ECONOMIC SUSTAINABILITY OF MARINE AQUACULTURE

A REPORT TO THE MARINE AQUACULTURE TASK FORCE

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SUMMARY

In the future, marine aquaculture production is likely to expand significantly in the United States and abroad. This paper deals with the present and future economic sustainability of aquaculture in the United States in light of this expectation. Economic sustainability requires the allocation of scarce resources to generate economic profits for investments in physical capital, knowledge, and technology that may endow future generations with the capacity to be at least as well off as the current generation.

Discussions about sustainability (or sustainable development) focus mainly on fairness in the distribution of economic welfare across generations. Due to this focus on intergenerational equity, international political discussions of sustainable development often are not directly concerned with economic efficiency. Economic efficiency is a necessary condition for achieving sustainable development, however, because it does not make sense to waste resources without cause. And efficiency is likely to increase the net benefits that can be shared both within and across generations.

Because economic sustainability is concerned primarily with the long-term maintenance of overall economic welfare or standard of living, it is sensible to think about economic sustainability at the level of aggregate consumption and investment flowing from the complete suite of human activities at the level of a nation, or the world as a whole.

In a setting where the focus is squarely on a limited segment of economic activity, it makes more sense to ask whether this activity is an economically efficient way of producing goods, or whether it is economically profitable when all private and public costs of production are taken into account. An activity such as marine aquaculture is more likely to contribute to overall economic sustainability if it generates positive economic profits when all costs of production are fully accounted for. For example, if growers realize profits only by ignoring the social costs of pollution, then aquaculture production may not be contributing to overall economic sustainability.

U.S. marine aquaculture may expand in the future through increased offshore and nearshore production of finfish and mollusks, and through land-based production of certain finfish and crustaceans. U.S. aquaculture production has grown by an average of six percent per year (in volume terms) since 1983; growth has been slower during the past decade, however. The U.S. Department of Commerce has stated its intention to develop marine aquaculture to reduce imports and to meet growing consumption and has called for a fivefold increase in U.S. aquaculture production, to \$5 billion/year, by 2025 (USDOC 1999). This implies a slightly higher rate of growth for the industry as a whole than it has exhibited historically; in particular it suggests significant growth in marine finfish aquaculture, which today accounts for less than six percent of U.S. aquaculture production (by volume). Nash (2004) suggests that this objective is consistent with a threefold increase in the volume of U.S. aquaculture production, and outlines possible production objectives for 2025 of some 700,000 metric tons (mt) of marine finfish (up from 25,000 mt today), 65,000 mt of crustaceans (18,000 mt today), and 345,000 mt of mollusks (100,000 mt today).

Most seafood products today are traded in a competitive international market. The United States currently imports about 70 percent of its seafood consumption, with an edible seafood trade deficit of $8.1 billion in 2005, largely because seafood is produced inexpensively abroad. Some 40 percent of seafood imports are aquaculture products. Based on market considerations, the most likely growth areas for U.S. aquaculture are nearshore and offshore mollusks, offshore finfish, land-based finfish, and onshore crustaceans.

There are three general categories of potential challenges to economic sustainability associated with this scenario for future U.S. aquaculture production:

- Disease transmission to wild stocks – for offshore finfish and shellfish.
- Escapes and interbreeding – for offshore finfish.
- Exploitation of forage fish stocks for aquafeeds – for carnivorous finfish.

Other challenges include pollution from organic wastes and the modification of habitat and ecosystem functions. These are more readily tractable through management practices and by focusing production in offshore waters with greater assimilative capacities. We deal here with what we consider to be the three most significant challenges.

Disease and parasite transmission to wild stocks: Infectious disease and parasites, such as sea lice in salmon and QPX in quahogs, are a significant economic problem for aquaculture producers, as they are for terrestrial farming operations. They represent both a direct cost to the farming operations and a potential external cost if disease or parasites spread from farmed animals to nearby wild stocks.

For example, research in British Columbia has linked Atlantic salmon farms to increased parasite loads (particularly sea lice) in wild salmon (Krkosek et al. 2005). This problem has led to requirements for the fallowing of Atlantic salmon netpens along the presumed migration route of wild juvenile Pacific salmon in the British Columbia salmon farming region, a management tool that has shown some success (Morton et al. 2005). In Maine, officials ordered the destruction of millions of caged salmon and effectively shut down parts of the local salmon industry in 2001 and 2002 in response to a severe infestation of infectious salmon anemia (ISA) virus in the state's salmon aquaculture industry.

Aquaculture faces the same general challenges in disease and parasite management as land-based forms of animal husbandry. The successful resolution of these challenges will require ongoing investment in research to develop a better understanding of relationships among environmental conditions, nutrition, susceptibility to disease or parasites, and the risks of transmission of disease and parasites to wild stocks.

Escapes and interbreeding: The issue of culture organisms, such as finfish, escaping to the wild remains unresolved for the marine aquaculture industry. Unintentional release (escape) of cultured fish from aquaculture operations is a direct cost (loss) to the farming operation and can also lead to external damages if the escaped fish produce negative consequences in the ecosystem by competing for habitat and food with wild stocks, or by altering the wild stock gene pool through interbreeding.

As in the broader problem of invasive (nuisance) species, the effects of aquaculture escapes are species and location specific. For example, repeated interbreeding of farmed salmon with wild stocks can in theory result in lower overall genetic fitness of the wild population and may have negative connotations for species survival or rebuilding if the wild population is endangered. The problem of escapes may be less severe if the species being cultured is native to the farming location and genetically homogeneous with local wild specimens, as is the case with certain shellfish in New England.

Exploitation of forage fish stocks for aquafeeds: The majority of the reduction fisheries that traditionally provide fishmeal and oils as inputs for aquaculture feeds are already fully exploited. As the demand for fishmeal and oils expands, these fisheries will come under additional pressures. If these fisheries continue to operate with inadequate or ineffective regulation, they must be considered unsustainable. The aquaculture industry recognizes the limitation that reliance on forage fish stocks for feed constituents represents to the future growth of carnivorous finfish production. The keys to resolving this issue are (1) proper management of forage fish stocks, and (2) development of alternative feed formulations that do not rely as heavily on fishmeal and fish oil.

Market forces will help resolve some of these challenges. For example, as feed demands exceed the capacity of reduction fishery stocks, prices of fishmeal and oils will rise, encouraging feed manufacturers to find alternative constituents. In other cases, market mechanisms can be combined with targeted intervention (such as labeling requirements) to encourage ecologically sound production. Some externalities, such as pollutant releases and escapes/genetic mixing, may be best addressed by the public regulation of operating practices.

Where pollutant discharges from aquaculture production facilities can be monitored and measured, effluents may be regulated as point sources, either through pollution taxes or by specifying discharge limits. Where discharges cannot be measured easily, combinations of market-based and command-and-control instruments may be needed, such as a combination of siting decisions, pollution standards, taxes, legal liability measures, and best management practices.

On the demand side, seafood certification and labeling (i.e., eco-labeling) has been identified as an effective market-based policy instrument for sustainable fisheries. Certification and labeling provides information to consumers, who may then choose to endorse ecologically friendly products. Increased sales will, in turn, stimulate production of eco-friendly products. The effectiveness of seafood labeling has been documented using empirical data. For example, Teisla et al. (2002) confirm that the implementation of dolphin-safe labeling has affected consumer behavior; and the dolphin-safe label has increased the market share of canned tuna. Results of a study of the UK seafood market by Jaffry et al. (2004) also indicate that a sustainability certification and labeling program is highly significant in affecting consumer choices.

In conclusion, projecting the sustainability of human activity requires assumptions about future economic activity, markets, prices, ecological conditions, and human preferences, and is therefore uncertain. It is useful to think of sustainability in probabilistic and relative terms; that is, one type of human activity may be more or less likely to be more or less sustainable than another. It is also important to specify the scale of economic activity: for example, marine aquaculture may be more sustainable at a modest scale (e.g. five million mt/yr) than at a significantly larger scale (50 million mt/yr).

There are significant conceptual problems with the application of the concept of "economic sustainability" to a specific activity such as aquaculture of marine finfish. The notion of economic sustainability is best applied to a broad cross-section of economic activity in aggregate, because the issue is whether investment in improved knowledge and capital will compensate future generations for the lack of resources that today's economic activity imposes on them. Nevertheless, the possibility that aquaculture may not be practiced (or practicable) the way it is today at some point in the future does not necessarily make it economically unsustainable at present. We elaborate on our definition of sustainability and its relationship to the focus of this paper in the first section.

This paper was written at the request of, and to provide background information for the work of, the Marine Aquaculture Task Force, a project of the Woods Hole Oceanographic Institution, with support from The Pew Charitable Trusts and the Lenfest Foundation.

ONE:

SUSTAINABILITY IN RELATION TO AQUACULTURE

The world demand for seafood products continues to expand. It is unlikely, however, that the annual harvest of fish from wild stocks can be increased significantly. Thus, aquaculture, where practicable, now is recognized as the only means of increasing the supply of protein from seafood. Marine aquaculture has now become a major source of seafood protein.

As the marine aquaculture industry expands, it has been confronted with concerns about its potential impacts on the environment and on other human activities. These criticisms include excessive nutrient releases from net pens and coastal ponds, depletion of forage fish stocks used as an ingredient in aquaculture feeds, escapes of genetically distinct or exotic cultured fishes, acceleration of the spread of fishborne diseases, among other effects. Further, questions have been raised about whether aquaculture in its various forms can be considered to be a “sustainable” human activity.

In this paper, we review the major concerns surrounding the sustainable development of the marine aquaculture industry. We review the economic and public policy literatures relating to marine aquaculture, identify and present conclusions relevant to the sustainability of aquaculture from these literatures, characterize priority economic and policy issues, place into context the economic dimensions of these issues, identify feasible institutional responses, and discuss potentially productive areas for future economic and policy research. This paper was written at the request of, and to provide background information for the work of, the Marine Aquaculture Task Force, a project of the Woods Hole Oceanographic Institution, with support from The Pew Charitable Trusts.

Discussions about sustainability (or sustainable development) focus mainly on fairness in the distribution of economic welfare across generations. For example, the 1987 report of the Brundtland Commission defines sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” Due to this focus on intergenerational equity, international political discussions of sustainable development often are not directly concerned with economic efficiency. Economic efficiency certainly is a necessary condition for achieving sustainable development, however, because it does not makes sense to waste resources without cause. And efficiency is likely to increase the net benefits that can be shared both within and across generations.

The notion of economic sustainability relates to the allocation of scarce resources in such a way so as to generate economic profits that are available for investments in physical capital, knowledge, and technology.[1] These investments would endow future generations with the capacity to be at least as well off as

[1] This definition of the term “sustainability” may differ from its use in other contexts. For example, in some contexts, the “sustainable growth” of aquaculture refers to continued sectoral growth, as measured in volume of product or sales revenues, at rates that equal or exceed historical trends. More generally, the term sustainable aquaculture may be used sometimes to refer to the continued financial viability of the sector. We employ the term “sustainable” here to refer to the operation of firms in an industry, such as aquaculture, in such a way that there is minimal economic waste, such as that arising through market failures.

the current generation. This definition of sustainability is similar to that proposed by Tilman et al. (2002) in their study of the sustainability of world agriculture:

> We define sustainable agriculture as practices that meet current and future societal needs for food and fibre, for ecosystem services, and for healthy lives, and that do so by maximizing the net benefit to society when all costs and benefits of the practices are considered. If society is to maximize the net benefits of agriculture, there must be a fuller accounting of both the costs and the benefits of alternative agricultural practices, and such an accounting must become the basis of policy, ethics, and action.

A key aspect of the definition of sustainability is its emphasis on the welfare of future generations. Economically sustainable aquaculture requires that resources are not overused or wasted in such a way that future generations would be disadvantaged in terms of optimizing their own welfare. As in most decisions about economically optimal allocations of resources, however, economic sustainability entertains the very real possibility that we may need to bear some level of environmental change or resource depletion in order to optimize societal welfare both now and in the future.

Economists and ecologists sometimes disagree about the most appropriate criteria for defining what activities or practices can be considered to be sustainable. Economic welfare criteria require that resources be used as efficiently as possible over time by both current and future generations. The economic notion of sustainability allows for the possibility of ecological degradation or even habitat loss or species extinction if it is consistent with the principle that future generations have the economic capacity to be as well off as the present generation.

The economic definition of sustainability has been referred to as “weak sustainability.” In essence, if the rents gained from the depletion of resources (or irreversible environmental degradation) are invested in capital and knowledge, and if these investments more than compensate for any costs arising from depletion, then the depletion can be considered sustainable. Examples of resource depletion resulting from marine aquaculture include the modification of habitat, competition between aquaculture escapes and endangered salmon runs, and the transmission of disease.

Many ecologists oppose the notion of weak sustainability precisely because it allows for the possibility of irreversible ecological change. Their preference is for a “strong sustainability” that constrains the choice of sustainable paths to those that do not lead to irreversible changes, such as species extinctions and the depletion of non-renewable natural resources. A powerful argument for strong sustainability is that we cannot know whether future generations might value the continued existence of a species, an ecological state, or a resource stock more highly than present generations do. Thus, they argue that economic efficiency may be a necessary but not a sufficient condition for achieving sustainable development. Additional conditions that would preclude irreversible ecological changes must be added in order to realize sustainability. Economists would respond that, if a political decision is made to preserve species or ecosystems in order to achieve a strong sustainability outcome, then sustainability still would require that resources be used as efficiently as possible, subject to the preservation constraints.

An important issue in this debate relates to the way in which we use resources today. Assume that we decide to prohibit certain forms of marine aquaculture because their adverse environmental effects are considered to be unsustainable in the strong sustainability sense. Without aquaculture, we may be forced to continue to rely upon wild-harvest fisheries for seafood protein. For a host of political and distributional reasons, however, we have been unable to manage many wild-harvest fisheries efficiently. The overexploitation of wild-harvest fisheries implies that there may be few—if any—resource rents to invest in capital, knowledge, and technology for future generations. Thus it is entirely conceivable that future generations could be less well off, precisely because the current generation has adopted a policy to prohibit marine aquaculture. In effect, the continued reliance on wild-harvest fisheries may be a less sustainable path than a policy that permits some irreversible environmental degradation through aquaculture but that relieves the pressure on wild stocks.

Of course, there is no guarantee that the development of aquaculture will lead to reduced landings from capture fisheries; even under reduced market pressure, some wild fisheries may continue to be fully (or over) exploited. Future wild capture landings depend on many factors, including management measures, total market demand, the scale of aquaculture production, and the degree to which cultured and wild fish are interchangeable from the consumer's point of view.

