in the United States. In some cases, such as channel catfish production, recirculation methods have not proven to be cost-effective (Losordo et al. 1989). However, commercial recirculating systems currently in operation in the United States produce a range of other fish, including tilapia, yellow perch, rainbow trout, and steelhead (Fig. 4.8 shows producers who raise these species using recirculating technology). Two of these systems are discussed below, and several others are discussed in the section earlier in this chapter on polyculture and hydroponics.

Since 1991, Aquafuture, Inc., has raised hybrid striped bass, which are highly amenable to production in recirculating systems (Losordo et al. 1989), in a 45,000 square foot building in western Massachusetts. This closed facility grows fish in huge tanks with constant water flow. Bass reach market size in only nine months, about twice as fast as in traditional production systems. Aquafuture requires only 150 gallons of water to produce each pound of hybrid striped bass (or 1,250 m^3/mt for comparison with Fig. 2.7). Effluent is treated before discharge, and is clean enough to exceed many drinking-water standards. Sludge is used to fertilize farm fields. Aquafuture processes hybrid striped bass on-site and markets fish to restaurants and other institutions in the northeastern United States. Aquafuture has begun a federally funded project to grow summer flounder in smaller versions of its bass facility, and is helping to train underemployed fishermen in coastal New England to operate these facilities (Herring 1994; J. Goldman, pers. comm.).

Integrated Food Technologies (IFT), located in Emmaus, Pennsylvania, raises a total of 500,000 pounds annually of hybrid striped bass, tilapia, steelhead, and yellow perch in tanks in a 60,000 square foot former factory. IFT operates a closed system that recirculates 98% of its water. IFT's effluent is treated by several methods. A portion goes to a municipal sewage-treatment center. IFT also has its own wastewater treatment system that uses a "sequencing bath reactor," a sewage-treatment technique that combines aerobic and anaerobic treatment in one chamber. The slurry from this reactor is then treated by 6,000 square feet of reed beds. Some wastewater is used in hydroponic crops, such as lettuce. IFT is a vertically integrated compay that includes an on-site hatchery, nursery, live food room, and processing facility (S. Van Gorder, pers. comm.).

Even for species such as catfish, for which high-tech recirculating technology appears not to be currently economically feasible in the United States, low-tech water recirculation could reduce water usage and nutrient loads in effluent. Boyd and Tucker (1995) propose such a system for catfish ponds. Most catfish ponds are drained for maintenance approximately once every 3 to10 years (Boyd and Tucker 1995). When draining occurs, the first 80% of the pond water should be transferred to an adjacent pond where it can be held for later reuse. The last 20% of the pond water, which contains most of the nutrient pollution, is then kept in the pond for approximately two days to allow pond organisms to break down solids and assimilate nutrients (Seok et al. 1995). If the entire pond must be drained immediately, the last 20 % of water can instead be transferred to a settling pond (Boyd and Tucker 1995). Economic analysis based on average costs for a hypothetical catfish farm in western Alabama shows that a tax of at least $10 per milligram per liter of biological oxygen demand would be required to encourage most producers to adopt such management practices (Cerezo and Clonts 1994).

Conclusion

Aquaculture need not be a polluting industry. Careful siting of aquaculture operations can help minimize environmental impacts. A wide variety of technologies and practices are available to make aquaculture facilities environmentally friendly, and many of these are now used on commercial fish farms. These technologies and practices must be more widely adopted if aquaculture is to be widely accepted as a clean and thus desirable industry.

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Chapter Four Notes

[1] 42 U.S.C. Sec. 13101-13109

A Salmon in Every Pot: Aquaculture for Economic Development

Introduction

In the past, environmental goals have often been portrayed as being in direct opposition to economic goals. Efforts to conserve forests in the Pacific Northwest, for example, have been condemned by members of the forest industry as taking jobs away from loggers who have few alternatives for employment.

Such polarized thinking has begun to change, with many opinion leaders now arguing that environmental protection and economic development go hand in hand if industries are developed in an environmentally and economically "sustainable" manner (for example, Porter and van der Linde 1995; Goodland and Daly 1996; Hart 1997; Magretta 1997). In other words, sustainable development must meet human needs not only for the present but for future generations. Development not only must be economically viable, but also must conserve natural resources, not degrade the environment, and be socially acceptable (FAO 1988).

If our society is to have the "win-win" goal of developing sustainable industries that are good for our economy and do not harm the environment, consideration of socioeconomic goals must be married with consideration of environmental ones. Under our existing laws, federal, state, and local governments generally regulate the environmental, but not socioeconomic, effects of various industries, including aquaculture. However, government should evaluate the socioeconomic consequences of aquaculture development when taxpayer funds are used to support it.

In recent years, federal and state governments have advanced aquaculture as a promising solution to the socioeconomic problems of some communities, particularly in rural and coastal areas. However, promises of social and economic benefits sometimes appear to be based as much on optimism as on careful appraisal of the record of aquaculture development. With this in mind, this chapter provides an overview and discussion of selected experiences with aquaculture development in the United States. These experiences are a guide to the range of outcomes that can be expected from investment in various aquaculture sectors.

Aquaculture to Assist Economically Depressed Communities

Rural and coastal communities in some parts of the United States face serious economic problems. For the past two decades, many rural communities have experienced declines in farm incomes and in mining and manufacturing jobs (USDA 1996a). In particular, small family farms have declined as farm mechanization and other factors have led U.S. agriculture to shift toward fewer, larger farms (USDA 1996a). As a result, poverty and unemployment rates in rural areas now exceed the national average, and many of these areas are losing population (USDA 1996a).

At the same time, declines in wild fisheries have led to severe restrictions on many segments of the U.S. commercial fishing industry. The situation is particularly severe in New England, where the

Catfish ponds. Courtesy of the Catfish Farmers of America.

number of fishing days has been sharply reduced on large fishing grounds off the coasts of Maine and eastern Cape Cod (Canfield 1997). Harvests of traditional stocks of groundfish, such as cod, haddock, and flounder, have been reduced by 35% over the last few years, and even greater restrictions may be implemented in the future (Canfield 1997). Dramatic increases in landings of previously ignored or less utilized species, such as squid, sea urchins, and dogfish, have for the most part prevented declines in the total weight and value of landings of finfish and shellfish in the entire Northeast region (NMFS 1996; Associated Press, 1997). Nevertheless, depleted stocks and harvest restrictions are creating economic troubles for many New England communities that are dependent on commercial fishing. Between 1986 and 1989, before the worst decline, an estimated $349 million in gross income and 14,300 jobs were lost annually due to reduced landings resulting from stock depletion (Massachusetts Offshore Groundfish Taskforce 1990). The New England seafood-processing sector alone reduced jobs by 37 % from a high of 7,470 in 1984 to 4,743 in 1993 (NMFS 1996).

Aquaculture offers opportunities to provide income and jobs in economically depressed rural and coastal areas in the United States. For example, the number of catfish farms in the principal catfish-producing states (Mississippi, Alabama, Arkansas, and Louisiana) increased 67 %, from 794 to 1,193, between 1982 and 1992 (USFWS 1997). In western Alabama, some small family farmers now farm catfish and other fish species as an income-diversification strategy (Skladany and Bailey 1994). Catfish production helps these individuals maintain their farms but provides few new on-farm jobs. In contrast, the catfish industry in the Mississippi Delta region, which includes some of the poorest regions of the United States, has generated a large number of jobs with large production facilities. According to industry statistics, catfish farms directly employ about 12,000 people in Mississippi, Alabama, Arkansas, and Louisiana (Catfish Institute 1996).

Further growth of the $162 million aquaculture industry in the northeastern United States (Spatz et al. 1996) is advocated as a way to supplement and replace jobs lost in the commercial fishing industry. In 1995 the U.S. Congress appropriated $30 million for the Northeast Fisheries Assistance Program, an emergency aid package used in part to encourage aquaculture development (NMFS 1996). The state of Massachusetts in 1995 published an aquaculture strategic plan (Massachusetts Coastal Zone Management 1995) and in 1996 hired an aquaculture coordinator to promote expansion of the industry, in part with the goal of creating employment opportunities for displaced fishermen. Most other New England states have also established aquaculture training programs (Goldsmith 1996).

Aquaculture development in economically depressed urban areas is also possible, although it has received far less attention than aquaculture development in rural and coastal communities. Relatively high labor and land costs potentially limit aquaculture in urban areas. Nevertheless, intensive farming techniques make aquaculture production feasible in abandoned factories or other low-priced properties. For example, Integrated Food Technologies grows tilapia, trout, and other fish in a huge recirculating system located in an old factory near Allentown, Pennsylvania (S. Van Gorder, pers. comm.). Connecticut Aquaculture, Inc., plans to raise tilapia in a recirculating system located in an old mill in Willimantic, Connecticut (Datz 1997). The mill's solid construction, designed to hold heavy looms, makes it able to support the considerable weight of large fish tanks (R. Fahs, pers. comm.). (See Box 5.1 for more information on recirculating systems and economic development.)

Aquaculture operations in urban areas have the advantage of being near large markets, including lucrative markets for live fish in many Asian-American communities. Proximity to markets means that urban operations tend to have low transportation costs, high product freshness, and the option to get products to market without paying middlemen (R. Eager, pers. comm.). An aquaculture operation in the heart of Atlantic City, New Jersey, for example, produces shrimp for casinos during the summer in outdoor tanks (J. McQueen, pers. comm.). The director of the Atlantic City Special Improvement District, an economic development program, runs this program to provide summer employment for about 20 people.

Structure and Socioeconomic Impacts of the U.S. Aquaculture Industry

The U.S. aquaculture industry is extremely variable in structure. Some sectors, particularly catfish farming in Mississippi and trout farming in Idaho, are quite mature. Production in these sectors is dominated by large, vertically integrated companies that benefit from economies of scale and generate large revenues and large numbers of jobs. The somewhat younger salmon farming industries in Maine and Washington State are also consolidating into a handful of large companies.

Other sectors, such as crawfish farming in Louisiana, catfish farming in western Alabama, and trout farming in Appalachia consist of small-scale produc-

Box 5.1: Recirculating Systems for Economic Development

Relatively few recirculating systems are now used to grow fish commercially in the United States, largely because of their high start-up and operating costs (see discussion of recirculating systems, including their many environmental advantages, in Chapter 4). Producers using recirculating systems often cover their expenses by selling extremely fresh or, in some cases, live fish at relatively high prices to niche markets, such as upscale restaurants. Producers may also process their products on-site, adding value to them.

Recirculating systems are a focus of at least one economic development project. In New England, Josh Goldman of AquaFuture, Inc., is working to transfer recirculating technology to commercial fishermen facing declining harvests of wild fish. With funding from a National Marine Fisheries Service (NMFS) Northeast Fishing Industry Grant, AquaFuture is constructing two demonstration growout facilities in Rhode Island and Massachusetts. These facilities are designed as prototypes for owner-operated farms, and they will be operated by commercial fishermen. Each facility will produce about 125,000 pounds per year of summer flounder, a prized flatfish with strict catch quotas in the Northeast. Flounder will be raised using a scaled-down version of the recirculating system technology that AquaFuture now uses to raise hybrid striped bass (J. Goldman, pers. comm.).

ers, many of whom have integrated aquaculture into terrestrial farms. In these sectors, relatively small numbers of new jobs and small amounts of new revenues are generated in comparison to more industrial aquaculture sectors. Nevertheless, income from aquaculture can allow small farmers to hold onto their farms and as a result contributes to the survival of struggling rural communities.

Shellfish farming ranges from large agribusinesses that produce oysters in Connecticut to part-time self-employment for commercial fishermen who produce hard clams on Cape Cod, Massachussetts. As with small-scale crawfish producers, small-scale shellfish producers create relatively few new jobs and generate small revenues. Nevertheless, small-scale shellfish aquaculture provides viable livelihoods for individual entrepreneurs.

A Closer Look at Selected Sectors of the U.S. Aquaculture Industry

Catfish Farming in the Deep South

Catfish farming in the Mississippi Delta has the largest economic impact of any sector of the U.S. aquaculture industry. Many former terrestrial farmers have now stopped growing cotton and other crops and have converted their farmland to catfish ponds; catfish farming is one of the most profitable enterprises for Delta farmers (Perez et al. 1996; Arkansas Aquaculture Plan 1991). In parts of rural Mississippi and Arkansas catfish farming is the base of the local economy and responsible for the majority of jobs (Drinkwater 1994). Catfish production and processing in Mississippi generates an estimated $1.7 billion in total industry output and $1 billion in total income, and accounts for nearly 75,000 jobs (6.3% of the state total) (Dicks 1996).

Filleting catfish at a processing plant. Courtesy of Louisiana Cooperative Extension Service.

Despite this impressive overall economic contribution, poor wages and working conditions have been an issue for at least some of the jobs fostered by the catfish industry. In 1990 and 1991, the primarily African-American workers at one major catfish processor in Mississippi engaged in a bitter, racially charged strike over low wages and poor treatment by white owners and managers (Campbell 1990; Dine 1990; Kilborn 1990). The Federal Occupational Safety and Health Administration fined the company, Delta Pride Processors, Inc., and compelled it to adopt measures to prevent worker injuries, such as carpal tunnel syndrome, from repetitive motions (OSHA 1991). Working conditions and compensation at Delta Pride and other unionized catfish processors have since generally improved so that they are approaching conditions and wages at meat- and poultry-processing plants (J. Fiedler, pers. comm.).

Mississippi dominates U.S. catfish production, making up about 70% of U.S. output (USDA 1996b). Alabama and Arkansas follow distantly with 13% and 10%, respectively (USDA 1996b). The industry in Mississippi differs from those of Alabama and Arkansas in structure, just as it does in output.

Catfish farming in Mississippi is a mature industry, with large, industrial farms run by specialized producers (Skladany and Bailey 1994). In 1996 average farm size in Mississippi was almost 300 acres, compared with 120 and 78 acres in Arkansas and Alabama, respectively (USDA 1996b). In Alabama and other areas outside of Mississippi, the catfish industry has a very different structure. Catfish production is often used as a farm diversification strategy and is integrated into terrestrial farms producing row crops, livestock, and timber (Perez et al. 1996; Skladany and Bailey 1994; K. Veverica, pers. comm.). In western Alabama, for example, there are now about 600 catfish farms (M. Masser, pers. comm.). Catfish production provides better incomes for members of farm families and other farm workers (Perez et al. 1996) but not a large number of new on-farm jobs. Approximately 1,900 new off-farm jobs have been created, primarily in supplying farm inputs and in catfish processing (M. Masser, pers. comm.). However, in Alabama there are signs that the industry is restructuring. Larger farmers are making catfish farming their main enterprise, and smaller producers are dropping out of the industry. There are few new entrants into the industry (M. Masser, pers. comm.).

Trout Farming in Idaho

As with the Mississippi catfish industry, the Idaho trout industry is a mature industry, producing almost 70% of U.S. farmed trout (ID DEQ 1996). Idaho trout farms create $70 million in economic activity and 1,000 jobs in Idaho (ID DEQ 1996). Most of these economic benefits are not directly from farm production, but rather from trout processing, feed mills, equipment production, and other activities. The economic multiplier for trout production is a factor of about 3 to 4 (ID DEQ 1996; Gary Fornshell, pers. comm.). Figure 5.1 shows jobs and economic activity produced by Idaho aquaculture.

The majority of Idaho's trout production comes from a few very large companies, each producing millions of pounds of trout annually (Brannnon and Klontz 1989; Wray 1997a; M. McMasters, pers. comm.). For example, Idaho boasts the world's largest trout farm, Clear Springs Foods, which produces 21 million pounds of trout per year (about 40% of total U.S. trout production) and employs about 400 people (Wray 1997a). Clear Springs is a completely vertically integrated company: Besides growing trout, Clear Springs has its own hatchery, manufactures feed, processes trout, and ships its finished products (Wray 1997a).

Figure 5.1. Economic Significance of Commercial Aquaculture* in the Eastern Snake Plain, ID in 1994

	Output ($ millions)	Earning ($ millions)	Employment (number of jobs)
Direct Effect	43.88	8.34	N/A
Indirect Effect	56.12	19.81	N/A
Total Effect	100.00	28.15	1,136

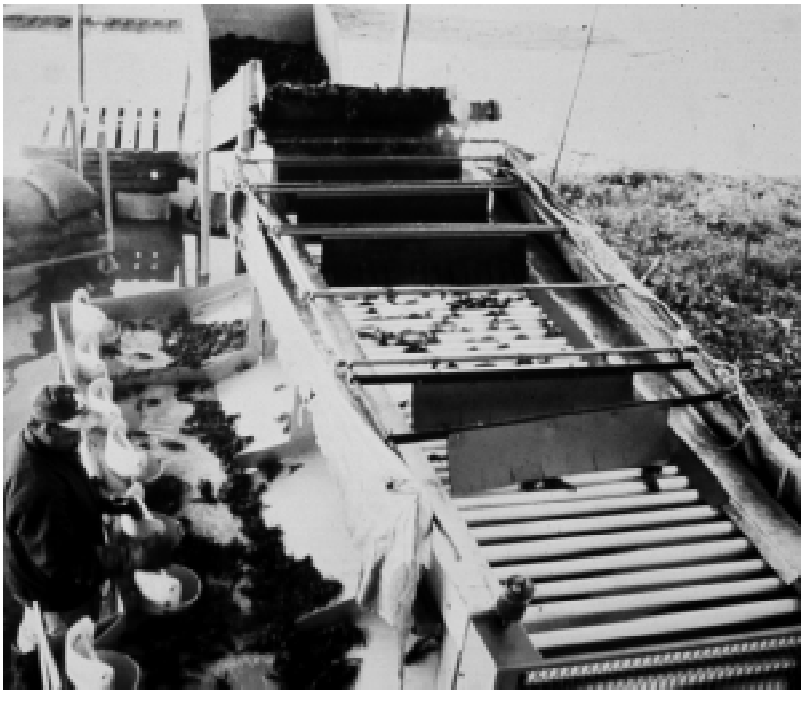
* Includes both fish production and processing; trout production and processing makes up most of the total production.
Source: Idaho Aquaculture Assn., in Idaho Water Resource Board 1997.

Idaho trout farming began as a sideline for terrestrial farmers. As the profitability of trout farming increased, many farmers made it their main activity (P. Mamer, pers. comm.). Continued expansion of trout farms now largely depends on improved production efficiency, because water for farms is increasingly limited (Jenkins et al. 1995). This circumstance has tended to favor large producers that benefit from economies of scale and limited entry of new producers (Jenkins et al. 1995). Nevertheless, there still are a large number of small trout farms in Idaho (M. McMasters, pers. comm.). A number of these smaller farms also produce beans, potatoes, and beef (P. Mamer, pers. comm.).

Salmon Farming in Maine and Washington

U.S. salmon farming is centered in Maine's Cobscook Bay and Washington State's Puget Sound. In both states, the salmon farming industry is dominated by large companies. Their economies of scale and vertical integration help them to compete with sources of wild-caught and farmed salmon. Together the Maine and Washington industries directly create 750 full-time jobs. Another 2,000 jobs are created indirectly (J. McGonigle, pers. comm.). Salmon farming in Maine provides jobs in communities economically devastated by the collapse of the area's herring fishery in the 1970's and 1980's (J. McGonigle, pers. comm.).

Top: Crawfish ponds. Bottom: Crawfish grading. Courtesy of the Louisiana Cooperative Extension Service.



Washington County, where most Maine salmon farms are located, is the poorest county east of the Mississippi, with unemployment rates ranging from 12% to 20%.

The U.S. salmon industry has consolidated as global competition has increased and prices for farmed salmon have plummeted. Over the past 10-15 years, the Washington State industry has consolidated from 10-12 companies to only two (Wray 1997b; P. Granger, pers. comm). One of these companies, Global Aquaculture USA, is much larger than the other, producing close to 80% of the farmed salmon in Washington (Wray 1997b). The Maine salmon industry has consolidated from a number of independently owned start-up firms in the early 1980's to a few multimillion-dollar, vertically intergrated companies (Conkling 1996), in large part owned by firms based in Norway and Canada (Bush and Anderson 1993). Leases for farm sites in Maine are now limited to 150 acres; however, some aquaculture advocates are pushing to amend state law to allow larger leases for farm sites (Conkling 1996; King 1997). For more information on salmon farming on the East Coast, see the Maine and New Brunswick case studies.

Crawfish Farming in Louisiana

Unlike other long-established sectors of the U.S. aquaculture industry, crawfish farming in Louisiana has remained a small-scale, part-time enterprise that is integrated with terrestrial farming in rural areas. More than 1,600 Louisiana farmers produce 18-27 million kilograms of farmed crawfish each year, which accounts for 90% of U.S. farmed crawfish production (Avery and Landreneau 1996). Farmed crawfish generally makes up 60% of Louisiana's total crawfish production. The wild and farmed crawfish industries together add more than $120 million to Louisiana's economy and directly and indirectly provide jobs for more than

7,000 people (Avery and Landreneau 1996).

Crawfish farming is easily integrated with other farm practices because it uses marginal agricultural lands, on-farm labor, and farm equipment outside of the peak farming periods (Avery and Landreneau 1996). Crawfish ponds are shallow and generally 25-40 acres in size. Many farmers rotate crawfish production with rice paddies and sometimes with soybean crops (De la Bretonne and Romaire 1990; Avery and Landreneau 1996).

Imports of inexpensive Chinese crawfish meat have skyrocketed in recent years, from 160,492 kilograms in 1992 to 2,537,137 kilograms in 1996 (Louisiana Cooperative Extension Service 1996). In March 1997, the U.S. International Trade Commission (ITC) issued a preliminary ruling that Chinese meat is being "dumped" at unfairly low cost on the U.S. market, and the ITC may impose a tariff on Chinese imports (Huner 1997). The future of the U.S. crawfish industry will depend in large part on the volumes of Chinese crawfish products imported to the United States (Huner 1997; St. George 1997).

Trout and Other Freshwater Fish Farming in Appalachia

The number of small-scale and often integrated freshwater fish farms is growing in the rural areas of Appalachia. Aquaculture in Appalachia began as a means to supplement wild stocks of gamefish. Consolidation in terrestrial agriculture has hurt many small family farms and has led farmers to search for alternative production systems. As a result, many farmers have become interested in raising fish for food (Dicks 1991; Jenkins et al. 1995; A. Spicer, pers. comm.). There are now more than 500 trout farms in Appalachia, and a small but growing number of catfish ponds (Dicks 1991).

Barrel trap for crawfish. Courtesy of Louisiana Cooperative Extension Service.

Researchers at West Virginia's Freshwater Institute work to support development of fish farming in Appalachia, believing that it can contribute to the sustainability of rural areas through efficient use of water and land and by providing an alternative source of income for farmers (Jenkins et al. 1995). The resources of small, terrestrial family farms are now available to be "recycled" for aquaculture (Jenkins et al. 1996). For example, underused farm labor, structures, and equipment from hog, poultry, and dairy farming can all be used in aquaculture (Jenkins et al. 1996). Aquaculture can easily be integrated with the traditional farm activities of Appalachia, such as grain and hay production, because the labor requirements for aquaculture are similar to those of terrestrial animal production by Appalachian farmers (Jenkins et al. 1996). Other regional resources, such as natural gas left over from West Virginia's gas wells, are also available to be recycled into aquaculture production. Box 5.2 describes a recirculating aquaculture system that runs on natural gas from shut-in wells.

The integration of aquaculture with terrestrial agriculture is well illustrated by one West Virginia farmer, who annually produces annually 10,000 pounds of rainbow trout using farm labor and a building once used for dairy and hog production. The farmer uses the dilute nutrient effluent from the trout raceways to water and fertilize a nearby pasture, which allows year-round growth of pasture grass, including high-quality forage for cattle during the winter. The farmer uses solids collected from the raceways as a soil amendment in hay fields. The farmer also processes the trout on his farm to add value to his product (Jenkins et al. 1996).

Box 5.2: Low-cost Energy for Aquaculture

Throughout West Virginia and Appalachia there are thousands of shut-in natural gas wells that no longer have sufficient pressure to be useful to the natural gas industry but are useful to fish farmers. The use of these wells facilitates cost-effective production of tilapia and hydroponic vegetables in recirculating systems in greenhouses — systems that would be prohibitively expensive with traditional power sources. In Tallmansville, West Virginia, one aquaculture-hydroponics system uses natural gas to run a boiler and to generate electricity for water pumps, fans, and lighting. This system annually produces 900 pounds of tilapia and more than 36,000 pounds of specialty lettuce and herbs. Development of the system has allowed the farmer to convert two seasonal jobs into full-time jobs. This system cost $40,000 to start up and has a net annual profit of about $20,000 (M. Jenkins, pers. comm.).

Rainbow trout. Courtesy of National Aquaculture Association.

Mollusk Farming on the East and West Coasts

U.S. mollusk farming is a diverse industry involving large and small producers along the East, West, and Gulf Coasts. Mollusk farming in coastal areas presents more opportunities for small businesses than does finfish farming (R. Rheault, pers. comm.), and mollusk production potentially can help coastal

Box 5.3. Commercial Fishermen Become Shellfish Farmers

Running an aquaculture operation, like any type of agricultural venture, is not an easy job. Fish farming not only requires large amounts of time and energy; it also requires producers to have a wide variety of knowledge and skills. Terrestrial farmers may readily become fish farmers because their existing husbandry and management skills are similar to those required for success in aquaculture. Commercial fishermen, on the other hand, are essentially hunter-gatherers and have very different skills from farmers (aside from their shared capacity for hard work). Fishermen may thus find becoming successful fish farmers a considerable challenge (Manci 1996). Shellfish farming may be an exception to this generalization, since shellfish farms tend to require less intensive husbandry than finfish farms. Fishermen who receive appropriate training may readily become shellfish farmers (R. Rheault, pers. comm.)

Underemployed and unemployed fishermen have become successful shellfish farmers in some areas of the Northeast and on the west coast of Florida. Most producers in the $4 million per year Cape Cod shellfish-farming industry are former full-time fishermen who started farming small shellfish leases as a sideline. After making sizable profits, these individuals gradually made aquaculture a larger focus. Today many individuals continue to combine fishing and shellfish farming (mostly of hard clams), farming a total of 200 three-acre leases. Many others are interested in entering the industry. During one recent year (1995-1996), 75 applications for shellfish leases were submitted and an additional 35 were under review (Aquaculture Association Newsletter 1996).

