Marine Aquaculture
IN THE UNITED STATES

Environmental Impacts and Policy Options

Prepared for the
Pew Oceans Commission by

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PEW OCEANS COMMISSION

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Abstract

Global aquaculture production is growing rapidly, with production more than doubling in weight and by value from 1989 to 1998. With many capture fisheries catches peaking, scientists, governments, and international organizations all point to aquaculture as the most important means to increase global fish supplies.

The aquaculture industry in the United States, which is dominated by freshwater catfish *(Ictalurus punctatus)* production, generates about one billion dollars each year. Marine aquaculture comprises roughly one-third of U.S. production by weight, and despite rapid increases in salmon and clam production, growth of U.S. marine aquaculture has been slow on average. Efforts to develop marine aquaculture in the open ocean could catalyze future growth.

Aquaculture has a number of economic and other benefits. But if it is done without adequate environmental safeguards it can cause environmental degradation. The main environmental effects of marine aquaculture can be divided into the following five categories:

1) Biological Pollution: Fish that escape from aquaculture facilities may harm wild fish populations through competition and interbreeding, or by spreading diseases and parasites. Escaped farmed Atlantic salmon *(Salmo salar)* are a particular problem, and may threaten endangered wild Atlantic salmon in Maine. In the future, farming transgenic, or genetically modified, fish may exacerbate concerns about biological pollution.

2) Fish for Fish Feeds: Some types of aquaculture use large quantities of wild-caught fish as feed ingredients, and thus indirectly affect marine ecosystems thousands of miles from fish farms.

3) Organic Pollution and Eutrophication: Some aquaculture systems contribute to nutrient loading through discharges of fish wastes and uneaten feed. Compared to the largest U.S. sources of nutrient pollution, aquaculture's contribution is small, but it can be locally significant.

4) Chemical Pollution: A variety of approved chemicals are used in aquaculture, including antibiotics and pesticides. Chemical use in U.S. aquaculture is low compared to use in terrestrial agriculture, but antibiotic resistance and harm to nontarget species are concerns.

5) Habitat Modification: Marine aquaculture spreads over 26,000 marine hectares, or roughly 100 square miles. Some facilities attract marine predators, and can harm them through accidental entanglement or intentional harassment techniques.

A number of technologies and practices are available to prevent or mitigate these environmental problems. Options to make U.S. aquaculture environmentally sustainable include:

- Developing strong effluent guidelines for aquaculture under the Clean Water Act;
- Supporting National Marine Fisheries Service and Fish and Wildlife Service activities under the Endangered Species Act to protect wild Atlantic salmon;
- Establishing an environmentally protective permitting program for offshore aquaculture;
- Improving state oversight of aquaculture;
- Championing research and development investments and cost-share incentives for sustainable aquaculture practices;
- Establishing a federal approval process for transgenic fish that mandates environmental protection;
- Supporting market incentives for environmentally sound fish-farming;
- Developing bilateral agreements with Canada to study and to minimize the impact of salmon-farming on wild salmon stocks.

Aquaculture and Mariculture **Glossary**

Aquaculture is the farming of aquatic organisms, including finfish, shellfish (mollusks and crustaceans), and aquatic plants. Farming implies some form of intervention in the rearing process to enhance production, such as regular stocking, feeding, and protection from predators. Farming also implies individual or corporate ownership of cultivated stock (FAO, 2000a).

Eutrophication is the process by which a body of water becomes enriched with organic material from algae and other primary producers (e.g., photosynthetic organisms). Eutrophication can be stimulated to harmful levels by the anthropogenic introduction of high concentrations of nutrients such as nitrogen and phosphorus.

Forage fish are small bony, pelagic fish such as anchoveta, sardines, pilchard, blue whiting, sandeel, sprat, and capelin. These fish constitute roughly one-third of the global annual fisheries catch, and they are mostly processed to produce fish meal and fish oil used in fish, poultry, and livestock feeds.

Mariculture is saltwater aquaculture, including coastal and offshore aquaculture operations as well as saltwater pond and tank systems. Prominent examples in the U.S. include Atlantic salmon and mollusk farms.

Netpens are netlike enclosures used to contain fish in bays, estuaries, lakes, and other water bodies.

Offshore aquaculture refers to aquaculture operations located in an exposed, open-ocean environment, such as the U.S. Exclusive Economic Zone, or EEZ (federal waters usually situated between 3 and 200 miles offshore).

Recirculating systems are enclosed aquaculture ponds or tanks that clean and recycle water.

I. The Practice of Aquaculture in the United States

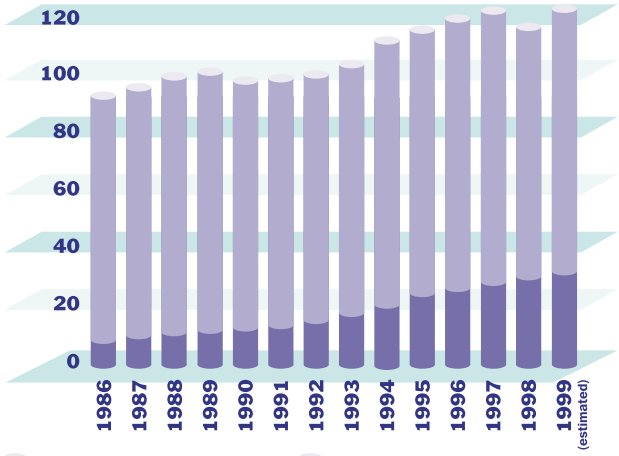
Aquaculture's Role in Global Food Supplies

Most Americans would be surprised to discover that their last seafood meal may have been raised on a farm rather than caught in the wild. Farmed fish (finfish and shellfish) supply one-third of the seafood that people eat worldwide, and that fraction is increasing (Tacon and Forster, 2000). In the United States, aquaculture provides almost all of the catfish and trout people consume, along with roughly half of the shrimp and salmon. Aquaculture is an increasingly important contributor to our diet and some experts assert it is the fastest-growing segment of U.S. agriculture.

Growth in aquaculture has many benefits, from job creation to new sources of seafood for consumers. However, aquaculture's growth also presents challenges. The industry is coming of age at a time when concern about the environment, including protection of marine ecosystems, is high. This report provides an overview of U.S. aquaculture and its potential environmental impacts, with a focus on effects from marine aquaculture, or mariculture. This report also discusses methods to prevent or mitigate environmental impacts, and suggests a number of policy options for making U.S. aquaculture more environmentally sustainable. It does not address aquaculture used in stocking programs that augment wild fish populations.

Figure One

World Fisheries Production



Worldwide Growth in Aquaculture

Since the mid-1990s, total global wild fisheries catch has plateaued at roughly 185 to 200 billion pounds (85 to 90 million t) (FAO, 2000b). At the same time, growing human population and affluence are increasing the demand for seafood. As a result, the global per capita supply of seafood from capture fisheries dropped from 23.99 pounds per person (10.88 kg) in 1984 to 23.32 pounds (10.58 kg) in 1998 (Tacon and Forster, 2000). Scientists, governments, and international organizations all point to aquaculture as the most important means to boost per capita fish supply.

Worldwide, aquaculture is growing rapidly (Figure One). Global production expanded at a

rate of more than ten percent per year over the past decade, reaching 87 billion pounds (39.4 million t) in 1998.* The total value of farmed aquatic products also more than doubled during the 1990s, jumping from 25.6 billion dollars in 1989 to 52.5 billion dollars in 1998 (FAO, 2000a). Mariculture currently comprises one-third of global seafood farming by weight, and cultivation of marine finfish and shellfish has been the fastest growing segment within aquaculture (FAO, 2000a).

"By live weight, U.S. aquaculture production in 1998 was roughly one billion pounds. This harvest was valued at just under a billion dollars...."

Aquaculture in the United States

The aquaculture industry's growth in the United States has been less pronounced but just as steady as global production. Instead of depending largely on fish-farming to meet demand, the U.S. has relied on high levels of seafood imports. While the U.S. ranks third in national consumption of seafood and fourth in total fisheries catch (NMFS, 2000a), the country ranks eleventh in aquaculture production with just 1.1 percent of global production by weight, or 1.6 percent by value (FAO, 2000a).

By live weight, U.S. aquaculture production in 1998 was roughly one billion pounds (445,000 t) (FAO, 2000a). This harvest was valued at just under a billion dollars (NMFS, 2000a), a 44 percent increase over 1991 production values (FAO, 2000a). In comparison, the value of the annual U.S. wild fishery catch over the past decade has been relatively steady at roughly 3.5 billion dollars (NMFS, 2000a).

There are approximately 4,000 aquaculture facilities in the United States (NASS, 1999), with an average annual production worth 243,000 dollars per farm. Except for salmon farms, which are typically owned by foreign multinationals (Jensen, 2001), these facilities tend to be small companies. Spread across all fifty states, U.S. farms collectively raise over 100 different species of aquatic plants and animals. Types of facilities include earthen and concrete ponds, netpens and cages, trays and longlines, raceways, and tank systems. They use fresh, brackish, or salt water (Figures Two and Three).

The bulk of U.S. aquaculture production is located in the South, particularly around the Mississippi Delta—the center of catfish-farming. Channel catfish *(Ictalurus punctatus)*, a freshwater species, account for more than 70 percent of seafood raised on farms in the United States by meat weight (NMFS, 2000a). Animals raised in marine and brackish water include salmon, clams, oysters, and shrimp; they accounted for 284 million pounds (129,000 t) of U.S. production in 1998 (FAO, 2000a). While the production of some marine species, such as the American oyster *(Crassostrea virginica)*, fell significantly over the past decade, growth of other species including hard clams *(Mercenaria mercenaria)* and Atlantic salmon *(Salmo salar)* was substantial (FAO, 2000a). Production of farmed Atlantic salmon grew by 468 percent between 1989 and 1998, and the industry continues to expand.