The most sustainable course of action is an empirical question, but it is subject to parameters that may be highly uncertain or even unknowable by the current generation. Among these parameters are the non-market values of marine ecosystems, the ecological relationships among components of marine ecosystems, future demands and prices, the rate of technological change, and the discount rate, among others. Some very preliminary theoretical models of aquaculture and fishery interactions suggest that it may be economically optimal for seafood protein to be produced by aquaculture only, by wild harvest fishing only, or by both activities together, depending upon the relevant parameter values (Phuong and Gopalakrishnan 2004; Hoagland et al. 2003).

The debate over weak versus strong sustainability as a basis for decision making cannot be resolved easily, and we make no attempt to resolve it here. What seems clear is that it does not make sense for the present generation to waste resources unnecessarily—either through the overexploitation of wild-harvest fisheries or the needless generation of pollution by aquaculture operators. And it is entirely consistent with both definitions of sustainability for aquaculture producers to be held to account for the external costs of their activities (as should wild harvest fishermen). The focus of this paper is therefore on the economic efficiency of marine aquaculture. We include in this focus some attention to irreversible environmental changes as well.

1.A. The concept of external effects

In determining whether or not an activity like aquaculture is efficient, and therefore could be sustainable, a critical issue is to ensure that all costs are accounted for fully. For example, if growers realize profits only by ignoring the social costs of pollution, then aquaculture production may be excessive, and it cannot be deemed to be efficient. Analogously, some types of aquaculture can lead to external benefits, such as the control of excess macronutrients (e.g., nitrogen and phosphorus) by shellfish operations. To the extent that aquaculturists cannot account for these social benefits[2], aquaculture production levels may be too low.

A critical need is the design and implementation of institutional measures that provide incentives for private growers to account for environmental costs or to increase production where environmental benefits can be realized (Tilman et al. 2002). These institutional measures may take the form of command-and-control regulations, market-based

[2] Social benefits (as opposed to private benefits) are those that accrue to people other than those engaged in the farming operation and their customers.

approaches, such as pollution taxes, or the voluntary adoption of best management practices. We discuss some potentially useful institutional measures in Section 7.

1.B. "SUSTAINABILITY" AS USED IN THIS REPORT

Because economic sustainability is concerned primarily with the long-term maintenance of economic welfare or standard of living, it is most sensible to think about economic sustainability at the level of aggregate consumption and investment flowing from the complete suite of human activities at the level of the nation or—ideally—the world. It is difficult to apply this notion of economic sustainability to a particular activity, such as marine aquaculture as practiced in the United States, because, while that activity may contribute to the overall economic sustainability of our way of living, it does not by itself determine the overall sustainability.

In a setting where the focus is squarely on a limited segment of economic activity, it makes more sense to ask whether this activity is an economically efficient way of producing goods, or whether it is economically profitable when all private and public costs of production are taken into account, including the costs associated with any losses of non-market environmental goods and services. An activity such as marine aquaculture is more likely to contribute to overall economic sustainability when it is economically efficient from a social point of view, i.e., when all costs are fully accounted for.

In this paper, we adopt the view that the goal of sustainable marine aquaculture is best pursued in the first instance by ensuring that all external effects are accounted for and internalized to the extent possible. Adequate investment in new knowledge and technology is also necessary for sustainability, but this requirement is not tied specifically to aquaculture and is best left to a broader examination of the sustainability of U.S. (or global) economic activity.

Section 2 of this paper reviews historical trends and forecasts for capture fisheries and aquaculture production and trade. Section 3 reviews the literature on economic effects, both internal and external, of aquaculture and summarizes projections of future aquaculture production and seafood supply and demand for the United States. Section 4 describes the negative external effects associated with aquaculture production, and Section 5 describes positive external effects. Section 6 summarizes what are in our view the major challenges to sustainability of marine aquaculture. Section 7 describes mechanisms by which these challenges can be addressed. Our conclusions are summarized in Section 8.

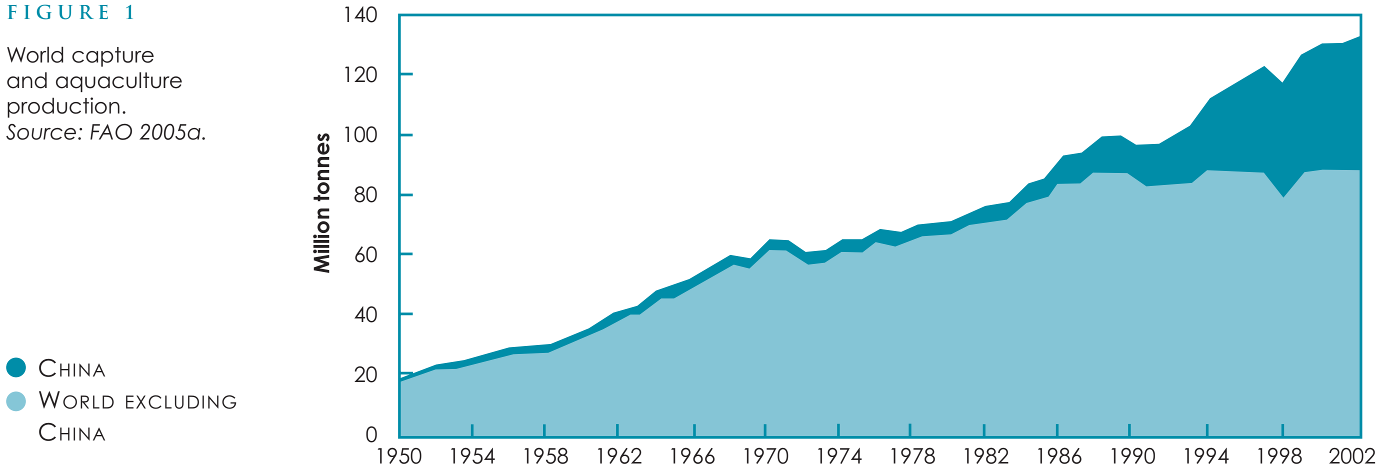
TWO:

AQUACULTURE PRODUCTION AND TRADE

Total annual world fisheries production, including capture fisheries and aquaculture in both freshwater (inland) and marine environments, has risen at a fairly steady pace from about 20 million metric tons (mt) in 1950 to about 156 million mt in 2004 (FAO 2005a). Until the 1980s, aquaculture accounted for less than ten percent of global production, and growth in capture fisheries provided most of the growth in global fisheries production. Since the mid-1980s, capture fisheries production has been stagnant at about 85 million mt/year, and the growth in overall production has been due to the growing output of aquaculture operations. About 75 percent of global production comes from marine and 25 percent from inland environments.

FIGURE 1

World capture and aquaculture production.
Source: FAO 2005a.



The United States is among the largest producers of fishery products from capture fisheries (Figure 2), contributing nearly five percent of global catch.

FAO's fishery production statistics are based on landings reported by national authorities. There is some uncertainty about these reported landings for certain counties, notably China (FAO 2005a). China reportedly accounts for more than 15 percent of marine and more than 25 percent of inland capture fisheries global production. Depending on the true nature of China's landings, it may be that the U.S. share of capture fisheries production is actually larger than suggested by Figure 2, and that global capture fisheries production has in fact declined slightly since the mid-1980s (Figure 3).

FIGURE 2

Capture fisheries top ten producing countries in 2002.
Source: FAO 2005a

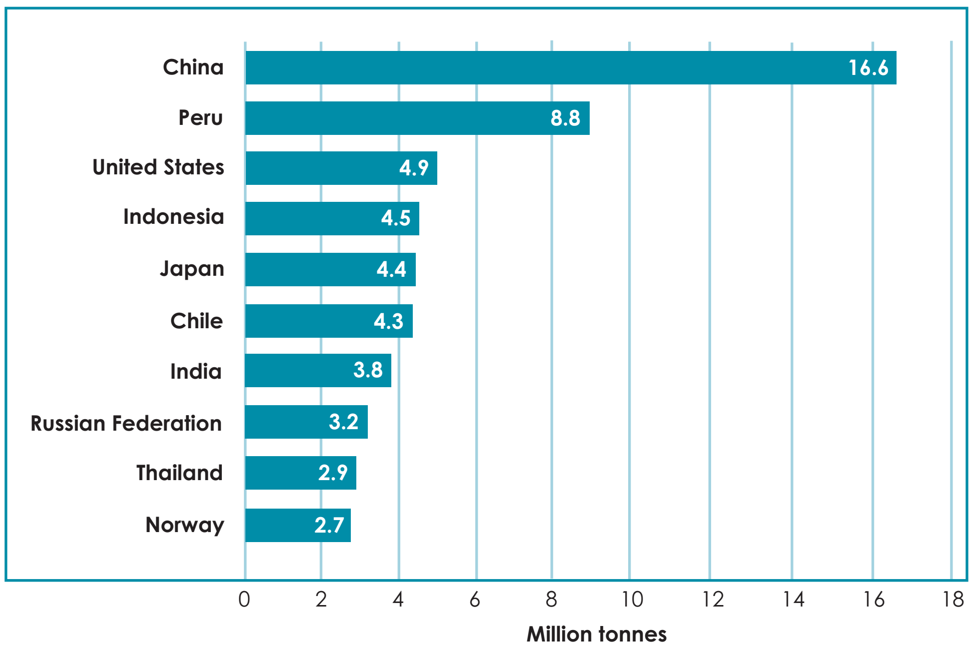
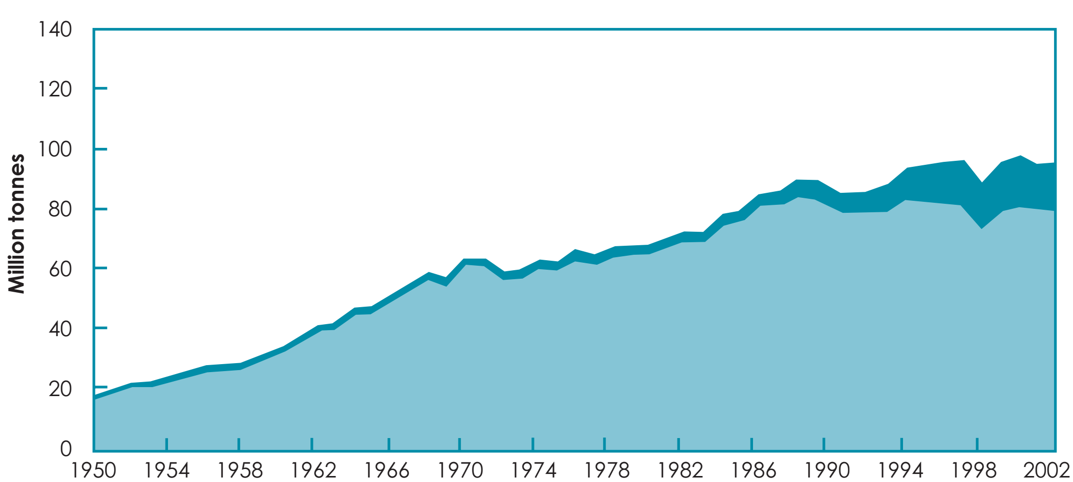


FIGURE 3

World capture fisheries production.
Source: FAO 2005a.

China
World excluding China



2.A. Aquaculture production in the United States and the World

Global aquaculture production generates 45 to 50 million mt of fisheries product annually, plus about 12 million mt of aquatic plants (mostly macroalgae). Of this total, nearly 70 percent is reportedly generated by China; as noted above, the Chinese production statistics may be subject to interpretation. Aquaculture now accounts for about 74 percent of global freshwater production (54 percent if China is excluded) and about 17 percent of global marine production (eight percent without China). About 60 percent of global aquaculture production comes from inland (freshwater) environments. Figure 4 shows the relative contribution of major species groups to global aquaculture production.

Figure 5 illustrates the growth trend of major species groups in aquaculture production.

FIGURE 4

World aquaculture production by species group in 2002.
Source: FAO 2005a.

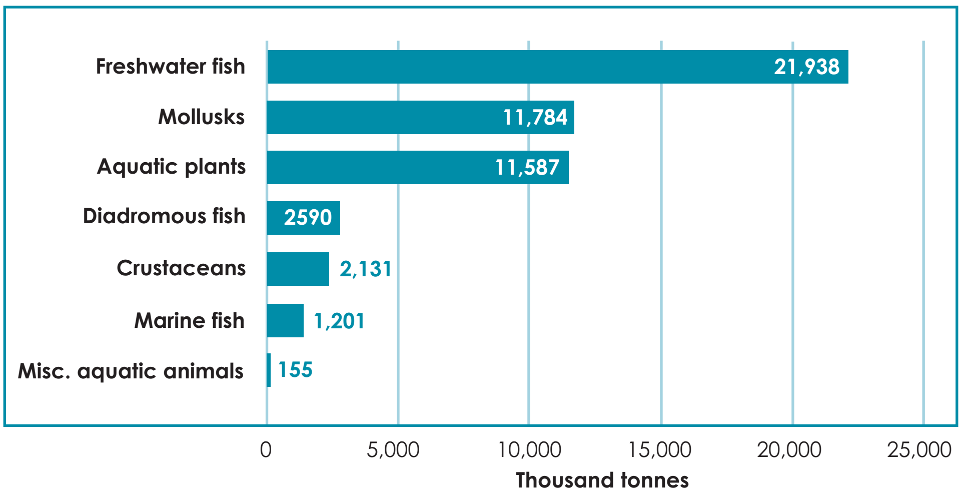


FIGURE 5

Trends in aquaculture production.
Source: FAO 2005a.