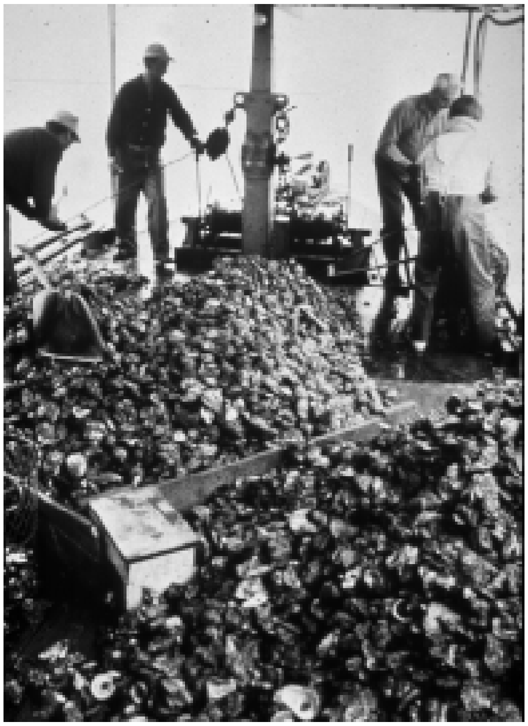
The Harbor Branch Oceanographic Institute, with funding from the Federal Job Training Partnership Act, has been retraining oyster harvesters, displaced fishermen, and others in oyster and clam culture, creating a rapidly growing hard clam industry in Florida. Many communities on Florida's west coast are facing economic problems as a result of a 1995 state-wide ban on gill-net fishing and depletion of wild fisheries. Over 200 displaced fishermen have been retrained as clam farmers, and they farm more than 700 acres of state-owned land in Dixie and Levy Counties. In 1995 this industry produced more than $5 million worth of clams, a four-fold increase compared to 1991 (Sturmer et al. 1997).

communities survive declining economic conditions (Skladany and Bailey 1994). Some former fishermen are now successfully employed in mollusk aquaculture (see Box 5.3).

There are several reasons why mollusk aquaculture is an easier business to enter than finfish farming in coastal areas. Mollusk production has fewer start-up costs than finfish production (R. Rheault, pers. comm.). Growing mollusks requires less intensive management and technical skill than many forms of fish farming, allowing relatively inexperienced producers to be successful. In addition, mollusk production generally faces less restrictive regulations than many forms of fish farming, at least in part because mollusks reduce rather than increase nutrient levels in marine waters (see Box 2.1 in Chapter 2). Nevertheless, the establishment of some new mollusk farms in the United States and Canada has faced opposition from fishermen and other individuals who view shellfish leases as conflicting with their interests (Dwire 1996; Weeks and Sturmer 1996).

Oyster farming in Connecticut and Washington State demonstrates the economic importance of mollusk aquaculture to some regions. Washington oyster growers range from growers producing a few hundred pounds annually to others producing millions of pounds, with most producing close to 100,000 pounds (D. Cheney, pers. comm.). One-half to one-third of Washington's production comes from Willapa Bay, where shellfish have been farmed for 150 years. There are only a few other industries in this area, and oyster farming is extremely important to its economic health.

Connecticut's oyster industry directly employs approximately 450 people and is worth almost $50 million — nearly 30% of the Northeast's total aquaculture production as measured by value (Spatz et al. 1996). Connecticut's oyster-farming industry reached its peak nearly 100 years ago, but declined in the 1930's largely due to water pollution. Assistance by the state, including the provision of oyster shells that are spread on the sea bottom for oyster larvae to settle on, has helped the industry to grow immensely in the last decade (Spatz et al. 1996). Connecticut's harvest of 750,000 bushels is second only to Louisiana's (Hosley 1997). The industry now consists of 25 firms situated on Long Island Sound, which together grow oysters on about 50,000 acres of leased bay bottom (J. Volk, pers. comm.).



Left: An oyster boat. Below: An oyster dredge. Courtesy of the Louisiana Cooperative Extension Service.

As in Washington, the size of these companies varies tremendously. Tallmadge Brothers Oyster Farm, founded in 1875, is the largest oyster producer in the Northeast. It leases 20,000 acres, employs 75 people (mostly family members), and owns 22 boats and 12 other oyster companies (P. Conkling, pers. comm.). Other producers are quite small, using one boat and as little as 20 acres of leases (J. Volk, pers. comm.). Like other northeastern states, Connecticut has established training programs, including vocational training programs at the high school and college levels, to encourage entry into shellfish farming (Goldsmith 1996). The oyster industry employs as part-time, oyster "seed" collectors a number of individuals who lost jobs in recent years at Connecticut defense plants (J. Volk, pers. comm.).

Being Realistic About Aquaculture and Economic Development

The U.S. aquaculture industry clearly provides economic benefits in a number of regions of the country. The most comprehensive — but still limited — study of the economic benefits from the U.S. aquaculture industry found that $5.6 billion of the U.S. gross domestic product (GDP) and 181,000 full-time equivalent jobs are linked to aquaculture production (Dicks 1996). Aquaculture production itself does not produce most of the economic benefits. The majority of jobs (65%) and economic activity (69%) do not come directly from fish farming, but rather from postharvest processing and other economic activities (Dicks 1996). These figures almost certainly underestimate economic activity linked to aquaculture, because this study is based on 1992 statistics and is limited to the five major sectors of aquaculture production: baitfish, catfish, crawfish, ornamental fish, and trout production.

In the context of the entire U.S. economy, however, aquaculture is responsible for only a tiny fraction of economic activity. In only two states does aquaculture make a significant contribution to state GDP: 2.5% of GDP and 6.3% of total employment in Mississippi, and 0.9% of GDP and 2.3% of total employment in Idaho (Dicks 1995). Nevertheless, even relatively small sectors of the aquaculture industry can provide important economic benefits to the communities and regions where they exist. As discussed above, catfish farming in western Alabama and trout farming in Appalachia enables some small farmers to keep their farms; salmon farming in northeastern Maine provides jobs in an area with high unemployment; and clam farming in western Florida and on Cape Cod provides income to unemployed or underemployed fishermen.

Despite the fact that aquaculture helps sustain some rural and coastal communities, aquaculture is not a cure to the problems facing them. Skladany and Bailey conclude from their 1994 assessment of aquaculture's role in community development in the United States that "Aquacultural development is not . . . a universal panacea for rural economic problems or declining coastal and marine resources. Aquacultural development is best understood as part of the solution to

Feed silos on a catfish farm. Courtesy of Louisiana Cooperative Extension Service.

these problems; in some areas the contribution of aquaculture will be small or non-existent, while in others it will be more significant (Skladany and Bailey 1994).

Efforts to promote aquaculture to achieve economic and social goals need to be tempered by realistic appraisals of what can be achieved. There are numerous obstacles to making an aquaculture enterprise successful. As discussed above, aquaculture is sometimes promoted as an industry that offers self-employment for displaced fishermen and others. However, some aquaculture sectors are dominated by large businesses, and small farmers may find it difficult to succeed. In addition, aquaculture is a difficult, risky field that can require considerable capital investment and training.

Aquaculture as Industrial Farming

Aquaculture is sometimes promoted for both economic and social ends — for example, to help revitalize fishing communities by providing displaced commercial fishermen new forms of self-employment. Nevertheless, aquaculture in the United States is often not a small-scale business. The sectors of the industry with the largest economic impacts are large-scale industrial enterprises — for example, catfish farming in Mississippi, salmon farming in Maine and Washington, and most trout farming in Idaho.

The development of mature sectors of the aquaculture industry mirrors changes that have occurred in terrestrial agriculture: steady declines in the number of producers, increases in the size of producers, and eventual domination by a limited number of large producers (OTA 1986). Some sectors of the aquaculture industry have evolved from small producers to very large, vertically integrated producers, akin to the evolution from small-scale to large-scale farms in the hog and poultry industries.

Some individuals argue that such large-scale aquaculture (and agriculture) has undesirable effects on the social structure of affected communities, and has less economic benefit than smaller, owner-operated farms. Skladany and Bailey (1994) note that aquaculture development can be successful in terms of economic development, but at the same time unsuccessful in terms of "community development." This phenomenon can occur if the benefits of aquaculture development are not broadly distributed to a community, but instead accrue mostly to a small number of investors who may reside elsewhere (Skladany and Bailey 1994; Bailey 1997). Producers who are part of a community may tend to hire local labor, purchase supplies locally, obtain financing inputs locally, or process fish locally – and thus have very large local economic impacts. In contrast, aquaculture operations run by outside corporations or outside investors may have less impact, because they may tend to obtain labor, financing, supplies, and processing services from outside sources. They may also be less committed to communities, and thus be less likely to protect local resources and to support public ventures, such as school bonds (Skladany and Bailey 1994; Bailey 1997).

Maine residents, for example, debate whether large-scale salmon farms will provide as much benefit to communities as small-scale farms (Working Waterfront 1996). Opponents of large farms point to the success of the Maine lobster fishing industry, which consists of many small, independent operators, dealers, cooperatives, and suppliers. The lobster industry provides modest incomes for most participants, but it has created large numbers of jobs locally that help to sustain families and communities (Working Waterfront 1996).

Other individuals believe that the evolution of large-scale aquaculture is

Figure 5.2. Examples of Losses Incurred from Disease in U.S. Aquaculture

Industry	Year	Losses ($ Millions)	% Value of Overall Industry
Trout	1988	2.5	4.3%
Catfish	1989	23	9.4%
Shrimp (Texas)	1995 *	11	N/A

Source: Meyer 1991; Meyer 1994; Verhovek 1995; NMFS 1996.
* One viral epidemic

Above: Channel catfish with external symptoms of viral infection. Below: Dead catfish. Courtesy of Louisiana Cooperative Extension Service.

inevitable. Frank Gjerset, president of Atlantic Salmon of Maine, the largest salmon farm on the U.S. Atlantic coast, argues that the size of Maine farms must increase if the industry is to compete globally with other salmon farms, which benefit from economies of scale and vertical integration (Conkling 1996). Moreover, only large companies tend to have sufficient funds to conduct the research and development that are necessary to advance technological development (Jensen 1991). In the Idaho trout industry, efforts of large producers to develop production technology and to aggressively market their products have largely been responsible for the industry's success (Brannon and Klontz 1989).

Small-scale fish farms will continue to exist, despite the trend toward large-scale production in some U.S. aquaculture sectors. Small-scale enterprises serve market niches, such as local markets for live fish and restaurants demanding extremely fresh, specialty products (Skladany and Bailey 1994; R. Eager, pers. comm.). Small farms often receive a price premium of $0.50 to $1.00 per pound for such niche products (R. Eager, pers. comm). On-site fish processing can help small aquaculture enterprises compete with the larger producers by allowing them to sell their products at higher prices (Skladany and Bailey 1994). Some small-scale producers form processing and marketing cooperatives, which provide strength in numbers while allowing small-scale producers to largely preserve their independence (Gempesaw et al. 1995). Finally, in some cases small production units may be more successful than larger farms, particularly if close attention is necessary to detect potential problems that quickly arise in aquaculture systems stocked with high densities of fish (Beem 1991).

Production Risks and Financing Difficulties

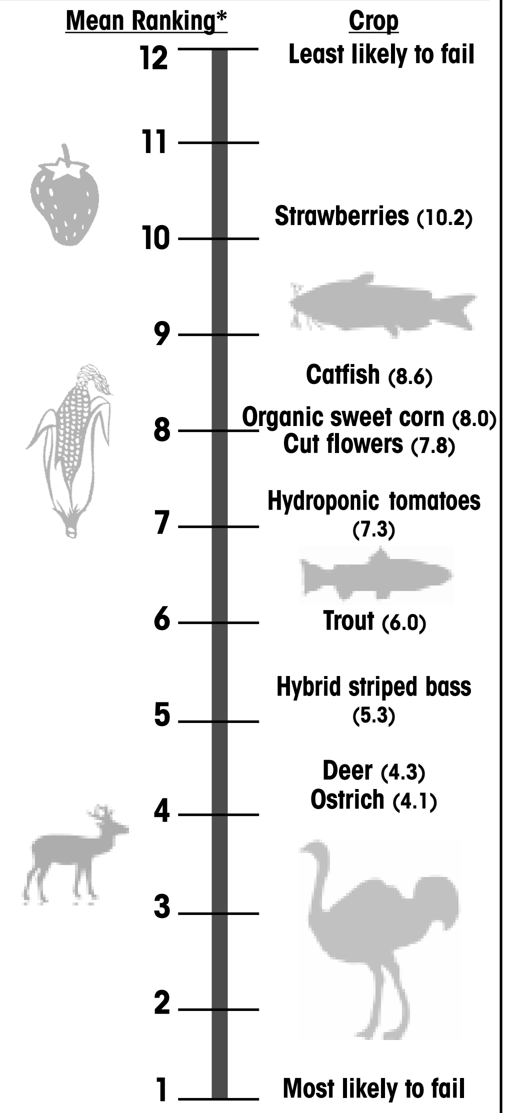
Succeeding in aquaculture can be difficult. Raising animals is generally a risky business. Aquaculturists, especially those operating systems with high stocking densities, face risks from diseases and changes in temperature and water quality. Such problems can wipe out all or most of a crop, leaving an aquaculturist with little or no income. Losses to disease particularly plague the aquaculture industry. As an extreme example, outbreaks of the Taura syndrome virus on Texas and South Carolina shrimp farms in 1995 led to the loss of more than 95% of crops of Pacific white shrimp (Joint Subcommittee on Aquaculture Shrimp Virus Working Group 1997). Figure 5.2 shows examples of losses from disease in U.S. aquaculture. Moreover, because aquaculture is a relatively new industry in the United States, there has been much less research to assist growers than in other types of animal production. There are huge gaps in knowledge about the nutrition and environmental requirements, disease agents, and even basic biology of many aquaculture species. As a result, when problems arise on a fish farm, there may be little scientifically based information on which to base solutions.

Aquaculturists also face risks from markets and must be able to navigate government regulations. Increases in production of wild or farmed fish in the United States or abroad can lead to price drops that can bankrupt producers. For example, price drops have plagued the salmon farming industry (see the New Brunswick case study). Many aquaculture operations require government approvals, for example, for use of bay bottoms to grow shellfish or to discharge water from raceways. Failure to obtain necessary approvals, including support of the community where a farm is proposed, can halt a proposed aquaculture operation (e.g. Phyne 1996; Weeks and Sturmer 1996).

Many large aquaculture operations have experienced serious problems, ranging from insufficient water resources to unprofitable growing systems, that have led to huge monetary losses and sometimes closure of facilities. “Unfortunately, far too many ‘aquaprenuers’ have gone after this multibillion dollar ‘Moby Dick’ in a rowboat: unprepared, under-financed and utterly doomed to failure” (Lee 1992). For example, during a six-month period in 1990 (see Lee 1992):

- J.R. Simplot Co. closed a two-year-old intensive tilapia farm in Idaho and lost $20 million due to inadequate water supplies.
- Aquaculture Technologies of Louisiana failed, leaving $9 million in debts and 2,000 acres of catfish ponds, largely because of poor management.

Figure 5.3. Risk of Insolvency of Alternative Agricultural Enterprises in Appalachia as Ranked by Agricultural Lenders



* Ranking is on a scale from 1 to 12 where 1 is the most likely to fail within five years and 12 is the least likely to fail within 5 years; based on a survey of lenders with 60 respondents. Source: Gempesaw et al. 1995.

Figure. 5.4. Some Financial Sources for Aquaculturiests Other Than Commercial Banks

Program	Sponsor	Comments
Farm Credit System	228 lending institutions owned by borrowers	Created by Congress. Now self-sufficient. Provides about 25% of credit to US agriculture.
Farm Service Agency	U.S. Department of Agriculture	Makes and guarantees loans. Lender of last resort for agriculture.
Rural Business Cooperative Service	U.S. Department of Agriculture	Loans and grants to businesses in rural areas.
504 Loan Program	U.S. Small Business Administration	Makes and guarantees loans to small businesses.
Economic Development Administration	U.S. Department of Commerce	Provide grants to businesses in economically distressed areas.
Community Development Block Grants	Housing and Urban Development	Loans to businesses in small communities.
State conomic development programs	Various state agencies	

Sources: Robinson 1993, OTA 1995, Stevens 1997.

- NAIAD Corp., the largest catfish farming and processing operation in Texas, filed for bankruptcy because of insufficient funds to pay $12.4 million in debts.
- Blue Ridge Fisheries of Virginia, once proclaimed the world's largest indoor catfish farm, was seized by a bank because the facility's recirculating system was not profitable.
- Bodega Farms closed a $9.5 million steelhead, coho salmon, and abalone farm in California, in part because the farm could not obtain permission to import fish. (Nevertheless, Bodega Farms has since become a successful enterprise [G. Lockwood, pers. comm.]).

Aquaculturists find it difficult to obtain affordable insurance to reduce the risks they face (Gempesaw et al. 1995; R. Eager, pers. comm.), and many banks and other financial lenders consider aquaculture a risky enterprise (Robinson 1993). In a survey of Appalachian lenders, researchers found that over half of the lenders stated that the financial status of aquaculture borrowers had worsened after loans were made (Gempesaw et al. 1995). Nevertheless, the risks of insolvency in aquaculture are not necessarily higher than in some other types of agricultural production. Figure 5.3 displays different alternative agricultural enterprises, including various forms of aquaculture, and risks of insolvency as considered by agricultural lenders in Appalachia.

Small producers can reduce some of the risks inherent to aquaculture by forming cooperatives or by producing a number of species. As discussed above, processing and marketing cooperatives can allow small farms to increase their returns. Integration of aquaculture with traditional agricultural activities can reduce risks of insolvency (Gempesaw et al. 1995). Production of a variety of aquaculture species reduces the risk of disease wiping out profits and reduces exposure to risks from fluctuations in market prices (R. Eager, pers. comm.).

Aquaculturists often cite obtaining adequate financial backing as one of the biggest obstacles they face (Spatz et al. 1996). Banks and other conservative financial sources are often unwilling to finance start-up aquaculture operations in regions where aquaculture is not already common (Robinson 1993; Gempesaw et al. 1995). As a result, many aquaculturists rely on private investors for funding (Gempesaw et al. 1995).

Prospective aquaculture producers are sometimes caught between difficulty in finding financial backing and substantial start-up and operating costs. Start-up costs for catfish farms are about $3,000 per acre of pond (Beem 1991). Recirculating systems can require several million dollars in start-up costs. Even a small family farm is expensive to start. In three years, South Carolina aquaculturist Rick Eager has invested nearly $500,000 on a 10-acre farm (R. Eager, pers. comm.).

Some aquaculturists believe that the federal government does not provide adequate financial support for development of fish farms, especially in comparison to federal support for traditional agriculture (G. Redden, pers. comm.). In an era of government budget cuts, however, the federal government is unlikely to provide aquaculture the huge monetary assistance it once gave to traditional agricultural commodities (Gempesaw et al. 1995). Nevertheless, there are some public programs that help aquaculturists obtain funding (McVey 1991; Robinson 1993; OTA 1995). Figure 5.4 displays some financing programs.

Conclusion: Economic and Environmental Sustainability in Aquaculture

Aquaculture is a risky business that requires considerable ability, long hours, and, in many cases, substantial start-up capital. Moreover, entrance into some of the more established fish-production sectors is limited. Aquaculture development is sometimes portrayed as a means to generate new jobs in economically distressed areas from owner-operated small fish farms. However, like other segments of the agricultural industry, aquaculture is experiencing consolidation toward larger farms. Large farms controlled by outsiders may generate fewer local benefits for communities than locally managed operations. Although some well-established aquaculture sectors produce large numbers of jobs, most of them are with processing companies and other upstream segments of the industry.

Despite these realities, aquaculture has played a significant economic role in sustaining the economies in some areas of the United States. Of note are some small terrestrial farms in relatively poor rural areas that have remained economically viable by diversifying to raise fish in addition to more traditional terrestrial crops.

The greatest benefits to rural and coastal communities will come from aquaculture enterprises that are not only economically profitable over the short term but also economically and environmentally sustainable over the long term. Rural and coastal areas have seen their share of polluting, extractive industries, and have experienced problems, ranging from overexploitation of coastal fisheries in New England to contamination of pristine areas by mining industries in parts of Appalachia. These industries have failed to provide long-term benefits for present communities. It is important that the industries that develop next in these areas focus not merely on short-term gain at the expense of the environment. While short-term profitability is necessary, aquaculture development should be environmentally sustainable and thus beneficial over the long term if it is to truly benefit rural and coastal communities.

Recommended Readings

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Net Result: Conclusions and Recommendations

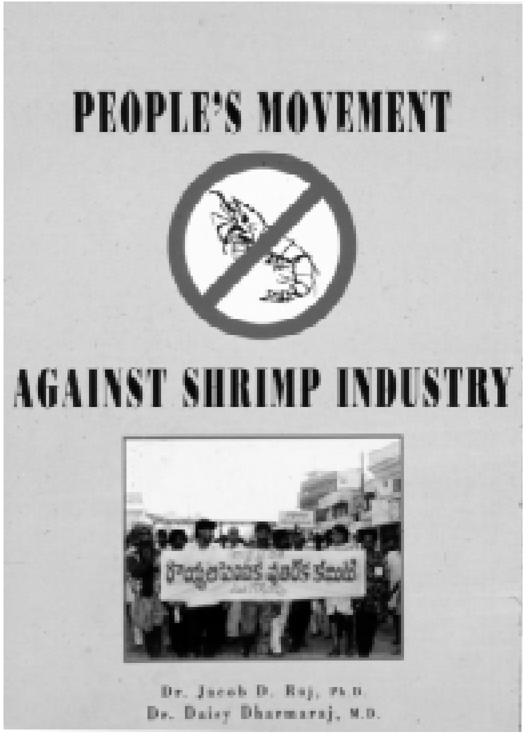
The phenomenal growth of aquaculture around the world has spurred considerable concern and controversy about environmental degradation caused by certain sectors of the aquaculture industry, particularly salmon and shrimp farming. In some countries, evidence of environmental damage has prompted governments to severely restrict or halt the expansion of aquaculture.

Environmental problems caused by salmon farms have led to moratoria on the expansion of sites for salmon netpens in three of the world's largest producers of farmed salmon – Norway, Ireland, and Chile (where the moratorium is limited to freshwater lakes) – and have led a Scottish government task force to recommend a similar moratorium (Sierra Club Legal Defence Fund 1997). In Canada, two recent reports by nongovernment organizations (NGO's) in British Columbia detail numerous environmental problems caused by the British Columbia salmon farming industry, including water pollution, introduction and spread of salmon diseases, and harm to predatory marine mammals, such as seals and whales (Ellis and Associates 1996; Sierra Club Legal Defense Fund 1997). However, the British Coumbia provincial government takes a more sanguine view. It recently published a 1,800 page report that concludes that if certain reforms are implemented the British Columbia salmon farming industry will pose only a low level of environmental risk at current levels of production (B.C. Environmental Assessment Office 1997).

Environmental and socioeconomic problems caused by a boom in shrimp farming along India's east coast led the Indian Supreme Court to rule in December 1996 that these farms must be removed (Fish Farming International 1997; Shrimp Tribunal). Problems attributed to Indian shrimp farms include destruction of coastal mangrove forests, discharge of untreated pond effluent, and displacement of subsistence fishermen (Parthasarathy 1995; Raj and Dhamaraj 1996). India's shrimp-farming industry is now trying to overturn the Supreme Court ruling (Fish Farming International 1997). Environmental degradation caused by shrimp farming is in no way unique to India. A number of publications have chronicled similar problems in southeast Asia and in Central and South America (for example, Primavera 1993; Hopkins et al. 1995; Clay 1996; Nixon 1996; Gujja and Finger-Stich 1996; Shrimp Tribunal).

Relative to the salmon and shrimp industries in other countries, environmental concerns and controversies about sectors of the U.S. aquaculture industry (for example, see Fleischman 1997) have to date been comparatively local and with a few notable exceptions (see Box 6.1), comparatively mild. One possible reason is that, with the notable exception of catfish farming, most individual sectors of the U.S. industry are smaller than the salmon- and shrimp-farming sectors in top producing countries, and thus have limited potential to cause large-scale environmental problems. Of course, the United States also enforces its environmental laws more stringently than many developing countries where shrimp

Above: Farmed Asian tiger shrimp. Courtesy of Conner Bailey. Right: Publication opposing the shrimp farming industry in Asia. Courtesy of PREPARE.



PEOPLE'S MOVEMENT

AGAINST SHRIMP INDUSTRY

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Dr. Daisy Dharmaraj, M.D.

farming occurs (Claridge 1996).

Nevertheless, disastrous experiences with shrimp and salmon farming in other countries provide cautionary tales for the U.S. aquaculture industry as producers and policy makers set the course for the U.S. industry's continued growth. Not only is environmental degradation undesirable in and of itself, but as discussed in Chapter 1, if the US aquaculture industry is to continue to expand and thrive, fish farms must be acceptable to the communities in which they are located. Otherwise, proposals to construct or expand fish farms may be hamstrung because opponents believe that all they receive from aquaculture facilities is their pollution (Costa-Pierce 1994).

This report discusses a range of environmental problems that can be caused by aquaculture and a variety of methods available to solve or avoid them. These methods provide the basis for this report's principal conclusion**: Aquaculture facilities constructed or operated without environmental protection in mind can cause serious environmental degradation and may ultimately be doomed to financial difficulty or failure. However, aquaculture need not be a polluting industry. A variety of strategies and technologies are now available to make fish farming environmentally sound.** From this conclusion flow a number of recommendations aimed at improving the environmental performance of U.S. aquaculture. Implementation of these recommendations rests on both the private sector (members of the aquaculture industry and consumers of aquaculture products) and the public sector (federal, state, and local governments).

Recommendations for the Private Sector

Recommendation One: Aquaculturists should adopt management strategies and technologies that make aquaculture environmentally sound. Many of these strategies and technologies are discussed in this report. They include:

- Using feeds with low fishmeal content, in order to lessen aquaculture's pressure on wild fisheries, and with nutritional and other characteristics that help aquaculturists minimize feed waste,

- Raising different species together, such as finfish with hydroponic vegetables or with mollusks (for example mussels), in order to make optimum use of water and nutrients and to minimize farm wastes,
- Treating wastewater by using sedimentation ponds, mechanical filters, constructed wetlands, or other methods,
- Using aquaculture sludge as fertilizer for crops, and applying sludge in a manner that avoids it being washed away in field runoff,
- Minimizing use of aquaculture drugs by practicing preventive medicine – for example stocking fish free of pathogens and parasites, minimizing stresses on fish, and vaccinating fish against disease,
- Minimizing use of chemical pesticides by preventing aquaculture pests from becoming a problem in the first place (such as by constructing ponds deep enough to discourage weed growth) and, if pests become problematic, adopting biological controls.
- Raising only native species, or non-native species that cannot survive and reproduce if they escape captivity,
- Constructing and maintaining aquaculture facilities in order to prevent or minimize the escape of farmed fish,
- Adopting predator-control programs that make aquaculture facilities unattractive to predators and that do not involve killing wildlife,
- Siting fish farms in locations where facilities are least likely to cause environmental harm - for example not in wetlands or other important ecological habitat,
- Growing fish in recirculating systems, that minimize water use and nutrient and biological pollution by aquaculture facilities.