The Future of U.S. Aquaculture

With supplies of wild seafood limited and demand rising, aquaculture will likely continue to expand in the United States. Citing the nation's 6.2 billion-dollar seafood trade deficit in part, the U.S. Department of Commerce (DOC) has called for a fivefold increase in U.S.

*Includes seaweeds.

Figure Two

1998 U.S. Aquaculture Production

Value of Prominent Farmed Marine Animals by Key-producing States

Salmon

- Maine $64.1 million
- Washington State $30 million*

Oysters

- Washington State $14.1 million
- Oregon $1.9 million
- California $1.3 million
- Massachusetts $1.1 million

*Estimated; exact figures are not available due to confidential data.

Clams

- Washington State $12.1 million
- Connecticut $12 million*
- Virginia $11 million
- Florida $9.5 million

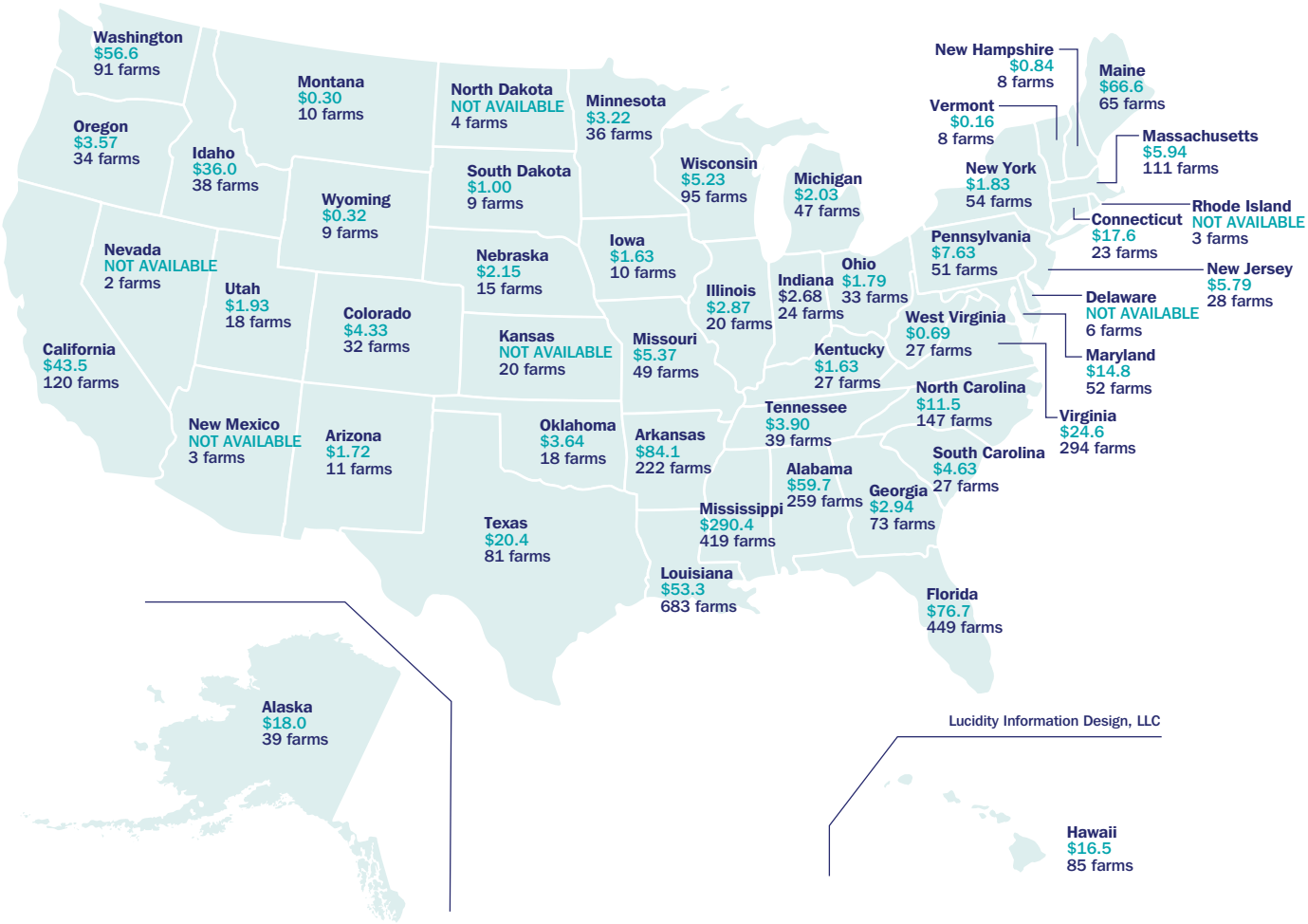
Shrimp

- Texas $8.4 million
- Hawaii $1.7 million

The major marine animals farmed in the United States are salmon, clams, oysters, and shrimp. The 1998 production of these organisms is recorded here as the value of the farmed product in millions of dollars.

Freshwater and Marine Aquaculture Production by State

There is significant regional variation in the number of aquaculture farms and the value of farmed aquatic products in the United States. States in the Mississippi Delta, which primarily produce freshwater catfish, represent the bulk of U.S. production. Washington State and Maine, the main salmon-farming states, are also large producers. Figures below state names represent total aquaculture sales in millions of dollars.



Source: USDA-NASS 1998 Census of Aquaculture

Figure Three

U.S. Aquaculture Production by Species, and Growth Since 1989

Chart of species with over 1,000 metric tons cultured in the United States in 1998

Species Note: Shellfish production data includes shell weight.	Common Name	1998 Production (metric tons)	Growth Since 1989
Ictalurus punctatus	Channel Catfish	255,990	40.1%
Crassostrea virginica	American Oyster	53,097	–39.6%
Crassostrea gigas	Pacific Oyster	31,715	–3.8%
Oncorhynchus mykiss	Rainbow Trout	24,995	–3.1%
Mercenaria mercenaria	Northern Quahog (hard clam)	19,943	379.0%
Procambarus clarkii	Red Swamp Crawfish	17,212	–42.6%
Salmo salar	Atlantic Salmon	14,507	468.0%
Oreochromis spp	Tilapia	8,251	—*
Notemigonus crysoleucas	Golden Shiner	7,434	–12.5%
Morone chrysops x M. saxatilis	Hybrid Striped Bass	4,257	819.0%
Cyprinidae spp	Carps/Cyprinids	2,005	—*
Penaeus vannamei	Whiteleg Shrimp	2,000	193.0%
Ruditapes philippinarum	Japanese Carpet Shell	1,896	27.2%
Mytilus edulis	Blue Mussel	1,196	–14.4%
All species		445,123	20.6%
All species excluding Channel Catfish		189,133	1.5%

*Tilapia and carp were not farmed in significant quantities in 1989.

Source: FAO, 2000a.

aquaculture production by 2025 (DOC, 1999). However, a number of economic, regulatory, and technological factors will influence the industry's growth rate.

One factor retarding the growth of the U.S. industry, and particularly mariculture, is the lack of available high-quality sites. Aquaculturists typically establish their mariculture operations in protected areas with abundant access to unpolluted water. The coastal zone is used for a variety of activities including fishing, recreation, wildlife protection, shipping and navigation, and aesthetic enjoyment. Frequently aquaculturists are hard-pressed to locate their facilities in appropriate coastal areas. Alaska—the state with the longest coastline—has altogether prohibited netpen and cage farming in coastal waters for the protection of native salmon populations and the human communities that depend upon them.

The lack of coastal sites has generated substantial private and government interest in developing an offshore aquaculture industry. Locating aquaculture in the U.S. Exclusive Economic Zone (EEZ)—federal waters usually between 3 and 200 miles offshore—has the

advantages of access to improved water quality, limited conflict from coastal landowners and other users, and independence from state regulations. While there are no purely commercial operations outside of state waters to date, several experimental operations have demonstrated the technical and possibly the economic feasibility of offshore aquaculture (Offshore, 2001; Helsley, 2001; Kent and Drawbridge, 2001; Langan, 2001). The higher costs associated with more durable offshore cage systems and their maintenance will likely necessitate that high-value species be raised in large quantities to make operations financially feasible.

The largest barriers to the expansion of aquaculture into the EEZ are 1) economic costs of operating offshore, 2) high economic and ecological risks from storm damage, 3) an unclear regulatory structure, and 4) ecological and other concerns associated with the large-scale use of the EEZ. To address the third problem, the National Oceanic and Atmospheric Administration (NOAA)* under the Clinton Administration submitted an offshore aquaculture leasing procedure to the Office of Management and Budget, which has not so far become law.

A second option for expanding mariculture is the use of recirculating systems. Properly sited onshore tank systems that filter and recirculate their water are a convenient way to avoid user conflicts concerning coastal water areas. Due to the relatively high costs associated with tank systems, less than ten percent of the 4,000 aquaculture facilities in the U.S. currently employ closed recirculation tanks (NASS, 1999). However, for some high-value animals such as marine shrimp, the added benefits of disease prevention, year-round production, and effluent control have stimulated a trend toward recirculating systems (Clay, pers. comm.).