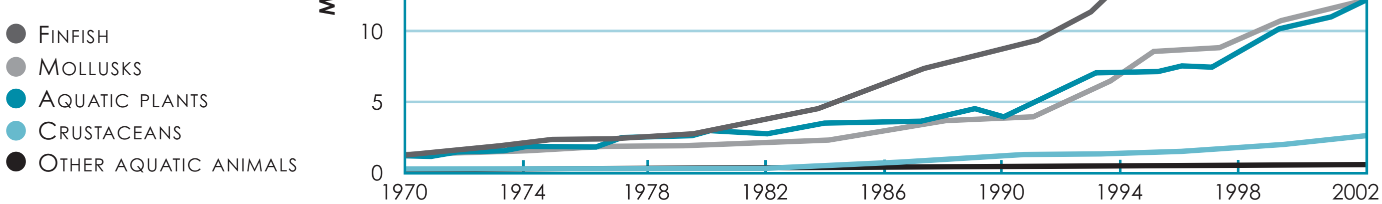
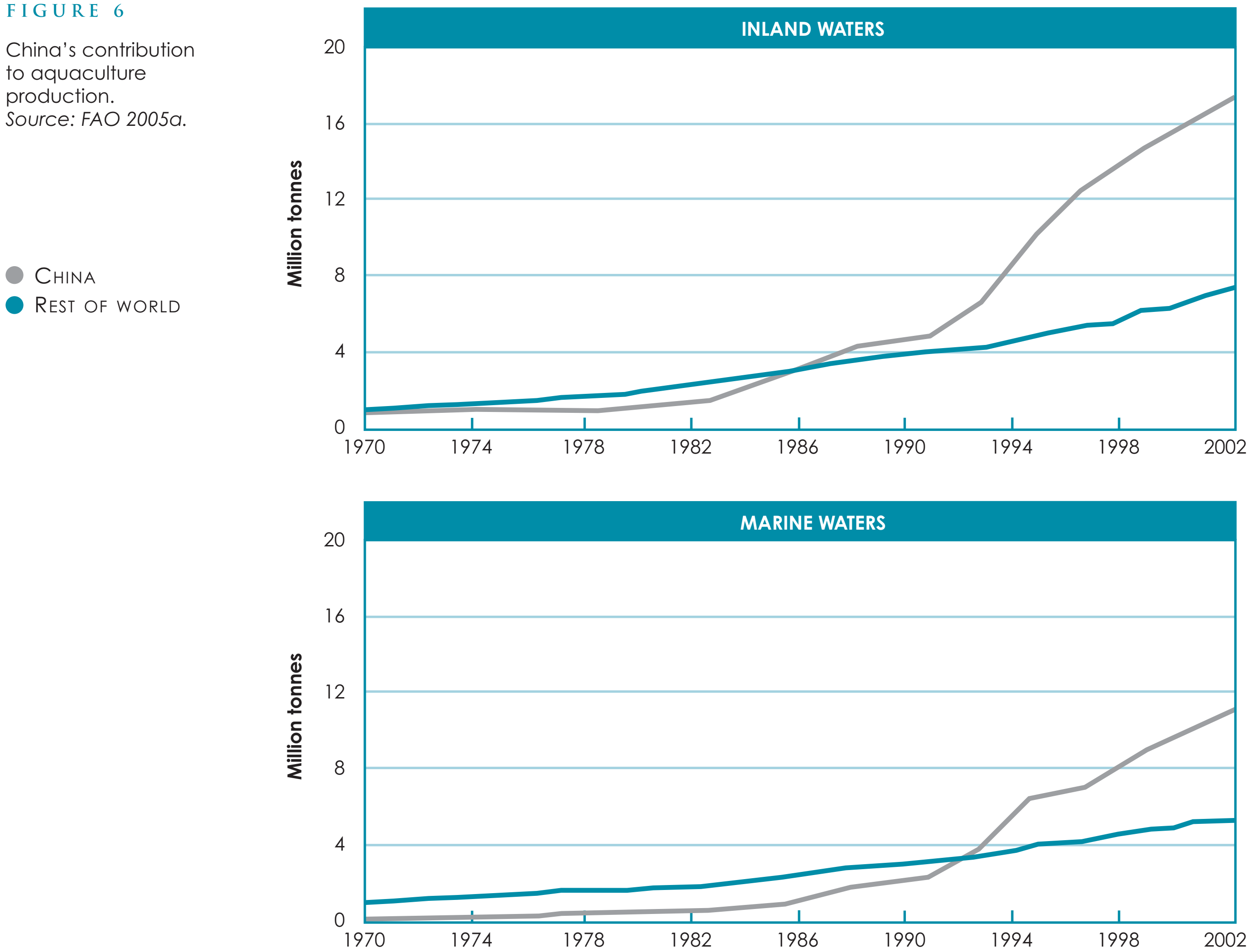


FIGURE 6

China's contribution to aquaculture production.
Source: FAO 2005a.



Note: Data exclude aquatic plants.

Much of the dramatic growth in global aquaculture production since the late 1980s is due to the production reported by China, and in particular to China's inland aquaculture production (Figure 6).

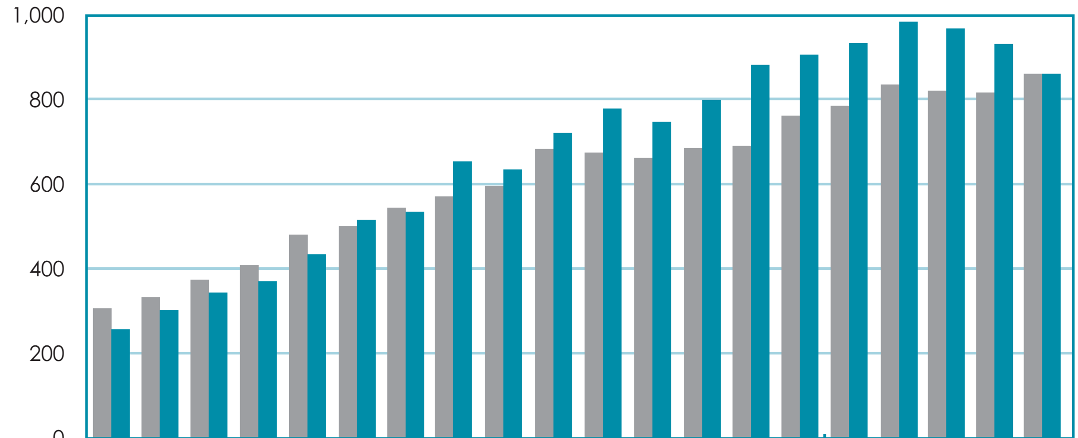
U.S. aquaculture production is about 400,000 tons/year, or about nine percent of all U.S. fisheries production (4.4 million mt/year). Although the United States accounts for about five percent of global capture fisheries production, it contributes only about one percent of global aquaculture production (three percent of global production excluding China). Figure 7 shows the development of U.S. aquaculture production in volume and value terms.

U.S. commercial fish landings (edible and industrial) were valued at $3.7 billion in 2004 (NOAA NMFS 2005). U.S. aquaculture production is valued at about $0.9 billion (see Table 1).

Catfish represented more than 70 percent of U.S. aquaculture production by volume and more than 40 percent by value as of 2002.

FIGURE 7

U.S. aquaculture production.
Source: Mississippi State University 2006.



	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Pounds	308	336	376	409	484	500	548	573	604	691	679	666	690	694	767	790	842	823	819	867
Value	259	307	348	372	437	520	540	655	636	724	782	751	806	886	910	939	987	973	935	866

TABLE 1

U.S. aquaculture production, including non-food species.

	volume (million lbs)		value (million $)	
	1999	2002	1999	2002
Total	**842.0**	**866.0**	**987.1**	**867.0**
Catfish	596.6	631.0	438.9	358.0
Clams	10.7	9.9	42.1	41.8
Crawfish	42.9	61.0	28.3	50.0
Mussels	0.5	1.4	0.8	3.2
Oysters	18.7	19.0	55.6	54.0
Salmon	39.1	28.0	76.8	28.0
Shrimp	4.6	9.0	13.7	27.6
Trout	60.2	54.0	65.0	58.0

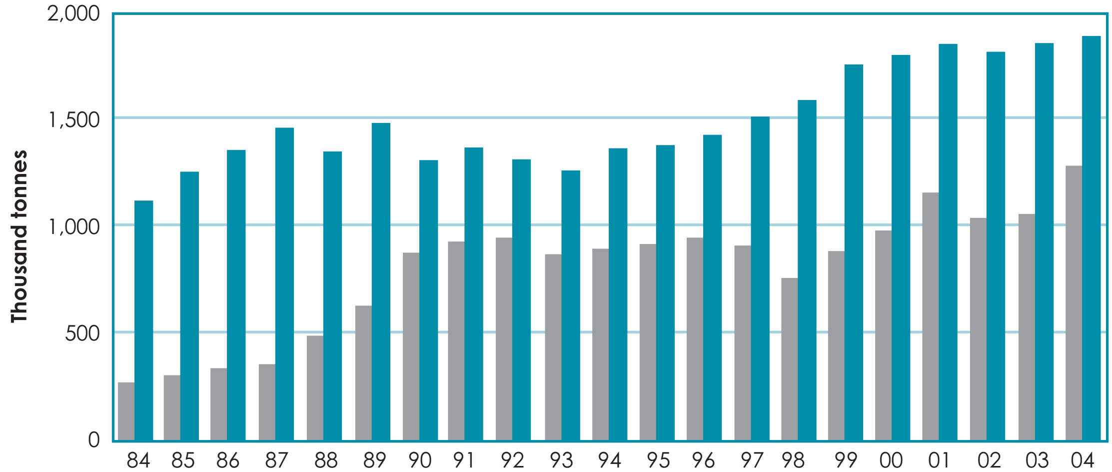
Sources: U.S. Joint Subcommittee on Aquaculture 2001; Mississippi State Univ. 2006.

2.B. U.S. SEAFOOD IMPORTS, EXPORTS, AND TRADE BALANCE

U.S. fish and seafood consumption was 4.9 billion pounds in 2004, or about 16.6 lbs/person (edible meat only; NOAA NMFS 2005). In terms of live weight equivalent, the total net U.S. supply of fishery products in 2004 was 11.2 billion lbs (about 5 million mt), including 4.4 million mt of domestic landings, 1.9 million mt of imports, and 1.3 million mt of exports. For 2005, U.S. imports of edible seafood products were valued at about $12.1 billion and exports at about $4.0 billion, for an edible seafood trade deficit of $8.1 billion. (Non-edible seafood product imports in 2005 were $13.0 billion, and exports $11.4 billion.) Figure 8 shows a time series of volume and Figure 9 shows the value of U.S. fishery product imports and exports.

FIGURE 8

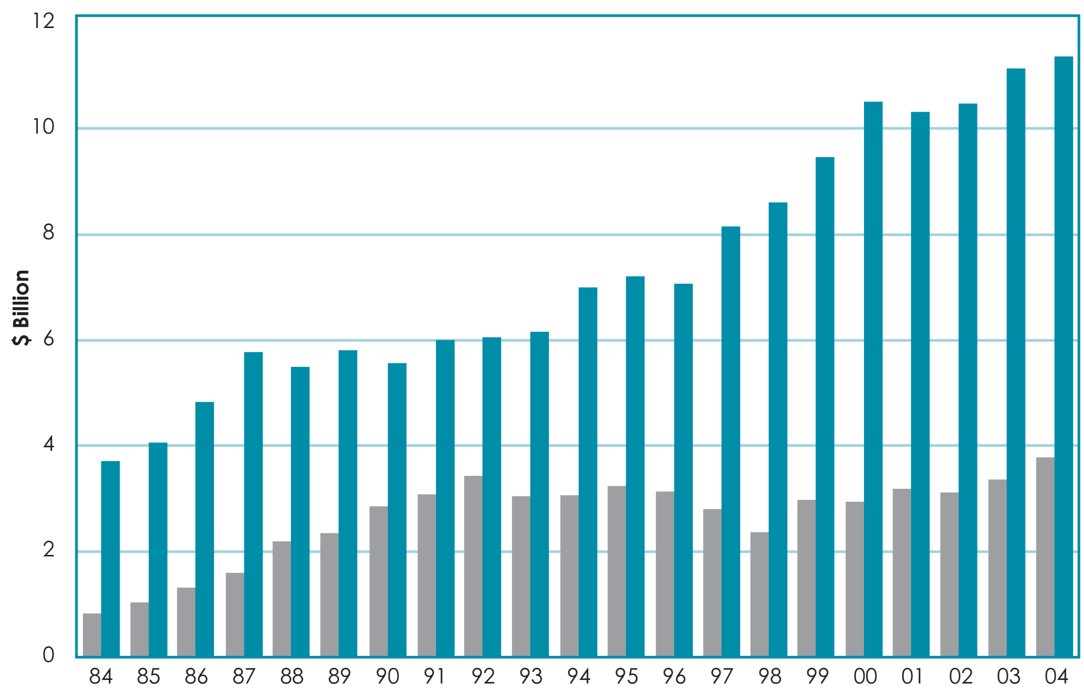
Volume of U.S. seafood foreign trade.
Source: NOAA 2005.



EXPORTS
IMPORTS

FIGURE 9

Value of U.S. seafood foreign trade.
Source: NOAA 2005.



EXPORTS
IMPORTS

Since 1989, edible fishery products have contributed more than 75 percent of the seafood trade deficit; and since 1995, edible products have contributed at least 85 percent of the deficit. The majority of the edible fishery product trade deficit consists of only five species groups: shrimp, crabs, tunas, salmon, and lobsters. Since 1997, shrimp has been the largest contributor to the edible seafood trade deficit. The contribution to the edible product trade deficit has generally been increasing for both salmon and crabs while the percentage of tuna and lobster products has been stable. Figure 10 shows the composition (by value) of U.S. seafood imports as of 2004.