Aquaculturists should seek to adopt source reduction approaches, which minimize their production of nutrient, synthetic chemical, or biological pollutants, in preference to pollution control approaches that simply treat or contain pollutants.

Along with fish farmers, suppliers of inputs to fish farms can play an important role in making aquaculture more environmentally sound by incorporating environmental performance criteria into development of their products. One notable example of such an undertaking is ongoing work by some feed manufacturers to reformulate fish feeds so that they contain less fishmeal and have nutritional and other characteristics that help fish farmers minimize feed waste.

Recommendation Two: The aquaculture industry should move away from raising finfish in netpens. Netpens are the type of aquaculture facility least amenable to control of nutrient and biological pollutants. There are few if any practical methods for collecting fish wastes from most netpens, and netpens are highly vulnerable to fish escapes. When carefully sited and monitored, limited numbers of netpens may not result in serious environmental harm (see Maine case study). Nevertheless, as discussed above, accumulating evidence shows that salmon netpens in many parts of the world are causing unacceptable environmental degradation of both marine waters and fresh waters (see also the New Brunswick case study; Weber 1997).

Netpens are not necessary to aquaculture: the fish species now raised in netpens can also be raised in ponds, raceways, and - best of all for the environment - recirculating systems. As discussed in Chapter 4, one U.S. company, Sargo™ FinFarms, even sells large floating tanks which contain their wastes and are designed as an alternative to netpens.

Netpens exemplify a very primitive "dilution is the solution to pollution" approach to mitigating environmental discharges. Netpen proponents often argue that pollution problems can be avoided by siting netpens in coastal waters with strong currents that sweep away wastes — a strategy akin to the practice earlier this century of building tall smokestacks, so that industrial air emissions would be carried away by the wind. We now know that the earth is not so vast that it can absorb all of mankind's insults, and that pollutants must be dealt with directly, and not just swept away to become another community's - or a another ecosystem's - problem.

Arguments that alternatives to netpens are cost-prohibitive ring hollow, since netpens simply externalize costs to the environment at the economic detriment of more environmentally responsible practices. Future aquaculture development should focus on aquaculture systems other than netpens that eliminate or facilitate treatment of aquaculture wastes.

Channel catfish. Courtesy of Louisiana Cooperative Extension Service.

Box 6.1: Salmon Netpen Aquaculture in Washington State

Environmental controversies have dogged the development of salmon netpen farming in Washington State. Commercial salmon farming began in Washington in the early 1970's and grew considerably in the 1980's. Shoreline residents, commercial fishermen, and local environmentalists all raised concerns about the industry, prompting the state in the late 1980's to prepare a Programmatic Environmental Impact Statement on salmon farming (WA DOF 1990). In 1989 a coalition of environmental organizations threatened to sue the U.S. Environmental Protection Agency (EPA) for failing to regulate pollutants from salmon netpens under the Clean Water Act, and EPA compelled Washington State to issue discharge permits (Barinaga 1990). The state issued three permits for netpens in 1990, which were then appealed by local environmental organizations (WA DOE 1997). The settlement of this appeal required a scientific netpen panel to produce a report, never completed, to provide a basis for new permits. In 1993 the Washington legislature passed legislation requiring that the State Department of Ecology set standards concerning water pollution and sediment degradation by marine netpen facilities.[1] In 1995 the Department promulgated two regulations to implement this legislation,[2] and in 1996 it issued 12 marine netpen permits. Local environmental organizations quickly appealed these permits to Washington's Pollution Control Board, among other things arguing that Atlantic salmon that escape netpens are an unregulated pollutant. The Board ruled quickly on the issue of salmon escapes, finding that Atlantic salmon meet the legal definition of a "pollutant."[3] The Board will hold hearings in 1997 to determine where escaped salmon cause harm and thus cause pollution (Doughton 1997).

In the meantime, about 45 netpen facilities are operating in Washington State marine waters. Fifteen of these facilities require discharge permits. The rest are small, mainly one or two public or Native American tribe pen facilities that do not require permits (WA DOE 1997).

Recommendation Three: Fish farmers should preferentially chose to raise, and consumers should preferentially chose to purchase, fish that are fed little fishmeal in their diets. A large fraction of farmed fish consumed in the United States, such as shrimp, trout, and especially salmon, are fed diets high in fishmeal. The result is often a net loss of fish protein, as more pounds of wild fish are fed to farmed fish than are ultimately harvested. Other types of farmed fish, such as catfish, tilapia, carp, crayfish, clams, oysters, mussels, and scallops, require little or no fishmeal in their diets. Aquaculturists can help to relieve pressure on wild fisheries by electing to farm these and other partially or entirely herbivorous fish, in preference to more carnivorous species. U.S. consumers can create a strong financial incentive for aquaculturists to farm herbivorous fish by choosing to purchase farmed herbivorous instead of farmed carnivorous species.

Recommendation Four: Organic certification and other "eco-certification" programs should be established that empower consumers to chose aquaculture products grown in an environmentally sound manner and give aquaculturists incentives to produce products which can bring higher prices. Consumers cannot now generally determine at the seafood counter whether fish was farmed (or wild-caught) in an environmentally sound manner. For example, an environmentally conscious consumer may chose to purchase catfish or tilapia because, as discussed in the above recommendation, these fish require little fishmeal in their diets. Yet such a consumer cannot discern whether the production of the fish he purchases was environmentally benign. For example, some catfish farmers kill large numbers of fish-eating birds, and some tilapia (a non-native fish) are farmed in locations where they may escape and establish harmful wild populations.

Eco-certification programs can help consumer use their pocketbooks to encourage environmentally sound production practices (Lefferts and Heinicke 1996, Schwartzman and Kingston 1997). Such programs certify or endorse products that meet specified environmental standards. Certification may be done by an independent nonprofit agency, by an industry-sponsored organization, or by government.

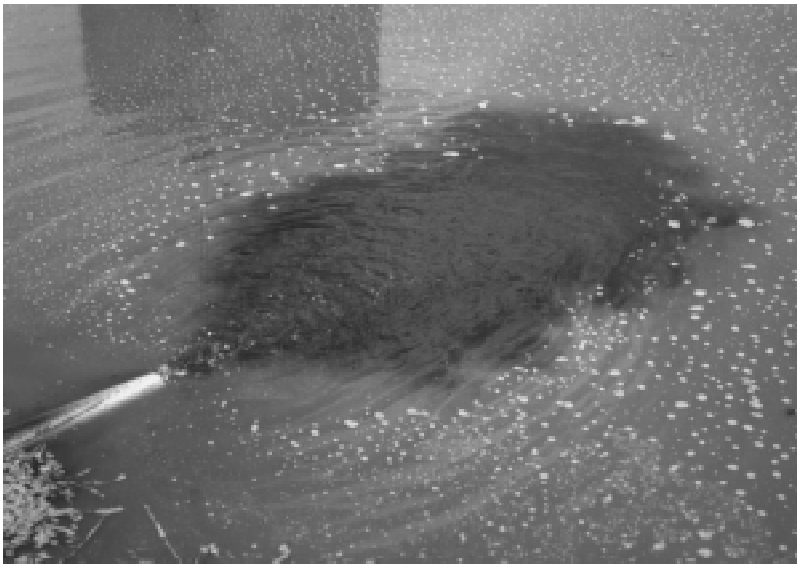
Organic certification is the predominant type of eco-certification for food in the United States. As discussed in Chapter 4, there are now no established organic standards for seafood, although the International Federation of Organic Agriculture Movements is in the process of developing standards.

Recommendations for the Public Sector

Government regulation of and support for aquaculture is a major force affecting the sustainability of aquaculture (Corbin and Young 1997). State and local governments implement widely varying laws that affect aquaculture facilities. A few states, such as Maine (see case study) and Minnesota[4] have enacted statutes designed specifically to apply to the siting and permitting of fish farms. However, aquaculture in most states is governed by regulations written for other purposes, such as to require review of proposed introductions of exotic species, to maintain the quality of state waters, and to protect populations of gamefish (Rubino and Wilson 1993). There are a number of articles and other publications that review at least some of these state laws in the context of aquaculture (for example, Thomas et al. 1992, Rychlak and Peel 1993, OTA 1993, Rubino and Wilson 1993, Ewart et al. 1995, Massachusetts Coastal Zone Management 1995, see Texas and Maine case studies). A review of state laws is beyond the scope of this handbook.

Federal regulations affecting aquaculture include permit requirements for discharging effluent from many aquaculture facilities, restrictions on killing avian and marine mammal predators, and oversight of drugs and pesticides used in

Crayfish harvesting. Courtesy of Louisiana Cooperative Extension Service.



Concentrated effluent from a catfish pond. Courtesy of Louisiana Cooperative Extension Service.

aquaculture (see Box 6.2). Unfortunately federal regulations covering several key environmental issues in aquaculture are deficient or nonexistent. Steps are recommended below to remedy inadequate oversight in three areas: enforcement of the Clean Water Act, regulation of introductions of nonindigenous species and transgenic fish, and oversight of open-ocean aquaculture.

The federal government influences aquaculture not just via regulation, but also via its support for aquaculture under a variety of programs (OTA 1995b). Three federal agencies – the Department of Agriculture (USDA), the Department of the Interior, and the Department of Commerce (which houses the National Oceanic and Atmospheric Administration) – are assigned responsibilities for aquaculture development under the 1980 National Aquaculture Act (NAA)[5] and the National Aquaculture Improvement Act of 1985.[6] Federal funding for aquaculture stood at $60 million in 1994, a 75% increase from 1988 (OTA 1995b). These funds were distributed among 25 different agencies, including $28.7 million from USDA, $13.9 million from the Department of Commerce, and $7 million from the Department of the Interior. The majority of this funding was targeted to research, including support for five USDA Regional Aquaculture Centers, which were established to facilitate aquaculture research, development, and demonstration projects. Federal funds also supported aquaculture through a number of programs designed to promote the economic health of the fishing industry and agriculture, and to promote rural development. OTA (1995b) provides a comprehensive overview of federal support for aquaculture, ranging from crop insurance to loan programs for small businesses.

Recommendation Five: EPA should implement the Clean Water Act for aquaculture by developing effluent limitations. Under the Clean Water Act, EPA is supposed to set effluent limitations for various industries – discharge quality standards for specific pollutants that are found to be achievable using particular technologies.[7] EPA has established effluent limitations for terrestrial feedlots but not for aquaculture "feedlots."

EPA's failure to set effluent limitations for aquaculture has several undesirable consequences. In some instances, EPA has not issued permits for aquaculture facilities, at least in part because EPA has not established how to evaluate permit applications. EPA's Region I office in Boston has received approximately 40 applications for NPDES permits for aquaculture netpens but has issued very few permits (P. Colarusso, pers. comm).

Very importantly, the absence of effluent limitations setting minimum national standards for aquaculture discharges has resulted in highly inconsistent regulation of aquaculture facilities in different states – an outcome inconsistent with the objectives of the Clean Water Act (see Box 6.3). In some states, many large aquaculture operations are virtually unregulated, and large quanti-

Box 6.2: Federal regulation of aquaculture

Effects of aquaculture on the environment and public health are regulated under a number of Federal laws, including:

The Clean Water Act (33 U.S.C. 1251 et seq.) – This law gives EPA the authority to issue National Pollution Discharge Elimination System (NPDES) permits for "point sources" of discharges, including effluent from "concentrated aquatic animal production facilities." Under provisions of the Clean Water Act, EPA has delegated permit granting authority to at least 39 states that meet certain qualifications. Maine and Idaho are two states with substantial aquaculture industries that do not have delegated authority: Aquaculture operations in these states remain directly regulated by EPA.

The Clean Water Act also gives the Army Corps of Engineers (ACOE) authority to grant "Section 404" permits to aquaculturists who want to convert areas defined as wetlands to aquaculture ponds or other facilities. In 1990, the Corps decided not to require a permit for pond construction on "prior converted" farmland, freeing from permit requirements many wetlands used for catfish production in the southeast (Rubino and Wilson 1993).

The Rivers and Harbors Act of 1899 (33 U.S.C. 403) – Under this law the ACOE requires "Section 10" permits for structures in navigable waters, such as floating netpens. The Corps has asserted authority under this statute and the Outer Continental Shelf Lands Act (43 U.S.C. 1331 et seq.) to require permits for open ocean aquaculture facilities – those constructed in the U.S. Economic Zone beyond state waters (generally between 3 and 200 miles from shore).

The Migratory Bird Treaty Act (16 U.S.C. 703 et seq.) –This statute, which implements several international conventions concerning conservation of birds and wildlife, gives authority to the U.S. Fish and Wildlife Service (USFWS) to require depredation permits to kill protected species of birds. Killing is permitted if birds are deemed responsible for serious economic damage to agriculture, including aquaculture (see OTA 1995).

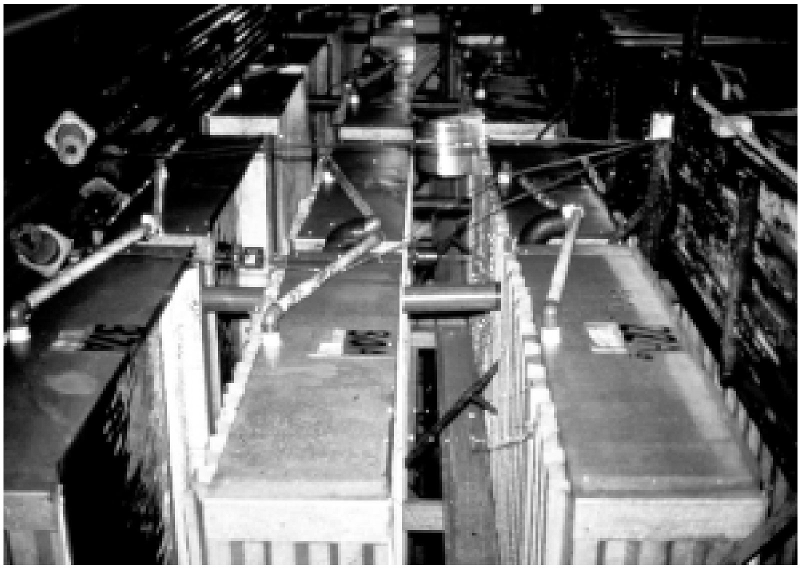
The Animal Damage Control Act of 1931 (7 U.S.C. 426-426c) – This Act is the primary for authority for management of injurious wildlife, including migratory birds, by the Animal Damage Control (ADC) program of the U.S. Department of Agriculture's Animal and Plant Health Inspection Service (USDA APHIS). ADC practices "wildlife damage management" using various non-lethal controls and by killing wildlife (USDA APHIS 1994).

The Marine Mammal Protection Act (16 U.S.C. 1361 et seq.) – This law prohibits, with a few exceptions, the harassment, hunting, capture, or kill of any marine mammals, including seals which may be predators at aquaculture facility.

The Lacey Act (16 U.S.C. 3371) – Enforced by the USFWS, this law was written to prevent commerce in wildlife taken in violation of various laws and treaties. Under 1981 amendments to the Lacey Act, the USFWS can enforce state laws prohibiting introductions of species into a state (OTA 1993). Some states have invoked the Lacey Act to prevent the farming and sale of some fish species that the state considers a game fish or to be threatened or endangered in the wild (Rubino and Wilson 1993). In general, however, USFWS enforcement is understaffed and underfunded (OTA 1993).

The Federal Insecticide, Fungicide, and Rodenticide Act (7 U.S.C. 136 et seq.) – Under this statute, EPA registers pesticides, including substances intended to control plants, insects, microorganisms, and fish, for use on specific crops, including fish. To be registered, pesticides must meet a variety of requirements intended to protect public health and the environment.

The Food, Drug, and Cosmetic Act (21 U.S.C. 301 et seq.) – The Food and Drug Administration (FDA) has broad authority under this statute to protect public health, primarily through oversight of food and drugs. Particularly relevant to aquaculture, FDA requires drug approvals for animal drugs, including drugs used in fish farming, and is responsible for seafood safety.



Indoor recirculating system. Courtesy of Louisiana Cooperative Extension Service.

ties of untreated fish wastes are regularly discharged into waterways.

Recommendation Six: The federal government should develop a comprehensive oversight framework for introduction of potential biological pollutants from aquaculture and other human activities. Federal oversight of introductions of potential biological pollutants is at best piecemeal – a "largely uncoordinated patchwork of laws, regulations, policies, and programs" (OTA 1993).

For the most part, federal regulation of biological pollutants from aquaculture is focused on importation of non-native or exotic species, rather than introduction of genetically differentiated fish populations or introduction of transgenic fish. The Lacey Act is the primary federal law used for excluding harmful imports of non-native organisms (OTA 1993). Under the Lacey Act, the U.S. Fish and Wildlife Service restricts importation to the United States of a limited number of types of fish and wildlife, including two taxonomic families of finfish. In 1977 the President Carter issued a potentially far-reaching Executive Order that could have established a national policy on biological pollutants (Executive Order 1977). In 1990, Congress passed the Nonindigenous Aquatic Nuisance Prevention and Control Act,[8] which created a task force to "develop and implement a program . . . to prevent introduction and dispersal of aquatic nuisance species." However, in practice, the Carter Executive Order has been ignored by most federal agencies (OTA 1993), and a comprehensive program to prevent introductions of aquatic nuisance species has not been established. An extensive overview of federal regulations and policies concerning non-native species can be found in OTA (1993).

State regulation of introductions of non-native species is highly variable, and on average state oversight is not adequately protective of the environment (Kurdilla 1988; OTA 1993).

Some introductions of potential biological pollutants are regulated hardly at all. Introductions of transgenic fish are a clear example. Only a small number of states regulate introductions of transgenic organisms, including transgenic fish. Transgenic fish are ignored by the federal framework for regulation of biotechnology products (OSTP 1986), and thus are not regulated by the federal government.[9] FDA will likely regulate transgenic fish for their safety as food, and the agency is considering accepting responsibility for oversight of the ecological effects of transgenic fish under the National Environmental Policy Act[10] (Miller and Matheson 1997, Matheson pers. comm.). however, FDA has few staff members with appropriate expertise to evaluate the ecological effects of transgenic fish, oversight of which more logically meshes with the responsibilities of the U.S. Fish and Wildlife Service and the National Marine Fisheries Service.

A number of options for improving federal regulation of non-native organisms, including transgenic organisms, are discussed in OTA (1993). These include greatly expanding the list of "injurious" fish and wildlife restricted under the Lacey Act; altering enforcement of the Lacey Act to establish a "clean list" of acceptable organisms, and restrict importation of fish and wildlife not on this list; and establishing Federal minimum standards for state regulation of introductions of non-native species. The scope of an improved regulatory framework for non-native organisms extends far beyond aquaculture, which is only one of many sources of introductions of biological pollutants. Thus this paper will not attempt to outline such a complex framework. Clearly, however, a concerted Federal effort to develop a coherent framework is essential to limiting future ecological harm by biological pollutants.

Recommendation Seven: The federal government should develop a regulatory framework for open-ocean aquaculture that includes strong environmental protections. As discussed in Chapter 4, several netpen or cage facilities are now being planned or built in the open ocean, beyond state controlled waters where they have historically been located. A number of federal agencies have asserted authority over

Box 6.3: Inconsistent Regulation of Aquaculture Effluent

Environmental standards for effluent from aquaculture operations varies considerably among different states and among different types of aquaculture systems. Consider netpen systems, for example. Minnesota, which suffered serious water pollution from netpens in freshwater lakes (see Chapter 2, Box 2.3) requires under state law that netpens meet the same water quality standards as other aquaculture facilities. Netpen operators must collect and treat their wastes, because collection and treatment is necessary for the protection of waters within the state (Minnesota Pollution Control Agency, no date). In contrast, Washington State simply requires netpen operators to implement specified best management practices, such as using "properly sized feed for the size of fish in an individual netpen" (WA DOE 1996a). The state's rationale is that it has not uncovered any economically achievable technologies for collecting and disposing of wastes from netpens (WA DOE 1996b).

However, Washington sets more stringent criteria for effluent from upland aquaculture facilities (such as raceways) than for marine netpens. Unlike marine netpen operations, upland facilities must meet specific standards for settleable and suspended solids in effluent (WA DOE, no date). Washington's regulatory disparities among aquaculture systems may have the environmentally undesirable consequence of favoring marine netpen aquaculture over upland aquaculture systems. Netpen operators do not have to treat their wastes to meet water-quality standards and thus may be able to externalize more of their environmental costs than upland facilities.

Regulation of discharges from aquaculture ponds also varies among states and raises an important, unresolved issue concerning application of the Clean Water Act to aquaculture. Under Federal regulations, fish farms and fish hatcheries that discharge more than 30 days per year are defined as "point sources" under the Clean Water Act. By implication, facilities that discharge fewer than 30 days – this includes most aquaculture ponds – should not be considered point sources. However, at least some aquaculture ponds arguably may meet the Clean Water Act's general definition of a point source, which includes "any . . . concentrated animal feeding operation . . . from which pollutants are or may be discharged." [11]

State governments have chosen different approaches to regulating aquaculture ponds. In Mississippi and Arkansas, the center of the very large U.S. catfish industry, state regulators have chosen to exempt catfish ponds from Clean Water Act permit requirements, because they do not meet the 30-day discharge threshold.. Mississippi has issued only one permit for an aquaculture facility, and Arkansas has issued none (B. Finch, pers. comm.). In contrast, Minnesota regulates ponds that discharge fewer than 30 days a year because they "may have high pollutant concentrations and loadings" (Minnesota Pollution Control Agency, no date).

open-ocean aquaculture, and "regulatory uncertainty has led to a largely ad hoc and unsatisfactory application of Federal environmental laws to the few open-ocean aquaculture projects proposed to date" (Hopkins et al. 1997).

The Army Corps of Engineers (ACOE) has taken the lead in regulating open-ocean aquaculture facilites, issuing several permits for them under authority from the Rivers and Harbors Act (RHA). However, there is good reason to fear that the ACOE permit process may fail over the long term to protect the environment (Hopkins et al. 1997). Under the RHA the ACOE has enormous discretion in deciding whether to issue a permit and how to weigh environmental and a broad variety of other impacts in its decisionmaking. Challenging a permit decision by the ACOE on environmental grounds would be extremely difficult. Moreover, the ACOE has little appropriate expertise to weigh ecological impacts in marine ecosystems. The National Marine Fisheries Service, which has broad scientific expertise in analyzing impacts on marine ecosystems and broad authority for fishery conservation under the Magnuson Act,[12] would be a far more appropriate lead agency to consider the environmental impacts of open-ocean aquaculture facilities (Hopkins et al. 1997).

Recommendation Eight: Government research and other support programs for aquaculture should emphasize environmental protection and the development of aquaculture operations that provide long-term social and economic benefits to economically distressed communities. Government supported research is critical to developing management strategies and technical advances to make aquaculture facilities more environmentally sound. Two "win-win" research topics that will help accomplish source reduction of pollutants and provide financial benefits especially stand out. First, fish species used in aquaculture need to be the subject of extensive selective breeding so that they become highly domesticated, and fish that escape aquaculture facilities do not survive and reproduce, causing biological pollution. Of course, breeding would also benefit to aquaculture by improving economically important traits of fish, such as growth rates. Second, recirculating aquaculture facilities, which allow comprehensive source reduction of aquaculture's environmental impacts, need to be further refined so that they are less costly and more reliable than they now are.

Government support for aquaculture development should target projects that can play a clear role in sustaining economically distressed communities or regions. As discussed in Chapter Five, examples include helping small terrestrial farms diversify their sources of income by raising fish in addition to more traditional terrestrial crops, and constructing recirculating aquaculture systems in old factories in urban areas. Government support should target aquaculture projects that are environmentally sound, and thus have the greatest potential to provide social and economic benefits over the long term.

Recommended Reading:

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Weber, M.L. 1997. Farmed Salmon: A briefing book. San Francisco: Consultative Group on Biological Diversity.

Chapter Six Notes:

[1] SHB 1169

[2] Chapter 173-221A WAC, Chapter 173-204 WAC

[3] *Marine Environmental Consortium v. State of Washington, Department of Ecology*, First Order on Summary Judgement (May 28, 1997)

[4] Minnesota Administrative Code 7050.0216

[5] 16 U.S.C. 2801 et seq.

[6] Public Law 99-198

[7] In theory, EPA is supposed to publish effluent guidelines as a first step towards promulgating effluent limitations. In practice, EPA has published effluent guidelines in conjunction with effluent limitations and the terms “effluent guidelines” and “effluent limitations” are sometimes used interchangeably.

[8] 6 U.S.C.A. 4722

[9] USDA has publishing voluntary safety guidelines for researchers developing transgenic fish (USDA 1995)

[10] 42 U.S.C. 4321 et seq.

[11] 33 U.S.C. 1362(14)

[12] 16 U.S.C. 1801 et seq.

Case Studies of Aquaculture Development

This report concludes with three case studies that provide detailed accounts of the development and the environmental effects of the aquaculture industry in different locations. The first case study, By Pamela Baker of the Environmental Defense Fund's Texas office, describes environmental problems and other conflicts caused by the growth of the coastal shrimp farming industry in Texas. Until recently, this industry was not subject to key environmental regulations.

The second and third case studies concern the growth of the salmon farming industry in New Brunswick, Canada, and across the U.S. border in Maine. The close proximity of New Brunswick and Maine salmon farms means that although these farms are in two different countries, they affect the same coastal ecosystem (see map at the beginning of the New Brunswick case study). The second case study, by Inka Milewski, Janice Harvey, and Beth Buerkle of the Conservation Council of New Brunswick, provides a detailed history of the New Brunswick and Canadian governments' promotion of salmon farming and concomitant lack of attention to the associated environmental harm. The New Brunswick salmon farming industry now faces numerous problems, including conflicts with fishermen, diseased salmon stocks, and public concerns about environmental degradation. The third case study, by Philip Conkling and Anne Hayden of the Island Institute in Maine, takes a less negative view of salmon farming. They argue that although a number of legitimate concerns have been raised about Maine salmon farms, the salmon industry has not caused serious environmental harm to date, in part because of the state of Maine's effective environmental regulation of the industry.