An emphasis on high-value carnivorous marine fish is driving much of the current investigation into new species for United States aquaculture production. These species include moi (Pacific threadfin), which is experimentally farmed in waters off Hawaii (Helsley, 2001); cobia, (Kilduff et al., 2001); mutton snapper (Benetti et al., 2001a); red drum (Holt, 2001); yellowtail amberjacks (Benetti et al., 2001b); and both white (Drawbridge, 2001) and black seabass (Cotton and Walker, 2001). Many of these fish are thought to have considerable market potential. A recent report suggests that production from the nascent U.S. halibut-farming industry may overtake wild halibut catches within two decades (Forster, 1999a). In addition to new species, the production traits of such traditionally farmed species as catfish and salmon are altered through selective breeding and genetic engineering (NWAC, 2000; Reichhardt, 2000; Zitner, 2001).

Overall, developments in offshore aquaculture, recirculation technology, and animal production traits will likely catalyze the U.S. marine aquaculture industry's growth. However, this growth rate may slow if market factors such as relatively inexpensive imports or negative public perception affect production. If the public perceives aquaculture as an environmentally damaging industry, aquaculture will certainly encounter increased resistance.

"Alaska—the state with the longest coastline—has altogether prohibited netpen and cage farming in coastal waters for the protection of native salmon populations and the human communities that depend upon them."

*NOAA is part of the U.S. Department of Commerce, and includes the National Marine Fisheries Service (NMFS).

II. Aquaculture and the **Marine Environment**

Like other forms of animal production, aquaculture can lead to environmental degradation. The environmental impacts of aquaculture vary considerably with the type of organism raised and the production system used; some aquaculture systems have little environmental impact at all. The main environmental effects of marine aquaculture can be divided into five categories: 1) biological pollution, 2) fish for fish feeds, 3) organic pollution and eutrophication, 4) chemical pollution, and 5) habitat modification.

Biological Pollution

Animals and other organisms themselves can be an important form of "pollution." Aquaculture facilities in the United States unintentionally release farmed fish and their parasites and pathogens into the environment. Some of these escaped organisms can harm native fish populations.

Introduced Species

Introduced species are animals released through human activities in areas outside their natural range. By feeding on native species or competing with them for food and habitat, introduced fish can reduce levels of biodiversity and even cause the displacement or extinction of native populations (OTA, 1993).

Historically, aquaculture has been an important source of foreign introductions. Many of these introductions resulted from intentional stocking efforts, legal or otherwise; however, some of the introductions occurred when non-indigenous species escaped from aquaculture facilities. Almost every major aquatic species farmed in the United States is either non-native or is farmed outside of its native range (USGS, 2000). Examples of currently farmed non-indigenous marine species include Pacific whiteleg shrimp (in Texas and South Carolina), Pacific (Japanese) and Eastern oysters on the West Coast, and Atlantic salmon in Washington State (USGS, 2000).

Farming Atlantic salmon in the Pacific waters of the West Coast has been especially controversial. Each year Pacific fishermen catch Atlantic salmon that have escaped from aquaculture operations in Washington State and British Columbia (McKinnell and Thomson, 1997). Some escapes occur through normal operational "leakage," where only a few fish are lost; large-scale escapes can occur when storms, marine mammals, vandalism, or human error damage the netpens. Between 1987 and 1996, scientists documented at least a quarter million Atlantic salmon escapes on the West Coast (McKinnell and Thomson,

1997), with another 350,000 escapes in 1997 alone (Fuller, 2000).

Although farmed escapees have lower survival rates than wild salmon (McKinnell and Thomson, 1997), they still compete with wild Pacific salmon stocks for food, habitat, and spawning grounds. As a result of continuing introductions, the number of Atlantic salmon seen returning to rivers and streams on the West Coast is increasing, and Atlantic salmon are now successfully reproducing in British Columbia rivers (Volpe et al., 2000).

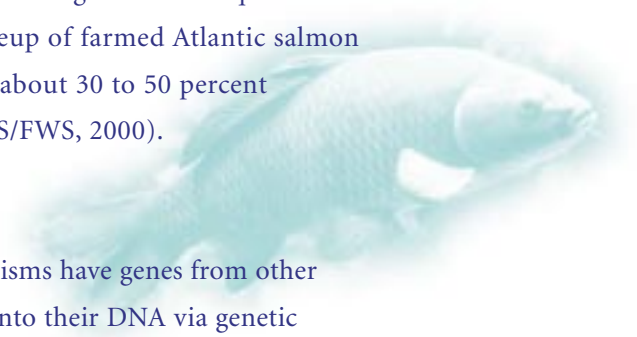
Native Species

Escapes of native species of farmed fish can also harm wild stocks, particularly when substantial genetic differences exist between the farmed and wild populations. Genetic differences often occur when farmed fish are specifically bred for aquaculture or are moved from one area to another.

Farmed fish that have been selectively bred for particular traits can be markedly different from wild fish. Highly selected strains often have smaller fins, larger bodies, and more aggressive feeding behavior (Fleming and Einum, 1997). Compounding these differences due to selective breeding, the genetic makeup of some fish, such as wild Atlantic salmon, varies significantly between regions due to evolved local adaptations (Hindar, 2001; Johnson, 2000). When farmed salmon escape, they can interbreed with wild salmon frequently enough to change the genetic makeup of some wild stocks (Hindar, 2001; McGinnity et al., 1997). This interbreeding can decrease the fitness of wild populations through the loss of adaptations and the breakup of beneficial gene combinations (HSRG, 2000), and wild stocks may be unable to readapt if escapes continue (Hindar, 2001).

In Maine, escaped farmed Atlantic salmon may threaten the survival of endangered wild stocks by flooding the wild salmon gene pool (FWS/NOAA, 2000). Maine salmon populations are particularly susceptible to genetic perturbations because of their very low abundance levels. For example, a December 2000 storm resulted in the escape of 100,000 salmon from a single farm in Maine, more than 1,000 times the number of documented wild adult salmon (Daley, 2001). Similarly, in the Magaguadavic River in neighboring New Brunswick, 82 percent of the young salmon (smolts) leaving the river in 1998 were of farmed origin (FWS/NOAA, 2000). Aquaculturists' use of European milt (sperm) exacerbates the risk of genetic consequences. The genetic makeup of farmed Atlantic salmon in Maine is now about 30 to 50 percent European (NMFS/FWS, 2000).

"As a result of continuing introductions, the number of Atlantic salmon seen returning to freshwater environments on the West Coast is increasing, and Atlantic salmon are now successfully reproducing in British Columbia rivers."



Transgenics

Transgenic organisms have genes from other species inserted into their DNA via genetic engineering techniques, usually to introduce or to amplify an economically valuable trait such as faster growth. Farming of transgenic fish will likely heighten concerns about escapes of

farmed fish. Scientists have genetically engineered at least 35 species of fish worldwide (Reichhardt, 2000), although no transgenic fish products are yet commercially available (Figure Four; FAO, 2000b). In the United States, the company Aqua Bounty Farms™ has applied to the FDA for permission to market genetically engineered Atlantic salmon* (Reichhardt, 2000; Zitner, 2001). These fish have an added growth-hormone gene from chinook salmon that may cause them to grow significantly faster than nontransgenic fish (CEQ, 2000).

Figure Four

Some Genetically Modified Organisms Tested for Use in Aquaculture

Transgenic Organisms	Foreign Gene (origin)	Desired Effect	Country
Atlantic salmon	Antifreeze protein – AFP (ocean pout)	Cold tolerance	United States, Canada
	Growth hormone – GH (chinook)	Increased growth and efficiency	United States, Canada
Coho salmon	AFP (ocean pout) and GH (chinook)	Increased growth	Canada
Chinook salmon	AFP (ocean pout) and GH (salmon)	Increased growth and efficiency	New Zealand
Rainbow trout	AFP (ocean pout) and GH (salmon)	Increased growth and efficiency	United States, Canada
Tilapia	AFP (ocean pout) and GH (salmon)	Increased growth and efficiency	Canada, United Kingdom
	GH (tilapia)	Increased growth	Cuba
	Insulin producing gene (tilapia)	Production of human insulin for diabetes	Canada
Salmon	Lysosome gene (rainbow trout) and Pleurocidin gene (flounder)	Disease resistance	United States, Canada
Striped bass	Insect genes	Disease resistance	United States
Mud loach	GH (mud loach)	Increased growth and efficiency	China, Korea
Channel catfish	GH (rainbow trout)	Increased growth	United States
Common carp	GH (salmon and human)	150% growth improvement; improved disease resistance	United States, China
Indian carps	GH (human)	Increased growth	India
Goldfish	GH and AFP (ocean pout)	Increased growth	China
Abalone	GH (coho)	Increased growth	United States
Oysters	GH (coho)	Increased growth	United States

Source: FAO, 2000b.

Transgenic Salmonid Fish Expressing Exogenous Salmonid Growth Hormone, United States Patent No. 5,545,808, August 13, 1996.

Like other farmed fish, escaped transgenics could damage wild stocks through increased competition and predation (Abrahams and Sutterlin, 1999; FAO, 2000b). Some transgenic salmon have 50 to 70 percent elevated basal metabolic rates; their increased appetites could raise the frequency of starvation for both escaped and wild fish in food-limited systems (Kapuscinski and Brister, 2001; Abrahams and Sutterlin, 1999). The main concern regarding transgenic fish, however, is that their introduced genes could spread throughout wild populations, and ultimately weaken them. Computer models indicate that, under certain conditions, breeding between wild fish and faster-growing transgenic fish could drive local fish populations to extinction (Hedrick, 2001; Muir and Howard, 1999).

In an effort to mitigate concerns about interbreeding with wild stocks, Aqua Bounty Farms™ states that it will sell only sterile female fish for use in netpens if its transgenic salmon are approved for commercialization. However, the technique Aqua Bounty Farms™ would use to make fish sterile may leave a small percentage of fish fertile, while wild males' attempts to reproduce with escaped sterile females may depress reproduction rates (Kapuscinski and Brister, 2001).