FIGURE 10

U.S. seafood imports by species in 2004. *Source: NOAA 2005.*

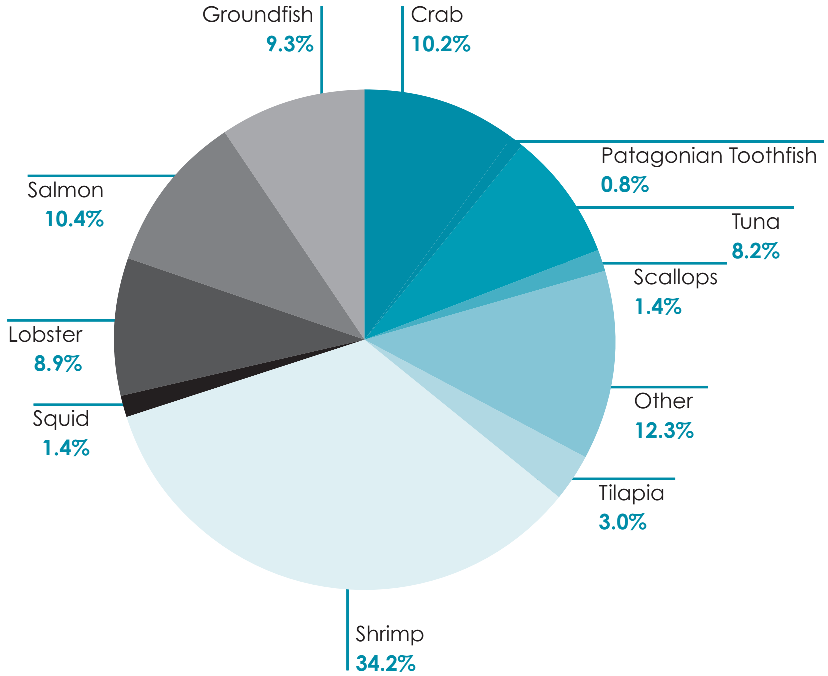


FIGURE 11

Recent U.S. seafood imports by exporting country. *Source: NOAA 2005.*

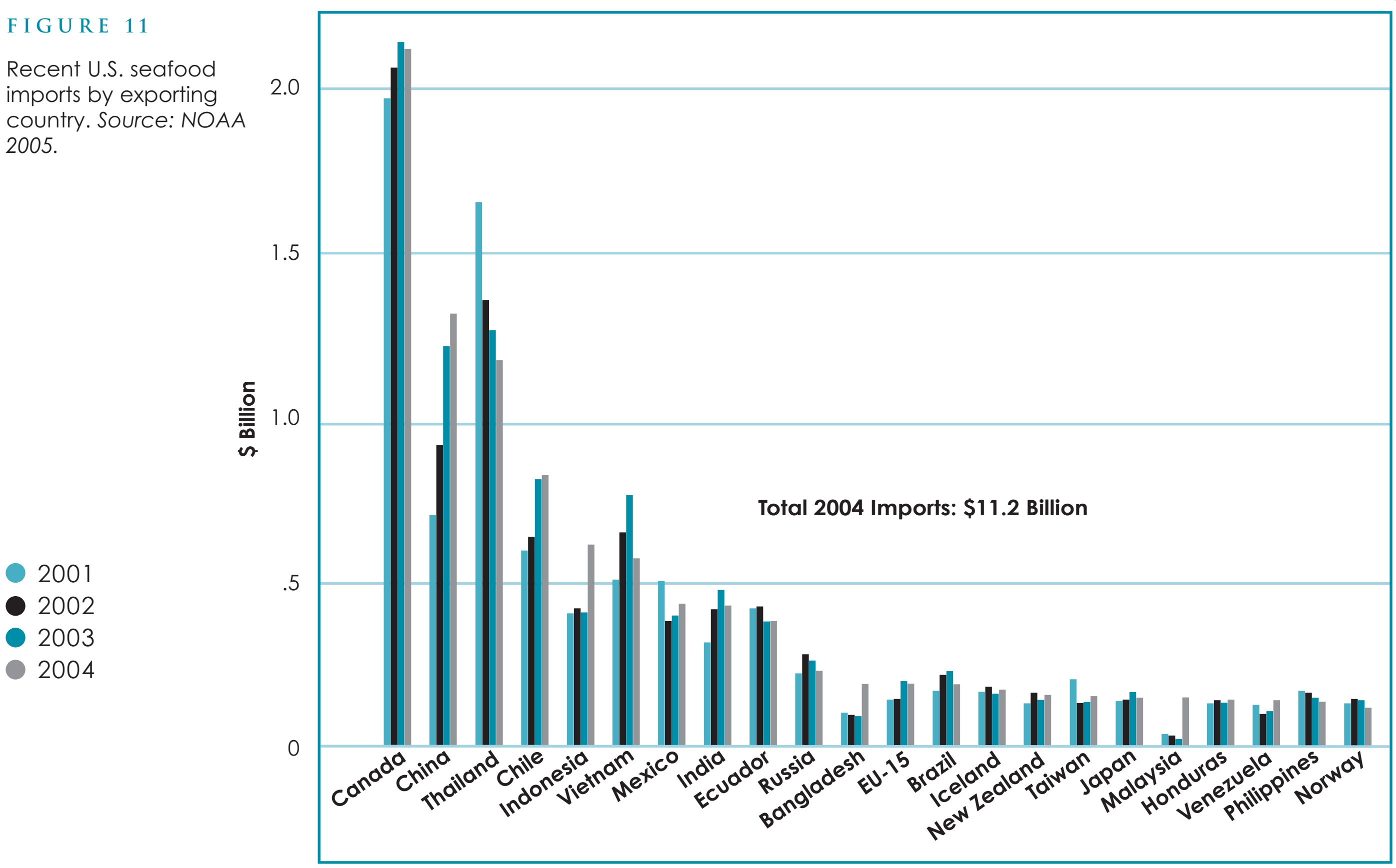
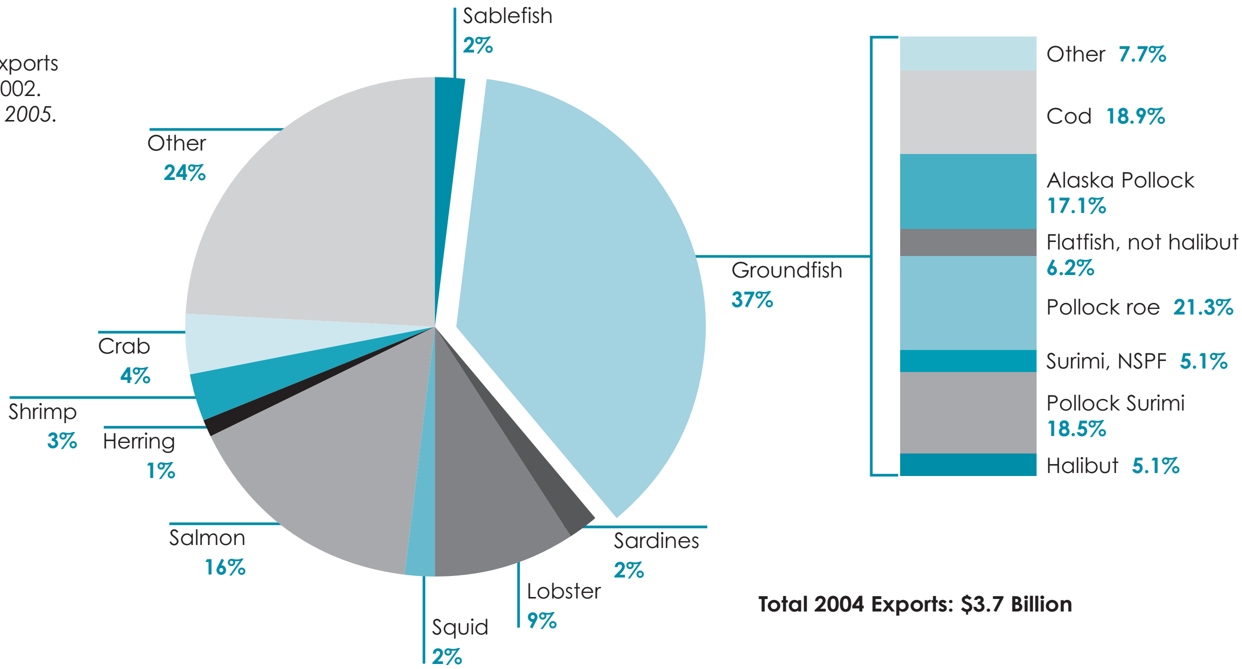


FIGURE 12

U.S. seafood exports by species in 2002. *Source: NOAA 2005.*



Reflecting the large global trade in seafood products, U.S. seafood imports come from a diverse set of exporting nations. Canada, China, and Thailand are the most significant sources of U.S. seafood imports (Figure 11).

Groundfish, salmon, and lobster are the largest contributors by value to U.S. seafood exports (Figure 12).

2.c. Forecasts of U.S. production and trade

U.S. commercial fish landings have fluctuated around 4.4 million mt/year since 1990 (NOAA NMFS 2005). While it is possible that better management of certain U.S. fish stocks (such as cod) and hatchery enhancement of wild stocks could increase wild capture landings in the future, there is little reason to expect aggregate landings to increase dramatically.

If the U.S. population continues to grow, as it has recently, by about one percent per year, and for a conservative projection we assume that per-person consumption of seafood remains roughly at present levels (16.6 lbs of edible meat/person-year[3]), U.S. seafood consumption will rise by 22 percent to about 6.2 million mt/year by 2025. If wild capture landings remain at 4.4 million mt/year, this leaves a shortfall of 1.8 million mt/year to be filled by some combination of aquaculture and net imports. (Nash [2004] assumes a scenario of slower population growth but rising per-person seafood consumption, leading to increased total consumption of just over 1 million mt/year.)

U.S. aquaculture production has grown by an average of six percent per year (in volume terms) since 1983; growth has been slower during the past decade. The catfish industry is the largest sector of the U.S. aquaculture industry. Since the early 2000s, catfish pro-

[3] Global seafood consumption is about 35.6 lbs/person-year, or twice the U.S. consumption rate.

ducers have faced stiff international competition and rising input and regulatory costs, both of which have affected the growth of the industry. There has been a steady decline of the wild-harvest mollusk fisheries, with the most significant loss in the production of American oyster. Furthermore, stringent regulatory requirements are considered to be limiting aquaculture development in the U.S. Other causes of the recent slowdown in growth of U.S. aquaculture are summarized by Nash (2004) as (1) competition in shrimp production from Latin America and Asia; (2) a series of hot summers affecting crayfish production; and, most important, (3) a decline in coastal areas available or suitable for oyster, clam, and mussel production. Both imports and exports of seafood products have grown at an average rate of about two percent per year for the past 15 years. If we used the demand projection described above, and assume that U.S. capture fisheries output remains constant while U.S. seafood imports and exports continue to grow at recent rates, then U.S. aquaculture industry output must increase by a factor of more than three, to 1.3 million mt/year, by 2025 in order to make up the net supply shortfall.

Of course, these projections are highly simplistic. Future seafood demand in the United States will vary with changing consumer tastes and food prices; and it is not clear that U.S. exports of seafood will continue to grow as they have in the past. A careful projection of future aquaculture production, and seafood imports and exports, would have to be based on projected future demand for particular types/species of seafood. It would also have to be based on assumptions about future prices, which in turn are linked to global production and to demand in other nations. One such global modeling exercise was carried out by Delgado et al. (2003), using the International Food Policy Research Institute (IFPRI) IMPACT model. The authors conclude that under their baseline assumptions, global seafood prices will rise by about six percent by 2020 as demand strengthens in developing nations. The net result is a significant reduction in net imports by the developed world as a whole, but not by the United States. Delgado et al. project net U.S. imports of food fish in 2020 around 1.5 million mt/year under baseline assumptions, with values ranging from a high of 1.7 million mt/year (with faster than baseline global aquaculture expansion) to 1.4 million mt/year (with slower global aquaculture expansion) and 700,000 mt/year (for a scenario involving ecological collapse).

On balance, it seems likely that the United States will remain a major net importer for seafood even if domestic aquaculture production can regain the rates of growth it achieved in the early 1990s.

THREE:

ECONOMICS OF COASTAL AND MARINE AQUACULTURE

3.A. Coastal and marine aquaculture typology

Many different species, growing activities, and technologies tend to get lumped together when the term “aquaculture” is used in common parlance, in the media, and even in policy discussions. This usage may be appropriate when comparing broad sectoral trends, such as FAO’s time series comparison of seafood production levels from both aquaculture and marine fisheries (Figure 1). From the standpoint of industrial organization, however, it is more appropriate to disaggregate the aquaculture sector into individual markets.

Economists try to understand the structure, conduct, and performance of firms in discrete product markets. Markets are distinguished primarily on the basis of the extent to which products sold in the market are close substitutes (Haldrup et al. 2005; Jaffrey et al. 2000; Clayton and Gordon 1999). For example, cod and haddock are close substitutes that might usefully be analyzed as products in the market for whitefish (Roheim et al. 2003). Alternatively, salmon and oysters are not close substitutes, and it would not be useful to consider them as part of the same market. For example, changes in the demand for salmon are unlikely to affect the demand for oysters, and vice versa. Importantly, aquaculture products typically are close substitutes for wild harvest fishery products of the same or related species (Dumas and Horton 2002). In other words, a market is defined primarily on the basis of product substitutability, not on the basis of production technologies.

Secondary characteristics of individual markets can include geographic locations (Asche and Sebulonsen 1999), production technologies, resources allocated to research and development, and advertising, among other characteristics (Saarni et al. 2003). These characteristics help to describe the market and the behavior of firms in the market, and they can provide insights into how firms and markets evolve over time, becoming more or less efficient. It is useful to begin to identify markets for aquaculture products, because it is likely that issues of sustainability may not be common across all markets. Economic research is only beginning to focus on the problems of the sustainability of aquaculture (Young et al. 1999). Typically, economic studies are focused on increases in production costs associated with regulations or practices that enforce certain “sustainable” practices, such as those for organic standards (Sutherland 2001).

In Table 2, we present a typology of aquaculture products grown in the United States. We sort the products into finfish, mollusks, finfish ranching, shrimp, and polyculture. Within each category we sort the products roughly into the production locations, including land-based, nearshore, and open-ocean. Unshaded products are in current production (see also Table 1); shaded products are emerging or proposed commercial prospects. Table 2 may be used to help organize our thinking about whether the characteristics of aquaculture production in a particular market, including the production practices and technologies and forms of pollution, imply that those types of aquaculture are unsustainable.

TABLE 2

Existing and potential aquaculture products in the United States.

(italic text indicates emerging/potential candidate species)

Finfish			Mollusks		Finfish Ranching	Marine Shrimp	Polyculture
offshore	**nearshore**	**land-based**	**offshore**	**nearshore**	**offshore/ nearshore**	**land-based**	**nearshore**
Cobia	Atlantic Salmon	Catfish	_Sea Scallops_	Oysters**	Pacific Salmon	Penaid Shrimp	_Salmon/ Mussels_
Moi	Steelhead Trout	Trout	_Blue Mussels_	Northern Quahog		Crawfish	_Finfish/Red Seaweed_
Cod	_Cobia_	Hybrid Striped Bass	_Red Abalone_	Goeducks		_Black Tiger Shrimp_	
Atlantic Salmon	_Cod_	Tilapia		Manila Clams			
Haddock		Ornamentals		Blue Mussels			
Fluke		Baitfish		Cultured Pearls			
Atlantic Halibut		_Fluke_		_Softshell Clams_			
Winter Flounder		_Walleye_		_Bat Scallops_			
Pacific Halibut							
Reef Fish*							
Bluefin Tuna							

*Proposed reef fish culture includes the red drum, red snapper, mutton snapper, greater amberjack, and red hind grouper.

**Cultured oyster species include the Eastern, Pacific, European flat, Kumamoto, and Olympic oysters.

In Table 3, we present a characterization of the degree to which an array of practices may be characterized as unsustainable. We note that this is a very general example, as we present aggregations of the individual product markets in terms of the type of fish (e.g., finfish, mollusks, finfish ranching, shrimp, and polyculture) and geographic locations (e.g., offshore, nearshore, land based). This typology is useful as an example, but we stress that in order to characterize the sustainability of any particular market, it will be important to understand the specific issues faced in that market.

In the left hand column of Table 3, we list those issues that we have identified from the scientific and policy literatures as having possible implications for the sustainability of aquaculture in the United States. Note that all of these issues, with the exception of the exploitation of forage fish stocks, represent the potential external costs of aquaculture of various types. Based on our review of scientific literature, we have also assigned a subjective ranking of the external effects ranging from significant adverse effects through significant positive effects, as indicated by symbols and colors in Table 3.