Case Study One

Coastal Shrimp Farming in Texas

by Pamela Baker
Environmental Defense Fund, Austin, Texas

Introduction

The Texas coast is characterized by a series of environmentally sensitive shallow bays and lagoons isolated from the Gulf of Mexico by a string of barrier islands. The resulting coastal ecosystems display a wide array of unique habitats and aquatic life. For example, the Laguna Madre, one of only three hypersaline lagoons in the world (lagoons have salinities higher than adjacent ocean waters), provides sanctuary to the early life stages of a multitude of the Gulf of Mexico's fish species, while the salt marshes of Aransas Bay are the winter home of the world's only surviving nesting population of whooping cranes. Important industries also rely on Texas' healthy coastal ecosystems. Commercial fishers in Texas bring in fish, crab, and shrimp worth about $200 million annually (Robinson et al. 1994). Tourism is also big business on the Texas coast — recreational fishers alone spend more than $546 million yearly (CCBNEP 1996).

Texas' intricate coastal ecosystems are being threatened by a relatively new industry on the coast — shrimp farming. Established in Texas in 1980, coastal shrimp farming relies heavily on the clean waters of Texas' bays and estuaries. Texas is the leading U.S. producer of farmed shrimp, contributing 70% of domestic production (USMSFP 1995). In 1994, the most recent year of disease-free production, Texas farmers harvested approximately 4 million pounds of shrimp worth $13 million (Reisinger 1995). The shrimp farming industry in Texas remains small, however, compared to Texas' wild shrimp fishery, which typically lands about 75 million pounds of shrimp each year (Robinson et al. 1994).

During the 1997 season, there were nine coastal shrimp farms in Texas, up from six in 1995. In addition, three farms are for sale or lease and two have been proposed but not yet built (see map). Coastal communities have identified environmental problems resulting from shrimp-farm operations. For example, sport-fishing guides blame shrimp-farm wastewater discharges for creating conditions unsuitable for some types of sport fishing, property owners adjacent to some shrimp farms report declining property values from nuisance conditions, and wild-shrimp fishers are concerned about the potential for harm to native shrimp stocks from escaped exotic shrimp species. These problems are intensifying with the shrimp-farming industry's accelerating growth, and some coastal communities are now hostile toward the industry.

To provide jobs and economic diversity for the coast, the state has provided incentives, including exemptions to water-rights permit requirements, in order to attract investors. Only one of six farms that discharged wastewater in 1996 had a state wastewater-discharge permit. Meanwhile, Texas regulatory agencies have directed little attention to shrimp farming. Citizens' organizations along the Texas coast are now urging state agencies to begin to recognize the environmental and economic consequences of the shrimp-farming industry.

The aim of this case study is to provide specific information on the following topics regarding coastal shrimp farming in Texas:

Austwell Aqua Farm's 12 five-acre ponds are located on a shallow secondary bay on the Texas Coast— a typical design for Texas' coastal shrimp farms. Photo courtesy of Texas Parks and Wildlife Department.

- The shrimp farming industry — its genesis, operation, production, and problems.
- Environmental impacts of shrimp farming — existing and potential impacts to the Texas coastline and their economic consequences.
- The regulatory framework for shrimp farming — evolution of existing regulations, gaps in those regulations, and citizen and nongovernmental efforts to exact more protective regulations.
- The future — forthcoming issues and possible steps toward a sustainable coastal shrimp-farming industry in Texas.

The story of the Texas shrimp-farming industry is colored by the failure of the Texas state government and the industry to adequately consider the environmental implications of shrimp-farm development. Environmental problems from the shrimp-farming industry now loom large for many Texans living near the Gulf of Mexico. Largely as a result of their concerns, both state government and the industry are beginning to take corrective actions.

The Industry

In the mid-1980's, the state of Texas identified shrimp farming as a way to create jobs and economic diversification for the Texas coast. The first shrimp farm in Texas, Harlingen Shrimp Farms, was established in 1980.[1] It was producing about 200,000 pounds of shrimp in 1986 (Treece 1996) when the state began promoting the industry and providing incentives to draw both domestic and foreign investors.

Today Texas is the leading U.S. producer of farmed shrimp, accounting for about 70% of production. Production has generally increased over the years, although fluctuations have been common. For the years 1990 through 1994, production was 1.5, 1.7, 3.8, 4.2, and 3.7 million pounds, respectively. Between 1992 and 1994, the value of the shrimp crop was in excess of $11 million per year, making shrimp the leading aquaculture crop in the state both in pounds and in dollar value during those years (Treece 1996). The estimated economic impact in 1994 alone was estimated at more than $41 million, with 868 jobs created (USMSFP 1995). However, in 1995 and 1996 production dropped to less than 2 million pounds (Treece, pers. comm.), due to disease outbreaks that caused high mortality rates among shrimp prior to harvest.

In early 1997 there were nine operational shrimp farms on the Texas coast. Two new coastal farms are proposed, and three farms not currently operating are for sale or lease. More than 1,500 acres of coastal lands are devoted to shrimp farming, and the industry has attracted both foreign and domestic investors. Encouraged by Texas State and the promise of success similar to that of Harlingen Shrimp Farms, investors from Taiwan established two shrimp farms on the Arroyo Colorado River in the mid-1980's — Arroyo Aquaculture Association and Southern Star Shrimp Farms.[2] Texas-owned Bowers, M&M, and R&G shrimp farms followed in the late 1980's, all located on Matagorda Bay. Four new farms began operations in 1996 and 1997 — St. Martin's Seafood Partnership and La

Bahia Shrimp Farm, both on Matagorda Bay, and Austwell Aqua Farms on San Antonio Bay (see map). Man Tai, on Copano Bay, began operating in 1996 but was out of business by 1997.

Texas' coastal shrimp farms all have similar operating strategies. Farms are located above the high-tide line on coastal lands and use pumps to bring bay water into the facilities. Wastewater is discharged back into the bays. Shrimp are grown in outdoor earthen ponds that vary in size from 0.6 to 10 acres each. Farms range in size from 70 to more than 450 acres, and have as few as four to as many as 94 ponds. Operations are "semi-intensive" (medium stocking density — 10,000 to 80,000 shrimp per acre) and/or "intensive" (high stocking density— more than 80,000 shrimp per acre), requiring around-the-clock management.

Because Texas winters are too chilly for shrimp farming, farmers are restricted to raising one crop of shrimp per year; shrimp are stocked during the spring and harvested in the fall. Shrimp go through a complicated series of developmental stages as they mature. In spring, farmers fill their ponds with water and purchase shrimp "postlarvae" (PL's). Some farmers first stock PL's in carefully monitored nursery ponds until shrimp reach the "juvenile" stage. Next, juveniles (or PL's if no nursery phase is included) are stocked in growout ponds. During growout, shrimp are fed commercial feeds. In addition, fertilizers are often used to stimulate growth of algae, a natural source of food for developing shrimp. Other amendments may also be added to improve water and soil chemistry.

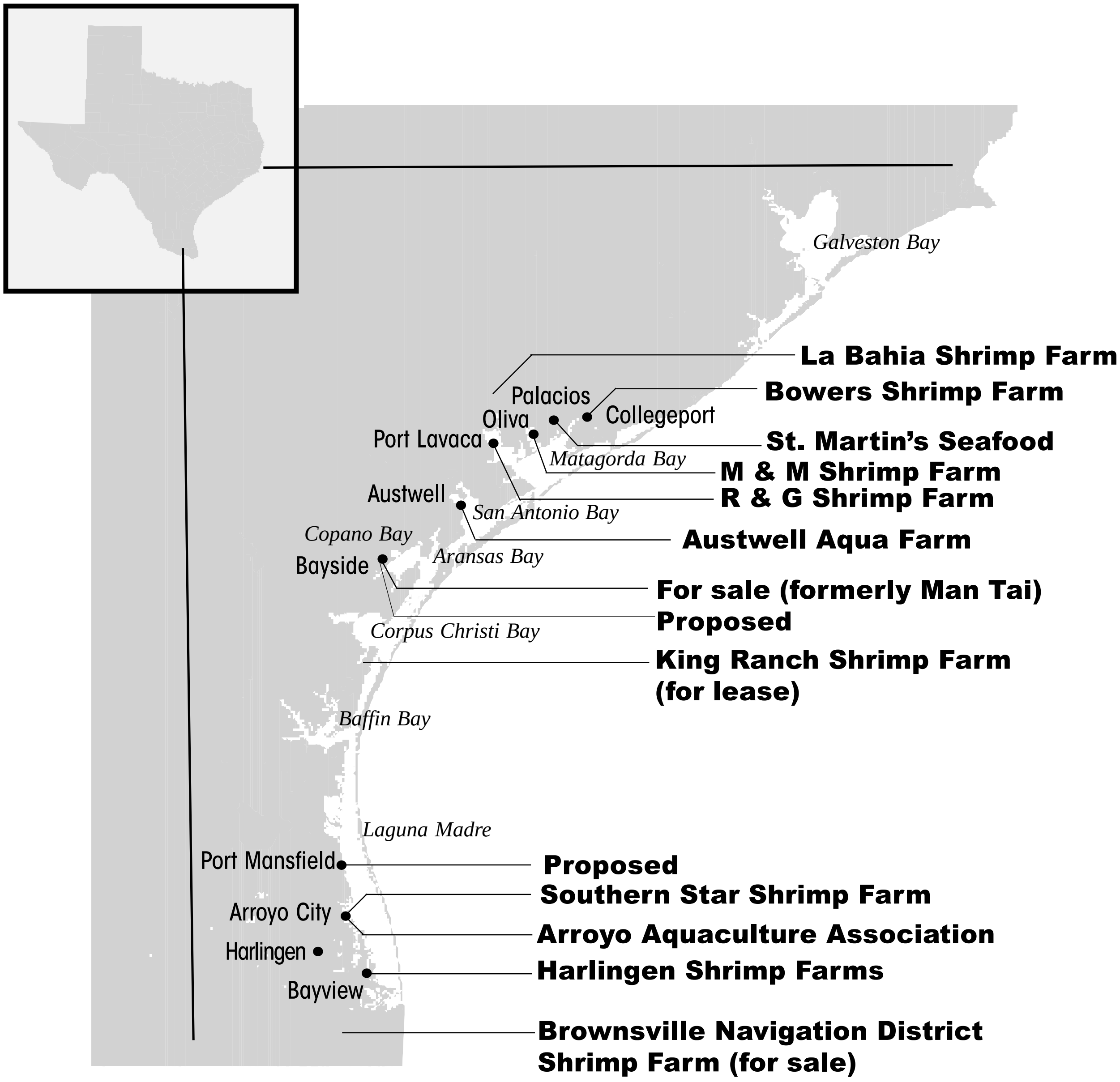
Shrimp are typically stocked at high densities, a practice that leads to poor water quality from uneaten shrimp feed and shrimp feces. As a result, farmers exchange large volumes of water — up to 30% of the farm's total volume per day (Lopez-Ivich 1996) — and use aeration devices to maintain adequate oxygen levels in pond water.

Shrimp remain in growout ponds until they reach market size. In the fall, they are harvested by a complete draining of the pond water through nets to recover the shrimp. During harvest, farms discharge up to 180 million gallons of wastewater per day (TNRCC 1995). Following harvest draining, pond bottoms are allowed to dry and oxidize. If soils

Paddlewheels for aeration — Top: At rest. Bottom: In motion. Courtesy of Rebecca Goldburg.

Location of Existing and Proposed Coastal Shrimp Farms in Texas

(June 1997)



have become acidic, a soil amendment (usually agricultural lime) may be added to enhance oxidization. This step prepares ponds for the next crop.

Texas' farms have been plagued with diseases that reduce production. The Taura Syndrome Virus (TSV) struck Texas' shrimp farms during the 1995 and 1996 production years. In 1995 TSV resulted in production losses of greater than 90% at nearly all farms (Hiney 1995). Farms that stocked the exotic Pacific white shrimp experienced significant mortality from TSV again in 1996, although survival rates were better than in the previous year (Treece, pers. comm.). Other diseases, both bacterial and viral, have also caused serious production losses over the years.

Environmental degradation and rising public outrage over it have become major industry concerns. Some of Texas' coastal shrimp farms have already taken steps to reduce the environmental impacts created by their farms. Two farms, Arroyo Aquaculture Association and Southern Star Shrimp Farms, set up a laboratory to test and monitor their wastewater quality. Increasingly farms are implementing best management practices (BMPs) such as: minimizing wastewater discharge by reduction of routine water exchange, using settling ponds to clean wastewater before it is discharged, and experimenting with natural filtration systems, such as wetlands. It is too early to assess the effectiveness of these BMP's; however, it is crucial that scientists begin to document any improvements resulting from their use.

Environmental and Economic Consequences

Coastal shrimp farms in Southeast Asia and Latin America, the major regions where shrimp are farmed, have caused serious environmental and socioeconomic problems. In some coastal areas, polluted effluent, destruction of coastal wetlands (mangrove forests), salinization of groundwater, and outbreaks of shrimp disease have harmed the productivity of traditional fisheries, agriculture, and shrimp farms themselves. The result has been social conflict and, for many people, loss of their livelihoods (for example, see Csavas 1993 and Landesman 1994).

In the United States, federal and state laws have helped avoid some of these problems. For example, wetlands have not been converted to aquacultural use pursuant to existing wetland protection laws. However, these laws have not provided adequate environmental safeguards for this new industry. The major sources of environmental degradation via Texas' coastal shrimp farms are the volume and content of wastewater discharges, the potential for introduction to coastal waters of diseases and exotic shrimp species, the poor siting of farms, and the entrainment of aquatic life.

Volume and Content of Wastewater Discharges

The central focus of the environmental debate regarding Texas' coastal shrimp farms is the volume and content of wastewater discharges. The volume of wastewater discharged varies based on farm size and management practices. One of the largest farms, Arroyo Aquacul-

Texas Parks and Wildlife Department data suggest discharges of solids from Harlingen Shrimp Farms contributed to the creation of this 15 acre sediment delta in the Laguna Madre. Courtesy of Texas Parks and Wildlife Department.

Feeding tray for shrimp. Courtesy of Rebecca Goldburg.

ture Association, has a state permit to discharge an average of 100 million gallons per day (MGD) and a maximum of 180 MGD (TNRCC 1995). Most farms, however, have no state permits. Data on discharge volumes of the industry as a whole are limited.

Shrimp-farm wastewater discharges often include total suspended solids (TSS) made up of uneaten feeds, shrimp feces, phytoplankton, and eroded sediments from pond levees and canals; nutrients from chemicals such as ammonia and orthophosphates; and chemical additives such as formalin and agricultural lime. The wastewater pollutant load depends on farm management practices such as stocking densities, feeding and fertilization rates, and the specific chemistry of the intake water. The effect of pollutants on the receiving body of water depends largely on its physical dynamics and characteristics — which vary greatly along the Texas coast.

An analysis of wastewater from three shrimp farms along the southern part of the Texas coast in 1994 showed high levels of TSS and low dissolved oxygen (DO), particularly during harvest (Lopez-Ivich 1996). The levels of nutrients and the relative oxygen requirements (measured as $CBOD_5$) varied considerably, perhaps due to intake water characteristics. (One farm draws water from the tidally influenced Arroyo Colorado, while another draws water from the hypersaline Laguna Madre.) At all farms, discharges and pollutant levels were highest during harvest, when ponds are completely drained to recover shrimp.

The cumulative impact of shrimp-farm wastewater discharges on Texas coastal waters as a whole, and the discharges of several farms on a single bay, is a serious concern. Already 1,500 acres of the Texas coast are devoted to shrimp farming. Matagorda Bay alone supports five shrimp farms. High levels of nutrients, TSS, and $CBOD_5$ from several farms could create conditions unsuitable for native organisms and result in biological and economic damage.

Chemicals used in coastal shrimp-farm operations are also at issue. In shrimp farming, chemicals are used to fertilize, sterilize, and fight bacterial and viral diseases. Although specific compounds used by Texas shrimp farmers are not currently identified, there are some agricultural chemicals commonly used in the industry. For example, inorganic fertilizers are used to stimulate phytoplankton blooms, and agricultural lime is used to neutralize soil pH in dry pond bottoms. The Food and Drug Administration (FDA) approves drugs to treat shrimp diseases. The FDA has approved the use of formalin, and several applications are pending for use of other chemicals in shrimp farming (USMSFP 1993). The Environmental Protection Agency (EPA), responsible for regulating chemicals used to treat water, has approved one algaecide for use in shrimp farming (Hopkins et al. 1995).

Shrimp-farm wastewater discharges have already been implicated as causing significant environmental impacts and economic harm. Sport-fishing guides on the Arroyo Colorado and the Laguna Madre, whose clients land redfish and spotted seatrout, among other species, blame highly turbid shrimp-farm discharges for declining sport-fishing productivity during farm discharge periods (B. Koch and L. Turner, pers. comms.). In Copano Bay and San Antonio Bay, water clarity is vital to successful sport fishing; the guides and residents of these bays note that even the perception of poor water quality keeps tourists away (L. Turner, pers. comm.). In Arroyo City, homes border the river where Texas' two largest shrimp farms discharge wastewater. Residents report drops in property values because of the foul discharges that flow past their homes (B. Koch and G. McRoberts, pers. comms.).

Potential for Introduction of Diseases and Exotic or Genetically Altered Shrimp Species

Texas coastal shrimp farms predominantly grow Pacific white shrimp (*Penaeus vannamei*). This species is native to Pacific waters off western Mexico south to Peru, and is the species preferred by the large shrimp-farming industry in Central and South America. Pacific white shrimp grow relatively quickly in farm ponds, and farmers regard them as a more profitable crop than native species, such as white shrimp (*P. setiferus*).

A large number of exotic (non-native) shrimp escaped in the 1980's into the Arroyo Colorado. State government agencies attempted to recover the shrimp, but many evaded capture. Although a few of these exotics were recovered from the wild the following year, exotic shrimp populations are not known to have become established in the wild (M. Ray, pers. comm.). Should exotic shrimp become established, the consequences are difficult to anticipate, in part because shrimp ecology is poorly understood. One possibility currently being investigated at the University of Houston is that an exotic shrimp species could exclude a native shrimp species from its preferred habitats (J. Lester, pers. comm.). Interbreeding between a native and an exotic species of *Penaeus* is a concern; weak hybrid *Penaeus* offspring have been produced in laboratory experiments. However, interbreeding in the wild may be unlikely due to differences in anatomy, breeding behavior, and other factors (Hopkins et al. 1995).

Perhaps a greater concern is the potential for breeding between native species and a domesticated line of the same species. Although there are no domesticated populations of any of Texas' native shrimp species, populations of other species, including the Pacific white shrimp, have been domesticated to some degree. Domestication typically results in reduction of genetic variability. If domesticated shrimp breed with wild shrimp, the genetic variability of wild shrimp populations could be reduced.

Viral and bacterial diseases have burdened Texas' coastal shrimp farms since the industry began. The result has been significant production loss due to shrimp mortality, reduced growth rates, and early harvesting. Laboratory studies confirm that some diseases, most recently the Taura Syndrome Virus, can be transferred from exotic to native shrimp at certain life stages under laboratory conditions (P. Frelier, pers. comm.). Fortunately no native wild shrimp populations are now known to be infected by this deadly virus.

The state requires that any exotic shrimp species stocked in Texas shrimp farms be "high health" shrimp derived from "specific pathogen free" populations.[3] These genetically "improved" shrimp are free of pathogenic agents with a known potential for significant economic impact. Use of "high health" shrimp is intended to prevent problems with diseases that could devastate farms' shrimp production, as well as wild stocks. Ideally "high health" postlarvae (PL's) are purchased by farmers from one of the three hatcheries in Texas. However, these hatcheries do not currently provide enough PL's to meet the demand of Texas shrimp farmers, which often forces farmers to import them. Of Texas' three hatcheries, only one was active in 1996. The shortage of PL's presents two problems. First, PL's imported from outside the country may not be reliably disease-free. (A 1996 viral outbreak is suspected to have originated from PL's imported from outside the United States.) Second, farmers must be able to fully stock their ponds in order to make money.

Poor Site Selection for Facilities

There are two main problems with site selection for shrimp farms along the Texas coast. First, Texas bays and lagoons are shallow, isolated from Gulf waters by barrier islands, and characterized by limited tidal movement. Wastewater discharges therefore may readily degrade adjacent habitats and interfere with recreation and other activities along the coast. For example, the average depth of Copano Bay, one of Texas' largest, is only 1.1 m. Copano Bay's "water residence time" (the time it takes the water to completely exchange with Gulf of Mexico waters through Aransas Pass) is three years (Orlando et al. 1991). Thus pollutants can remain in the bay for a very long time.

Second, shrimp farms located within residential areas have generated considerable conflict. In Arroyo City, two shrimp farms, Arroyo Aquaculture Association and Southern Star Shrimp Farms, are both located directly across the street from residents' homes. The farms' operations expose Arroyo City residents to public nuisances such as abhorrent odors, vermin, flies, and excessive noise. Nearby homes and property have lost value, inflicting economic hardship on the community's residents (B. Koch and G. McRoberts, pers. comms.).

Entrainment of Aquatic Life

Aquatic plants and animals are entrained (caught) by intake screens as coastal shrimp farms draw in bay water to fill ponds and exchange water. In fact, to supplement the shrimps' diet of commercial feeds, farms rely on entrainment of algae and other minute organisms that pass unharmed to ponds through intake screens. Other organisms are killed because they are too large to pass through the screen but not strong enough to move away from an intake pipe. Immense quantities of water are exchanged under current management regimes, potentially entraining large numbers of estuarine organisms in various life stages. This phenomenon creates a "by-catch" effect in which large numbers of nontarget organisms, such as larvae of commercially and recreationally important fishery species, are killed inadvertently during water intake. Although the impacts of entrainment from shrimp-farm intake systems have not been documented by scientific research, data from power plants indicate entrainment losses as a potential threat to some fish populations (Holland et al. 1986).

The Regulatory Structure

The Texas state government initially viewed its role not as a regulatory one, but as one of promoting shrimp farming to create jobs and a more diversified economy on the Texas coast. In 1986 the Texas Department of Commerce began to actively promote shrimp farming. In 1987 the state legislature passed a law exempting shrimp farms from state water-rights permit requirements (Texas Water Code Ch. 11.1421). In 1989 the Texas Fish Farming Act designated shrimp farming as an agricultural activity, giving shrimp farmers agricultural tax breaks. During the 1980's experts at Texas A&M University's Sea Grant Program began providing support and technical assistance to shrimp farmers.

The federal government has also

played a significant role in promoting the U.S. shrimp farming industry, which is largely in Texas. More than $20 million in federal funds over the past 10 years have gone to the U.S. Department of Agriculture's (USDA) Marine Shrimp Farming Program (USMSFP). The USMSFP was established to reduce the United States' $2 billion trade deficit in shrimp by developing technologies that would make domestic shrimp farmers competitive on the world market (Rosenberry 1995).

The current regulatory framework for shrimp farming in Texas evolved haphazardly and is widely recognized — by state legislators, regulatory agencies, shrimp farmers, environmental groups, and concerned citizens — to be inadequate. The 1989 Texas Fish Farming Act gave the Texas Department of Agriculture (TDA) responsibility for most aspects of shrimp farming, from marketing and promotion to environmental regulation. However, besides collecting license fees (Texas Agriculture Code Section 134.011), the TDA has never implemented a program.

Several state and federal agencies have limited authority to regulate shrimp farming in Texas. The Texas Natural Resources Conservation Commission (TNRCC) has authority to require state permits for any activity producing a wastewater discharge (Texas Water Code Sections 26.034 and 26.121); however, only recently has the TNRCC required a few shrimp farms to apply for these permits. Similarly, U.S. Clean Water Act (CWA) regulations require that most Texas coastal shrimp farms obtain a National Pollution Discharge Elimination System (NPDES) permit (40 CFR Ch. 122.24); however, the U.S. Environmental Protection Agency (EPA), which administers NPDES permits in Texas, has not enforced this regulation. During the 1996 production season, only one of the six shrimp farms that discharged wastewater had a state permit, and none had a NPDES permit.

In the early 1980's Harlingen Shrimp Farms, Texas' first commercial coastal shrimp farm, applied for both state and federal wastewater discharge permits. TNRCC determined that the farm would not need a state permit because it was not expected to produce a significant source of pollution. The EPA issued Harlingen Shrimp Farms a NPDES permit during its first year, but in subsequent years did not require one from this farm (Jaenike 1997) or any other coastal shrimp farm in Texas. Harlingen Shrimp Farms' experience may have set the stage for the state's weak posture on shrimp-farm effluent.

The Texas Parks and Wildlife Department (TPWD) and U.S. Army Corps of Engineers (ACOE) are actively using their authorities to regulate some aspects of shrimp farming. The TPWD exercises its authority requiring exotic species permits for import, sale, possession, or release of exotic shrimp (Texas Parks and Wildlife Code Section 66.007, Texas Agriculture Code Sections 134.020, and 30 TAC Ch. 57.111-.134), and requiring farmers to use "disease-free" exotic shrimp for culture (31 TAC Ch. 57.114). To lower the risk of escapes, the TPWD ensures that farms have a three-screen system at the discharge, and requires that ponds be constructed above the 100-year flood plane. The ACOE, pursuant to the U.S. CWA, requires all farms to obtain permits for placing intake pipes across intertidal wetlands into the bays. However, these agencies' authorities are not broad enough to allow them to provide more extensive environmental safeguards.

This piecemeal regulatory structure has serious gaps. Perhaps most importantly, no agency is responsible for monitoring or controlling diseases during the production process. Although TPWD issues exotic species permits, they have no authority over shrimp during production. In the case of a disease outbreak in

Southern Star Shrimp Farm is Texas' largest, with 94 five-acre ponds. Driven by citizen protests, the state regulatory agency required this farm to obtain a state wastewater permit in 1994, making it the first of only three farms to date to obtain a permit. Courtesy of Texas Parks and Wildlife Department.

either exotic or native shrimp species, TPWD can ask farmers to voluntarily quarantine infected ponds and halt discharges, but they have no authority to enforce such actions.

Mounting pressure on government agencies from coastal citizens and environmental groups is prompting change. After several attempts to officially exclude coastal shrimp farms from the state's wastewater discharge permitting process by including them in a "permit by rule" procedure, TNRCC in June 1997 elected to require all coastal shrimp farms to obtain individual permits (30 TAC 321.271-321-280, Subchapter O). At a minimum, this process will obligate shrimp farmers to provide detailed plans for wastewater treatment, consider the impacts of their operations on the surrounding environment, and participate in public hearings.