Overall, the use of transgenic fish in aquaculture represents a major new environmental uncertainty, and their approval will be highly contentious. Ironically, a new study questions the advantages of fast-growing transgenic fish (Devlin, 2001). Both transgenesis and traditional breeding increase fish growth rates; however, transgenesis does not appear to markedly increase the growth rates of fish already bred for fast growth (Devlin, 2001).

Disease and Parasites

Many diseases and parasites are capable of spreading between farmed fish and wild stocks. Historically, a number of diseases and parasites were introduced through aquaculture operations, and aquaculture can magnify the level of those diseases already present (NMFS/ FWS, 2000). In the early 1900s, for example, the Japanese oyster drill and a predatory flatworm were introduced to the West Coast with the Pacific oyster, and at that time they contributed to the decline of native oyster stocks (Clugston, 1990). Accidental disease and parasite introductions are now much better controlled, but recent experiences in salmon- and shrimp-farming indicate that problems remain.

Some disease outbreaks on salmon farms appear to impact wild populations today. Sea lice—parasites that eat salmon flesh—are a serious problem on salmon farms and can even kill fish (McVicar, 1997; Finstad et al., 2000). Norwegian field studies observe that wild salmon often become heavily infected with sea lice while migrating through coastal waters (Finstad et al., 2000), with the highest infection levels occurring in salmon-farming areas (McVicar, 1997; Hindar, 2001). While these parasites are relatively common, sea lice epidemics have occurred in wild salmon and trout in every major salmon-farming country (Finstad

et al., 2000). Sea lice may also serve as a host for other lethal diseases, such as Infectious Salmon Anemia (ISA) (Johnson et al., 1997).

In January 2001, ISA was detected for the first time in the United States at a Maine salmon farm, and has since shown up in two more farms (Journal, 2001). ISA appears to be moving south from New Brunswick, where it made its first North American appearance in 1996. Since then, the disease has been detected in both escaped farmed fish and wild fish (FWS/NOAA, 2000; NMFS/FWS 2000). To protect Maine's Atlantic salmon from ISA and other introduced diseases, the National Marine Fisheries Service (NMFS) is considering mandatory escape-prevention and sea-lice control measures (NMFS/FWS, 2000).

Farmed shrimp also experience elevated disease incidence because the animals are often raised in high densities and are physiologically stressed. During the 1990s, the shrimp-farming industry in the United States and abroad was rocked by viral diseases that spread throughout the world, costing the industry an average of one billion dollars yearly since 1994 (Lightner, 1998). The presence of at least two of these shrimp viruses has now been documented in wild shrimp in the Gulf of Mexico (JSA, 1997; Ray, pers. comm.). However, marine viruses are little studied and there is only one known example—the "IHHN" virus in Mexico—where shrimp farm outbreaks might have depressed wild shrimp populations (JSA, 1997).

To reduce the effects of biological pollution, aquaculture facilities can grow fish that are unlikely to harm wild fish populations. Raising native fish species is generally preferable to raising non-natives unless escaped non-natives are unable to survive and reproduce outside of the farm (e.g., due to cold winters). Problematic genetic interactions can be reduced by farming fish away from endangered or threatened populations of the same species, and by escape-proofing facilities (FWS/NOAA, 2000). Options for minimizing escapes include using improved cage and pond designs, and moving fish out of netpens and into land-based facilities.

Stocking certified pathogen-free fish, reducing fish stress, and filtering or ozonating effluent from pond and recirculating tank systems can minimize disease transmission. The state of Texas requires shrimp facilities with virus problems to retain their wastewater until viral particles become inactive (Ray, pers. comm.).

Fish for Fish Feeds

Although aquaculture is sometimes promoted as an alternative to capture fisheries, some types of aquaculture use huge quantities of wild-caught fish as feed in the form of fish meal and fish oil, and thus indirectly affect marine ecosystems thousands of miles from fish farms (Naylor et al., 2000). Fish meal and fish oil are produced primarily from processing small, oily fish such as anchovies, sardines, and menhaden, which are caught for this purpose. A huge quantity of these "forage" fish—roughly a third of the global catch—is turned into fish meal and fish oil each year (FAO, 2000b). Salmon, eels, striped bass, and many other marine and brackish water species are

carnivores, and they rely on large amounts of fish meal and fish oil in their diets (Figure Five). Some omnivorous animals such as shrimp are also fed large amounts of fish meal and fish oil (Tacon and Forster, 2000).

Fish meal is used in feeds for a variety of farmed animals including poultry, pigs, and fish. In 1998, compound aquaculture feeds—pelleted fish food—consumed more than 40 percent of total fish-meal production (the equivalent of twenty billion pounds of forage fish) and over three-quarters of the world's fish oil—shares that have increased markedly in the past decade (Tacon and Forster, 2000). However, total world fish-meal and fish-oil production has not changed significantly in recent years (FAO, 2000b; Tacon and Forster, 2000). Many industry experts expect that within a decade, the global aquaculture industry will use two-thirds of world fish-meal production, and there may already be a serious fish-oil shortage (Starkey, 2000). Others predict that ongoing industry efforts to reduce the amount of fish meal in feeds may be more successful, ultimately decreasing fish-meal and fish-oil consumption by aquaculture (Tacon and Forster, 2000).

If the demand for fish meal continues to rise, market pressure to produce fish meal will increase. Fish meal prices have risen over the past several decades (FAO, 2001), and could double in coming years (Hardy, 2000a). Most harvested forage fish stocks are already fished to their maximum, and the average trophic

Figure Five

Estimated 2000 Fish-meal and Fish-oil Use in World Aquaculture

Fish	Production (million pounds)	Production Using Compound Feeds (million pounds)	Wild Fish Used in Compound Feeds (million pounds)	Ratio of Wild Fish to Fed Farmed Fish*
Marine Finfish	2,083	1,250	5,157	4.13
Eel	492	392	1,843	4.69
Salmon	1,953	1,953	4,762	2.44
Marine Shrimp	2,707	2,220	4,996	2.25
Trout	1,168	1,168	1,709	1.46
Tilapia	2,363	970	545	0.56
Milkfish	829	331	311	0.94
Catfish	1,060	913	273	0.30
Fed Carp	22,167	8,201	3,075	0.38
Filter-feeding Carp	12,169	0	0	0
Mollusks	20,150	0	0	0

*This column represents the ratio of wild fish used in fish meal to farmed fish produced using compound feeds, or pelleted fish food. For example, it takes an average of four pounds of wild fish to produce one pound of marine finfish fed with compound feeds.

Source: Naylor et al., 2000 (methodology); Tacon and Forster, 2000 (data).

"Increased catches of forage fish would reduce the amount of food available for predators such as large fish, marine mammals, and seabirds."

level of fish raised in aquaculture is rising (Pauly et al., 2001). Nevertheless, several stocks such as krill and certain mesopelagic fish could be further exploited if the price of fish meal rose high enough (FAO, 1997; FAO, 2000c). Increased catches of forage fish would reduce the amount of food available for predators such as large fish, marine mammals, and seabirds (Naylor et al., 2000).

A November 2000 study by the European Commission's Scientific Committee on Animal Nutrition found that among the many animal feed ingredients studied, fish meal and fish oil were the most heavily contaminated with dioxins and PCBs (EC, 2000). The committee is now considering measures to limit dioxin and PCB levels in human food and animal feed. Some of the fish meal and fish oil used in North American fish feeds comes from the same sources used in Europe. However, there are no publicly available data on dioxin and PCB levels in U.S. farmed fish or the extent to which dioxins and PCBs accumulate in the marine environment near aquaculture operations. A small Canadian pilot study found that a single serving of farmed salmon contained three to six times the World Health Organization's recommended daily intake limit for dioxins and PCBs (Easton, 2001).

Feed is the largest cost component in many intensive aquaculture production systems. As the price of fish meal rises, feed manufacturers are likely to substitute grains, oilseeds, fish and meat trimmings, and processing wastes (Hardy, 2000a). Currently, these substitutes are less digestible than high-quality fish meal, and their use can result in slower growth and increased levels of organic waste such as fecal matter (Adelizi et al., 1998; Hardy, 2000a).

Replacing fish oil is particularly problematic. Vegetable oil substitutes may decrease fish growth rates, change fish flavors, and reduce the concentration of healthful omega-3 fatty acids in some species (Adelizi et al., 1998; Hardy, 2000a). Ongoing research is attempting to address these problems.

Farming noncarnivorous fish such as catfish, tilapia, and carp requires less marine protein, and already forms the basis of aquaculture within developing countries (Tacon and Forster, 2000). Encouraging farmers to raise and consumers to purchase fish that are relatively low on the food chain would help reduce aquaculture's dependence on forage fish.

Organic Pollution and Eutrophication

Nutrient pollution, particularly nitrogen pollution, is a primary cause of environmental degradation in marine waters (NRC, 2000; Boesch et al., 2001). Half of U.S. estuarine waters are already moderately to severely eutrophied—overenriched with organic material. Eutrophication is expected to worsen in 70 percent of coastal areas over the next two decades (EPA, 2001). The adverse effects of eutrophication include low dissolved oxygen levels, murky water, death of seagrasses and corals, fish kills, low- or no-oxygen "dead zones," and possibly harmful algal blooms (Boesch et al., 2001; EPA, 2001).