The value of the assessment presented in Table 3 is that it helps to rank potential sustainability issues by broad type of aquaculture. Thus, we can see the several high-priority problems faced by nearshore finfish aquaculture, including organic pollution, disease transmission, escapes, reliance on forage fisheries in fishmeal, and bioaccumulation. In a comparative sense, nearshore mollusk aquaculture appears relatively benign; its physical side effects may even be beneficial on balance. Given limited resources for attending to the array of pollution problems presented

TABLE 3

Typology of Aquaculture Forms and Preliminary Assessment of Physical Effects

(items in the leftmost column represent potential sustainability issues)

- Significant negative effect
- Moderate negative effect
- Neutral or no effect
- Significant positive effect
- Moderate positive effect

Note: all effects are negative unless preceded by "+". "Z" = zero, "M" = moderate, "S" = significant.

	Offshore Finfish	Nearshore Finfish	Land Based Finfish	Nearshore Mollusks	Offshore Mollusks	Offshore Fish Ranching	Nearshore Fish Ranching	Coastal Marine Shrimp	Polyculture
Organic Pollution and Eutrophication	M	S	M	Z	Z	Z	M	S	M
Chemical and Pharmaceutical Pollution	Z	M	M	Z	Z	Z	Z	S	Z
Habitat Modification	Z	Z	Z	Z	Z	Z	Z	S	Z
Disease Transmission to Wild Stock	S	S	Z	M	M	Z	Z	Z	M
Escapements and Interbreeding	S	S	Z	M	M	Z	Z	Z	M
Exploitation of Forage Fish Stock	S	S	S	Z	Z	S	S	Z	Z
Takings of Protected Species	M	M	Z	Z	M	M	M	Z	M
Direct Depletion of Natural Stocks	Z	Z	Z	Z	Z	S	S	Z	Z
Bioaccumulation of Carcinogens	S	S	S	Z	Z	M	M	Z	Z
Increased Productivity from Nutrient Input	+M	+S	Z	Z	Z	Z	Z	Z	+M
Nutrient Removal	Z	Z	Z	+S	+M	Z	Z	Z	+M

by aquaculture in the United States, such a comparison should aid decision makers in allocating these resources as effectively as possible. Again, we note that specific conclusions with respect to sustainability in specific markets will require a careful examination of the characteristics of those markets. Such a characterization would be clearly needed in future research efforts.

3.B. Economic literature on the external costs of aquaculture

Economic studies of the external costs of aquaculture operations are only just beginning to emerge and only a few can be found in the published literature. One reason for the absence of studies of this type is that the sector is in an early growth phase, particularly in the United States. Another reason is that several forms of aquaculture, including nearshore marine shellfish, recirculating system culture, and extensive pond culture generally produce minimal pollution loading to the surrounding environment.

In addition to studies on the external costs, a number of studies have been published on the economic impacts of aquaculture (O'Hara et al. 2003; Thacker 1994). These studies attempt to show the importance of the aquaculture sector in relation to the total economy. In particular, these types of studies elucidate the linkages between aquaculture and other industries, both in physical units and in dollar terms. These studies do not focus on the costs to the economy of unsustainable activities, such as effluents, the release of pathogens, escapes, or other forms of pollution from aquaculture.

Most of the work on the economics of externalities focuses on the adverse effects of shrimp culture in coastal ponds in developing countries (Barbier et al. 2002 [Thailand]; Be et al. 1999 [Vietnam]; MacDougall 1999 [Ecuador]; Primavera 1997 [Indonesia]). Other studies focus on the adverse effects arising from the culture of eels in Taiwan

(Huang 1997) and trout in West Virginia (Smearman et al. 1997). Smearman et al. (1997) examine the costs of downstream pollution in the growing of trout in West Virginia. These authors estimate that pollution prevention costs are only about six percent (about 11 cents per kilogram of fish) of production costs, suggesting that effluent filtration units can be a cost-effective means of reducing pollution from this type of aquaculture.

With respect to shrimp farming, Barbier et al. (2002) look at the adverse effects of mangrove deforestation for building shrimp ponds on artisanal marine demersal and shellfish fisheries in Thailand. The authors find that, depending upon the elasticity of demand, the construction of 30 km^2 of shrimp ponds may lead to surplus losses of up to \$0.4 million per year.[4] In the United States, shrimp farming is focused in Texas and South Carolina, although operations are now coming on line in other regions, including the Midwest farmlands. Concerns in the coastal states focus more on the spread of pathogens and the release of a nonnative species (especially the Pacific white shrimp) than on issues of deforestation, salinization, or sedimentation, which tend to be priorities in developing nations. We are unaware of any studies estimating the economic costs of these types of effects in the U.S. shrimp aquaculture sector.

3.C. Prospects for the growth of U.S. marine aquaculture

Large-scale U.S. aquaculture activities will have to compete in a global market for seafood products with foreign producers, many of whom operate in low-labor cost locations and under less stringent regulatory regimes than those that prevail in the United States. Therefore, U.S. aquaculture must either develop extraordinary efficiencies (most likely through technological innovation and automation) or focus on local/regional niche markets with live/fresh product that cannot be sourced competitively from other parts of the world.

The U.S. Department of Commerce has stated its intention to develop marine aquaculture to reduce imports and to meet growing consumption and has called for a fivefold increase in U.S. aquaculture production, to \$5 billion/year, by 2025 (USDOC 1999). This implies a slightly higher rate of growth for the industry than what it has exhibited historically. The Department of Commerce plan does not specify what species are to be the sources of this increase in production. Nash (2004) suggests that if the \$5 billion figure is interpreted in nominal dollar terms (that is, dollars not adjusted for inflation), this objective is consistent with a threefold increase in the volume of U.S. aquaculture production, roughly consistent with the simple projection described above. Nash describes a "realistic" production objective for 2025 of 1.1 million metric tons of finfish (about 700,000 mt excluding freshwater fish), 65,000 mt of crustaceans, and 345,000 mt of mollusks (see Table 4). His projections still require a major shift in emphasis from the historic "base" of U.S. finfish aquaculture (freshwater catfish) to saltwater species.

It is worth noting that the ability of increased aquaculture production to eliminate or reduce the nation's seafood trade deficit may be limited by species-specific issues. For example, shrimp account for more than half of the U.S. trade deficit in edible seafood, and shrimp consumption has grown strongly in recent years. Most observers consider it unlikely that the United States will develop a large domestic shrimp farming industry because of the large space requirements of typical shrimp farms, coupled with the high cost of coastal lands, and because of the availability of inexpensive imports. In all likelihood, therefore, the United States

[4] It has been reported that mangrove forests in Thailand have made a remarkable recovery in recent years resulting from relocation of shrimp farms away from mangrove areas, preservation efforts, and reforestation (Fast and Menasveta 2003).

TABLE 4

Possible U.S. aquaculture production targets proposed by Nash (2004)

Group	Sub-group	US production, mt/yr, 2004	Projected increase, mt/yr	Target for 2025, mt/yr	Percent increase
Mollusks	All	~100,000	245,000	345,000	245
	American oyster	40,000	10,000	50,000	25
	Pacific oyster	35,000	60,000	95,000	170
	European oyster	<1,000	5,000	5,000	>500
	Mussels	<2,000	80,000	80,000	>4,000
	Clams	25,000	80,000	105,000	320
	Scallops	<1,000	5,000	5,000	>500
	Abalones	<1,000	5,000	5,000	>500
Crustaceans	All	~18,000	47,000	65,000	260
	Crayfish	14,000	35,000	49,000	250
	Freshwater prawn	<1,000	3,000	3,000	>300
	Marine shrimp	4,000	9,000	13,000	225
Fish	All	~340,000	760,000	1,100,000	225
	Anadromous fish	25,000	100,000	125,000	400
	Freshwater fish	~315,000	70,000	385,000	20
	Saltwater fish	<1,000	590,000	590,000	>60,000
Totals		**~458,000**	**1,052,000**	**1,510,000**	**230**

will continue to import large quantities of shrimp in the future. If aquaculture is to reduce the overall U.S. seafood trade deficit in this scenario, it will have to produce other species for export, competing with low-cost producers in the global seafood market. Because that does not seem likely, it may be unreasonable to expect U.S. aquaculture to eliminate or even reduce significantly the nation's seafood trade deficit. From an economic point of view, of course, it is not a problem for the U.S. to be a net importer of seafood if other nations are more efficient at producing it, so long as there are other productive sectors that provide a balancing flow of net U.S. exports.

Nash (2004) cites the following factors as critical to the successful growth of U.S. aquaculture:

- Increased per-person U.S. consumption of seafood;
- Successful marketing of aquaculture products in the United States;
- Security of tenure and legislation to facilitate marine aquaculture ventures;
- Availability of capital;
- Availability of aquafeeds; and
- Improved economic and social conditions for aquaculture in the coastal zone.

On balance, the best prospects for growth in U.S. marine aquaculture are likely to be in shellfish culture (oysters, mussels) and some species of finfish for high-end fresh-product markets, including salmon and cod, among others (see Table 2). For species like salmon, for which U.S. producers face a large and competitive global industry, U.S. production will likely succeed best in local or regional niche markets rather than in price competition in the global market.

FOUR:

ADVERSE EFFECTS OF AQUACULTURE OPERATIONS

In this section, we summarize the adverse external effects of aquaculture production.

4.A. DISPLACEMENT OF EXISTING OCEAN USES

Most types of marine aquaculture (net pens, longlines, seabed planting) occupy areas of the ocean or seabed for extended periods of time. This physical occupation of ocean space may preclude the conduct of other types of ocean uses, including fishing, navigation, boating, or habitat preservation. In economic terms, marine aquaculture can be considered to be sustainable to the extent that it results in net benefits that exceed those of the alternative uses. More generally, exclusive uses of the ocean will impose opportunity costs in terms of foregone benefits from any excluded alternative uses. Exclusive uses such as marine aquaculture are sustainable as long as the net benefits from these uses exceed the opportunity costs.

In some cases, marine aquaculture operations do not need to exclude all other uses of the ocean. For example, a bottom-growing shellfish lease may be compatible with surface navigation, recreational boating, and recreational fishing. In this case, in order for a combination of ocean uses (including marine aquaculture as one such use) to be considered sustainable, the benefits of the combination of uses must exceed the opportunity costs of all other potential excluded uses, either alone or in feasible combinations.

Estimating the value of alternative uses (and non-uses, such as habitat preservation) is not always easy. The net economic surpluses from alternative uses or compatible combinations of uses must be estimated, forecast into the future, and discounted into present values. These would then be compared with similar estimates of potentially excluded uses. Where non-uses are involved, specialized methodologies must be applied to estimate nonmarket or passive use values.

All valuation approaches involve uncertainty, which makes the decision process more difficult. Some jurisdictions apply legal decision rules, such as the so-called "public trust doctrine," that establish priorities for certain uses over others. For example, navigation and fishing, which tend to be transitory uses of the ocean, usually are priority public trust uses applied at the state level in decisions over the allocation of uses in state coastal waters and tidelands. Although the public trust doctrine may simplify decision making, it does not necessarily imply that the ocean use decisions it prescribes are economically sustainable.

The potential for conflicts between commercial fisheries and marine aquaculture is one of the most important cases of the displacement of existing ocean uses. Conflicts between these two uses are likely to become more significant as aquaculture continues to expand worldwide. Hoagland et al. (2003) cite some examples of interactions between marine aquaculture and fisheries, including the following:

- At an FAO-sponsored meeting in 1986, which was focused on the problems of small-scale fisheries in the western

Mediterranean, the participants identified "major problems in the competition between aquaculture and fisheries . . . over uses of space, living resources, human and financial resources, and market competition for seafood" (Charbonnier and Caddy 1986: 47).

- In the early 1990s, in northwest Connemara, on the west coast of Ireland, local fisherman perceived that the "expansion of [salmon] farms result[ed] in an increasing number of restricted areas for fishing" (Steins 1997, page 3). The fishermen formed a shellfish cooperative to secure aquaculture licenses so that they could safeguard access to their historical fishing grounds.
- In the Norwegian town of Vega, conflicts between aquaculture and the commercial herring fisheries have been settled through the use of a "first in time, best [sic] in right" rule (Doksroed 1996). The application of this rule, however, may be made difficult by fluctuations in fish stocks that lead to variations in the level of fishing activity and therefore in the extent to which fishermen are using areas of the ocean.
- Off the coast of Martha's Vineyard, Massachusetts in 1996, the siting of an experimental aquaculture growout facility for sea scallops was delayed in part because of the opposition of commercial fishermen to the site originally proposed on the basis of historical patterns of fishing (WSC 1998).
- In New Zealand, Hickman (1996, page 452) notes that the 30-year history of aquaculture has been one of competition for coastal waters and that "on occasions direct competition has occurred between aquaculture and traditional fishery interests." Most recently, permit applicants for green-lipped mussel longline culturing operations have come into conflict with southern scallop fisheries in Tasman Bay and Golden Bay.
- In British Columbia, a debate continues over the ecological and economic impacts of establishing a capacity for growing sablefish (black cod). Studies have shown that the benefits of sablefish aquaculture accrue mainly to Asian consumers as a consequence of reduced prices. The costs of sablefish aquaculture, which fall mainly on coastal communities in British Columbia, include lower prices for locally harvested wild sablefish and the potential, but unquantifiable, ecological risks associated with the transmission of parasites and pathogens from high-density aquaculture operations to wild stocks and escapes (Sumaila et al. 2006).

With respect to economic sustainability, it should be recognized that an overexploited fishery represents a case where the economic value of an ocean use may be small or nonexistent. Specifically, resource rents may be driven to zero in the stereotypical open-access fishery. In this case, the value of other ocean uses, including marine aquaculture, may well exceed the value of an overexploited fishery. An important question to be addressed is whether the commercial fishery can be managed to optimize yields, and, if so, whether the resource rents from an optimally managed fishery exceed the value of marine aquaculture.

4.b. Pollution of the marine environment

An estimated 130 kg of nitrogen and 25 kg of phosphorus are released to the marine environment from a typical net pen fish farm for each ton of fish produced (Islam 2005). Nutrient emissions from fish farms are considered to be among the most significant environmental effects of aquaculture operations (Papatryphon et al. 2004). However, there is little or no information about the economic cost of this kind of pollution.

Many studies have quantified the waste output of coastal shrimp farms. Shrimp farms vary in terms of culture density (intensity), with output between 1,000 and 2,000 kg/ha-year for semi-intensive farms and between 4,000 and 5,000 kg/ha-year for intensive operations in Texas (Samocha et al. 2004), with feed conversion ratios of 2.7 for semi-intensive and 2.3 for intensive farms. Jackson et al. (2004) examined discharge from shrimp farms in Australia and found mean net discharge loads of 4.8 to 85.7 kg/ha-day of total suspended solids, from 1.0 to 1.8 kg/ha-day of total nitrogen, and from 0.11 to 0.22 kg/ha-day of total phosphorus.