Complimenting this process, the TNRCC and TPWD have established a Memorandum of Understanding (MOU) for interagency review procedures for wastewater permits (30 TAC 7.103). The MOU contains two important elements. First, TPWD must review and comment on all wastewater discharge permit applications from coastal shrimp farms before TNRCC makes any determinations. Second, for new exotic species applications, TPWD cannot issue a permit to a shrimp farmer until he has received his state wastewater-discharge permit.

TPWD has drafted rules to control disease outbreaks. The rules would require certification of exotic shrimp as disease-free before importation; establish quarantine and testing procedures to be implemented following deaths of shrimp (of both exotic and native species) on farms; and require monthly disease monitoring of all shrimp ponds that discharge to state waters. To close a loophole in the TPWD/TNRCC MOU, existing shrimp farms would be required to obtain a TNRCC permit (or prove that they are diligently pursuing a permit) before receiving a renewal of an exotic species permit. Finally, shrimp hatcheries in the state would be required to certify monthly that their stocks are disease-free and to document this certification to TPWD. If hatcheries cannot provide certification, they would be quarantined. These rules may be implemented in late 1997.

At the federal level, EPA in 1996 began to require Texas coastal shrimp farms to apply for NPDES permits. Although EPA has received applications from eight of Texas' shrimp farms (as of April 1997), it may be as late as 1998 before permit applications are reviewed because EPA is currently developing "conditions" to be used in evaluating these permits (K. Baskin, pers. comm.).

The Texas State Legislature has now recognized the state's need for leadership to help correct these problems and to balance the benefits of a more diversified coastal economy with the need to protect natural resources and existing coastal uses. In September 1996 a Senate Natural Resources Interim Subcommittee issued a report, *Texas Aquaculture Industry—Aquaculture and Its Effects on State Bays and Estuaries*. This report, which focuses almost exclusively on coastal shrimp farming, recommends interagency permit review, delegation of responsibility for disease control during production, and scientific studies to determine the effects of wastewater discharges and the causes of disease transfer to and among farms. Implementation of these recommendations alone would not establish sufficient environmental safeguards. Nevertheless, they are an important step toward acting on the environmental concerns of citizens and environmental groups regarding coastal shrimp farming.

Citizen and Nongovernmental Actions

Citizens concerned about environmental degradation from coastal shrimp farming have organized a grassroots movement along the Texas coast to reform shrimp-farming practices. The movement began in south Texas in 1991, with the formation of the Coalition for the Protection of the Arroyo Colorado. This group and others have been imploring state agencies and their legislative representatives to better regulate the three coastal shrimp farms in south Texas. They ultimately persuaded TNRCC to require Arroyo Aquaculture Association and Southern Star Shrimp Farms to apply for state wastewater-discharge permits. The groups have helped to make the public and government officials aware of the economic and environmental harm to neighboring bays, estuaries, and communities caused by coastal shrimp-farming operations.

This grassroots movement has spread north along the Texas coast as the coastal shrimp-farming industry has grown. Grassroots organizations include the Matagorda Bay Foundation, the Coalition for the Protection of Hynes Bay and the Aransas National Wildlife Refuge, Neighbors Interested in the Copano Environment, the Calhoun County Resource Watch, and the Coalition for the Protection of Copano Bay. These groups, following the south Texas example, are attempting to work with state agencies and legislators to compel coastal shrimp farms to implement better environmental safeguards.

National and regional environmental organizations are also involved in these efforts. The Audubon Society, Sierra Club, Coast Conservation Association (CCA),[4] and Environmental Defense Fund (EDF) have joined forces with the grassroots movement. In 1995 the CCA led an unsuccessful attempt to enact legislation requiring compilation of data on the characteristics of shrimp-farm wastewater, and placing a moratorium on the construction of new farms until an appropriate regulatory structure was in place. In 1996 EDF issued a report detailing the environmental problems caused by the coastal shrimp farming industry in Texas (Baker 1996). Early in 1997 EDF prepared a briefing book with materials to assist citizen groups in providing key information to legislators and their staffs (EDF 1997).

These grassroots and larger organizations have forged an informal alliance, and are now working together to influence state policies on coastal shrimp farming in Texas. Alliance priorities include:

- a study of the impacts of shrimp-farm discharges and water use,

- a moratorium on new discharges until a study of environmental impacts is completed,
- enforcement of the state's waste-water-discharge permitting authority,
- implementation of a disease-monitoring and -control program,
- a greater voice for coastal county governments in making siting decisions, and
- performance bonding to provide funds in case of emergencies.

Many of these priorities were compiled in a "citizen's bill" for presentation to the 1997 Texas State Legislature.

Driven by the efforts of citizen's and environmental groups, the 75th Texas State Legislature nearly passed promising new legislation sponsored by Senator J. E. "Buster" Brown and Representatives Judy Hawley and Gene Seaman. This legislation represented both agreements and compromises among citizen's groups, environmental groups, shrimp farmers, and legislators on several key points, including:

Studies — Two studies should be conducted, with partial funding from industry. One study would concern the impacts of waste discharges, the other potential vectors for disease transmission. The study would provide critical information, although it would not be as comprehensive as the alliance recommended.

Moratorium — A short moratorium (until May 1998) should be implemented.

Permits and licenses — TNRCC, TPWD, and the Texas Animal Health Commission (TAHC) should jointly regulate the industry. All coastal shrimp farms would obtain state wastewater-discharge permits from TNRCC, exotic-species permits from TPWD, and an aquaculture license from TAHC. Environmental consequences would be considered before permits or licenses were issued.

Disease monitoring and control — The TAHC should be responsible for disease control on farms, and TNRCC should halt discharges from ponds with diseased shrimp. The alliance realized that stronger controls are necessary but might be difficult to achieve before the proposed studies were completed.

Unfortunately no agreement was reached on creating a greater role for coastal county governments in siting of shrimp farms or on requiring performance bonds.

The Texas Senate passed this bill on April 18, 1997, and the House of Representatives' State Recreational Resources Committee also unanimously passed it on May 19, 1997. Unfortunately a procedural controversy unrelated to the shrimp-farm legislation nullified consideration of 52 Senate bills awaiting first-round debate in the House of Representatives, including the shrimp-farming legislation. Because the Texas State Legislature meets only every other year, shrimp-farming legislation cannot be considered again until 1999.

Unfortunately, without this legislation, threats from polluted discharges, disease outbreaks, and poor siting may

Arroyo Aquaculture Association — Although regulated by the state, this farm's state permit allows it to discharge up to 180 million gallons per day into the Arroyo Colorado, a state designated shrimp nursery. Courtesy of Texas Parks and Wildlife Department.

continue to endanger the state's bay and estuarine resources and resource users.

Texas is making limited progress toward more environmentally responsible coastal shrimp farming. TNRCC's new commitment to requiring state wastewater-discharge permits and new TNRCC and TPWD interagency coordination procedures are steps in the right direction.

Discussion: 1997 and Beyond

In retrospect, the 15-year history of coastal shrimp farming in Texas has revealed that shrimp farmers and state regulators could have taken early steps to either avoid or mitigate the industry's environmental problems. For more than a decade, Texas shrimp farmers have had indisputable evidence from not only Texas but from around the world that the shrimp-farming industry has caused environmental degradation and economic hardship in many communities. Taiwan provides a good example, especially since many of Texas' shrimp farms are backed by Taiwanese investors.

Taiwan was a world leader in farmed-shrimp production until 1989, when the industry collapsed, never to recover. Production plummeted because of devastating shrimp diseases, which appear to have resulted from the combined effects of very high stocking densities, too many farms too close together, and poor water quality (Rosenberry 1994). Given this and other examples, Texas shrimp farmers and state officials should have recognized that cautious shrimp farm development and environmentally conscientious farm management were in order from the very start, to protect the interests of both shrimp farms and coastal communities.

Second, early warnings of environmental problems and strongly voiced public concerns should have prompted Texas to reevaluate its minimal regulatory policies. For example, in light of the state's inexperience with shrimp farming, TNRCC and EPA should have used their existing wastewater-discharge permitting authorities to clearly identify and take action to prevent potential wastewater pollution problems and conflicts with existing economic uses of coastal areas. Many questions still remain unanswered. What are the assimilative capacities of Texas' bays and estuaries to handle shrimp-farm wastes? What are the cumulative impacts of several farms on one bay system? How real is the threat of either diseases or escaped cultured shrimp impacting native populations? Texas agencies still have considerable work ahead.

Third, Texas should have required real evidence of economic diversification and job creation on the coast in order to justify continuing to promote the industry. Although the state's promotional efforts have helped to establish the coastal shrimp-farming industry, coastal communities are not clearly reaping extensive benefits. The estimated economic impact in 1994 of Texas' shrimp-farming industry — including production, sale of feeds, and purchases of equipment and supplies, in addition to on-farm activities — was more than $40 million, with 868 jobs created (USMSFP 1995). Much of this economic impact is realized outside of coastal communities, and some is realized outside the state. Coastal communities have gained one new processing plant, one operational shrimp hatchery, and a few jobs on shrimp farms. (Austwell Aqua Farms, for example, employs just six full-time people.) The state should analyze the true costs and benefits of the shrimp-farming industry, particularly to coastal communities where farms are located, before further promoting the industry.

The shrimp-farming industry itself, not just Texas state government, must take responsibility to prevent further environmental degradation. The intense pressures from coastal citizens groups and imminent state regulatory action have driven the shrimp-farming industry to investigate options to operate in a more environmentally friendly manner. Industry is beginning to implement low-technology best management practices, such as holding wastewater in settling ponds to clean it before discharge, and reducing or eliminating routine water exchanges to reduce overall discharges.

Researchers at Waddell Mariculture Center in South Carolina are experimenting with more elaborate methods for environmentally sound shrimp farming. Waddell researchers are recirculating pond water, cleaning it with natural filtering systems involving wetlands, bivalves, and aquatic plants. Their goal is to nearly eliminate wastewater discharges (Sandifer and Hopkins 1996). Researchers at the University of Texas Marine Science Institute are also experimenting with a recirculating shrimp-farm system. Water is cleaned with "biofilters" of waste-decomposing microorganisms and then treated with ozone to kill microorganisms before being piped back into shrimp tanks (C. Arnold, pers. comm.). This technology will be tried out on a commercial scale on the Texas coast beginning in late 1997 (W. Pettibone, pers. comm.).

High-technology and capital-intensive indoor recirculating systems, which seek to raise shrimp in a completely enclosed and totally controlled environment, have been attempted in Texas, but without clear success to date. The most prominent of these is Penbur Farms, a multimillion-dollar enclosed shrimp farm in central Texas that has had minimal commercial production in its first two years of operation. Penbur has been poorly managed, however, and it remains unclear whether the farm's technology is feasible. The farm came under new management early in 1997, and environmental organizations and others hold out hope that it will become a successful model for environmentally friendly shrimp production.

Environmental groups will continue to actively work to make shrimp farming environmentally sound in Texas and elsewhere. EDF, for example, is considering the use of market strategies for the global shrimp industry that might include approaches such as "eco-labeling" for shrimp, similar to "dolphin-safe" labeling for canned tuna (Goldburg 1997). Farms that produce shrimp in an environmentally friendly manner would be certified, possibly allowing producers to sell shrimp at higher prices to environmentally conscientious consumers.

Worldwide there are at most only a few examples of environmentally sustainable commercial shrimp farms. Nevertheless, there is no inherent reason why shrimp farming must be an environmentally destructive industry. An environmentally sound shrimp-farming industry would benefit Texas and the United States. If the industry's problems can be solved, farmed shrimp can help satisfy the U.S.'s multibillion-dollar appetite for shrimp without threatening Texas' treasured bays and estuaries.

Texas Shrimp Study Notes

[1] Known as Laguna Madre Shrimp Farms at that time.

[2] Formerly known as Taiwan Shrimp Village and Hung's Shrimp Farm, respectively.

[3] "Specific pathogen free" (SPF) refers to captive populations — known to be free of certain diseases – that are maintained and selectively bred at a breeding center. "High health" refers to shrimp derived from SPF populations that have been appropriately protected from disease and found negative for diseases in periodic screenings.

[4] Formerly the Gulf Coast Conservation Association or GCCA, an organization with many sportsfishers among its members.

After the Goldrush: Salmon Aquaculture in New Brunswick

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Introduction

Charlotte County in southwestern New Brunswick, Canada, lies just east of Washington County, Maine, across the St. Croix River. The county stands guard to the mouth of the Bay of Fundy and encompasses the inhabited islands of Grand Manan, Deer Island, and Campobello, 200 smaller islands, and more than 50 small mainland communities.

The coastal and marine ecosystems of Charlotte County are distinguished by strong currents passing between its islands and ledges and by very high tides (6 m/19.7 feet). These features ensure that nutrients are well mixed and distributed. The result is a marine region noted for its high biological productivity and diversity. These ecological conditions foster the traditional fisheries — such as herring, lobster, scallops, and groundfish, and to a lesser extent clams, periwinkles, and dulse — as a cornerstone of the county's social and economic well-being, despite recent downturns in several wild fisheries in Atlantic Canada. They have also provided the appropriate conditions for the development of salmon aquaculture, which has additionally been supported by scientific curiosity, generous government support, and (until recently) good market conditions.

Introduced in 1978, Atlantic salmon farming in New Brunswick is still located exclusively in Charlotte County. Annual sales approach CDN$100 million, and represent 95 % of the total value of aquaculture products in Atlantic Canada. Since its beginnings in New Brunswick, salmon aquaculture has been considered by all levels of government as an economic miracle for a region beset by seasonal employment fluctuations and dramatic declines in marine fish populations. This has made government reluctant to adequately consider the real costs of the industry, both ecological and economic. As a result, government has failed to establish a regulatory and policy framework for the industry that would meet even minimal sustainability criteria.

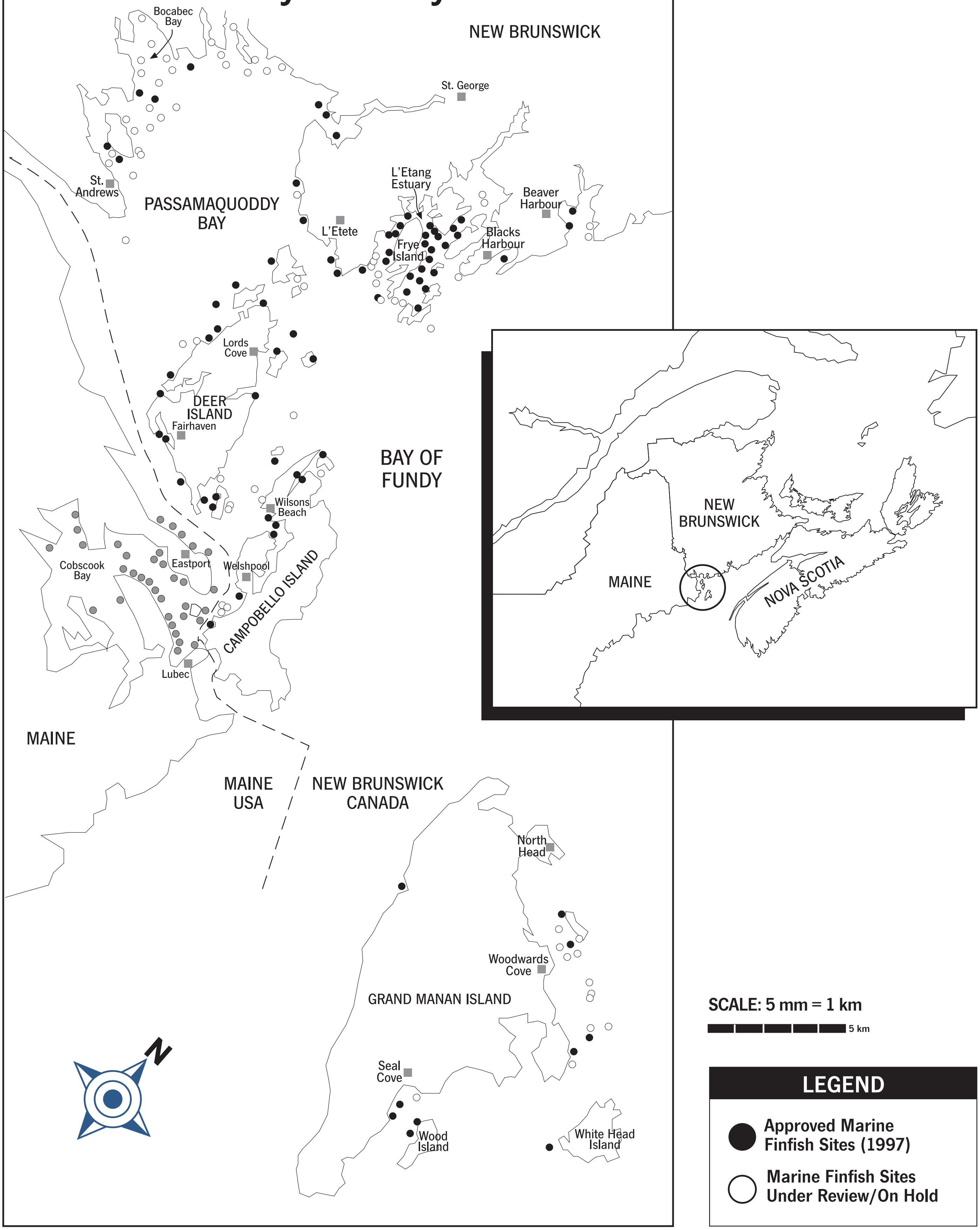
This case study examines New Brunswick's salmon aquaculture industry from its inception and outlines the resulting public policy issues, including environmental impacts, public subsidies, conflicts with traditional fisheries, and constraints on the future development of finfish aquaculture in this region.

While this case study examines only the Canadian industry, Cobscook Bay in Maine is adjacent to the Canadian waters of Passamaquoddy Bay and has the highest concentration of salmon aquaculture activity in that state. In assessing the overall impact of this industry on the marine ecosystem in the outer Bay of Fundy, it is important to consider the nature and extent of the entire finfish aquaculture enterprise in the region. The accompanying map includes both Canadian and American operations.

The Industry

Prized by commercial and recreational fishers alike, Atlantic salmon, "the king of fish," has been the subject of extensive scientific research and management activities in Canada for at least a

Marine Aquaculture Sites: Bay of Fundy



century. From 1969 to 1972 a large commercial firm, Sea Pool Fisheries, made the first attempt at rearing Atlantic salmon as a commercial product in a land-based seawater facility in Nova Scotia. More than $5 million was invested in this operation. When it failed because of financial and technical mismanagement, aquaculture acquired a bad reputation. Less ambitious attempts to grow Atlantic salmon in marine sea cages were also unsuccessful.

In 1976 Dr. Arnold Sutterlin, a scientist at the federal Department of Fisheries and Oceans Biological Station in St. Andrews, New Brunswick, accepted an invitation to spend a sabbatical year in Norway. In the early 1970's Norwegians had made some major breakthroughs in raising Atlantic salmon in marine enclosures. Dr. Sutterlin's considerable knowledge of salmon physiology, particularly the process of smoltification — the physiological and behavioral changes young salmon undergo in order to make the transition from freshwater to saltwater — was of special interest to them.

When Dr. Sutterlin arrived in Norway, annual production of farmed-reared salmon in that country hovered around 2,000 tons. He became convinced of the feasibility of a similar industry in Atlantic Canada, envisioning that salmon aquaculture could provide a secure, community-based industry to buffer the troughs of the inshore herring weir fishery that dominated the fishing economy at the time (Buerkle 1993). (Weirs are large stationary herring traps built adjacent to shorelines.) On Dr. Sutterlin's return to Canada, he and other federal government scientists assisted the New Brunswick government, a private company, Marine Research Associates, and some herring weir fishermen in establishing an experimental salmon farm in Lord's Cove, Deer Island. In 1978, 3,500 salmon smolts were placed in sea cages and in 18 months 6 tons of salmon, at 3.3 kilograms average weight, were ready for market. They sold at $7.70/kg (dressed), for a total value of more than CDN$46,000, and demonstrated that salmon farming was possible in this region.


New Brunswick salmon farm. Courtesy of Gilles Daigle.

Nonetheless the industry got a slow start. By 1984 only five salmon farms were operating, producing 255 tons. A major constraint on salmon aquaculture development to that point had been the availability to commercial growers of smolts, young salmonids that are ready to make the transition from freshwater to a marine life (Saunders 1995). Until 1979 there had been no market demand for smolts and therefore no private sector interest to fill the demand. Government hatcheries supplied the new industry with leftover smolts after stocking rivers.

Then in 1985 Sea Farm Canada, a large Norwegian company, in partnership with the equally large Canadian company Maple Leaf Mills, applied for permission to build a commercial smolt production facility at Digdeguash Lake, just inland from the coastal salmon sites. A year later the new hatchery put 1 million smolts on the market. The same year the local company Connors Brothers Ltd., the largest sardine producer in Canada and a

Salmon being chilled during harvesting. Courtesy of New Brunswick Department of Fisheries and Oceans.

subsidiary of George Weston Limited, Canada's largest food conglomerate, began a commercial smolt-production operation. (Connors Brothers also began a sea-farming operation and would become, after a major buy-out in Maine, the single largest producer of farmed salmon on the East Coast of North America.)

With a key constraint to production overcome, the number of salmon farms in south-western New Brunswick jumped from 5 in 1984 to 28 in 1986, all within a small area at the mouth of the Bay of Fundy. The average per- site production of salmon was 25 tons (more than 7,000 fish) raised in eight to ten sea cages, almost triple the production of the first farm. But these farms were profitable only as long as the market price did not fall below $7.80/kilogram ($3.55/pound). In 1986 the price for farmed salmon was $12.69/kilogram. This high price drove ever-increasing demand for farm-site leases by new entrants into the industry. That year a moratorium of sorts was imposed on new site applications to allow the government to catch up on the backlog of approvals. However, new sites continued to be announced as the department worked through the backlog.

By the late 1980's the Charlotte County coast had the look and feel of a gold rush. But instead of sluice boxes on riverbanks, sea cages of all shapes and sizes dotted the shoreline. There were 52 farms in operation at the end of the first decade, a tenfold increase in six years. Total tonnage production value had reached CDN$71.9 million, and service industries needed to support the salmon rush such as net and feed manufacturers had been established. What were locally referred to as "salmon mansions" sprang up along the winding roads to the coast, the first outward evidence that salmon farming was paying off for those early farmers.

The rapid growth of the industry led some salmon farmers to realize they needed a coordinated voice to represent their interests. In 1987 they banded together to form the New Brunswick Salmon Growers Association (NBSGA). This organization's mandate was to engage in government and community relations; research and development into technical aspects of salmon; and the promotion of New Brunswick salmon to major markets such as New York and New England (75%-80% of Charlotte County salmon goes to the U.S. market) (Telegraph Journal 1996b). Over the next decade the association would receive more than CDN$4.3 million in government contributions for its work.

By the early 1990's the number of new farms coming into production and the volume of salmon being produced began to show signs of slowing down. In 1990 there were 52 farms. Five new farms were added in 1991 and three in 1992, bringing the total to 60. Between 1992 and 1996 a total of 14 new farms were licensed, bringing the total to 74. And while salmon production had been almost doubling every year since 1979, the annual volume was rising only 14%-17% per year. At the same time, the price paid to the farmer was also dropping.

Government as Catalyst and Industry Promoter

The federal Department of Fisheries and Oceans (DFO) supported salmon-related research and development in New Brunswick even before the first salmon farm was ever established. Once the industry began, this support took the form of contract studies, the supplying of smolts to pioneer fish farmers, biological advice to interested parties, and access to fish health services. DFO established partnerships with universities and other research organizations to access research grants from government sources. The federal department named Employment and Immigration Canada (now Human Resources Development Canada) sponsored unemployed people in aquaculture-technician training programs that were starting up at provincial community colleges.

The provincial Department of Fisheries, with its historic mandate to promote the fishing industry (the federal DFO was the regulatory body) took longer to get its feet under it. A 1983 policy made no particular note of salmon aquaculture as an up-and-coming industry, not distinguishing it from several other aquaculture efforts (New Brunswick Department of Fisheries 1983). The provincial government at that point had no sense of salmon aquaculture's potential and thus was wholly unprepared to consider regulation when the industry took off. Only several years later did the industry become regulated, well after it had established itself as a major development in the coastal zone.

The real engine of the salmon gold rush was the sudden availability of government monies to develop the industry. The Atlantic Canada Opportunities Agency (ACOA) was established in 1984 as another in a long line of regional agencies with an explicit mandate to infuse capital into underdeveloped regions of the country in the name of economic development.

From 1985 to present, ACOA pumped more than CDN$34 million into New Brunswick's salmon aquaculture industry. Sixty percent of this money made its way to the salmon industry as direct contributions and grants for farm, hatchery, and processing-plant expansions; marketing; and research and development (Fig. NB-1). The balance took the form of interest-free and provisionally repayable loans, interest buy-downs, and loan guarantees. In addition, millions of dollars were available through a variety of other federal and provincial initiatives, including joint agreements.

Despite the rapid growth of the industry fueled by this funding, there was still pressure to expand further and faster. In 1988 the House of Commons Standing Committee on Fisheries and Oceans undertook a study to identify barriers to aquaculture development in Canada in order to facilitate growth of the industry.

Its report cited (as did a 1984 Industry Task Force report) jurisdictional issues, poorly designed and uncoordinated financial assistance programs, gaps in fish health and diagnostic services, and the lack of national objectives (a "grand design") as factors preventing the industry from fulfilling its potential.

Government As Industry Regulator

With both the federal and the provincial government heavily promoting, supporting, and subsidizing the growth of salmon aquaculture, neither was in any position to credibly regulate the burgeoning industry. For the first 10 years (1979-1989) finfish aquaculture was virtually unregulated. Individual farms required cage-site approvals and licenses, which were administered by two provincial government departments. The Department of Natural Resources and Energy administered Crown lands (lands owned by the government) and granted leases within the coastal zone (submerged Crown land) for sea farm operations. The Department of Fisheries granted licenses to operate. But no environmental permits or approvals were required by environment departments at either the federal or the provincial level.