Like terrestrial livestock and poultry operations, aquaculture (except farmed shellfish) can contribute to nutrient loading. However, unlike terrestrial operations, aquaculture wastes often enter the aquatic environment directly, either because fish are farmed in natural bodies of water (e.g., salmon in netpens) or aquaculture effluents are emptied into them (e.g., some shrimp and catfish ponds). Organic wastes from aquaculture may include uneaten food, feces, urine, mucus, and dead fish. As much as 70 percent of total phosphorus and 80 percent of total nitrogen fed to fish may be released into the water column through organic wastes (Beveridge, 1996), and approximately 80 percent of those nutrients are available to plants and may contribute to eutrophication (Troell et al., 1997).

Though aquaculture's share in national nutrient loading is small, eutrophication is a cumulative problem. EPA recognizes that aquaculture "contributes nutrients and pathogens to environmentally sensitive areas such as the Gulf of Mexico, the Chesapeake Bay, and other estuaries, rivers, lakes, and streams throughout the country" (EPA, 2000a). Eutrophication is difficult to address precisely because it is often caused by many, predominantly small, sources.

Nutrient loading from aquaculture can be significant on a local scale. A salmon farm of 200,000 fish releases an amount of nitrogen, phosphorus, and fecal matter roughly equivalent to the nutrient waste in the untreated sewage from 20,000, 25,000, and 65,000 people, respectively (Hardy, 2000b). In some areas with intensive cage farming, such as L'Etang Inlet in New Brunswick, Canada, nitrogen and phosphorus additions from aquaculture are the largest anthropogenic source of nutrients (Strain et al., 1995). In 1997, four of about twelve salmon netpens in Washington State discharged 93 percent of the amount of "total suspended solids" into Puget Sound as the sewage treatment plant serving the city of Seattle (Whiteley, pers. comm.).

Netpen farming can also alter the seabed. A wide body of literature documents raised levels of organic matter underneath cage operations (Beveridge, 1996), which change the chemical and biological structure of the sediment. Effects reported from salmon-farming include a dead zone under pens in severe cases, surrounded by a ring of decreased animal diversity. Impacts can extend roughly 500 feet (150 m) from the site (Beveridge, 1996), although 100 feet (30 m) is a more usual limit (EAO, 1998).

In nutrient-limited waters, modest additions of nutrients from netpens can increase biodiversity and productivity, which may be desirable to fishermen. In most cases, however, siting netpens in areas with high flushing rates is critical to preventing problems from wastes. Seaweed biofilters can also reduce nutrient loads around netpen operations (Chopin et al., 1999; Troell et al., 1997). Seaweeds can improve water quality by removing ammonia and phosphorus, and by oxygenating the water. If marketable plants are farmed next to netpens and the use of pesticides and other

chemicals is limited, the pollution-control method can pay for itself. For example, the seaweed, *Porphyra*—commonly known as nori—is used in sushi rolls. *Porphyra* is an excellent nutrient pump, as well as a high-value cash crop that can be integrated into salmon-farming operations (Chopin et al., 1999).

"Not all forms of aquaculture contribute to nutrient loading. Filter-feeding mollusks can clarify the water by consuming plankton in aquatic ecosystems, significantly improving water quality."

Pond aquaculture is typically less detrimental to water quality than netpens since pond walls contain the water. However, eutrophic effects depend on the frequency and volume of discharges, as well as the characteristics of the receiving waters. If ponds are rarely discharged, nutrient pollution is reduced because microbial processes and deposition inside ponds remove nutrients and organic matter (Lutz, 2001). Frequently drained shrimp ponds, however, have been a problematic source of water pollution in Texas (Boyd and Clay, 1998; Baker, 1997).

Effluents from aquaculture ponds can be readily treated. Constructed wetlands or settling ponds (where effluents lie quiescent so solids can settle out) can remove nearly three-quarters of the nitrogen and phosphorus in the effluent, and 96 percent of the total suspended solids (Boyd et al., 2000). Management practices, such as using grass cover on embankments and proper placement of water exchange pipes can reduce levels of suspended solids (Boyd et al., 2000). After the recent enactment of environmental regulations in Texas, several shrimp farms changed management practices and built retention ponds, reducing discharged solids and ammonia levels by over 98 percent (Hamper, 2001).

Not all forms of aquaculture contribute to nutrient loading. Filter-feeding mollusks can clarify the water by consuming plankton in aquatic ecosystems, significantly improving water quality. Mussel farms can remove nitrogen from water at a 70 percent higher rate than occurs in surrounding waters (Kaspar et al., 1985). Before their population crash in the 1950s, oysters in the Chesapeake Bay filtered the water in the entire estuary every three to four days (CBP, 1999). Moreover, shellfish farmers are often among the loudest advocates for clean water.

In some instances, mollusk-farming has harmed the marine environment by depriving wild filter-feeders of food (FAO, 1991) and generating anoxic sediments through feces deposition (Grant et al., 1995; Kaspar et al., 1985). However, these negative impacts occur only when farms are too large and densely seeded. Such impacts have not been reported in the United States.

Chemical Pollution

A wide range of chemicals are used in aquaculture, including antibiotics, parasiticides (parasite-killing drugs), pesticides, hormones, anesthetics, various pigments, minerals, and vitamins. Chemical use varies widely from sector to sector (Figure Six). For example, finfish farms and hatcheries typically use a variety of chemicals, while mollusk systems rarely use chemicals. The concerns about the use of chemicals center on both their potential effects on human health and on natural ecosystems.

Figure Six

Some Chemicals Used in Aquaculture and Potential Environmental and Health Effects

Type of Chemical	Examples of Chemicals	Potential Risks	Chemical Usage
Antibiotics[i]	Oxytetracycline (Terramycin); Sulfadimethoxine-ormethoprim (Romet[30]®); Amoxicillin trihydrate	Development of resistant bacteria; residues in food	Used on catfish and salmonids to treat various fish diseases
Parasiticides	Cypermethrin[ii] (Excis®)	Acute toxicity to marine organisms	Controls sea lice outbreaks on salmon
	Carbaryl[iii] (Sevin®)	Acute toxicity to marine organisms	Reduces burrowing shrimp infestations on oyster beds in Washington State
	Trichlorfon[iv]	Acute toxicity to marine organisms	Kills parasites in ornamental fish ponds; "special local need" permit required
	Formalin[v] (Parasite-S®)	Toxic; irritant to handlers	Controls fungus, protozoa, and trematodes on finfish
Fertilizers[vi]	Various nitrogen, phosphorus, and trace element mixes	Contribute to nutrient enrichment	Stimulates algae production in pond systems
Anesthetics[vii]	Methanesulphonate (Tricaine-S®)	Suspected carcinogen	Anesthetizes finfish
Spawning Hormones[viii]	Human chorionic gonadotropin (Chorulon®)	Minimal	Induces spawning in finfish
Oxidants[ix]	Potassium permanganate	Explosive; irritant to handlers	Used in pond systems to kill disease organisms and phytoplankton
	Hydrogen peroxide	Irritant to handlers	
	Calcium hypochlorite	Toxic; irritant to handlers	
Algicides and Herbicides	Copper sulfate[x]	Toxic to aquatic life at high dosages; irritant to handlers	Used in pond systems to reduce nuisance plant growth
	Chelated copper[xi]	Toxic to aquatic life at high dosages	
	Simazine[xii]	Effects on liver and thyroid in humans; carcinogen	
	2,4-D[xiii]	Effects on the blood, liver, and kidneys in animals; possible carcinogen	
	Diquat bromide[xiv]	Effects on kidneys in humans	
	Potassium ricinoleate[xvi]	Minimal	

[i] Angulo, 1999; NRC, 1999a.
[ii] Ernst, 2001.
[iii] MOA, 2001.
[iv] Schnick, 2000.
[v] Boyd, 1999.
[vi] Boyd, 1999.
[vii] Cho and Heath, 2000.
[viii] Schnick, 2000.
[ix] Boyd, 1999.
[x] Boyd, 1999.
[xi] Boyd, 1999.
[xii] EPA, 2000c.
[xiii] EPA, 2000b.
[xiv] Boyd, 1999.
[xv] <http://www.scorecard.org/chemical-profiles/summary.tcl?edf_substance_id=85%2d00%2d7#hazards>
[xvi] Boyd, 1999.

Drug Use in Aquaculture

Since the market for most aquaculture drugs is relatively small and the FDA approval process is costly, only five drugs have been approved by the FDA for disease-treatment in U.S. aquaculture (Schnick, 2000). Additionally, veterinarians may prescribe any human or animal drug for certain nonapproved uses in animals, including food fish (NRC, 1999a), and FDA allows the use of Investigational New Animal Drugs (INAD) for experimental purposes.

Two of the FDA-approved aquaculture drugs are antibiotics. There is limited data on the extent of antibiotic use in animal agriculture (Mellon et al., 2001), including aquaculture. U.S. aquaculturists, however, cannot legally feed their fish antibiotic-containing feed on a daily basis (FDA, 1997a), and thus rely much less on antibiotics than do most terrestrial animal producers or some overseas fish producers.

Concerns About Drug Use

The application and containment of drugs in aquaculture is more complicated than in terrestrial livestock operations because drugs typically must be administered in water, often as components of fish feed (NRC, 1999a). Once in the water, drugs readily disperse into the environment, where they can have an impact on or accumulate in nontarget species.