Pond culture, like cage culture, results in some organic loading of water and sediments. Responsibly practiced pond culture need not have negative ecological effects. For example, studies of catfish culture as practiced in the United States have found no evidence of significant environmental degradation due to facility effluents (Stephens and Farris 2004). As in other types of aquaculture, optimized formulation and application of feed reduces organic loading of the environment. In ponds, residual loading of the water is managed by flushing and water exchange.

Nutrient loads and settlement of solids from aquaculture can be problematic if they exceed the natural assimilative capacity of the local marine environment and lead to adverse changes in the ecosystem (see Section 4.c. below). The problem tends to be most significant for intensive (high-density) coastal shrimp ponds and nearshore finfish farms where waste inputs are concentrated by limited water depth and circulation. The likelihood of negative effects is minimal for well-designed open ocean farming operations, where larger depths and ocean currents can provide a more significant dilution of inputs than the typical nearshore setting. In all cases, however, the effects depend on both input levels and the assimilative capacity of the surrounding waters.

Aquaculture waste can be managed or mitigated using a variety of techniques and policies. Some of these have been summarized by Tacon and Forster (2003):

- Requiring treatment of farm effluents prior to discharge;
- Limiting the concentration of inorganic/organic materials and/or nutrients in effluent;
- Establishing limits on total nutrient discharge from a farm;
- Limiting the scale of aquaculture in a geographic region;
- Limiting the total quantity of feed a farm can use in a certain time period;
- Fixing maximum permissible nutrient levels in feed compounds;
- Banning the use of potentially risky feed items;
- Banning the use of certain chemicals on the farm;
- Prescribing minimum feed performance criteria;
- Requiring codes of conduct, best management practices, etc.;
- Requiring the development of sediment management strategies; and
- Requiring the implementation of an environmental monitoring program.

The effectiveness of technology-based pollution control measures in Norwegian salmon aquaculture has been examined independently by Asche et al. (1999) and by Tveteras (2002b). Data from Norway between 1980 and 2000 exhibited a declining trend in feed conversion ratio (e.g., less feed input per unit production) and in the applications of antibiotics and chemicals, even as production was expanding. Because feed generally is the most costly input, contributing around 50 percent of production costs, gains in feed efficiency lead to both increased productivity and reduced effluents. Tveteras (2002b) argues that industry growth can be achieved together with pollution reductions by encouraging technological innovations in industry-specific, pollution-reducing inputs. In the Norwegian salmon aquaculture industry, growth in supply has been associated with reduced environmental problems in both relative and absolute terms.

Other recent advances in aquaculture waste treatment include the use of bacterial bio-filters and bio-filtration of nutrients by aquatic plants (algae) and filter feeders (shellfish) in integrated polyculture or multitrophic aquaculture (Troell et al. 2005; Neori et al. 2004). Algae and shellfish account for a large fraction of global marine aquaculture production, and the integration of these crops with finfish production can, in certain settings, help alleviate nutrient loading from finfish growout operations.

In addition to pollution by nutrient inputs, aquaculture operations can pollute the local environment with antibiotics and other medications designed to prevent disease in cultured organisms. Although there has been considerable concern over the human health implications of high levels of antibiotics in some farmed shrimp (Graeslund and Bengtsson 2001), and about the ecological consequences of residual antibiotics in sediments of shrimp ponds in Asia (Le and Munekage 2004), the intensity of antibiotic use in most types of aquaculture operations has declined in recent years (Garcia and Massam 2005; Asche et al. 1999; Tveteras 2002a, b), and this type of pollution is not likely to constitute a significant threat to the sustainability of marine aquaculture in the United States.

4.c. Modification of habitat and ecosystem functions

Organic enrichment of the local ecosystem due to aquaculture waste (unused feed and animal waste products) can cause or contribute to eutrophication of the surrounding environment (Howarth et al. 2000; GESAMP 1990; NRC 1994; Valiela et al. 1997, 1999). Unused feed and fecal matter settling to the bottom can also lead to localized changes in benthic habitat underneath fish cages and in shrimp ponds by increasing oxygen consumption by heterotrophic organisms within the sediment. This can lead to significant changes in benthic ecology if the sediments become anoxic (Islam 2005).

No comprehensive estimates exist of the economic losses imposed by habitat and ecosystem modifications due to marine aquaculture. The nature and severity of effects are tied to the scale and nature of the aquaculture operation and the flushing/mixing and assimilative capacity characteristics of the local environment. For example, Costanzo et al. (2004) found elevated nutrient and phytoplankton concentrations in tidal mangrove creeks receiving effluents from shrimp farms, but the extent and severity of effects depended heavily on farm operations. Bongiorni et al. (2003) found that increased levels of organically enriched particulate matter released by net pen fish farms in the Red Sea have a mixed effect on coral growth, producing faster vertical growth rates but reduced lateral growth due to burial of coral nubbins in the vicinity of the farm. Finally, fish farm effluents may have positive economic effects (such as increasing wild fish populations) in environments that are naturally low in nutrient content and biological productivity, such as some areas of the Mediterranean (Machias et al. 2004) and possibly Hawaii.

4.d. Accidental releases of cultured organisms

The issue of cultured organisms, such as finfish, escaping to the wild remains unresolved for the marine aquaculture industry (Agnalt et al. 2004; Nash et al. 2005). Unintentional release (escape) of cultured fish from aquaculture operations is a direct cost (loss) to the farming operation and can also lead to external losses if the escaped fish produce negative consequences in the ecosystem. Up to two million cultured salmon may escape annually from aquaculture operations in the North Atlantic (McGinnity et al. 2003).

If the cultured species is not native to the culture location and can thrive outside the farm, escapes can lead to the introduction of a new (invasive) species to the ecosystem with all of the ecological and economic implications that this entails (Costello and McAusland 2001; Horan et al. 2002). The effects are species and location specific. For example, Metcalfe et al. (2003) have found that although juvenile farmed Atlantic salmon are inherently larger and more aggressive than wild-origin fish, the hatchery environment reduces both their ability to compete for territories with wild resident fish and their long-term reproductive success (see also Nash 2003; Nash and Waknitz 2003; McGinnity et al. 2004; Weir et al. 2004 and 2005; and Naylor et al. 2005). Nonetheless, repeated interaction of farmed salmon with wild stocks can result in lower overall genetic fitness of the wild population and may have negative implications for species survival or rebuilding if the wild population is endangered (McGinnity et al. 2003). In some cases initial reproductive success of escaped fish may be high (Garant et al. 2003). The problem of escapes may be less severe if the species being cultured is native to the farming location and genetically homogeneous with local wild specimens, as is the case with certain shellfish in New England (see 4.e. below).

Pimentel et al. (2000) assembled a comprehensive review of invasive species and associated cost estimates for the United States and published an update of economic cost estimates in 2005 (Pimentel et al. 2005). According to their survey, the total damage and control cost is at least $120 billion per year[5] and might be found to be "several times higher" if they were "able to assign monetary values to species extinctions and losses in biodiversity, ecosystem services, and aesthetics" (Pimentel et al. 2005). Of the $120 billion in total damage and control estimates, $2.5 billion are associated with aquatic nuisance species. The aquatic cases from the report by Pimentel et al. are summarized in Table 5. The invasive species include weeds, fish, arthropods, and mollusks. They may establish in different aquatic environments such as wetlands, rivers, lakes, and marine waters. States having experienced significant aquatic nuisance species impacts include California, Florida, and Hawaii. Also, zebra mussels have caused significant impact in the Great Lakes region.

4.e. Genetic interaction between wild and cultured stocks

The issue of cultured fish escaping to the wild, and their possible competition for food and habitat and genetic mixing with wild stocks, remains unresolved for the marine aquaculture industry (Agnalt et al. 2004). Much of the attention surrounding escapes and genetic interaction has centered on salmon aquaculture. There are two concerns: direct interaction (interbreeding, genetic mixing) between cultured and wild fish affecting the wild stock gene pool; and indirect interaction (a separate breeding population of escaped cultured fish outcompeting wild fish for habitat and food). Economic data on these effects are sparse.

Oakes (1996) examined the threat posed by escapes of farmed Atlantic salmon in British Columbia on the region's native salmonid stocks, and found that despite substantial levels of escapes from farms, there was little likelihood of either direct or indirect genetic mixing (through establishment of competing breeding populations) because of a "low incidence of Atlantic salmon immi-

[5] Including plant and animal species, both terrestrial and aquatic, as well as human diseases.

TABLE 5

Aquatic nuisance species cases and annual costs reported by Pimentel et al. (2000, 2005)

General Type	Specific Name	Impact on	Specific Impacts	Location	Costs/year
Pest weed	Purple loosestrife	Wetland	Changing ecosystem structure Reduced biomass of native plants and animals	48 states	$45 million
Aquatic weeds	Hydrilla Water hyacinth Water lettuce	Rivers Lakes	Altering ecosystems Choking waterways Altering nutrient cycle Reduced recreation	Hudson River FL	$110 million
Fish	Grass carp 138 species introduced 40+ species with negative impact	Fresh water	Altering ecology Reducing water quality Species extinction	mild climates (FL, CA, HI)	$5.4 billion
Aquatic invertebrates	100 species introduced Green crab	Marine water	Affects native softshell clams, shellfish beds, oysters, crabs	New England	$44 million
	Zebra mussel	Fresh water	Reduce food and oxygen for native fauna Covering native mussels, clams, and snails Clogs water intake pipes, etc.	Great Lakes Lake St. Clair	$1 billion
	Asian clam Shipworm	Bay	fouling	CA San Francisco	$1 billion $205 million

gration into British Columbia rivers and the occurrence of reproductive isolating mechanisms." Stokesbury and Lacroix (1997) studied the potential impact of juvenile Atlantic salmon escapes from hatcheries near the Magaguadavic River in New Brunswick, Canada, and found that more than half of the smolts sampled at the mouth of the river were escapees. They also reported that cultured smolts found in the mouth of the river tended to be larger than wild smolts of similar age.

Escapees from culture operations pose no genetic mixing problem if the cultured fish are genetically identical to wild stocks. However, it is in the nature of animal husbandry that growers select broodstock for traits such as rapid growth and low mortality of offspring. As a result, even cultured fish drawn from native populations will eventually diverge genetically from the wild stock. The problem can then be resolved by culturing sterile fish that are not capable of reproducing in the wild. Several studies have shown that sterile or reproductively inviable diploid or triploid salmonid hybrids are commercially viable and effectively block genetic mixing if they do escape (Galbreath and Thorgaard 1995). (This does not resolve the potential problem of escaped fish occupying nesting sites or competing for other resources with wild stocks.)

The problem of possible genetic interaction is not limited to salmonids; it extends to other fish species and to shellfish. For example, Doroshov (2000) has examined the potential interactions between escapes of cultured sturgeon, which are grown both in medium-scale commercial production systems and in ponds, and native stocks in the coastal waters and rivers of Florida and the U.S. east coast. Hawkins and Jones (2002) have assessed the risk of genetic mixing due to the interstate acquisition of abalone juveniles in the expanding shellfish farming operations of Western Australia.

4.F. ENHANCED SPREAD OF DISEASE OR PARASITES

Infectious disease and parasites, such as sea lice in salmon and QPX in quahogs, are a significant economic problem for aquaculture producers (Bricknell and Dalmo 2005; Agnalt et al. 2004), as they are for terrestrial farming operations. This represents both a direct cost to the farming operations and a potential external cost if disease or parasites spread from farmed animals to nearby wild stocks. While studies have quantified the direct cost to fish farms and shellfish culture operations from disease and parasites, there are few economic data on the potential cost of disease spreading to wild stocks.

For example, outbreaks of acute infectious pancreatic necrosis in Scottish Atlantic salmon (Roberts and Pearson 2005) have led to immediate losses of more than 50 percent of fry and post-smolts in farming operations in Shetland, Scotland, and Ireland. In addition, the disease left many of the surviving fish chronically emaciated and prone to sea lice infestations. In British Columbia, research has linked Atlantic salmon farms to increased parasite loads (particularly sea lice) in wild salmon (Morton et al. 2005; Krkosek et al. 2005). This problem has led to requirements for fallowing of Atlantic salmon net-pens along the presumed migration route of wild juvenile Pacific salmon in the British Columbia salmon farming region, a management tool that has shown some success (Morton et al. 2005). And in Maine, officials ordered the destruction of millions of caged salmon and effectively shut down parts of the local salmon industry in 2001-02 in response to a severe infestation of infectious salmon anemia (ISA) virus in the state's salmon aquaculture industry (Melroy 2002, Gustafson et al. 2005). Resulting economic losses exceeded $20 million in Maine's $100 million salmon industry in 2001 and 2002.

Gozlan et al. (2005) describe how the (deliberate) introduction of the Asian cyprinid *Pseudorasbora parva* (a type of carp) appears to have carried to European waters an intracellular eukaryotic parasite that is causing increased mortality and inhibiting spawning in the endangered native European cyprinid *Leucaspius delineatus*.

Extensive ongoing research on management of disease and parasite infestation in fish, including especially fish farm settings, is leading to better understanding of relationships among environmental conditions, nutrition, and susceptibility to disease or parasites (Boshra et al. 2006; Bricknell and Dalmo 2005).