The only legislated environmental requirements came under the federal Fisheries Act, which assigns responsibility to DFO for protecting fish habitat. However, DFO has never exercised its powers to deny permission to site an aquaculture operation where it might harm fish habitat or to charge a farm for releasing substances "deleterious to fish" into the water column. Instead it has assumed an

Figure NB-1. Funding Provided by the Atlantic Canada Opportunities Agency (ACOA) in Support of New Brunswick's Salmon Aquaculture Industry from 1985-1996

Type of Financial Assistance	Amount of Financial Contribution (SCND) by Project Type (number of grants)			Total Financial Assistance
	Sea farm development, feasibility studies, workplans, hatcheries, processing plants	Marketing, research and development, trade shows, conferences	Cage, net, feed, and boat manufacturing, fish health services, fish waste disposal	
Contributions and Grants	10,403,112 (116)	8,547,354 (73)	4,560,468 (45)	23, 510,934.00
Provisionally Repayable Contribution	73,640 (1)		228,240 (1)	301,770.00
Repayable Contribution	3,856,818 (25)	100,000 (1)	1,256,636 (9)	5,213,454.00
Interest Buy-down Loan	1,485,789 (28)		544,478 (9)	2,030,267.00
Action Loan	487,500 (2)			487,500.00
Loan Insurance	2,804,430 (6)			2,804,430.00
Total Financial Assistance	**19,111,289.00**	**8,647,354.00**	**6,589,822.00**	**34,348,465.00**

advisory role to the provincial government in siting decisions and a research role on environmental impacts. As an adviser to the provincial government, DFO has recommended against several sites based on fish habitat considerations. In a majority of cases, however, the provincial department has ignored these recommendations.

Not until December 1988, ten years after the first fish went in the water, did the provincial government introduce an Aquaculture Act, to be administered by the Department of Fisheries. By this time, 52 farms were operating and producing fish valued at nearly CDN$75 million. The impetus for the act came largely from the onslaught of applications for new farm-site leases and licenses; government needed rules for orderly development of the industry. Despite the urgent need for regulation, the act was not given Royal Assent proclaiming it enforceable until October 1991, when the regulations to the act were finally prepared.

The act includes conditions to which licenses may be subject, such as measures to prevent disease, parasites, toxins, or contaminants from spreading to other aquaculture sites and to prevent environmental degradation. Licenses now limit production to 18 kilograms (about 5 full-grown salmon) per cubic meter of cage space.

Licensees must submit annual reports containing environmental monitoring records, although no regulation spells out exactly what parameters these records must include or what minimum standards must be met. Licensees must also maintain accurate records on the presence of diseases and submit reports on the types and amounts of any chemotherapeutants applied at each site. However, the public does not have access to the information provided in these environmental monitoring and chemotherapeutant reports, which are deemed confidential by the Aquaculture Act. The minister refused a request for such information made by the authors under the provincial Right to Information Act.

Worker at salmon netpen. Courtesy of New Brunswick Department of Fisheries and Oceans.

The regulations empower the provincial government to refuse to issue a lease or occupation permit, and to refuse to issue, renew, or amend an operating license if the following conditions exist: conflicts with other fishery activities; conflicts with other resource users; interference with ecologically or environmentally sensitive areas; or unacceptable environmental risks. Many examples exist of approvals that should not have been issued under these conditions.

In 1989 full jurisdiction over the industry was consolidated within the provincial fisheries department, starting with a change of name to Department of Fisheries and Aquaculture (DFA). A protocol was signed transferring responsibility for leasing marine sites for aquaculture purposes from the Department of Natural Resources and Energy to DFA. In addition, a federal-provincial Memorandum of Understanding (MOU) gave DFA lead responsibility for aquaculture development and the licensing and leasing process, subjugating federal fish habitat responsibilities to provincial discretion. With no other department having jurisdiction, this left DFA with the double, and conflicting, duties of both promoting and regulating the burgeoning salmon aquaculture industry.

Once in full command, DFA established the Aquaculture Site Evaluation Criteria Committee, which comprised representatives from industry, interest groups (not environmental), and government agencies charged with providing advice on appropriate guidelines for decisions on leasing marine sites. DFA also set up the Aquaculture Environmental Coordinating Committee, which comprised representatives of the salmon industry and federal and provincial government agencies charged with coordinating environmental monitoring activities for salmon farms.

DFA continued to provide generous support to the industry. This included free fish-health and diagnostic services through the services of a fish veterinarian. Also provided were scuba-diving services to collect morts (dead salmon) and to check nets and cages for damage and for "fouling" by the growth of marine organisms.

A Public Environmental Agenda Emerges

Not everyone was completely enamoured of the industry and its economic potential. Coastal residents and conservation groups became concerned about waste discharge from aquaculture operation, loss of coastal habitat, and the use of antibiotics and pesticides. They also raised questions about the danger of genetic "pollution" if escaped farmed salmon should mate with wild stocks, as well as the danger of disease transmission from farmed to wild stocks.

After a few years of scrutinizing the burgeoning aquaculture industry, in June 1990 the Conservation Council of New Brunswick, the largest citizen's environmental watchdog group in the province, released the first comprehensive statement about the ecological implications of seacage aquaculture in Atlantic Canada. The report, entitled *Aquaculture in the Bay of Fundy: The Need for Sustainable Development* documented a number of problems that had emerged over the previous half decade. In the absence of routine environmental monitoring information about New Brunswick facilities, the Conservation Council's report relied heavily on experience and research in other parts of the world for its analysis, predicting that the problems were either present but not acknowledged, or predictable, given the growth and concentration of the industry.

The Conservation Council report stated that nutrient loading from uneaten feed and salmon feces threatened marine life through eutrophication, habitat degradation, and the increased production of algae and phytoplankton. It also cited the lack of information on the fate and effect of antibiotics, pesticides, and biocides used to control disease and parasite outbreaks. Genetic pollution caused by escaped farmed salmon breeding with wild stocks could cause drastic alteration in the genetic makeup of local salmon stocks, potentially eliminating entire salmon populations from particular rivers. Genetically engineered "super salmon" would pose a similar threat. The report contained a number of recommendations for greater environmental regulation and development of a coastal-zone management plan. It also urged a moratorium on finfish aquaculture until legally binding environmental controls were implemented.

This marked the first time the salmon aquaculture industry, touted as an economic miracle, had been publicly called to task for its environmental implications, actual and potential. Both the industry and government reacted very strongly. The provincial daily newspaper, *The Telegraph Journal*, carried the story "Pollution Charge Upsets Province's Fish Farmers," leading with the statement that New Brunswick fish farmers have "taken offence at a[n] environmentalist's group which says their industry is polluting the Bay of Fundy." The New Brunswick Salmon Growers Association took the position (also the position of DFA) that the salmon would be the first to suffer if fish farming was polluting the ocean. Then-president Blair Moffat stated, "Salmon farming requires clean water and there are salmon farms stocked with salmon that have operated for almost ten years with no negative impact or loss of fish." (This statement was made despite disease problems at the cage sites exacerbated, if not caused, by the conditions described by the Conservation Council report.)

Even the Minister of Fisheries and Aquaculture stepped into the fray, an indication that the Conservation Council report cut close to the bone. Hon. Denis Losier was quoted as saying the claims concerning the effects of aquaculture on the marine environment were "unfair." In a prepared statement, the Minister said he wished to "set the record straight before New Brunswick's aquaculture industry is unjustly depicted as destroyer of the Bay of Fundy marine environment." He stated, "In setting up the aquaculture industry we have consulted various industry, government, scientific and local groups to ensure the orderly development of aquaculture would take place within a sustainable development framework."

The defensiveness of the industry association and the Minister did not go unnoticed or unchallenged. An editorial in the Charlotte County weekly paper called Denis Losier's reaction "knee-jerk." Although supportive of the $70 million industry in the county, editor Tom Moffatt wrote:

> *When criticisms were made by the Conservation Council and two fisheries organizations [Fundy Weir Fishermen's Association and the Charlotte County Clamdiggers' Association] of the province's monitoring and regulation of salmon rearing, Losier's reaction was to vehemently and bitterly attack any and all of the criticisms, and to attack the individuals who made the points. Aquaculture is too valuable in southwestern NB for Losier's attitude . . .The criticisms of the organizations concerned have a basis in fact. The province does not have an overall policy for the salmon farming industry. It keeps talking about declaring the Aquaculture Act, but it hasn't done so. Losier does not have an effective policy for determining where new sites should or should not be placed in order not to interfere with other vital fisheries. Recent decisions . . . show this clearly, when decisions on specific sites were made against strong advice of ecologists and fisheries biologists.*
>
> *The relations of personnel in DFA have too often been too cozy with those in the industry . . .There must be an independent enforcement service, for the sake of the aquaculture industry. At present, there is insufficient information about the effects of salmon rearing on the shallow water areas in which many are situated. And there is little information on the effect of chemicals coming from salmon into the water, which may effect the movement of other species like herring which fear salmon* (St. Croix Courier 1990).

Finally the issues had been flushed out. Charlotte County residents had been observing greasy coatings on beach rocks, smelly deposits on clam flats, and increased presence of algae in the water. Their largely anecdotal concerns, which had been discussed only informally on wharves and in kitchens, had now been given a voice. Despite its denials and protestations, the government could not ignore the message that the industry was being watched.

Environmental Problems Unmasked

The provincial Department of the Environment (DOE) had neither the mandate of nor expertise in marine environments, nor was there provision in provincial legislation for environmental-impact screening of potential or existing cage sites. Prompted by concern within the department and growing public pressure, DOE requested to monitor existing cage sites for certain environmental criteria. This request was granted, and funding was provided for a limited program. DOE got down to the business of monitoring cage sites in 1991.

Meanwhile the Huntsman Marine Science Centre, a university-based research center, presented its preliminary results of a two-year study on the environmental effects of aquaculture on bottom habitat under four salmon farms at the 1991 annual meeting of the Aquaculture Association of Canada in St. Andrews, New Brunswick (Lim 1991). The study suggested that impacts on the bottom were limited to the area immediately below the cages and that no effects were detected 50 meters from the cages (Pohle et al. 1994). However, other studies of salmon farms have demonstrated that benthic impacts can be measured up to 150 meters away from cages (Weston 1990) and within an area up to 10 times larger than the farming area, depending on the scale of farm operation (Homer 1991).

The Huntsman study did confirm what had been reported in a number of other studies: that there was an increase in the number of *Capitalla capitata,* a polychaete worm used as an indicator of organic enrichment. At one site, the number of *Capitalla* rose from a seasonal low in the summer of approximately 3,000 worms per square meter beneath the cage to a seasonal high of almost 20,000 per square meter by the fall. Perhaps the most significant result of the study was data on how rapidly the bottom community had changed with the onset of farming. Despite the limited scale of operation at one site, researchers found significant reductions in species diversity and increases in bacterial biomass within two months of commencing operation.

The results of the first year of monitoring by the Department of Environment were released to industry at the Aquaculture Association of Canada's annual meeting in Vancouver, British Columbia, in 1992. The report found that industry's reliance on the high tides and strong currents of the Bay of Fundy to supply clean, oxygenated water and to flush out oxygen-depleted water and soluble waste products had been misplaced. Despite what had been often described as a "veritable river flowing through most sea cages," 37 of 48 sea-farm sites monitored in 1991 had moderate to high environmental impact ratings (Chang and Thonney 1992). The release of noxious gases from the sediments was reported under all eight high-impact sites and under 10% of the sites (29) that had moderate impacts.

The preliminary conclusions from the first year of monitoring, although downplayed, confirmed that all farms sites had some impact on the environment but suggested that most benthic impacts are confined to the area beneath the cages. The report stated that much of the impact on the bottom would be swept away offshore during the winter months. While little is known about the currents in southwestern New Brunswick, this assumption contradicts two studies that show that suspended solids and dissolved elements from aquaculture sites would be transported back inshore (Hunter and Associates 1982; Trites and Garrett 1983). The report suggested that siting cages in deeper, more exposed areas would help minimize environmental impacts.

Subsequent environmental monitoring by DOE (1992-1993) had similar results. Of the 34.6 hectares of seabed directly impacted by sea cages — immediately under the cages, plus a 10 meter "zone of influence" around each cage set — (an insufficient distance according to other studies (Homer 1991; Chang and Thonney 1992) — eight sites encompassing 8.3 hectares, nearly one-quarter of the area, were classified as heavily degraded. At heavily degraded sites, impacts included "moderate to heavy gas bubbling, the absence of fish, invertebrates and sediment-dwelling organisms, the accumulation of fish feces and fish feed on bottom through a tidal cycle or thick bacterial mats, and in severe cases, anoxia." Conditions in the remaining area ranged from "slight enrichment to conditions which limit the use of the seafloor solely to oxygen tolerant species such a worms" (Thonneyand Garnier 1992-1993).

This report would end the involvement of DOE in aquaculture monitoring. Funding for the program was not renewed. The next year, environmental monitoring of the industry was handed to DFA. In a subsequent budget-cutting exercise, monitoring responsibility was handed over to the industry itself. Licensees are required to submit annual reports on certain parameters to the Minister. Requests under the provincial Right to Information Act for recent monitoring results for purposes of this paper were refused under provisions of the Aquaculture Act that make such reports confidential, and under provisions of the Right to Information Act that protect information not "owned" by government (since the monitoring was paid for by industry, the data is deemed by the department to be owned by the farm owners). The authors were directed to make specific requests to individual salmon farm owners, who are under no obligation to comply.

A recent scientific report summarizing various ecological issues in the Bay of Fundy provides a succinct overview of problems demonstrated in the salmon-aquaculture industry in New Brunswick. It states that because fish farms confine large numbers of fish in a very small area (some farms contain as many as 250,000 fish weighing up to 3.5 kilograms each), a large quantity of particulate and dissolved organic waste is continually released in a small area over an extended period (Percy et al. 1997).

"There is concern that the added nutrients could foster eutrophication and possibly trigger microalgal blooms in the vicinity of the cages that would have lethal or sublethal effects on fish stocks. It has indeed been possible to demonstrate significant localized declines in oxygen and increases in ammonia concentration in the immediate vicinity of fish cages, particularly in situations where tidal flushing is restricted.

The impacts of aquaculture wastes accumulating in benthic sediments are thought to be potentially more serious . . . . The decomposition of these accumulated organic wastes may result in a negative redox potential in sediments, release noxious gases such as ammonia, methane, carbon dioxide and hydrogen sulfide, and significantly increase the biological and chemical oxygen demand in the sediment and also in the overlying water" (Percy et al. 1997).

Using figures from Swedish scientists that equate nitrogen and phosphorus discharge from a salmon aquaculture facility to raw human sewage discharge, aquaculture operations in Charlotte County, with a population of 30,000, are contributing the raw sewage equivalent of nitrogen and phosphorus from 87,000 to 200,000 people[1] (Folke et al. 1994). Figure NB-2 illustrates the annual inputs of nitrogen and phosphorus from a variety of human and natural sources to the Letang Inlet, a marine tidal inlet (9.3 miles in length) with the highest concentration of salmon farms in southwest New Brunswick (Strain et al. 1995).

Figure NB-2. Annual Estimated Input of Nitrogen and Phosphorus to the Letang Inlet, Bay of Fundy, New Brunswick

Source	Amount (mt)	
	Nitrogen	Phosphorus
Runoff	10.8	0.66
Precipitation	17.0	0.45
Sewage Treatment[1]	3.8	0.70
Pulp Mill	3.1	N/A
Back Bay Fish Cannery	8.0	1.11
Blacks Harbour Fish Plant[2]	61.0(220.0)	8.4(30.0)
Aquaculture[3]	290.0	45.0

Source: Strain 1995.

1. From sewage treatment plant serving the town of Blacks Harbour (population 1200).
2. The numbers in brackets reflect pre-1991 discharge levels.
3. In 1992, there were 22 fish farms in the Letang Inlet.

Disease Problems Unmasked

The oft-stated public position of DFA and the industry has been that if the salmon are healthy, environmental effects are negligible, implying that salmon in New Brunswick farms are indeed healthy. Yet diseases have been present since before the massive expansions of the late 1980's. Fish are stressed by poor water-quality conditions and crowding, which increase their susceptibility to infection by a variety of pathogens. A disease outbreak in 1984 and 1985, which cut into salmon profits and temporarily created a shortage of smolts, was the first sign of problems.

Furunculosis, a bacterial disease, was first reported in 1984 in four hatcheries and two sea-cage sites. In 1985 it showed up in four hatcheries and five cage sites (Hammel 1995). Furunculosis is one of the most serious diseases of farmed salmon, partly because the bacterium causing the disease quickly develops resistance to antibiotics. The bacterium is present in wild and farmed salmon populations, but it does not multiply or survive for any length of time off the fish host unless there is a high organic load in the water (Roberts and Shepherd 1990). Since organic material in the form of uneaten feed and feces are constantly present in sea cages, and the furunculosis-causing bacteria are known to persist in salmon that are "carrier fish," the threat of furunculosis outbreak became constant. Outbreaks occurred again in 1989, 1990, 1993, and 1994. By 1989, the New Brunswick government had begun to develop a program to identify and restrict the movement of furunculosis carrier fish between licensed aquaculture facilities.

The most vivid demonstration of the promotion of fish disease by fish wastes occurred in the mid-1980's in Dark Harbour Pond, a relatively large saltwater pond behind a barrier beach with only a narrow channel to provide tidal flushing. Because of the shelter provided, this pond was initially seen as an ideal sea-cage site. However, suspended solids accumulated quickly, and only a few years after the start of aquaculture operations in the pond, salmon developed bacterial kidney disease and serious parasite infestations. Moreover, the pond as a living ecosystem was essentially killed. The site had to be completely abandoned for several years while the pond flushed itself out. Today a much smaller salmon farm is located there. While Dark Harbour is exceptional because of its low flushing rate compared to other farm sites, the experience there underlined dramatically that the assimilative capacities of marine ecosystems are limited.

Disease problems continued to plague the industry into its second decade. In 1989 New Brunswick reported its first case of the disease Hitra caused by the bacterium *Vibrio salmonicida*. Over the next two years, only two other cases were reported. But in 1993 a major outbreak occurred with nearly half of all cage sites infected. Salmon farmers turned for advice to experts in Norway, where Hitra was first reported in 1977 and where huge losses had occurred in 1979. The Norwegians had identified a number of key factors, such as high stocking densities and poor water quality, that contributed to and determined the severity of Hitra outbreaks. But despite vaccinations and better management, they had not been able to prevent them. By 1993, they had moved to a system of fallowing sites for six to eight months, and they legislated lower stocking densities, daily removal of mortalities, and disinfection of all blood and mortalities in an attempt to control the disease. However, New Brunswick salmon farmers viewed fallowing and limits on stocking density as unaffordable luxuries, largely because by 1993 profit margins for New Brunswick salmon farms had become quite narrow. Instead of requiring these measures, New Brunswick's response in 1993 was to vaccinate that year's smolts.

Numerous other disease outbreaks have occurred on New Brunswick salmon farms. These include other bacterial diseases (infectious pancreatic necrosis, enteric redmouth, and vibriosis) and viral diseases (infectious haematopoietic necrosis and infectious pancreatic necrosis). Figures for fish losses due to disease are not readily available.

The latest disease troubles started late in 1996. Haemorrhagic kidney syndrome has hit several farms, and while the numbers of fish affected remain relatively low, concern is high. After months of work, at the time of writing veterinarians have no idea what is causing the disease — bacteria, virus or some other agent — or what to do about it. Disease specialists have not determined whether the kidney failure brought on by the disease is killing the fish or whether it is a symptom of something larger. According to Dr. Larry Hammell, a fish veterinarian at the Atlantic Veterinary College, growing fish together in high densities and with tough competition for food often stresses the fish, making them more vulnerable to disease. As a result, wild fish that carry disease without being affected can transfer illness to fish farms with devastating effects (Telegraph Journal 1997b).

The quantity of antibiotics used during the early years of the industry to prevent and control disease outbreaks was very large (one government official called it "impressive"). Usage dropped to 400 grams/ton of fish produced by the late 1980's. Based on 1989 New Brunswick production figures of 3,993 tons, 1.6 tons of antibiotics were being used annually. By the early 1990's it was down to 200 grams/ton (compared to Norway's 165 grams/ton) (Stewart 1994).

Until 1990 there were no federal government standards for the elimination of medication, antifoulants, or pesticide residues in salmon. The government's regulatory approach was to wait for the manufacturers of the trademark products to come forward with the necessary data on elimination rates and bioaccumulation so that their products could be certified for use in aquaculture. Essentially the industry was left to self-regulate. Some industry associations adopted American-set standards of 45 days of "withdrawal time" to clear any medication before marketing their product. But these standards were not legally enforceable, and some farmers used a much shorter (21-day) withdrawal period.

In 1990 the federal Department of Fisheries and Oceans Inspection Branch began to monitor and report on drug, pesticide, and chemical residues in farmed salmon. Growers became responsible for documenting any therapeutic treatment they used and for confirming that they complied with prescribed withdrawal times (Therapeutant Aquaculture Workshop 1993). Any farmed salmon destined for domestic or international export had to be processed in facilities registered under Fish Inspection Regulations. These plants were required to evaluate incoming fish to ensure that drug-residue limits were not exceeded.

In 1993 DFO reported that, of 362

lots of salmon and 30 lots of trout examined for oxytetracycline (an antibiotic), 12 lots exceeded the action alert level (0.1 ppm) (Department of Fisheries and Oceans 1997). By 1996 there were virtually no samples of salmon tested by DFO with detectable levels of antibiotic residues. However, DFO testing did detect mercury (0.03 - 0.11 microgram/gram), dioxin (0.18 - 1.07 picogram/gram), and polychlorinated biphenyls - PCBs (0.16- 0.17 microgram/gram) in some samples. There has been no public discussion of the presence or source of these contaminants. We conjecture that the most likely source is salmon feed, which is largely made from wild fish. In April 1997, DFO's responsibility for drug, pesticide, and chemical-residue testing in fish products was transferred to a newly created federal agency, the Canadian Food Inspection Agency.

Sea Lice

Hard on the heels of a major Hitra outbreak, Bay of Fundy salmon farmers were confronted with a relatively new problem. In 1994 a serious infestation of sea lice in most of the farms cost the industry CDN$10 million in lost salmon, more than 10% of farmgate revenues. Sea lice are constantly present in the wild, with no significant effect on wild salmon populations. The crowded, stressed conditions of salmon farms, however, provide a perfect breeding ground for this tenacious parasite. While adult fish can tolerate hundreds of sea lice, which attach themselves to host fish, causing skin ulcerations and bleeding, the market value of the fish is greatly diminished by the resultant scarring. Young salmon are much more vulnerable and can die when attacked by as few as four or five parasites.

In 1995 losses to sea lice were predicted to be roughly CDN$15-20 million. Salmon prices were already dropping due to market conditions, and prices for fish coming out of sea lice-infested farms were even lower. Growers became desperate. At a conference in September 1995, John Kershaw, DFA's director of aquaculture, said, "As of today, we're fighting a losing battle. Farms are going bankrupt. This is the industry's biggest challenge . . . We're in survival mode" (Percy et al. 1997).

The Conservation Council, in a public statement, drew attention to its 1990 report, which recommended that a strict limit be set on the number of fish per cage site and that biological controls be developed to treat sea lice. Neither of these recommendations was adopted. As a result, *"the unacceptably rapid expansion of the industry and poor management practices on the part of some growers, coupled with warmer than usual water temperatures have created the conditions for an explosion in sea lice populations and the use of insecticides and antibiotic drugs in our coastal waters. Dead crabs, lobsters and sea urchins are starting to appear and fishermen are concerned about the impact on clam and scallop spat [some of the chemicals used to combat sea lice are toxic to crustaceans]. We reiterate our call for limits on the number of fish per license; we urge the government to ensure that fallowing becomes a required practice; and that biological controls be implemented"* (Sou'wester 1995).

At that point, no pesticides were registered for use in salmon farming. Through intense lobbying, federal emergency registration was granted for hydrogen peroxide and the insecticide pyrethrin. Hydrogen peroxide quickly disassociates to form harmless compounds. It is more expensive to use than pyrethrin, however, with applications at a single site costing an estimated CDN$100,000. Pyrethrin is described by Agriculture Canada as "highly toxic to fish and other cold-blooded animals" and should be kept out of water. Agriculture Canada requires a 100-meter buffer zone to protect water supplies during aerial applications to terrestrial farm fields. "Direct application to a body of water will likely result in significant mortality rates to aquatic invertebrates, possibly affecting the growth and survival of higher animals in the food chain," according to a Pesticides Directorate bulletin (Agriculture Canada 1987).

To treat sea lice, infected salmon are drawn up to the water surface in tarpaulins and then bathed in solutions of these chemicals. Once the treatment is completed, the used bathing solution is then dumped into the water. Repeated applications are necessary to prevent reestablishment of lice on the host fish.

The veterinary drug ivermectin was also used to treat sea lice. A parasiticide commonly used in livestock, ivermectin was administered as a feed additive. According to Dr. Mansen Yong, chief of the Human Safety Division of the Bureau of Veterinary Drugs in Ottawa, who was contacted by the press at the time, there was no research on how much drug residue remains in treated salmon or how the drug affects marine ecosystems. He stated that he would not have approved its use in salmon farming. Nonetheless Canadian drug laws allow a veterinarian to prescribe any registered drug without government permission, unless certain uses are specifically prohibited.

Cypermethrin, a pesticide chemically related to pyrethrin that is toxic to crustaceans, never received an emergency registration in Canada, although it was being used to treat sea lice in the United States and Europe. In 1995 an anonymous memo began circulating throughout the aquaculture industry instructing growers on the use of cypermethrin and how to protect themselves from detection by regulatory authorities. That same year, after complaints by the Conservation Council, a local grower was found guilty of illegally using cypermethrin and was fined CDN$500.

Feeding salmon. Courtesy of New Brunswick Department of Fisheries and Oceans.

Cypermethrin would make news again in 1996 following a disaster at a local lobster pound. In July 60,000 lobsters (more than 80,000 lbs, valued at CDN$700,000) being held in a tidal empoundment before being shipped live to markets mysteriously died. After traces of cypermethrin were detected in samples of lobster from the pound, four companies that owned the lobsters filed notice of legal action against several salmon operations in the vicinity of the lobster pound, as well as against DFO and others. The plaintiffs charged that toxic chemicals used by one or more of the defendant siteholders escaped and contaminated the aquatic environment, including the lobster pound, causing mass mortality and sickness and resulting in heavy losses. They charged that DFO was ignoring the illegal use of organo-chlorinated pesticides by aquaculture siteholders (Evening Times Globe 1995). The case has yet to be heard.