The use of parasiticide drugs to control sea lice is particularly controversial in the U.S. and abroad. Maine salmon farms use the parasiticide cypermethrin as an INAD (Belle, pers. comm.). Aquaculturists apply cypermethrin by holding salmon near netpens in tarps filled with a mixture of seawater and parasiticide. When the treatment is completed, the farmers dump both the salmon and the parasiticide-laden water back into the netpen (Ernst et al., in press). One Canadian study demonstrated that plumes of cypermethrin, which is toxic to marine invertebrates, can remain in the water up to five hours and travel distances up to half a mile (Ernst et al., in press). The industry is pursuing FDA approval of ivermectin (Schnick, 2000), a relatively toxic parasiticide that kills parasites in cattle and swine (FDA, 1997b) and is used to treat sea lice in Europe and South America.

Antibiotic Resistance

Antibiotic use in U.S. aquaculture does not significantly threaten the marine environment. The use of antibiotics, however, is arguably a health risk for people and farmed fish, since it promotes the spread of antibiotic-resistance in both human and fish pathogens. At least a few types of bacteria associated with fish, such as *Streptococcus,* can be pathogenic to humans (Weinstein et al., 1997). If strains of these bacteria develop higher levels of resistance to antibiotics, infections by these bacteria may be difficult to treat. More generally, resistance can potentially spread to other types of bacteria, including human pathogens, through gene transfer mechanisms special to bacteria (Dixon, 2000).

Several important fish pathogens have become resistant to many drugs used in aquaculture, including the two commercially available antibiotics approved by FDA (Dixon 2000), making them more difficult to control.

A U.S. Center for Disease Control and Prevention (CDC) literature review indicates that certain antibiotic resistance genes in *Salmonella*—bacteria that can cause severe food poisoning in people—might have emerged following antibiotic use in Asian aquaculture (Angulo, 1999).

Pesticide Use in Aquaculture

Unlike terrestrial agriculture, pesticides are seldom used in marine aquaculture. However, there are some applications. More than a dozen types of herbicides are approved for use in U.S. aquaculture facilities to control aquatic weeds, algal blooms, and fouling organisms. Most herbicides are used in pond and tank-based aquaculture, although netpen operators often treat their nets with paints that contain copper-based algae killers (Belle, pers. comm.). While copper is toxic to many aquatic organisms, the copper compounds aquaculturists use appear relatively safe when applied in approved dosages (Eisler, 1998; Boyd and Massaut, 1999). Under a special permit, aquaculturists use the carbamate insecticide Sevin to control burrowing shrimp infestations in oyster beds in Willapa Bay and Grays Bay, in Washington State (MOA, 2001).

The use of antibiotics, parasiticides, and pesticides in aquaculture can be minimized through a number of practices, including minimizing stress to fish, vaccinating fish, fallowing netpens, and applying Integrated Pest Management (IPM). Stress is a contributing factor in the majority of fish health problems; consequently improving water quality, lowering stocking densities, and avoiding handling fish can improve the animals' natural resistance (Rottman et al., 1992). Injecting fish with vaccines also reduces antibiotic use; a number of fish vaccines have now been developed and their use continues to increase (NRC, 1999a). IPM options include using biological controls to reduce pest populations. For example, some European salmon farmers stock netpens with wrasse—small fish that feed on sea lice and fouling organisms. Cunner, a similar fish, may have potential in North America (Belle, pers. comm.).

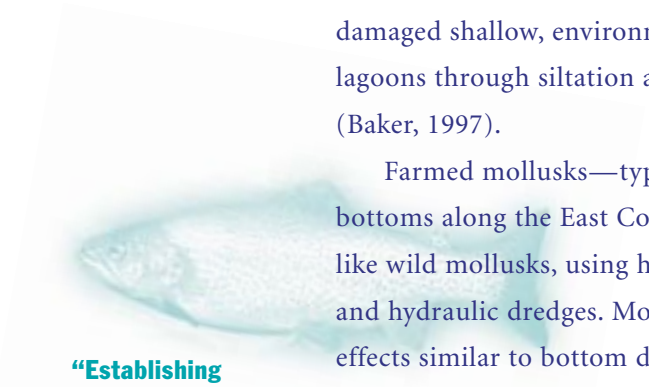
"The use of antibiotics, parasiticides, and pesticides in aquaculture can be minimized through a number of practices, including minimizing stress to fish, vaccinating fish, fallowing netpens, and applying Integrated Pest Management (IPM)."

Habitat Modification

Direct Habitat Conversion

Like other forms of food production, aquaculture requires space. Aquaculture operations cover approximately 321,000 acres (130,000 ha) of fresh water in the U.S., 80 percent of which is located in the South (NASS, 1999). Marine aquaculture currently uses an additional 64,000 acres (26,000 ha) of salt water—roughly 100 square miles, or less than half a percent of total state waters. Most of this area is used for farming mollusks on the ocean bottom (NASS, 1999).

For marine aquaculturists, obtaining sites that fishermen and coastal landowners do not contest can be a challenge. From an ecological perspective, clustering or poor siting of mariculture operations can obstruct wild animals' use of their natural surroundings. Hatchery structures in the U.S. and netpens in New Brunswick may block passage of migrating fish (HSRG, 2000; Milewski et al., 1997). In Texas,



"Establishing aquaculture facilities several miles from areas where marine mammals haul out of the ocean can substantially reduce predation."

poorly sited coastal shrimp ponds have damaged shallow, environmentally sensitive lagoons through siltation and eutrophication (Baker, 1997).

Farmed mollusks—typically grown on bay bottoms along the East Coast—are harvested like wild mollusks, using hand rakes, tongs, and hydraulic dredges. Mollusk dredging has effects similar to bottom dredging by commercial fishermen, altering the bottom habitat and temporarily reducing levels of biodiversity (Kaiser et al., 1996). Harvesting mollusks from off-bottom systems, such as the rafts and lines commonly used on the West Coast, avoids severe bottom disturbance.

Aquaculture also affects habitat by creating large aggregations of fish that are a lure to predators. Birds, seals, and other predators often feed at aquaculture sites, where they can become entangled in netpens and suffocate (Moore and Wieting, 1999; Wursig, 2001). Cormorants and great blue herons are the animals most frequently killed (Rueggerberg and Booth, 1989).

Predator Control Programs

Predation, or "depredation," is a serious problem at marine aquaculture facilities. In marine netpens, mammals such as seals, sea lions, and river otters often prey on farmed fish, by reaching through the nets and gouging them (Rueggerberg and Booth, 1989; OTA 1995a). Populations of some seals are on the rise (NMFS, 2000b), and seal predation at netpens may worsen.

Prior to 1995, U.S. salmon farmers were allowed to shoot seals preying on their fish, though Congress has since prohibited killing seals (Wursig, 2001). Instead, aquaculturists employ a variety of nonlethal techniques to keep animals away from their sites, such as dogs, vessel chases, and acoustic harassment devices (OTA, 1995a).

Acoustic deterrents include small firecrackers—known colloquially as seal bombs—and intense underwater loudspeakers called acoustic harassment or deterrent devices (AHDs or ADDs) (Wursig, 2001). All of these devices may cause disorientation, pain, or hearing loss in marine species, including fish, sea turtles, and marine mammals (Hastings et al., 1996; NRDC, 1999). This noise pollution affects the surrounding marine habitat, causing other marine mammals that do not prey on farmed salmon (e.g., killer whales) to avoid the area (Morton and Symonds, in review). Both the impacts of acoustic deterrents on marine mammals and their effectiveness in deterring predators require further investigation (NRDC, 1999).

Siting may be the most effective means to reduce interactions with some predators, such as sea lions. Establishing aquaculture facilities several miles from areas where marine mammals haul out of the ocean can substantially reduce predation (Wursig, 2001). Other operational methods include properly tensioning netpen lines and employing thicker ropes to avoid entanglement, using double nets to reduce predation, and rotating deterrence techniques to minimize predator habituation (Moore and Wieting, 1999).

III. Perspectives and Options

Environmental Impacts of Marine Aquaculture in Perspective

In a number of countries with large marine aquaculture industries, fish-farming—and particularly shrimp- and salmon-farming—is a major cause of environmental degradation (Naylor et al., 1998). Shrimp-farming in developing countries, for example, has caused extensive loss of mangrove forests and other wetlands, water pollution, and salinization of soil and water (Boyd and Clay, 1998).

In the United States, the marine aquaculture industry is small and better regulated. It has not caused widespread environmental problems. The present effects of U.S. aquaculture on the marine environment do not come close in gravity to many other environmental problems, including the decimation of wild stocks and habitats by the U.S. fishing industry (NRC, 1999b). Effects of marine aquaculture are minor compared to changes in ocean temperature, coral bleaching, and coastal flooding likely from global warming (IPCC, 2001).

Nevertheless, there are strong reasons to do more to address the environmental effects of U.S. aquaculture. Aquaculture may be the only means to markedly increase seafood production, and can be less detrimental to marine ecosystems than fishing. Moreover, aquaculture may be a more desirable way to raise animal protein than terrestrial production. Contrasted with other meats, farming fish is a relatively efficient means of supplying protein (Forster, 1999b), mainly because fish are cold-blooded and have low metabolic rates. In short, aquaculture is here to stay; the challenge is to ensure the young and growing industry develops in a sustainable manner and does not cause serious ecological damage.

Some environmental impacts of U.S. marine aquaculture have considerable immediacy. Since organisms cannot be recalled once they are released, biological pollution is often permanent. Atlantic salmon populations, for example, may become permanently established in the Pacific if escapes from Washington State and British Columbia farms continue.

Nowhere are the risks from biological pollution more acute than to endangered runs of wild Atlantic salmon on the East Coast. One factor that motivated the federal government's November 2000 decision to list the remaining runs of Atlantic salmon in Maine as endangered was the "continued use of non-native American salmon and detection of aquaculture escapees in Maine rivers, with the potential for interbreeding and competition for habitat and food" (NMFS/FWS, 2000). Only 22 wild Atlantic salmon were documented as returning to spawn in Maine

rivers in 2000, although returning spawners probably totaled about 150 fish (FWS/NOAA, 2000; Goode, pers. comm.). It appears that little time remains to protect these few salmon.