4.G. DEPLETION OF FORAGE FISH STOCKS AS AN INPUT INTO AQUACULTURE FEEDS[6]

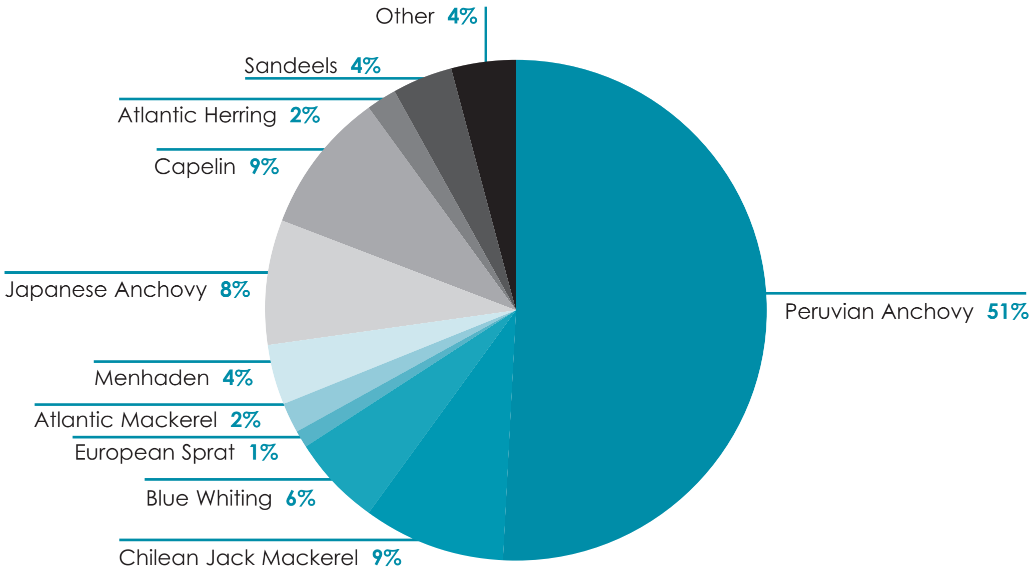
Worldwide, the culturing of high-priced carnivorous fish has been growing at annual rates of more than 13 percent, faster than the production of other seafood products (FAO 2005a). In the United States, three out of the four fastest-growing aquaculture species are carnivorous species, including Atlantic salmon (Goldburg et al. 2001). At current fishmeal and fish oil inclusion levels in aquafeeds, a kilogram of cultivated carnivorous fish requires between 1.0 and 3.9 kilograms of wild fish, depending upon the species being cultured (Tacon 2005; Naylor et al. 2000). Of note, significant efficiencies have now been achieved through the implementation of best management practices in the salmon aquaculture industry, where the economic feed conversion ratio (FCR) (the ratio of total feed applied to total live fish produced) has been reduced from more than 2.0 to a range of 1.0 to 1.5 within the last two decades. This FCR level is now the lowest of all the major carnivorous aquaculture species (Tacon 2005).

Approximately one third of all capture fisheries production is cooked, pressed, dried, milled, and reduced to fishmeal and fish oil.

[6] This section has been adapted and modified from an unpublished research paper written by Laure S. Katz, a Summer Student Fellow at the Marine Policy Center of the Woods Hole Oceanographic Institution during the summer of 2005 (Katz 2005).

FIGURE 15

Reduction fish by species in 2002 (percentage by species of 19 mmt of fresh fish used to make fishmeals and oils) (FAO 2005a).



In 2003, 19 million mt of fresh raw fish (plus six million mt of trimmings from fish processing) were used to generate approximately 5.6 million mt of fishmeal and 0.9 million mt of fish oil (FAO 2005). This fishmeal and fish oil is utilized in animal feeds, aquafeeds, fertilizers, and pharmaceuticals. Aquaculture's share of the consumption of fishmeal and fish oil has risen steadily as the industry has expanded. In 1988, the production of aquafeeds used only 10 percent of global fishmeal output; by 2002, it used 46 percent (Tacon 2005). In the absence of likely price increases with expanding demand, at the current rate of increase, aquaculture would use more than all conventional supplies of fishmeal before 2020 and of fish oil before 2010.

Two thirds of the 19 million mt of fresh fish used to make fishmeal and fish oil come from dedicated reduction fisheries, which are found primarily in South America, Europe, Asia, and the United States. The vast majority of these reduction fish are small pelagic species, thought to play critical roles in ecosystem food webs (Heath 2005). Further, stocks of these fish are highly responsive to environmental variability (Sandweiss et al. 2004). The major reduction fisheries and their percentage contribution to global fishmeal and fish oil production are shown in Figure 15.

The upwelling of nutrients along the western coast of South America makes it one of the most productive areas of the world's oceans, allowing it to support the Peruvian anchovy, which is the world's largest fishery. In large part due to their catches of anchovies, Peru and Chile produce almost two thirds of the global catch of reduction fish. Chilean jack mackerel, also caught in Peru and Chile, is the second-largest reduction fishery after Peruvian anchovies. These fisheries are susceptible to natural climatic variations such as the El Niño Southern Oscillation (ENSO), which disrupts oceanic upwelling. Thus, the stocks of both Peruvian anchovies and Chilean jack mackerel are highly variable and decline dramatically in response to ENSO events (NOAA 2004; Caviedes and Fik 1992).

After South America, the Nordic countries – Denmark, Norway, and Iceland – make the most significant contribution to the world's reduction fish supply. Reduction fisheries in this region include capelin, blue whiting, sand eels, Atlantic horse mackerel, Atlantic herring, and European sprat. The Japanese anchovy, caught off of Southeast Asia, and menhaden, from the U.S. southeast coast and the Gulf of Mexico, are the next most important contributors, in terms of volume, to world fishmeal and fish oil production. Both are used almost exclusively by domestic fishmeal and fish oil production plants. The six largest reduction fisheries are classified as either fully exploited or overexploited, however, leaving little room for expansion of the fishmeal and fish oil industry (Asche and Tveterås 2004).

The use of fishery resources as a component of feed stocks for aquaculture has been characterized as an unsustainable aspect of fish farming (Papatryphon et al. 2004). This critique may be misplaced, because issues of sustainability arguably should reside at the level of the individual reduction fishery, not in the end use markets. Interestingly, Kristofersson et al. (2006) have found that the structure of the market for fishmeal has changed in the last decade. Fishmeal prices now are significantly higher and exhibit more variance than soybean meal prices, implying an expansion of demand for fishmeal per se. The increased use of fishmeal for carnivorous aquaculture cannot fully explain this change, however, as the growth in this end use has slowed. The structural change in the fishmeal market is more likely driven by the combination of increased demand in the pork, poultry, and aquaculture end uses for specialized feed formulations.

A world market model developed by the International Food Policy Research Institute predicts that by 2020 the real price of fishmeal and fish oil could increase by 18 percent (Delgado et al. 2003). An increase in fishmeal price would lead to several effects in the aquaculture end use market. First, aquaculture producers will begin to seek substitute sources of proteins and oils. Considerable discussion centers on whether adequate substitutes exist, but the increase in price will provide an incentive for research and development in substitutes and in alternative growing technologies (Drakeford and Pascoe 2006). We may even begin to see the increased use of bycatch and fish trimmings as sources of fishmeal and oils. Further, aquaculture producers may decide to switch to the growing of other species that require less fishmeal or that can be raised on an herbivorous diet.

Second, significant increases in the price of aquafeeds may be incorporated into and thereby raise the farmgate cost of carnivorous aquaculture species, leading to higher prices for these products. Consequently, seafood consumers will begin to substitute with other sources of protein, curbing the growth in sales of carnivorous aquaculture species. Lower demands for cultured fish will begin to slow the rate of demand for fishmeal and oils.

Third, a rise in the price of forage fish could potentially force additional fishing pressure on reduction fisheries. This last effect has led to concerns about whether the aquaculture of carnivorous fish can be considered to be sustainable. In order to answer this question, we need to understand the status of conservation and management measures for the forage fisheries themselves.

Using a bio-economic framework, Asche and Tveterås (2004) demonstrate that, in the absence of strong regulation, an expansion of demand for fishmeal and fish oil could increase fishing pressure and lead to the depletion of reduction fisheries. In an open access fishery, price increases lead to new entry or greater fishing effort, pushing an overexploited stock further towards depletion. At low numbers, a fish stock may be more susceptible to climatic variability and other environmental disturbances. Further exacerbating the situation is the fact that most reduction fish exhibit strong schooling behavior, making them more vulnerable to fishing. In an open access system, schooling species might be more susceptible to stock collapse. The authors conclude that effective management can prevent reduction fisheries from being depleted, even when faced with a price increase as a consequence of increased demand for fishmeal and oils. Sustainability, therefore, is clearly the responsibility of the managers of reduction fisheries not of the end users, including the pork, poultry, and aquaculture producers.

We consider two primary criteria to assess the sustainable use of forage fisheries for aquafeeds: (1) the current status of the stock; and (2) the effectiveness of the management scheme and enforcement. A comparison of these two criteria for all of the major forage fisheries is presented in Table 6.

Fishery exports constitute a large portion of foreign income in Peru and Chile. Despite limited resources, the governments of these countries have made substantial efforts to regulate their reduction fisheries to ensure a sustainable harvest. On paper, Peruvian anchovies and Chilean jack mackerel are relatively well managed. The commercial fishing vessels in both countries are monitored with satellite tracking systems. In each country, the fish stocks are assessed on a regular basis by the respective national fishery research institute. Peru's Instituto del Mar studies the health of fish populations in relation to climatic oscillations in the Pacific Ocean. Even strict management measures cannot eliminate the inherent risk to these fisheries during an ENSO event, however.

Although the South American reduction fisheries appear to be biologically sustainable, their regulations are not necessarily optimal (that is, resulting in exploitation near maximum economic yield), nor are they necessarily implemented effectively. Quotas and restrictions on fishing effort are aimed at maximum sustainable yield (MSY) levels, not at the more conservative maximum economic yield (MEY) levels. Neither Peru nor Chile has incorporated the use of individual transferable quotas (ITQs) into the management of its reduction fisheries. Legislation is currently pending to introduce ITQs in Chile, however, and an ITQ system for anchovy is under debate in Peru (ISB 2005). While existing regulations appear effective on a superficial level, the implementation of these regulations needs to be further evaluated. It has been documented that strong commercial fishing interests, particularly in Chile, have interfered with the execution of Chilean fisheries management plans.

Implementation difficulties plague the European reduction fisheries as well. Superficially, European reduction fisheries appear to be well managed. The blue whiting fishery, which has virtually no regulation, is a notable exception. ICES has characterized many of Europe's reduction fisheries as having excessive yields or exhibiting a reduced reproductive capacity (ICES 2003). The lack of international cooperation has been the greatest barrier to achieving sustainable harvests in Europe. Although agreement on management measures is reached at the level of the EU Fisheries Council, the enforcement of each country's individual quota remains a significant challenge. Further, many countries continue to subsidize their fishermen, thus contributing to the maintenance of overcapacity.

The U.S. menhaden fisheries are regulated by the Atlantic States Marine Fisheries Commission and the Gulf States Marine Fisheries Commission. Environmentalists, marine biologists, and sports fishermen have criticized the management measures implemented by these commissions, claiming that menhaden is being harvested unsustainably. Notwithstanding these criticisms, the stocks are classified as healthy. Regulation varies from state to state, but is generally strong. Recently managers have paid particular attention to setting quotas in vulnerable areas such as the Chesapeake Bay, but their recommendations have met with widely differing responses from different states. Maryland has banned menhaden fishing in the Chesapeake, while Virginia has endorsed a proposed five-year cap on the menhaden catch in its own bay waters (ASMFC 2006). Thus, although the menhaden fishery enjoys some degree of management and regulation,

TABLE 6

Comparison of management systems for the world's major forage fisheries.

Species	Share of Global Production	Stock Status	Management System
South America			
Anchovy	51%	Healthy, recovered rapidly from 1997 ENSO.	Relatively strong management and monitoring based on MSY. Not necessarily efficient.
Chilean Jack Mackerel	9%	Slowly recovering from 1997 ENSO. 50% of 1994 peak.	Relatively strong management and monitoring based on MSY. Not necessarily efficient.
Europe			
Capelin	9%	Status of Icelandic stock is unknown. Barents Sea stock has reduced reproductive capacity.	Strong management, including the use of ITQs.
Sandeel	4%	Reduced reproductive capacity. North Sea fishery expected to be closed. .	Some precautionary regulation to protect predator species. Strong regulation is in place, but stocks are already depleted.
Blue Whiting	6%	Full reproductive capacity, but unsustainably harvested.	No international agreement on management. Scientific advice is ignored.
Atlantic Horse Mackerel	2%	Status unknown, but believed to be declining. No expansion is recommended.	Strong management, including the use of ITQs.
Atlantic Herring	2%	Norwegian stock is within safe biological limits. Baltic stock is exploited outside safe biological limits.	Strong management, including the use of ITQs.
Sprat	1%	Stock believed to be healthy, but status is unknown; strong recruitment in 2004.	Regulated under herring bycatch regulation.
United States			
Menhaden	4%	Gulf of Mexico stock is healthy. Atlantic stock is healthy, but fully utilized.	Management varies by state, but is theoretically strong. Attention paid to vulnerable areas.
Asia			
Japanese Anchovy	8%	Stock status unknown, but catches have steadily increased with no population crashes.	Stock believed to be fished beyond MSY. No catch limits as of 2000.

Sources: FAO 2005 and the websites of the relevant Regional Fisheries Management Organizations (July-August 2005).

a great deal of controversy over its sustainability remains (Price 2005).

Total catches of Japanese anchovy from China and Japan have increased rapidly in the last fifteen years. Although no significant crashes in the stock have occurred, the almost complete absence of regulation for this fishery in either country leaves it vulnerable to overexploitation. No quotas have been implemented, and FAO includes it among seven of the world's top 10 species (in terms of landings) that are either fully exploited or over-exploited (FAO 2005a).

In conclusion, the majority of the reduction fisheries that traditionally provide feed for aquaculture are already fully exploited. As the demands for fishmeal and fish oil increase, these fisheries will come under additional pressures. If these fisheries operate with inadequate or ineffective regulation, they should be considered to be unsustainable. Owing to a combination of scientific uncertainty, implementation conflicts, and natural variability, however, even the well-managed fisheries are at risk of being depleted. The sustainability issue is unquestionably at the level of the wild-harvest fisheries in these countries. Nevertheless, as a major consumer of forage fish in aquafeeds, aquaculture is likely to be criticized increasingly as a source of this potential unsustainablity.

4.H. Costs associated with fossil fuel use

A general concern about the sustainability of economic activity, including marine fisheries and aquaculture, is the use and correct pricing of hydrocarbon fuels as an input. As Tyedmers and others have pointed out (Tyedmers 2000; Tyedmers et al. 2005), marine finfish aquaculture and marine capture fisheries as practiced today require substantial inputs of fossil fuels. For carnivorous finfish aquaculture, feed costs represent about 50 percent of the cost of production; and fuel costs in turn represent the largest component of feed costs. Because hydrocarbons burned as fossil fuels represent a nonrenewable resource the use of which also entails environmental costs such as the release of greenhouse gases, and because the full use value of these fuels is not typically reflected in the price that fishing operations (and others) pay for the fuel, it is possible that fossil fuel is being used excessively in marine fisheries today, and that the prices of marine fishery products (including reduction fishery inputs to aquafeeds) are artificially low and do not reflect the true economic cost of producing and using them.