Late in 1995 the pesticide asamethiphos, trade name Salmosan, was registered for aquaculture use in Canada. This product has been used in Norway, Scotland, and Chile, and is far less expensive than hydrogen peroxide. Salmosan requires only a 48-hour withdrawal time, compared to 30 days for pyrethrin and

180 days for ivermectin, thus allowing growers to continue its use to within two days of harvesting fish. Provincial politicians as well as DNA put extreme pressure on the federal Pest Management Regulatory Agency to fast-track the registration process in order to get a legal and affordable tool into the hands of salmon growers before more operations went under. Although new chemical products often take from three to five years to get through the registration process, Salmosan was pushed through in less than a year. No Canadian testing was done prior to Salmosan's approval, which was based on European environmental data provided by the manufacturer. Its potential benefit to farmers was largely unrealized, however, as the sea-lice epidemic waned by 1996.

Genetic Pollution

The Atlantic Salmon Federation (ASF), an international lobby for recreational salmon fishermen headquartered in St. Andrews, New Brunswick, has been leading the effort to highlight and deal with genetic pollution due to escape of farmed salmon.[2] Because of its location within 10 kilometers of 70% of New Brunswick's salmon farms, and because three salmon-smolt hatcheries are situated in its watershed, ASF has made the Magaguadavic River the focus of research on interactions between farmed and wild salmon. In 1983, four years after the first salmon farm was established, 5.5% of that river's salmon run was comprised of cultured salmon. In 1994 and 1995 the number was 90%. ASF also learned that sexually immature salmon are entering the river, even though salmon typically enter rivers only to spawn. The number of returning multi-sea-winter salmon, as compared to one-sea-winter salmon, has also declined. The latter produce fewer eggs than the former, and as a result, wild fish are not reproducing at a high enough rate to maintain their populations (St. Croix Courier 1997b). Research has yet to prove direct relationships between the anomalies observed in wild stocks and the dominance of escaped cultured salmon. However, the preponderance of escapees in this river system suggests a connection.

Despite this research, the federal and provincial governments have not moved on the Conservation Council's and the ASF's recommendations to use only sterile stock on fish farms. ASF has publicly accused federal DFO of showing a bias toward the aquaculture industry to the detriment of wild stocks. They charge that DFO's dual responsibility for protecting wild Atlantic salmon stocks and promoting the development of salmon aquaculture constitutes a conflict of interest (St. Croix Courier 1997b).

Genetic engineering

Responding to demand for sterile stocks and other marketable changes to salmon characteristics, researchers are now genetically altering salmon for the future. Scientists at the University of New Brunswick have been developing "triploid" salmon for 15 years. These fish, which have three instead of the usual two sets of chromosomes, do not mature and thus the fish cannot breed. Triploidy is now used to induce sterility in a number of fish species, and farming triploid salmon could largely solve the problem of escapees breeding with wild stocks. Triploid salmon, however, are still experimental (see discussion of triploidy in chapter 4).

Researchers are also genetically engineering salmon for the aquaculture industry, inserting new genes that give salmon new, economically advantageous characteristics, such as rapid growth. In experiments, salmon smolts with inserted hormone genes grow to full market size in one year, rather than the current 18 months.

Salmon are also being genetically engineered to tolerate otherwise lethal subfreezing ocean temperatures that occur along most of the Canadian Atlantic coast. Until 1987 many people believed that the nearshore bays, coves, and estuaries of the lower Bay of Fundy were favorable for salmon aquaculture because they were protected from the cooling effects of wind and open seas. But the relatively shallow depth and great tidal mixing in these sheltered areas make them vulnerable to rapid cooling. During the winters of 1987, 1989, and 1993, "super chills" in the salmon-growing areas of New Brunswick and Maine caused water temperatures to fall below -0.7°C to -0.8°C, the approximate lower lethal temperature for most salmonids, killing large numbers of fish (Saunders 1995).

Moving salmon farms offshore where winter water temperatures are more moderate is not now a practical option. Sea-cage technology is still too expensive (and largely untested) to make salmon farming economical in the rough, open waters outside the Fundy Isles zone. Canadian researchers are now approaching the problem of super chills by genetically engineering salmon. These fish contain genes from another cold-water fish that code for an antifreeze protein. If researchers can get engineered salmon to produce large enough quantities of these proteins, their tolerance of cold water should increase (Hew and Fletcher 1997).

Before any of these "superfish" can be put into sea cages, however, a sterile fish would have to be produced to prevent insidious problems of genetic pollution from the interbreeding of wild fish with escaped genetically engineered fish. Although the salmon industry is now publicly leery of genetically engineered fish because the public and consumers may react negatively to them, researchers expect the profit motive to ultimately prevail as fish farmers opt for the fast-growing aberrations (Telegraph Journal 1996a).

Conflicts with Traditional Fisheries

In May 1989, 21 angry licensed lobster fishermen confronted the provincial Minister of Fisheries and Aquaculture (DFA) with a petition objecting to the approval of a new salmon farm site. The site, developed by Norwegian-owned Sea Farms Canada Ltd., was in a traditional lobster-fishing area and a known spawning ground for both lobster and scallops. Fishermen claimed they had already lost fishing ground for 400-500 lobster traps in

Atlantic salmon. Courtesy of New Brunswick Department of Fisheries and Oceans.

the same area to the expanding aquaculture industry. The new Sea Farm site would eliminate grounds for another 300-400 traps. In addition, the fishermen objected to the rate of aquaculture expansion, citing pollution caused by fish feed on the sea bottom, by salmon morts (dead fish) and processing wastes being dumped into coastal waters, and by the loss of traditional fishing grounds to the extent that fishing was becoming "unfeasible." The letter accompanying the petition read, "We are willing to share the fishing grounds but are not willing to give them up altogether. It appears that is what the expansion of the aquaculture industry is heading for" (Telegraph Journal 1989). Both federal and provincial fisheries officials had assured fishermen, off the record, that the Sea Farm site would not be approved. The fishermen were understandably upset when the contrary decision was made.

This and similar conflicts between traditional fisheries and fish farming have continued within the restricted Bay of Fundy coastal zone. Federal fisheries scientist Rob Stephenson characterized the conflict as "unusual in its intensity and scope . . . [I]n southwestern Bay of Fundy both aquaculture and traditional fisheries utilize a relatively narrow coastal zone. Since space is limited and utilization is high, there is increasing competition among users and greater potential for confrontation" (Stephenson 1990).

The traditional fisheries are still the economic backbone of Charlotte County, with a combined value (including processed sardines) of approximately CDN$120 million. Herring, lobster, scallops, groundfish, and clams were traditionally harvested in the very territory where the salmon aquaculture industry has become established. Thus the issues raised by fishermen were not academic, but had arisen from their direct experience with the sudden appearance and rapid growth of this industry in the midst of rich and historic fishing grounds.

The vesting of all siting and licensing authority in New Brunswick's DFA in 1989 removed power from the federal DFO to effectively protect fish habitat or maintain capacity in the traditional fishing industries. Federal scientists repeatedly advocated a system of coastal-zone management within which decision making on aquaculture facility siting would occur. However, coastal-zone jurisdiction is foggy at best, and without provincial support, nothing has happened (Stephenson 1990).

Two fishermen's organizations have been especially vocal on this subject. Larry Foster, president of the Charlotte County Clamdiggers Association, and Jack Boone, president of the Fundy Weir Fishermen's Association, both believe that the salmon-aquaculture industry has damaged their members' livelihoods, and they both supported the Conservation Council's call in 1990 for strict regulatory controls. Mr. Foster, referring to clams dying on some beaches adjacent to salmon farms made the following statement at the Conservation Council news conference in June 1990:

We are a traditional fishery that has been greatly reduced. We lost about 60% of our best clam beds in December 1988. We lost them because the Federal Department of Environment did a survey and found Fecal Bacteria Counts that were too high. The documents DFO puts out tell me that the industry was worth about $2,000,000 a year before the beaches were closed. It is worth about $200,000 the year after. I don't really need a government document to tell me that. I know that we had as many as 300 to 400 people working the beaches before the closures. I know that we have more diggers on welfare now. I suspect that our industry is going to be even worse off the more cages that go in.

I hear that some scientists say that the added nutrients that are going into the *water at the sea cages may be allowing more algae to grow. As I understand it, the algae make the Paralytic Shellfish Toxin. Does that mean that we will have more and longer closures caused by PSP? Given the run-around I've got from DFO over the last few years with no answers or help coming from them, I can do nothing but fully support the resolutions being put forward by the Conservation Council* (Charlotte County Clamdiggers Assocation 1990).

Jack Boone noted that his industry had also declined dramatically in recent years. Herring weir fishermen have raised concerns that salmon cages may be blocking normal routes taken by herring, thus interfering with the weir fishery. Salmon wastes (offal and morts were being routinely dumped within coastal waters) and the permanent presence of live salmon (which prey on herring) may keep herring away from nearby weirs. The herring fishermen also cited competition for space by weirs and cage sites. According to Mr. Boone, "Aquaculture is the provincial government's baby, and you know how a mother will protect her children. The province has taken the stance that aquaculture can do no wrong, and you can't say it can do any wrong" (Telegraph Journal 1990).

An Industry Struggles to Survive

The future of salmon aquaculture in southwest New Brunswick is uncertain. Low prices in the face of ever-increasing production from Chile are increasingly pushing independent salmon growers to the financial edge. With the production volume of farmed salmon rising steadily, the price per pound has been dropping since its peak of CDN$6.00 per pound in 1987 (see Figs. NB-3 and NB-4). It hit an all-time low of $2 per pound in January 1997.

Exacerbated by continuous problems with diseases and sea-lice outbreaks,

Figure NB-3.Salmon Prices in New Brunswick, 1979-1997

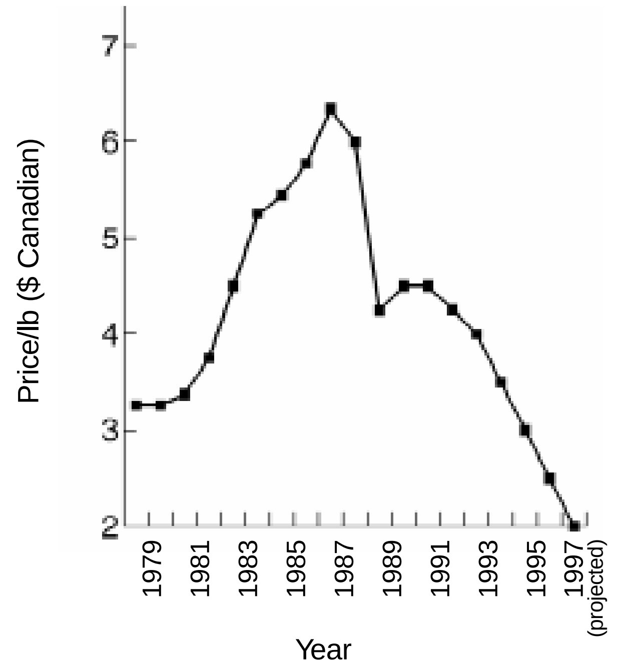
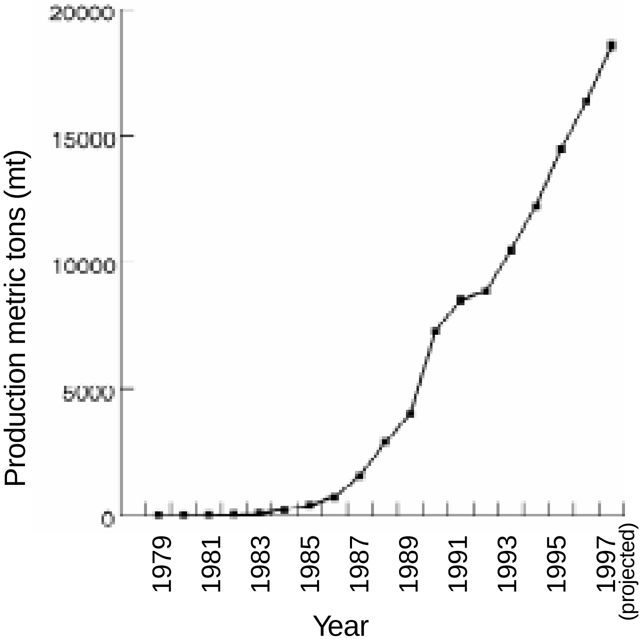


Figure NB-4. Salmon Production in New Brunswick, 1979-1997



Data for figures NB-3 and NB-4 is from the New Brunswick Department of Fisheries and Aquaculture many small growers over the years found it an attractive option to begin growing salmon under contract to large operations, especially Connors Brothers. Ltd. With the cushion of large-scale production, vertical integration (Connors produces its own feed and smolts as well as farmed salmon), and the corporate giant Weston behind it, that company was able to weather the various storms. This put Connors Brothers in a position to either buy out failing operations or take them on as contractors. Contracts provide a guaranteed price to the grower while supplying all the inputs. (While the details of these contracts are not available, nor is the actual number of growers now under contract, anecdotal information suggests the number is significant.)

For remaining farmers, the choice is expand or die. Current thinking is that farms need to produce from 200,000 to 300,000 fish to remain profitable in today's flooded market. (The average number of fish per site in 1997 is 70,000, although some farms are much larger.) Only the large corporate farms (Connors Brothers and Stolt Sea Farm) would meet this size criteria easily. Others require additional sites for expansion, and there are none available. Two companies — Connors Brothers and the smaller, independent Ocean Horizons — have expanded into Chile, ironically contributing to the competitive forces keeping prices down for New Brunswick growers. The need for more space sets existing salmon growers in direct conflict with a provincial government policy of favoring new entrants into the industry when new site approvals are handed out. Between 5 and 15 new sites could be approved over the next 24 months. There are 57 applications in government files waiting to be processed.

Veteran salmon farmer Skip Wolf predicts that site-approval permits themselves will become marketable commodities. Already there are examples of sites being approved for applicants who have no intention of getting into the salmon-farming business. Instead they are leasing their sites at premium prices to existing operations that are looking for places to expand. "The government is giving new applicants money for doing nothing," says Wolf. "The province is quick to take credit for salmon aquaculture successes so they must also take responsibility for its shortfalls (Telegraph Journal 1997a).

With a capital requirement of CDN$2 million to get started and an 18-month turnaround time before any product is ready for sale, new entrants find it difficult to capitalize their operations in what has become a high-risk industry. Increasingly, large operators are seeking out new entrants to form partnerships where the new site is combined with existing experience, money, and even marketing venues. Thus the industry in New Brunswick is becoming increasingly consolidated into fewer independent operations that are much larger in production capacity. One successful grower predicts a drop from more than 60 companies involved in salmon aquaculture to half that number over the next few years.

At this point, it is not clear how far the wholesale price of salmon will drop. In Canada, the governments of Nova Scotia and Newfoundland are anxious to repeat the apparent success of salmon aquaculture in New Brunswick. New countries are entering the market. According to one trade publication, there is no end in sight to growth of the farmed-salmon industry worldwide (Johnson and Associates 1996). Norway is expected to produce almost 1 million metric tons of salmon annually within 10 years. Production in Chile and the United Kingdom are considerably ahead of Canada, followed by the United States, Japan, the Faroe Islands, and soon Australia and New Zealand.

1997 and Beyond

Several key questions arise when considering the future of salmon aquaculture in southwest New Brunswick.

- *Where can the industry expand?* There are very few locations in Atlantic Canada where salmon farming can take place. Cold water temperatures and rough seas restrict where salmon can be farmed using conventional sea-cage technology. Alternative species are being cultivated that can withstand colder temperatures, all in varying states of readiness for commercial production. Halibut will enter commercial production this year alongside salmon farms. Rainbow trout are already being grown at a modest level. Haddock, Arctic char, and many others are all candidates within the next few years. There is also the potential to genetically engineer salmon to withstand colder temperatures. Regardless of technological fixes on the horizon, if the governments' target to double aquaculture production by the year 2000 is to be met, a further concentration and intensification of the industry in the limited zone at the mouth of the Bay of Fundy will be sanctioned, in the face of growing opposition from concerned citizens, environmental groups, and traditional fisheries interests.

- *How many finfish farms can the area accommodate without dramatically altering the productive capacity of the marine ecosystem that supports the traditional fisheries?* There is no compelling evidence that public and elected officials have given any consideration to the potential long-term impacts of intensive fish farming despite evidence of habitat decline, increased danger of parasite infestation, and ongoing disease problems in salmon.

The Bay of Fundy Ecosystem Project, a collaboration of scientists engaged in a wide range of marine research disciplines, has now publicly acknowledged the following issues as constraints to the further development of the industry:

- Habitat degradation from waste deposition and nutrient loading;

- Ecological and genetic consequences for wild populations of finfish, especially Atlantic salmon, of extensive interbreeding with farmed stock;

- Highly concentrated stocks in fish farms becoming foci for recurring outbreaks of fish diseases or parasites that may spread to local wild populations;

- The poorly controlled use of a range of increasingly toxic chemotherapeutants to control disease and parasites; and

- The many outstanding questions about the impacts of these chemicals on the survival and marketability of wild finfish and shellfish stocks in the vicinity, as well as on other marine life (Charlotte County Clam Diggers Association 1990).

A larger question relates to the total "ecological footprint " or the broader claim of finfish aquaculture on the marine environment. Primary productivity over 1 square kilometer of ocean surface is required to produce 1 ton of salmon; thus production of 16,000 tons (current) in the outer Bay of Fundy is already drawing down ecological resources from an area

Netpens viewed from the water. Courtesy of Gilles Daigle.

approximately three times that of the entire bay. Since fish feed is largely comprised of wild fish, the health of these stocks could become a major constraint on salmon-aquaculture development. Folke and Kautsky have estimated it takes 5.3 tons of herring to produce 1 ton of farmed salmon (Telegraph Journal, 1990). This inefficient conversion results in a significant net loss of food protein available for human consumption, not unlike that lost in the raising of beef.

Salmon aquaculture is now poised to impose an even greater ecological footprint. A new krill fishery proposed for the Scotia-Fundy region has as its market the salmon-feed industry. Krill as an additive to salmon feed improves the quality of flesh and provides a natural source of pink color to the fish (a dye now serves this purpose). Scientists acknowledge krill to be central to the marine food chain as a source of food for myriad species, from the smallest of fish to the greatest of whales. Despite government rhetoric around maintaining key ecological supports for wild fish stocks, a decision in favor of an experimental krill fishery is expected. Once the door is opened, it will be impossible to close again, short of disaster.

In October 1996 the David Suzuki Foundation in British Columbia released a thorough and well-documented report on the unsustainability of salmon aquaculture in that province (Ellis and Associates 1996). One of the key recommendations was to replace open sea cages with closed containment systems on land. Critics of the industry in New Brunswick have not yet made a similar recommendation. However, the Conservation Council is now considering this and other possibilities in the context of the industry today. Even so, CCNB's 1990 analysis of problems and recommended measures for dealing with them continue to stand up to scrutiny.

As is clear from experiences with terrestrial agriculture, raising animals intensively under feedlot conditions gives rise to problems on an ongoing basis. However, the marine context is much less predictable and much less well understood than the terrestrial one, setting up sea-cage aquaculture for unforeseen and not readily observable problems.

What is now required is a valuation of all the ecological supports to and costs of the salmon-aquaculture industry in order to determine its true costs and benefits. Unless there is a dramatic change in the industry's direction, in all likelihood such an analysis will reveal industry deficits.

New Brunswick Case Study Notes

[1] Our calculations were based on 1996 production figures of approximately 16,000 metric tons of salmon raised on dry feed. This is the best-case scenario. Waste estimates would be 36% higher for farms that use wet feed. (And some do, since salmon seem to prefer it.)

[2] Their research was presented at a symposium organized by the International Council for the Exploration of the Seas (ICES) and the North Atlantic Salmon Conservation Organization (NASCO) as recently as spring 1997.

New England Aquaculture: A Case Study of Maine

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Introduction

In the face of the near collapse of important components of the region's prolific wild fisheries, the aquaculture industry in New England—especially in Maine—has experienced significant growth. From 1987 to 1996, the annual value of farm-raised seafood in Maine grew nearly seventeen-fold, from $5 million to $67 million. By 1992 Maine already was the source of more than one-third of the total aquaculture production in the northeastern United States. Salmon farming, Maine's primary form of aquaculture, is likely to continue to grow in volume, although salmon prices have fallen; just across the border in New Brunswick, Canada, salmon aquaculture has become a $100-million industry.

Regulations that apply to aquaculture remain different from state to state, which may partially explain why the industry's growth has been fast in some New England states, while others have lagged. Until recently in Massachusetts, for example, aquaculture sites could not be licensed unless they were located in areas that could not support populations of commercially valuable marine species, virtually guaranteeing that aquaculture sites would be restricted to biologically marginal or nonproductive sites. By contrast, aggressive promotion of aquaculture by the state of Connecticut has helped lead to an industry worth more than $60 million and producing 94% of New England's oysters.

Maine has the largest and highest value sector of New England aquaculture. With 7,005 miles of coastline, including 2,479 miles of island shoreline, Maine's potential for coastal aquaculture far outstrips that of its New England neighbors. Moreover, marine aquaculture continues to expand in Maine for several reasons. Demand for seafood is growing worldwide, at a time when many wild stocks of fish are declining. The high quality of Maine's marine waters and Maine's proximity to major markets offers Maine growers a competitive advantage over those in other areas. New species, both native and exotic, are being cultivated. Organisms are also cultivated for nonfood uses, including pharmaceutical and biomedical applications. Technological advances, such as the development of fish pens designed to withstand open-ocean conditions, are continually expanding the opportunities for aquaculture. Finally, government support for marine aquaculture appears to be increasing at both the state and federal level.

The growth of aquaculture in Maine has not been without controversy, however. In particular, most aquaculture facilities are now located along the northeastern-most part of the Maine coast. Attempts to locate aquaculture operations farther southwest along the mid-coast of Maine have been controversial. Proposed new facilities have had difficulty gaining local support for a variety of reasons, including fear of corporate control, conflicts with traditional fishermen and summer residents, and environmental concerns.

This case study focuses on the environmental impacts of Maine's growing aquaculture industry. At least to date,

Salmon netpens near Cross Island, Maine. Courtesy of Christopher Ayres.

Maine aquaculture appears to have not caused serious environmental degradation. This case study explores some of the reasons for this, and includes:

- A historical overview of the development of Maine's aquaculture industry, particularly salmon farming;
- A summary of Maine's regulatory framework for aquaculture;
- A discussion of the available scientific information concerning a variety of environmental issues concerning Maine aquaculture;
- A discussion of the potential of ecosystem and coastal zone management in helping to guide the further development of Maine aquaculture.

A Brief Historical Overview

Access to rich inshore fishing grounds close to coastal fishing villages created a foundation for growth and prosperity for settlers of coastal New England. In the early years of settlement, New England fishermen, like the Native Americans before them, could catch fish like smelt, alewives, and salmon that literally choked coastal streams and rivers during spawning runs and had access to "shoals" of spawning cod and herring that were within a stone's throw of shore.

In the early 19th century, New England fishermen began exploiting more distant fishing grounds for species like cod, herring, and mackerel that were even more abundant farther offshore on Georges, Brown's Sable, Roseway, and the Grand Banks. With the introduction of steam-powered engines and the otter trawl (a type of fishing gear) at the beginning of the 20th century, fishing became more efficient, and inshore fish and shellfish populations declined, in many cases to a fraction of their former productivity. As a consequence, many New Englanders have had to think of alternatives to fishing wild stocks. Aquaculture has been increasingly viewed as a potentially valuable industry to expand in New England waters.

In its early years, aquaculture in New England was viewed as a means to promote economic activity in coastal states and towns, by providing jobs to fishing communities experiencing declining income from wild fisheries. Originally viewed as a strategy to employ the small farmer and to supplement income for fishing families, aquaculture has grown especially during the past decade into a large corporate industry. In 1992 the northeastern portion of the U.S. aquaculture industry produced an estimated value of $146 million dollars; by 1994 that figure was up by 11% to $162 million dollars (Spatz et al. 1996). Today Maine and Connecticut are the largest aquaculture producers of all the New England states.

Maine marine aquaculture covers 1,282 acres of ocean, comprising about 80 ten-year government leases (W. Hastings, pers. comm.). With the most productive environment for raising salmon in New England, Atlantic salmon (*Salmo salar*) farms form the mainstay of the Maine aquaculture industry. Many other species are farmed as well, including other finfish such as steelhead trout (*Oncorhynchus mykiss*), shellfish species such as oysters (*Crassostrea virginica*), mussels (*Mytlis edulis*), and hardshell clams (*Mercinaria mercinaria*), and even nori (*Porphyra yezoensis*), a type of seaweed.

Since its introduction in 1970, Maine salmon farming has changed dramatically. Long gone are the days when start-up farms and small entrepreneurs staved off declines in local wild fish such as herring and created thousands of jobs in labor-intensive, arguably inefficient operations. Facing economic challenges such as declining prices, large bankruptcies, and difficult financing, Maine salmon farming has been transformed and is now dominated by a few vertically integrated large operations, worth millions and facing fierce competition.

One of the largest operations, Atlantic Salmon, Maine, Inc., is also one of the most forceful participants trying to expand the industry southward and outward from Cobscook Bay in northeastern Maine, where it was centered during its first decade. The issue of expansion is important, not just because the value of salmon ocean-netpen operations has quickly become Maine's second most valuable harvest, behind only lobsters, but also because the industry insists it must get much bigger in order to compete with the scale of operations that characterize salmon farming internationally.

The remainder of Maine's aquaculture industry, largely shellfish production, is much smaller than Maine's salmon industry. There are 27 shellfish leases on the coast of Maine that occupy about 300 acres of water. About half of all these leases (14) are for oyster farms on the upper Damariscotta River that occupy 79 acres. These farms grow oysters both directly on river bottom and on suspended structures. Most of the remaining leases are for raising blue mussels. Mussels are grown on the sea bottom, on lease sites averaging 25 acres.

Regulation of the Environmental Impacts of Maine Aquaculture

Environmental concerns about aquaculture — particularly the pen culture of finfish — have long been a topic of discussion among government officials, environmentalists, shorefront homeowners, and researchers. These concerns have led Maine to develop an extensive regulatory structure for oversight of individual aquaculture operations. Maine has, however, declined to adopt a comprehensive approach to coastal

Box ME-1. Major Regulations Governing Maine Aquaculture

Federal Regulations

- The River and Harbor Act of 1899 requires that any structure in or over navigable waters qualify for a Section 10 permit from the U.S. Army Corps of Engineers, certifying that the project will not impede navigation or negatively affect environmental quality.

- Hatcheries require a National Pollutant Discharge Elimination System (NPDES) permit, issued by the U.S. Environmental Protection Agency (EPA) under the Clean Water Act. To date, EPA has received approximately 40 applications for NPDES permits for salmon netpens in Maine (P. Colarusso, pers. comm.); however, the agency has issued very few of the requested permits, in part because EPA has not developed relevant policy.