Other biological impacts from aquaculture may not pose immediate threats to endangered species. Nevertheless, potential introductions of marine diseases, parasites, and transgenic fish could permanently harm fish populations and even marine ecosystems.

Aquaculture's dependence on marine fisheries for fish meal and fish oil is also a high priority, particularly if it encourages increased harvests of forage fish. Many types of aquaculture will continue to diminish rather than augment marine fish supplies until this dependence is altered (Naylor et al., 2000). In a sense, U.S. aquaculture development is already playing a leading role in addressing dependence on fish meal and fish oil, since domestic catfish production makes the United States the only industrialized country with an aquaculture industry that is not mainly based on production of carnivores (FAO, 2000a). However, many fish raised in the United States, such as salmon, trout, shrimp, and hybrid striped bass, have diets with moderate to high levels of fish meal and fish oil. With its considerable scientific capacity and large supplies of such alternative feed ingredients as soybeans, the U.S. is well positioned to be a leader in addressing this global issue.

Other environmental impacts of aquaculture, such as effects on water quality, may be locally problematic but are small contributors to much larger problems nationally. NOAA's goal of establishing a large offshore aquaculture industry, if successful, could have substantial effects on the marine environment. To be potentially profitable, commercial offshore aquaculture will need to raise highly valuable fish on a large scale. Most commercially valuable marine finfish are carnivores, and large-scale offshore finfish cultivation would likely exacerbate, rather than decrease, aquaculture's dependence on forage fish for fish feeds. Huge offshore finfish feedlots would also likely suffer many of the same problems that now dog salmon farms, such as effluent discharge and fish escapes.

Proponents argue that effluents would have little effect in most offshore waters, and that fish escapes will have minor consequence if fish for farms are carefully chosen (Stickney, 1994; McVey, pers. comm.). However, the cumulative environmental effects of a large offshore finfish industry could be quite detrimental. Certainly, other types of large-scale animal production, such as land-based "factory" farms for hogs and poultry, are highly polluting. Production of native mollusks, such as mussels and sea scallops in New England, could be a more benign focus for offshore aquaculture development.

Government Oversight of Aquaculture

Making aquaculture environmentally sound will require a variety of approaches by the public and the private sectors. Government regulation of and support for aquaculture is a major force affecting its sustainability (Corbin and Young, 1997). A variety of local, state, and

Figure Seven

Federal Regulation of Aquaculture*

Effects of aquaculture on the environmental 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 44 states that meet certain qualifications. EPA is now developing "effluent guidelines," essentially minimum standards, for EPA and state discharge permits for aquaculture.

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.

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 offshore aquaculture facilities—those constructed in the U.S. Exclusive Economic Zone beyond state waters.

The Migratory Bird Treaty Act

(16 U.S.C. 703 et seq.) This statute, which implements several international conventions, gives authority to the U.S. Fish and Wildlife Service (FWS) 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.

The Endangered Species Act of 1973

(16 U.S.C. 1531 et seq.) This Act is the primary authority for the protection of animal and plant life threatened with extinction, or likely to become endangered in the foreseeable future. Section 7 of the Act requires that no federally associated activity, including the issuance of federal permits or approvals, harms the continued existence of species listed under the Act.

The Marine Mammal Protection Act

(16 U.S.C. 1361 et seq.) This law prohibits, with a few exceptions, the harassment, hunting, capture, or killing of any marine mammals, including seals which may be predators at aquaculture facilities.

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 other pests, 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 has broad authority under this statute to protect public health, primarily through oversight of food and drugs. The FDA is responsible for approving animal drugs, including transgenic fish and therapeutants used in aquaculture. It is also responsible for seafood safety.

*Updated from Goldburg and Triplett, 1997.

federal regulations apply to aquaculture, although lawmakers did not write most of them with aquaculture specifically in mind. Federal regulations that affect fish-farming include permit requirements for many marine aquaculture sites, restrictions on killing bird and marine mammal predators, and oversight of drugs and pesticides (Figure Seven). State and local laws covering aquaculture are difficult to characterize because they vary enormously (Goldburg and Triplett, 1997; Wirth and Luzar, 2000). The steps recommended below will help to strengthen environmental oversight of aquaculture through legislation and regulations.

The federal government also influences aquaculture via a number of nonregulatory programs. Federal funding for aquaculture has risen during the past decade. The United States Department of Agriculture (USDA) and the National Oceanic and Atmospheric Association (NOAA) are the two main agencies supporting aquaculture research. USDA's current budget for aquaculture is approximately 50 million dollars, and NOAA's is roughly 12 million to 14 million dollars (Broussard, pers. comm.). Aquaculturists are also eligible for a number of government programs that provide loans and other aid to farms and to small businesses (OTA 1995b; Goldburg and Triplett, 1997). Both the federal government and the private sector can establish marketplace incentives for ecologically sound aquaculture.

The impacts of aquaculture can cross boundaries, and international agreements are another potential tool to address environmental impacts. Canadian and U.S. salmon farms are geographically adjacent to each other on both the East and West coasts (Figure Eight), suggesting that U.S.-Canadian cooperation is important on many salmon-farming issues. Globally, the World Trade Organization is the key arbiter of the movement of goods across borders. Strengthening the ability of nations to restrict imports of aquaculture products based on concerns about production practices could go a long way toward the protection of living marine resources.

Policy Options

1) Federal regulations

Effluent guidelines: Under the Clean Water Act, Congress directed the EPA to establish industry-by-industry "effluent guidelines"—discharge quality standards for specific pollutants that are achievable using the best available technologies. The EPA has never promulgated effluent guidelines for aquaculture. States delegated by the EPA to issue discharge permits now have highly inconsistent regulations for aquaculture facilities—an outcome at odds with the objectives of the Clean Water Act (Goldburg and Triplett, 1997). In January 1999, EPA agreed to propose effluent guidelines for aquaculture by June 2002, with a final rule due in June 2004 (EPA, 2000a). EPA needs to complete environmentally protective, practical guidelines in a timely manner. The guidelines should cover biological pollutants as well as nutrients, organic matter, and chemicals.

Figure Eight

2000 Atlantic Salmon Aquaculture in the United States and Canada

Source: Canadian Department of Fisheries and Oceans, Maine Department of Marine Resources, National Marine Fisheries Service, Washington Department of Fish and Wildlife, and Dorie Brownell (Ecotrust).

"The increase of NOAA and USDA appropriations for aquaculture research with targeted environmental goals is critical in helping the industry meet conservation efforts."

Protection of wild Atlantic salmon under the Endangered Species Act: Among the measures that federal officials have identified as critical to restoring wild Atlantic salmon in Maine, there are a number of actions concerning the salmon-farming industry. These include requiring the use of North American salmon milt and preventing the escape of farmed salmon and the spread of salmon diseases (NMFS/FWS, 2000). Federal and state agencies as well as the aquaculture industry should support NMFS and FWS decisions and activities under the Endangered Species Act to protect the remaining wild salmon runs. To help implement protections for wild salmon, public or private funding could support multistakeholder processes to help develop strong but practical disease management and other plans.

2) Federal legislation

Incentives to protect water quality: USDA now provides financial incentives to terrestrial crop producers who pursue certain conservation options. Conservation incentives, especially for water-quality protection, could be extended to animal producers in the next Farm Bill (Harkin, 2001). These incentives could include loans or cost-share programs for aquaculturists willing to prevent water pollution by establishing settling ponds, recirculation systems, floating bags and tanks, polyculture systems, and other cost-intensive measures.

Research and development investments toward sustainable aquaculture: Except for the salmon-farming industry, U.S. aquaculture is dominated by small- to medium-size companies, many of them owner-operated, with limited capacity to fund research and development. Government-funded research thus plays a major role in the development of new technologies and practices for U.S. aquaculture. The increase of NOAA and USDA appropriations for aquaculture research with targeted environmental goals is critical in helping the industry meet conservation efforts (Figure Nine).

Establish a two-stage program for offshore aquaculture permits: Department of Commerce (DOC) promotion of offshore finfish aquaculture should be predicated on careful evaluation of the potential cumulative environmental effects of a large offshore finfish aquaculture industry. Congress should mandate either a study by the National Research Council's Ocean Studies Board or an environmental impact statement-like study by DOC to examine the potential cumulative environmental impacts of a large offshore finfish aquaculture industry.

The Army Corps of Engineers (ACOE) has taken the lead in regulating offshore facilities, issuing permits under the Rivers and Harbours Act of 1899 and the Outer Continental Shelf Lands Act (Hopkins et al, 1997). However, the ACOE does not have a clear environmental mandate under those Acts, and lacks expertise to fully weigh ecological impacts in marine ecosystems. Congress should require the development of a comprehensive and environmentally oriented permitting system for offshore aquaculture,

mandating that facilities receive both National Pollutant Discharge Elimination System (NPDES) permits from EPA under the Clean Water Act and approvals from NMFS, based on a standard of no significant adverse effect to living marine resources. Rules for this permit system should take into account the results of the study of potential cumulative impacts, and should not be proposed until after the study is complete. The rules could also require compliance with a code of conduct for offshore aquaculture, which NOAA is currently developing (DOC, 2000).

Establish federal regulations for introductions of new organisms, including transgenic organisms: Federal oversight of introductions of new organisms is at best piecemeal (Simberloff, 1996; OTA, 1993). Most states have applicable regulations for introductions of nonindigenous species, including fish, although the regulations vary in effectiveness (OTA, 1993). The FDA has declared that the agency will regulate transgenic fish under the animal drug provisions of the Federal Food, Drug, and Cosmetic Act (CEQ, 2000). The FDA is the appropriate agency to consider

Figure Nine

Selected Research and Development Priorities

Biological Pollution

- Escape-proof netpens and enclosed marine systems
- Effective sterility treatments
- Transgenic fish impact modeling
- Genetic markers for transgenic fish
- Disease testing in wild shrimp and salmon

Fish for Fish Feeds

- Efficient vegetable-based feeds
- Energetically-efficient domesticated stocks
- Exact dietary requirements for non-carnivorous species
- Marketing non-carnivorous species

Nutrient Pollution

- Polyculture techniques to reduce nutrient loads
- Cost-effective recirculating systems
- Effluent treatment systems
- Enclosed marine systems such as bags and floating tanks
- Low polluting, high efficiency diets

Chemical Pollution

- Continued vaccine development
- Survey of drug use in aquaculture
- Disease-resistant and disease-free stocks
- Integrated pest management systems for fouling organisms and parasites
- Environmentally benign chemical alternatives

Habitat Effects

- Offshore siting criteria
- Off-bottom mollusk grow-out systems
- Effectiveness and impacts of non-lethal predator controls, particularly AHDs and ADDs
- Operational Best Management Practices to reduce interactions with predators

the safety of transgenic fish as food, but the agency has little expertise and at best a slim legal mandate to base approval decisions on the ecological impacts of these fish.

Congress could establish a federal permitting system, which would be administered by NMFS and FWS, covering the introduction and conditions of use for new organisms for aquaculture and other purposes. Permits should clearly be required for introductions of non-indigenous species to the marine environment, including the EEZ, since organisms introduced to the marine environment easily cross state boundaries. Permits should be required for all outdoor uses of transgenic fish, based on evidence of their ecological safety.

3) State legislation

Improved state oversight: State oversight of marine aquaculture, including impacts of wastewater discharges and introductions of new species, varies considerably in its scope and protectiveness of marine resources (Wirth and Luzar, 2000; Goldburg and Triplett, 1997; OTA 1993; Figure Ten). In an effort to improve state oversight on the East Coast, the Atlantic States Marine Fisheries Commission is now developing voluntary guidelines for marine aquaculture. While such guidance is useful, it does not necessarily translate into state action. States with large or growing mariculture industries, such as Maine, Florida, and Hawaii, should consider strengthening their oversight. States should not exempt aquaculturists from environmental laws or enforcement mechanisms, as Florida has done by prohibiting its Department of Environmental Protection from initiating proceedings against registered aquaculturists who contaminate ground or surface water (Figure Ten).

4) Market sector incentives

Organic standards for farmed fish: USDA's National Organic Standards Board is now considering the development of federal organic standards for aquatic species, including farmed fish. Organic certification represents a gold standard to many consumers who are willing to pay a price premium for organic products. Well-crafted organic standards for farmed fish should be encouraged as a market incentive for environmentally sound aquaculture, though organic aquaculture systems may have to be pond- or land-based to be consistent with principles of organic agriculture (NOSB, 2001).

Private sector programs to encourage environmentally sound aquaculture: Even many environmentally conscious consumers are unaware of the ecological harm caused by some types of fishing and fish-farming. A number of institutions, such as the Monterey Bay Aquarium, National Audubon Society, Chefs Collaborative, and Environmental Defense, currently make recommendations to institutional and individual consumers about farmed and wild-caught seafood purchases based on environmental criteria. The Marine Stewardship Council certifies several types of wild-caught fish as sustainable, and at least one U.S. company—Ecofish—markets ecologically friendly seafood products. Institutions supportive of marine conservation

Figure Ten

Selected States Laws Regulating Mariculture

State	Siting Requirements	Effluents and Monitoring
Alaska	Finfish farming prohibited in Alaska.[i] Bivalve aquaculture sites must be in areas classified as appropriate and receive permits from the Department of Environmental Conservation.	Aquaculture effluents prohibited. Monitoring occurs annually at shellfish farms.[ii]
California	Department of Fish and Game (DFG) examines impacts on fish and wildlife before issuing an Aquaculture Registration.[iii] Coastal siting through the DFG, Dept. of Health, Coastal Commission, regional water quality boards, and federal ACOE.[iv]	Regulations vary within California. Effluent limits and monitoring requirements are set by California's nine regional water quality boards.[vi]
Florida	Farming in marine waters requires a submerged lands lease administered by the Department of Agriculture and approved by the State Cabinet.	Under a new law, the Florida Department of Agriculture requires registered aquaculturists to implement Best Management Practices (BMPs). BMPs are still under development, and are not established for farms in marine waters. BMPs supersede state water quality standards; the Department of Environmental Protection is prohibited from proceeding against registered aquaculturists to recover any costs or damages.[v]
Hawaii	Hawaii has no siting requirements specific to aquaculture, although land-based aquaculture facilities must be on zoned agricultural land. Approvals to farm in marine waters involve a number of authorities, with the Department of Land and Natural Resources ultimately issuing leases.[vi]	Hawaii does not have any water quality regulations specific to aquaculture. Effluents must meet the Hawaii Department of Health's water quality standards.
Maine	The Department of Marine Resources (DMR) issues leases for farms in marine waters. DMR requires a video of bottom characteristics and water quality testing data. Leases cannot exceed 150 acres per person, and finfish pen leases typically must be at least 2,000 feet apart.[vii]	Maine is in the process of taking over regulation of effluents under the Clean Water Act from EPA. Most Maine salmon farms have never been issued wastewater discharge permits by EPA. All salmon facilities pay a fee of one cent per pound of whole fish harvested into a salmon monitoring, research and development fund.[vii] Each site is monitored annually by SCUBA divers. Benthic communities in the shadow of pens must remain fundamentally unchanged.
Texas	Aquaculture siting is regulated on the local level. Statewide guidelines on sensitive habitats as well as mandatory Environmental Site Reports for shrimp farms are currently being developed by the Texas Parks and Wildlife Department.[ix]	Wastewater discharge permits for shrimp farms are issued by a committee representing several state agencies, with Texas Natural Resource Conservation Commission issuing the final permits for wastewater discharge. Pond design must prevent groundwater contamination and solid waste must be protected from storm water. A combination of BMPs and water quality standards are used to control effluents.
Washington State	Siting is based largely on county regulations.	Washington requires wastewater discharge permits for most marine finfish facilities. Permits require facilities to develop pollution prevention plans and comply with BMPs.[x] Periodic monitoring examines carbon levels in the sediments. Impacts may extend up to 100 feet from each netpen.[xi]

[i] Alaska Statute §16.40.210 (2001). This prohibition does not include fishery rehabilitation or enhancement activities, nonprofit salmon hatcheries, or ornamentals outside of state waters.
[ii] Pers. comm. Mariculture Officer, Alaska Dept. of Natural Resources. 5/10/01.
[iii] Title 14, Division 1, Subdivision 1, Chapter 9, §235.
[iv] Pers. comm. Bob Hulbrock. California Aquaculture Coordinator, Dept. of Fish and Game. 5/8/01.
[v] Rule 5L-3, Florida Administrative Code.
[vi] Pers. comm. Leonard Young. Aquaculture Specialist, Hawaii Department of Agriculture, Aquaculture Development Program. 5/9/01.
[vii] 12 M.R.S.A. §6072.
[viii] 12 M.R.S.A. §6078.
[ix] Texas Agriculture Code, Chapter 134.031 (1999).
[x] WAC §173-221A-110.
[xi] WAC §173-204-412.

should serve seafood from environmentally sound fisheries and fish farms and support efforts to educate consumers.

"The United States and Canada should establish cooperative agreements to minimize the impacts of salmon-farming on wild salmon."

5) International agreements

Cooperative agreements with Canada: The North Atlantic Salmon Conservation Organization (NASCO) involves numerous governments in the conservation of wild Atlantic salmon (NASCO, 2001), but it is slow to act and lacks enforcement authority (Goode, pers. comm.). Moreover, the U.S.-Canada Pacific Salmon Treaty does not directly concern aquaculture. The United States and Canada should establish cooperative agreements to minimize the impacts of salmon-farming on wild salmon. Candidate matters for agreement include tagging of wild Atlantic salmon to aid data collection and fish-health management measures to check the spread of salmon diseases.

World trade in sustainable aquaculture products: Most farmed seafood eaten in the United States comes from abroad, and the impacts of U.S. consumption of aquaculture products on marine resources cannot be addressed solely by domestic measures. However, even though the United States is a major seafood consumer, it now has limited influence over seafood production practices abroad. Some U.S. aquaculturists fear that comparatively strict environmental regulations in the United States will raise their costs, and that consumers will purchase cheaper seafood imported from countries with lax environmental oversight. World Trade Organization rules now limit the ability of the United States and other countries to restrict demand for fish based on production practices, although restrictions can be based on product safety (e.g., antibiotic residues) (Wilson, 1994; Naylor et al., 1998). A new round of world trade talks will begin soon, and should emphasize environmental sustainability, with the goal of allowing environmental considerations in the production of traded-food commodities to play a far larger role in trade decisions.

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Connecting People and Science to Sustain Marine Life

The Pew Oceans Commission is an independent group of American leaders conducting a national dialogue on the policies needed to restore and protect living marine resources in U.S. waters. After reviewing the best scientific information available, the Commission will make its formal recommendations in a report to Congress and the nation in 2002.

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