- Particularly large or environmentally significant projects and may need to meet the requirements of the National Environmental Policy Act, often require an Environmental Impact Statement.

- Federal permits are reviewed at the state level for consistency with state coastal zone management policies.

State Regulations

- Leases are required for finfish culture or suspended culture of any marine organism. Leases are limited to ten years and 100 acres. No person may lease more than 150 acres (or 200 acres for bottom culture of shellfish).

- The lease application must characterize the physical and ecological impact of the project on existing and potential uses of the site, provide an environmental evaluation of the site, describe the degree of exclusive use required by the project, and include written permission of riparian land owners whose land may be used.

- The Department of Marine Resources must conduct an assessment of the proposed site and surrounding area to determine the possible effects of the lease on commercially and ecologically significant flora and fauna, and conflicts with traditional fisheries.

- The Department of Environmental Protection must certify that any discharge will not violate state water classification standards.

- The Department of Inland Fisheries and Wildlife must evaluate potential impacts on threatened, endangered and protected species.

- A lease is granted for the operation if there is an available source of organisms for aquaculture, and if the proposed operation will not unreasonably interfere with navigation, riparian owners' rights, local ecosystem functions, or public recreation areas.

- Active finfish operations must comply with the requirements of the Finfish Aquaculture Monitoring Program.

- For hatcheries, the Department of Inland Fisheries and Wildlife requires a cultivation license, the Department of Environmental Protection requires permits for intake and discharge of water, and the Department of Marine Resources requires permits for importation and/or transportation of fish.

planning that would involve analysis of potential aquaculture sites in the context of natural ecosystems and other uses of marine waters.

Maine's aquaculture statute dates from 1973. In 1987 this statute was amended to require an increased level of environmental review of proposed and active lease sites by the Maine Department of Marine Resources (MDMR). Environmental concerns were further addressed in 1989 and 1990 by a legislative study commission, a US-Canadian workshop on aquaculture impacts, and strategic planning for the aquaculture industry (Office of Policy and Legal Analysis 1990; Gulf of Maine Working Group 1990; Maine State Planning Office 1990).

As a result of these activities, Maine's aquaculture statute was again amended in 1991. The revised statutory and regulatory language requires both an extensive environmental evaluation of proposed lease sites by the applicant and MDMR, and the development and implementation of a finfish aquaculture monitoring program. With expertise drawn from Puget Sound, where salmon farming was already occurring on a large scale, MDMR and the Maine Department of Environmental Protection (MDEP) designed a monitoring program to be conducted by MDMR and paid for by a fee on salmon production (Parametrix 1990; MDMR 1994). The result was the establishment of Maine's Finfish Aquaculture Monitoring Program (FAMP), implemented in 1992 (See Box ME-1).

Environmental Impacts of Aquaculture in Maine

Aquaculture in Maine has the potential to cause a variety of water-quality, ecological, and other environmental impacts. Issues of concern include organic loading on the benthos (bottom environment) and water column, use of aquaculture-related drugs, introduction of exotic species and genetically engineered fish, interbreeding of farmed and wild salmon, spread of diseases and parasites, control of predatory mammals and birds, habitat alteration, and trash.

Organic Loading on the Benthos

Excess feed, feces, and other organic matter from fish farms can accumulate on the benthos and result in substantial alteration of the benthic community (for example, Wu 1995; Henderson and Ross 1995; Hansen 1994). While the biomass (the total amount of living matter) and the diversity of species living beneath a fish farm may initially increase, opportunistic species begin to dominate and biomass eventually decreases. At this point, mats of bacterial-mold called *Beggiatoa* begin to form, indicating that decomposition of materials under pens has become anaerobic (occurs without oxygen).

Maine's Finfish Aquaculture Monitoring Program (FAMP) is the most comprehensive effort to assess the degree and effect of organic loading beneath Maine's fish pens. Monitoring includes:

- monthly, confidential production reports by lease-holders;
- semi-monthly dissolved oxygen monitoring in July, August, and September;
- annual dissolved oxygen "water column profiles" in August;
- video recordings in the spring and fall of the bottom beneath and adjacent to the cages;
- biennial sediment redox layer depth determinations (measures of sediment chemistry) during the fall;
- biennial sediment grain-size analyses in the fall; and
- biennial censuses of benthic animals (such as worms) in the fall.

The first four years of data from the program indicate that the vast majority of sites sampled for dissolved oxygen meet or exceed the current state minimum

Feeding salmon. Courtesy of Caitlin Owen Hunter.

standard of 85% dissolved oxygen saturation. Sites that did not meet the minimum standard were almost always within 5 meters of the cage system. The data show that dissolved oxygen concentrations recover rapidly within a short distance of the cages and that, in all cases, dissolved oxygen saturation 100 meters downstream of the cages is the same or only slightly below current values (Heinig 1996).

Three sites have been identified by the program as degraded. In each case, the operators voluntarily implemented mitigation measures that prevented severe degradation (Heinig 1996).

Data indicate that salmon farming alters the benthos, but that the harm is not as severe as had been anticipated. In areas with slower currents and softer sediments, the impact of the pens is limited to the area directly beneath the pens. Where current speeds are greater and sediments are more coarse, effects of the pen are more widely distributed but less intense due to distribution of the organic material over a wider area (C. Heinig, pers. comm.).

Communities of benthic organisms recover relatively rapidly after salmon pens are removed, but netpen sites remain vulnerable to future degradation. Data from an abandoned, highly impacted site indicate that the benthic community recovered within 18 months. Dragging of fishing gear along the bottom may have contributed to the rapidity of this recovery by oxygenating sediments (Heinig 1996). Nevertheless, this site may still have relatively high levels of organic matter in the sediment. If aquaculture is reinstituted on this site, benthic communities may be harmed more rapidly than at a site where netpens were not previously present (C. Heinig, pers. comm.).

At a salmon cage site near Swan's Island, Maine, Findlay et al. (1995) found both accumulations of organic matter and bacterial mats beneath the pens. Communities of microscopic and larger organisms were typical of those found in enriched sediments. Increases in carbon flux (a measure of organic loading) were not measurable 10 meters from the pen. Storms periodically resuspended sediments and dramatically reduced carbon loading. They may be a more significant factor affecting benthic communities than organic loading by salmon pens.

Shellfish grown in suspended culture (as opposed to directly on the bottom) may cause changes to the benthos similar to those found under salmon netpens. Filter-feeding shellfish "package" phytoplankton and other food into larger particles known as feces and pseudofeces, which are deposited on the bottom. On the other hand, one study (Grant et al.

1995) found that mussels falling from a farm to the benthos helped maintain benthic communities by providing food for scavenger organisms and by making the bottom more topographically variable. Suspended culture of shellfish is now conducted in relatively few places in Maine; its use may expand in the future.

Organic Loading in the Water Column

Organic loading of the water column by uneaten salmon feed and by salmon feces and other metabolic products also concerns Maine's environmental regulators. Along much of the Maine coast, strong tides, winds, and currents disperse nutrients from fish pens, although upwelling of nutrient-rich bottom waters of the Gulf of Maine is estimated to be a much larger source of nutrients than fish netpens in coastal waters (B.Vickery, pers. comm.).

Cobscook Bay is the site of the majority of Maine's finfish farms (see map at the beginning of the New Brunswick case study). The high tides that bring relatively warm bottom water into the bay in the winter make it an ideal place to grow Atlantic salmon. The narrow entrance to Cobscook Bay restricts water flow. Thus, at least in theory, the bay is more vulnerable to organic loading than coastline more open to ocean currents and storms. Research sponsored by the Nature Conservancy shows that Cobscook Bay has relatively high nutrient levels and relatively low levels of algae growth ("primary productivity," as measured by chlorophyll levels). Nutrient levels are comparable to areas that are polluted by sewage and other land-based sources of nutrients. Unlike such areas, however, Cobscook Bay does not have large amounts of algae growth.

Salmon farming undoubtedly contributes to Cobscook's Bay's nutrient load; however, nitrogen may also be supplied to the bay from the open ocean (Garside 1996). In the marine environment, nitrogen is generally the nutrient in shortest supply, and the shortage of nitrogen limits the growth of phytoplankton, seaweed, and other forms of plant life. In many coastal waters, plant growth continues until nitrogen supplies (in the form of nitrate and ammonium) are depleted; the result is water with low nutrient and high chlorophyll levels – the reverse of the situation in Cobscook Bay.

There are at least two possible explanations for the unusual nutrient status of Cobscook Bay. The first theory is that plant growth is consumed by herbivores in the bay. If plant growth is consumed at a sufficiently high rate, plants would not grow fast enough to deplete nitrogen. Bivalves (such as mussels and clams) are the herbivores most likely to be capable of consuming phytoplankton at a sufficient rate (Garside 1996). According to the second theory, very high currents remove phytoplankton from the bay before they reach their full growth potential, preventing them from consuming nitrogen in the bay.[1] Further research is required to determine the cause of the bay's unusual nutrient status, to determine the role of plants and animals in governing the bay's ecosystem, and to estimate the relative contribution of salmon pens to nutrient loading in the bay.

Use of Aquaculture-related Drugs

Concerns about drugs used in aquaculture include toxicity to nontarget organisms, uptake by wild fish and shellfish, inhibition of microbial degradation beneath pens, and selection for antibiotic-resistant pathogens (Redshaw 1995). Antibiotics, used to treat disease in farmed fish, can be fatal to other aquatic species. However, Maine salmon farmers now typically vaccinate their fish against disease, and the use of antibiotics on Maine's fish farms has dropped by 90%

since 1993 (C. Bartlett, pers. comm.).

Only four drugs are approved for use in aquatic species in the United States. Trials for two new drugs used to treat sea lice (parasites that can injure or kill fish) are underway in Cobscook Bay. One drug, hydrogen peroxide, is toxic to sea lice and caustic to farm workers, but breaks down into harmless end products: water and oxygen. The other drug, cypermethrin, is a synthetic "pyrethrin" insecticide that is toxic to crustaceans and has the potential to affect nontarget species. Both chemicals are administered as a bath. Fish are collected in a tarp, the chemical is added, and the fish are held for a period of time. When the treatment is completed, the fish are released back into the pen, and the chemical is released into the environment.

In order to generate data on the safety of these drugs, the U.S. Food and Drug Administration (FDA) is requiring study of the effects of the chemicals on nontarget species, including clams, mussels, sea scallops, lobsters, and urchins (Bell 1995). Although the trials are not complete, preliminary evidence indicates that nontarget species are not affected by the chemicals at the concentrations proposed for treating sea lice (C. Bartlett, pers. comm.). A different study[2] on lobsters resulted in no lobster deaths under or around a treated lobster pen, but a 99% mortality rate within the pen (J. McGonigle, pers. comm.).

Introduction of Exotic Species

Introductions of exotic, or nonnative, species have dramatically altered the species composition of fish communities in Maine's freshwater lakes and rivers. In marine waters, the state of Maine has permitted introduction of an exotic species of seaweed, described below. In addition, the European and Japanese oysters (*Ostrea edulis* and *Crassotrea gigas*) were introduced to marine waters before Maine began to review proposed introductions of exotics.

Although Maine's aquaculture regulations do not address introduction of exotic species, MDMR requires hearings to be held on the proposed introduction of any nonindigenous species. In addition, the International Council for Exploration of the Seas (ICES), whose members include the countries bordering the North Atlantic, have endorsed a Code of Practice to Reduce the Risks for Adverse Effects Arising from Introduction of Marine Species. This code calls for proposed introductions to be reviewed by ICES for assessment of potential impact. It also recommends that brood stock of the species proposed for introduction be quarantined, and that only their progeny, once proven to be disease-free, be introduced (Sindermann 1986).

Porphyra yezoensis, a species of seaweed (nori) native to Japan is to date the only permitted introduction of an exotic species for marine aquaculture in Maine. In 1990 Coastal Plantations, Inc., applied for an aquaculture lease to grow this species. With no explicit regulations to follow regarding introduction of an exotic species, MDMR followed an ad hoc process to review this application. MDMR permitted the seaweed farm after ICES concluded that *P. yezoensis* itself posed no threat to Maine's coastal ecosystem, because cold water temperatures would prevent this seaweed from reproducing in Maine's coastal waters (K. Honey, pers. comm.). ICES recommended procedures to prevent other organisms, parasites, and diseases from being imported with the nori.

Other applications for introductions of exotic species are less likely to be approved in the immediate future, but may eventually be approved with appropriate technological safeguards. For example, a shellfish grower in the Damariscotta River area has proposed introducing the Japanese oyster, *Crassostrea gigas.* This oyster grows rapidly and is popular with consumers in some areas. Small-scale introductions of *C. gigas* to Maine waters in the past have not resulted in the establishment of wild populations, most likely because water temperatures are too cold for these oysters to successfully spawn. Nevertheless reproductively viable *C. gigas* individuals are unlikely to be legally introduced to Maine in the near future, because aquaculturists and others are concerned that *C. gigas* might acclimatize to Maine waters and establish wild populations (Shatkin 1992). In other parts of the world, introduced Japanese oysters have caused ecological harm; in New Zealand and Australia, they have spread rapidly, displacing native species.

The creation of sterile oysters may allow *C. gigas* to eventually be grown in Maine. Triploidy, the genetic manipulation of gametes to produce rapidly growing, sterile offspring, is now commonplace in oyster production. Triploidy is not perfect, however; a very small fraction of oysters may still be able to reproduce. Thus triploidy is not considered sufficient to protect Maine waters from invasion by *C. gigas.*

Tetraploidy, a new genetic technique for producing sterile offspring, may provide sufficient control of *C. gigas* reproduction to allow for safe introduction in Maine (Guo et al. 1996). Laboratory research indicates that tetraploid-generated offspring are 100% sterile; however, field trials have not yet confirmed these findings. In addition, researchers still need to assess the potential for "vertical" transmission of diseases from one generation to the next via gametes, and to develop a means of easily distinguishing sterile oyster seed from nonsterile seed, in order to enforce Maine's prohibition on importation of nonsterile seed (W. Mook, pers. comm.). The Maine Aquaculture Association and the Maine Aquaculture Innovation Center are developing a process for determining how these organizations should address the proposed introduction of tetraploid *C. gigas.*

Interbreeding of Farmed and Wild Atlantic Salmon

The United States Fish and Wildlife Service (USFWS) has determined that salmon aquaculture poses a significant threat to wild stocks of Atlantic salmon. Threats to wild stocks are of special concern because the USFWS has proposed listing stocks of Atlantic salmon in seven rivers in eastern Maine as threatened under the Endangered Species Act (USFWS 1995). USFWS has identified several concerns about salmon aquaculture:

- First, escaped fish pose a threat to the genetic integrity of Atlantic salmon populations in several rivers.
- Second, escaped salmon could disturb the redds, or egg beds, of wild fish.
- Third, as will be discussed in a later section, concentrations of caged fish increase the vulnerability of wild fish to disease.

Regarding the first concern, salmon return to their natal rivers as a means of reducing the exchange of individuals and genes between populations. In this way, adaptations to river-specific environmental conditions are conserved (Skaala 1994). Interbreeding has the potential to result in decreased fitness of the wild stock for their particular environment.

The large number of farmed compared to wild salmon makes the escape of farm-raised fish an important issue in Maine — particularly when the even greater number of farmed salmon in nearby New Brunswick are considered (Sowles and Churchill 1995). Debate over the potential effects of escaped farm-raised fish is complicated, however, by the fact that salmon restoration efforts have over decades introduced fish from the same brood stock into many of Maine's rivers, thus potentially blurring river-specific genotypes. Sowles and Churchill (1995) conclude that "if interbreeding and/or competition issues are found valid *and* unique 'wild' stocks representing natal rivers exist *and* these stocks are deemed valuable enough to protect, then the potential for impact is great."

The state of Maine has responded to the proposed listing of Atlantic salmon as threatened by developing an Atlantic Salmon Conservation Plan, which details the measures the state will take in protecting wild Atlantic salmon in the proposed rivers. One section of the plan calls for the aquaculture industry to lend its expertise in restoring the genetically distinct Atlantic salmon populations in two rivers in eastern Maine (C. Bartlett, pers. comm.).

Introduction of Genetically Engineered Fish

No genetically engineered, or "transgenic," species are now cultured in Maine waters, but many growers are interested in growing transgenic fish, shellfish, and seaweed. In 1994 the Maine Legislature established the Commission to Study Biotechnology and Genetic Engineering to advise the legislature on the adequacy of existing state regulation of genetically engineered products and activities and to make recommendations for change. The commission's final report identified regulation of genetically engineered marine species as one of three key issues concerning the use of genetic engineering in food production (Lenardson 1996).

Feeding fish. Courtesy of Caitlin Owen Hunter.

The report notes that the federal government does not now "regulate and protect against environmental and ecological risks in the development and aquaculture" of fish and shellfish products:

> *As Maine is a primary site for the development of aquaculture industries, the Commission is concerned that the absence of effective regulation in this area may create ecological risks . . . Currently, about 40 or 50 labs around the world are working on transgenic fish, with about a dozen labs located in the United States. Most of the research has focused on transforming growth hormone genes from other species to create fish which grow more rapidly in aquaculture settings . . .The principal environmental risk associated with the development and aquaculture of transgenic fish is that they will escape and interbreed with wild species, thereby threatening the genetic integrity of wild stocks* (Lenardson 1996).

Implementation of Maine's recently developed Atlantic Salmon Conservation Plan (discussed above), which focuses on minimizing escape of cultured fish and preventing such fish from entering rivers where wild stocks occur, would also address concerns regarding escape of genetically engineered fish.

Introduction of Diseases and Parasites

Diseases of pen-reared fish may be considered a threat when the diseases are exotic, occur at higher frequencies than in wild populations, or lead farmers to administer drugs that are released to the environment. Yet all animals carry an array of diseases and parasitic organisms. Various factors, including environmental conditions, nutrition, and stress due to handling and crowding, influence if and when diseases and parasites will overwhelm an animal's defense mechanisms. Once farmed fish become sick, the crowded conditions on the vast majority of fish farms provide maximum opportunities for rapid transmission of pathogens and parasites (Stewart 1994).

The finfish industry in Cobscook Bay has experienced two epidemics, one caused by a cold water *Vibrio* bacterium known as hitra, which occurred in 1992, and the other by parasitic sea lice, which occurred in 1995. These organisms are not considered exotic in Maine. Hitra was initially controlled with antibiotics and is now prevented with a vaccine. The sea lice epidemic is being brought under control by improved management (one action was to reduce salmon densities) and by the use of experimental drugs described above.

There is no evidence that either the hitra or sea lice epidemics caused increased disease or parasitism in wild salmon in Maine. Wild fish may resist infection because they live under less crowded and less stressful conditions than farmed fish. Timing may also help protect wild fish from sea lice. Densities of sea lice are low in the spring, since cold winter temperatures kill these parasites. Adult wild salmon return to their natal rivers and wild salmon smolts migrate out to sea in the spring, and thus tend not to be exposed to high concentrations of sea lice from farms.

Maine law requires that any fish to be transferred to a new location, including broodstock, gametes, and smolts, must be tested for disease. In addition, dead or sick fish are tested on a voluntary basis. Data from these tests indicate that disease incidence in Maine dropped significantly in recent years, since the advent of salmon vaccinations (C. Bartlett, pers. comm.).

Outbreaks of disease in wild salmon are uncommon in Maine. Furunculosis is the only known source of disease-related mortality in Atlantic salmon in New England (USFWS 1995). Nevertheless, any future disease outbreaks in wild salmon populations may warrant further research into aquaculture's potential role in disease transmission.

Control of Predatory Mammals and Birds

Salmon farms attract natural predator species such as seals and birds. Seals, in particular, can consume large numbers of salmon, and salmon farmers try to prevent seal predation. However, while Maine salmon farmers were once allowed to shoot seals, they may no longer do so. Effective January 1995, the National Marine Fisheries Service (NMFS) banned the killing of seals, based on anecdotal evidence that seals were being shot in the vicinity of Maine's fish farms in the early 1990's. Cobscook Bay area salmon farmers had not shot seals for several years prior to the ban (C. Bartlett, pers. comm.).

Seals and birds can become entangled in nets on Maine salmon farms (Sowles and Churchill 1995), although such entanglement is rare (C. Bartlett, pers. comm.). Entanglement of marine mammals and reptiles, including endangered species, has also been reported in Massachusetts, particularly in Cape Cod Bay (Massachusetts Coastal Zone Management Office 1995).

Acoustic deterrent devices (ADD's), used by many of Maine's salmon growers, may help prevent entanglement by discouraging seals and other animals from remaining near salmon netpens. Use of ADD's in British Columbia, Canada, is reported to have resulted in a decline in the abundance of harbor porpoises, and not just salmon-farm predators, in the vicinity of the ADD's (Ellis and Associates 1996). Harbor porpoises in Maine are a different species than occurs in British Columbia, and they do not appear to be deterred by ADD's: Harbor porpoises remain common near fish pens during the summer months when they are in the Gulf of Maine (C. Bartlett, pers. comm.). Nevertheless, the continual use of ADD's during the night, a current practice of Cobscook Bay salmon farmers, may be unnecessarily harsh to seals (C. Bartlett, pers. comm.) Triggering devices may soon be available that would activate ADD's only at times of day when seals approach salmon netpens.

Habitat Alteration and Discharge of Trash

Habitat alteration and discharge of trash also have the potential to harm the environment. Bottom culture of shellfish directly alters the water bottom through such activities as deliberately altering the bottom in order to improve shellfish survival, and seeding and harvesting of shellfish. Massachusetts state officials believe that the "use of the intertidal area for bottom culture also raises concern over the potential loss of resting and feeding areas for migratory birds . . . Monoculture may threaten the intertidal ecosystem" (Massachusetts Coastal Zone Management Office 1995). Dragging of equipment to harvest mussels disturbs the benthic environment (Sowles and Churchill 1995). Some individuals even speculate that mussel dragging is threatening lobster populations and other fish species whose young inhabit mussel beds.

Salmon farms contribute significantly to the debris that accumulates along the shores of Cobscook Bay and other salmon-growing areas. Although commercial fishing and other marine activities also generate debris, aquaculture clearly generates considerable debris, such as feed bags, totes, and abandoned pens. To their credit, salmon-industry representatives in the Cobscook Bay area regularly participate in cleanups and provide boats and manpower when large structures, such as abandoned pens, must be removed from the water (C. Bartlett, pers. comm.).

The Role of Ecosystem and Coastal Zone Management

Ecosystem management is an important tool that should be used to manage Maine's marine environment (Quintrell and Flatebo 1995), and may ultimately be as important to the aquaculture industry as disease control, good brood stock, and efficient management practices.

The environmental sustainability of aquaculture depends on the net impacts of individual farm sites on surrounding marine ecosystems, and thus the siting of farms is an important factor in their sustainability (Wu 1995). However, siting criteria are not now based on the ability of marine ecosystems to assimilate nutrients and other impacts of proposed farms, because such information is not available. Future scientific management of aquaculture requires long-term monitoring of the environment in the vicinity of the farms, in order to obtain data on which to base improved siting criteria (Levins 1994).

The ecological impacts of aquaculture should be considered in the context of natural disturbances experienced by the ecosystem where farms are located. On at least one site in Maine, disturbance by organic loading is apparently outweighed by the effects of episodic storm events (Findlay et al. 1995). Although aquaculture can disturb communities of endemic organisms, it is not clear if the degree of disturbance by aquaculture exceeds the degree of natural disturbances that estuarine communities have evolved to accommodate (Simenstad and Fresh 1995).

The degree of disturbance by aquaculture depends on the scale of the impact in both time and space.

For example, benthic effects tend to be localized to within 50 or 100 meters of a farm site but may take several years to show severe degradation, while nutrient loadings in a well-mixed estuary may spread throughout a region covering 100 square kilometers in a very short period of time and affect bloom dynamics with time scales of days (Silvert 1994).

When disturbance caused by aquaculture exceeds natural levels, the effects can potentially ripple through the ecosystem, affecting populations of a number of organisms (Simenstad and Fresh 1995).

Ideally regulation and promotion of aquaculture should be considered within the context of comprehensive ecosystem and coastal management. At least two countries have developed systems to help them achieve this end. In Norway, a nationwide assessment of the suitability of the Norwegian coastal zone and rivers for aquaculture was developed as a standardized tool for coastal zone planning. Called LENKA, this model incorporated environmental impacts, existing uses, site suitability, and assimilative capacity in an estimation of net potential aquaculture capacity for a given area. Data collected to test LENKA have now led to the development of newer models with greater predictive power (Kryvi 1994).

In Canada, the Department of Fisheries and Oceans has begun to develop a "decision support system based on a geographic information system database" that will allow managers to track the information required for site applications, including requirements for proper management to minimize environmental impacts (Keizer 1994). The "decision support system" will consist of two parts: a series of interconnected models that, run in series, will indicate limits to a site's capacity to tolerate caged fish, and a database of hydrographic and physical data, restricted areas, and competing uses of marine waters (Silvert 1994).

A similar comprehensive system of analysis could improve the future of Maine aquaculture, potentially avoiding some of the environmental impacts discussed above while exploiting the natural assimilative and productive capacity of coastal Maine.

Salmon rising for feed at Swan's Island, Maine, farm. Courtesy of Christopher Ayres.

Conclusion

Maine has escaped many of the environmental problems that have beset marine aquaculture elsewhere in the world. Maine is fortunate to have high tides and high-energy storms that flush wastes from farms. Moreover, implementation by Maine government officials of a variety of regulations, including conservative siting criteria, extensive pre and post-lease site evaluations, and long-term monitoring requirements have apparently helped to prevent serious environmental degradation by aquaculture. However, several potential environmental problems warrant continued or expanded monitoring and research. These include the contribution of netpens to eutrophication, the impact on wild Atlantic salmon, both genetically and through the spread of diseases and parasites, and the effects of introductions of exotic species and genetically engineered fish.

Management of this growing industry on an ecosystem basis and within the context of comprehensive coastal planning is Maine's best hope for maintaining a healthy marine environment and a sustainable aquaculture industry.

New England Aquaculture Notes

[1] Evidence in support of this theory comes from research on horizontal patterns in chlorophyll concentrations in the bay. Concentrations are lowest along the main axis of flow in and out of the bay and highest in the innermost portions of the bay: "Increased residence time means that the phytoplankton have more time to grow before they are advected out of the system by tidal currents" (Phinney 1996). This phenomenon may explain why, in some years, benthic algae mats grow extensively on the bay's flats: Attachment to the sediments allows the algae to grow without being swept away by the tides (J. Sowles, pers. comm.).

[2] Research was conducted by University of Maine researcher Michael Opitz.

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