The external environmental cost of carbon emissions from fossil fuel combustion have been estimated at about $30/ton of carbon, or $0.07/gallon of gasoline (Parry 2005). Including possible economic damages arising from geopolitical implications of oil dependency for western nations, such as the United States, the total external cost of fossil fuel use is estimated to be $0.20 to $0.24/gallon (Parry 2005). While automotive fuel is already taxed in most western nations at levels in excess of this, the same may not be true of fuel used by fishing vessels. For example, the United States does not impose road taxes on diesel fuel purchased for fishing vessels, and as a consequence, diesel fuel for fishing boats typically costs about $1/gallon less than diesel fuel purchased for automotive use. Other nations have explicit subsidies for fishing vessel fuel; for example, Australia traditionally has subsidized diesel fuel in fisheries at rates close to $1/gallon (ADPL 2001).

If there are significant distortions in the pricing of fuel for reduction fishery vessels, the correct pricing of fossil fuels to reflect the true economic cost of their use, combined with proper management of reduction fish stocks, could improve the economic efficiency and prospects for sustainability of marine aquaculture. While fossil fuel pricing is a possible concern in the effort to ensure a sustainable marine aquaculture industry, it is an equally—or perhaps more—significant concern in the sustainability of capture fisheries and other kinds of agricultural production.

FIVE:

POSITIVE EFFECTS FROM AQUACULTURE OPERATIONS

The growth of aquaculture production has positive external effects as well. We summarize the main positive effects in the following sections.

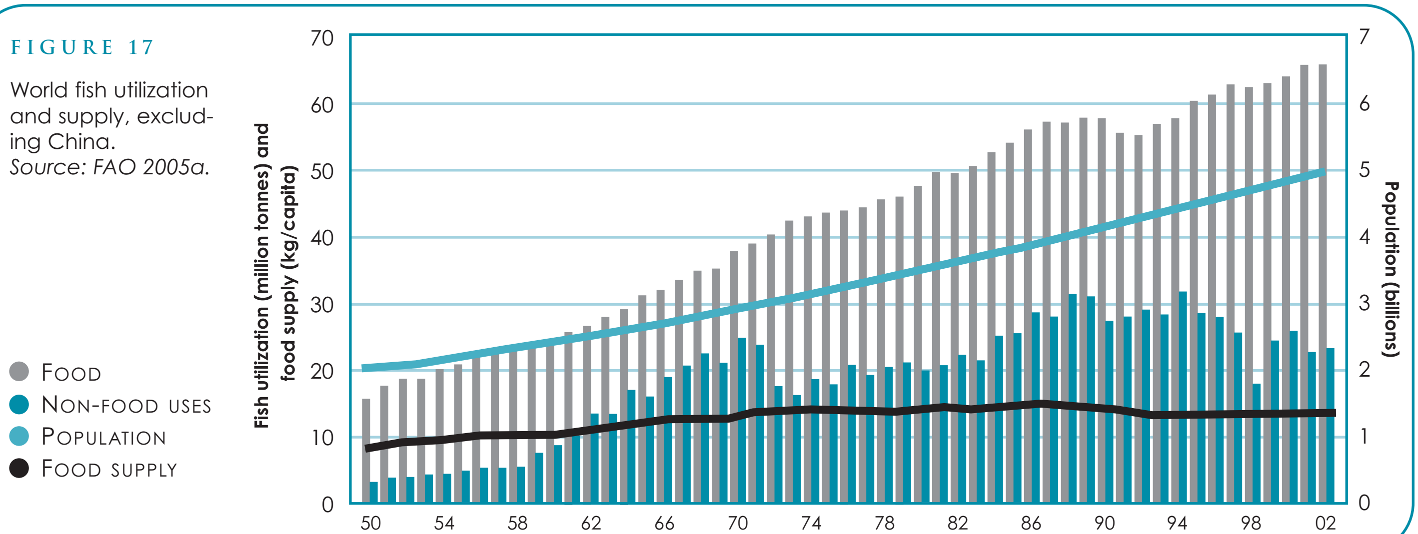
5.a. Increased supplies of seafood

Global aquaculture today produces 40 to 45 million mt of seafood annually, and accounts for 74 percent of freshwater and 17 percent of saltwater seafood consumed by humans (54 percent and eight percent, respectively, if Chinese production is excluded). Aquaculture has produced an expansion in the supply of seafood, particularly of species highly valued by consumers, which would not have been possible from capture fisheries even if they were managed for optimal yield. Seafood provides about 15 percent of total protein for human nutrition globally, and the expansion of aquaculture has allowed global seafood consumption to remain fairly steady (around 13 kg/person/year; see Figure 17) despite population growth and overexploitation of many capture fisheries. Unlike most other major sources of protein in the human diet, seafood still is produced largely by "hunting" in the wild, because the oceans are more "off limits" to human development than terrestrial ecosystems. With growing world population, however, it is increasingly becoming infeasible to meet the demand for seafood solely or primarily through wild harvest methods.

In addition to increasing total supply, aquaculture can in some cases improve the reliability and reduce the seasonality of seafood supply over what is possible from

FIGURE 17

World fish utilization and supply, excluding China.
Source: FAO 2005a.



capture fisheries. Aquaculture can also, in principle, improve the nutritional value and health effects of seafood by controlling feed constituents. Some wild capture fish stocks, including swordfish and tuna, bioaccumulate toxins such as heavy metals and dioxin from the marine environment. In aquaculture operations, these can be controlled by selecting or detoxifying ingredients of aquafeed (International Aquafeed 2005). Of course, the health implications of aquaculture can also be negative if farming practices are not appropriate (e.g., high levels of antibiotics in farmed shrimp) or if feeds are assembled from inputs that include contaminants (Hites et al. 2004). Nevertheless, the health benefits of seafood consumption are significant (Wolk et al. 2006) and appear to outweigh the potential risks of toxin bioaccumulation (Rembold 2004).

5.b. Increased economic growth and employment

Several studies have examined the economic contribution of marine fish farms with output ranging from 250 to 500 mt/year (Kam et al. 2003; Tveteras 2002a and b; Posadas and Bridger 2003; Bjorndal 1990). The average output per farm of 568 salmon farms in Norway was 277 mt/year (Tveteras 2002a). Large salmon farms in the United States currently produce from 150 to 2,900 mt/year, with the average around 1,000 mt/year (USEPA 2002). Proposed future production facilities are larger, with projected output capacity ranging from 1,000 to over 20,000 mt/year.

Current labor productivity for fish farms ranges from 30 to 200 mt fish/man-year (Forster 1999). For proposed projects, labor productivity up to 500 mt fish/man-year has been suggested, depending on the level of automation and the species produced. Reported labor cost (wages) range from $30,000/man-year (e.g., harvester) to $60,000/man-year (e.g., manager or captain).

At present, U.S. aquaculture contributes about $1 billion to gross domestic product and supports an estimated 180,000 jobs. If the industry grows to $5 billion in annual value (see Section 2.c above), NOAA projects employment of 600,000 (NOAA 2005). These projections are likely to be optimistic. For a large farm with output of 2,000 mt/year, assuming labor productivity of 300 mt/man-year, the total labor requirement is seven persons (including captain, divers, harvesters, manager, and office staff). Generally, offshore aquaculture operations are not expected to be labor intensive; and this would certainly have to be true of any competitive aquaculture operation based in the United States.

In addition to jobs in the production sectors (i.e., fish farms), a significant number of jobs may be created in the economy due to indirect and induced effects in the industries linked to the production sector (e.g., hatcheries and processors).

5.c. Relaxation of fishing pressure on overexploited wild fish stocks

The production of fish by marine aquaculture interacts with the production of fish from wild harvest fish stocks in a variety of ways. In general, much of the public's attention has been directed at the adverse environmental effects of aquaculture operations on the wild-harvest fisheries and the marine environment. The economic impacts of many of these environmental interactions are discussed throughout Sections 4 and 5 of this paper.

Two main types of interactions may result in the relaxation of fishing pressure on wild harvest stocks. One of the most important of these interactions concerns the effects of competition in the market for seafood between cultured and harvested fish. A second type of interaction concerns the combined spatial and ecological effects of aquaculture. In Section 5.e. below, we discuss the potential for the positive (or adverse) effects on wild harvest stocks of setting aside areas of the ocean for aquaculture operations.

From an economic perspective, it makes sense to conceptualize the industrial organization of seafood supply in terms of each species of fish constituting a distinct market. The market for each species potentially may be supplied with product that is "manufactured" with alternative technologies. Each of these technologies may be able to supply only a limited amount fish at the same marginal cost; for example, wild capture fisheries can (sustainably) supply only a certain fraction of the aggregate supply of salmon reaching the global market today. For many established aquaculture technologies, such as many shellfish growing operations, aquaculture production may exhibit lower marginal costs than wild harvesting. For other emerging aquaculture technologies, such as finfish growing in the open-ocean, wild-harvest fishing still may exhibit lower marginal costs than growing.

Each market may have its own peculiarities. For example, groundfish species—including cod, haddock, pollock, and flatfish—often are considered to be very close substitutes (Roheim et al. 2003). In fact, economists often model the market for "whitefish" to include the groundfish as well as aquaculture products, including catfish, tilapia, and hybrid striped bass. Whether this classification is sensible really depends upon the extent to which consumers are willing and able to discriminate among whitefish species. Often producers will engage in marketing campaigns designed to differentiate their products. This practice is very common for aquaculture products, where producers or distributors will argue that their product is superior on the basis of quality, freshness, or some other desired characteristic. If successful, aquaculture products may command a premium in the market that justifies the use of production technologies with higher marginal costs. Other factors, such as proximity to consumers, may play an important role in certain markets (e.g., farming of moi in Hawaii).

In cases where aquaculture exhibits marginal costs that are equal to or lower than wild-harvest fisheries, aquaculture producers may be able to capture a significant portion of the market for the relevant product. In this case, prices may remain steady or possibly decline, even in the face of expanding demands for seafood. In the case of a price decline, fishermen will cut back on fishing effort, and harvest pressures will be relaxed. Alaska salmon and quahogs may be good examples of this process.

Where commercial fishing clearly is more cost effective than aquaculture, it may be useful to think of newly emerging or prospective aquaculture technologies as "backstops" for the production of fish from commercial wild fisheries. As wild fishery stocks become depleted, and if demand remains steady or expands, we expect price to rise. This effect will bring aquaculture technologies on line, thereby acting as a cap on further depletion of commercial fisheries.

Some economic models have begun to examine the market interactions between aquaculture and wild-harvest fisheries (Jin et al. 2005; Phuong and Gopalakrishnan 2004; Hoagland et al. 2003). These models suggest that it is possible, but unlikely, that seafood in some markets could be completely supplied by marine aquaculture firms. It is probable that production will come from both commercial fisheries and aquaculture for a variety of fish species for the foreseeable future. The economic models are still very theoretical, and much work remains to be done to understand the implications of market interactions between competing seafood production technologies.

5.D. Removal of excess nutrients from the ocean

Nutrient loading has become one of the most important agents of adverse ecological change in coastal ecosystems (Howarth et al. 2000; GESAMP 1990; NRC 1994; Valiela et al. 1997, 1999). Most efforts to address nutrient overenrichment problems have focused on source reduction of nutrient inputs. This tends to be difficult and expensive, as the main nutrient sources—septic systems, atmospheric deposition, and fertilizers—cannot be reduced without significant technological or behavioral change. In certain cases, it may be equally effective and less costly to mitigate the effects of nutrients after they have entered the water. One such approach involves removing nutrients and improving water quality in estuaries by using bivalve mollusks as natural biofilters.

Several lines of evidence suggest that the propagation and harvesting of bivalve mollusks may be a viable method for removing nitrogen from estuaries and improving coastal water quality. First, shellfish sequester nitrogen in body tissues, and shellfish harvesting can remove a substantial amount of nitrogen directly from coastal waters (Rice 2000). Second, empirical and theoretical work suggests that filter feeders (including bivalve mollusks) may control primary productivity by grazing off phytoplankton at high rates, thereby reducing the likelihood of algal blooms under increased nutrient enrichment (Carpenter and Kitchell 1988; Cloern 1982; Dame and Libes 1993; Officer et al. 1982; Newell 1988). Third, laboratory and field studies of benthic filter feeders have shown that shellfish greatly influence nitrogen transformations in aquatic systems (Dame et al. 1989; Newell et al. 2002). In particular, filter-feeding shellfish produce biodeposits, the presence of which in sediments may increase the rate of denitrification — the conversion of biologically active nitrogen (NO_3^-) into elemental nitrogen (N_2) that diffuses to the atmosphere (Newell et al. 2002; Rice 2000). Denitrification — especially when increased by shellfish biodeposits —may be an even more potent tool for nitrogen removal than direct harvesting of shellfish (LaMontagne et al. 2002; Rice 2000).

Little is known about the precise economic value of this kind of nutrient removal, but it is a potentially significant positive externality associated with shellfish aquaculture in coastal water bodies affected or threatened by eutrophication. Positive results have been demonstrated in the context of existing shellfish aquaculture operations, including oyster farms in Australia (Gifford et al. 2005) and mussel farms in Sweden (Lindahl et al. 2005). Reduction in the level of ambient dissolved nutrients has also been reported in water circulated through semi-intensive shrimp ponds in Honduras (Teichert-Coddington et al. 2000), where dissolved nutrients are converted by phytoplankton into particulate matter and consumed by the shrimp.

5.E. Establishment of effective marine protected areas in aquaculture zones

Ocean areas that are set aside for marine aquaculture operations may necessitate the exclusion of other uses of the ocean. For example, net pen operations are incompatible with commercial fisheries and navigation because they involve the physical occupation of ocean space. As a consequence, aquaculture zones may act as a kind of refuge for commercially exploited species. In theory, as refuges, aquaculture zones could enhance commercial fish stocks, and this effect would be considered to be a positive externality.

The practical extent to which aquaculture zones act as marine protected areas is unknown, but we expect that it is only minor. In most cases, aquaculture zones are not of sufficient scale to affect the size and population structures of commercially exploited stocks to any significant extent. Nash (2004) notes that, even if marine aquaculture production in the United States were to triple, the spatial requirements would be less than one percent of the current total geographic area now conserved through the national program of marine sanctuaries. While aquaculture operations may be locally productive, particularly where nutrients are being added to the system, we cannot expect that such effects extend regionally or globally.

An important consideration is that aquaculture operations may change the structure, composition, and biodiversity of a local marine ecosystem. Thus, while aquaculture zones may provide a marine refuge, and aquaculture operations may enhance primary productivity, the ecosystem may differ from what might be characterized as “normal.” While there may be great uncertainty about the characteristics of a normal marine ecosystem and its dynamics in any particular area (or whether a normal marine ecosystem even exists in reality), the potential changes induced by aquaculture zoning should be weighed against the beneficial refuge and enhanced-productivity effects.

Again, given the scale of aquaculture operations, we expect that modifications to local ecological characteristics will be minor in most cases. Exceptions exist, particularly in cases where aquaculture is thought to affect protected species (Atlantic salmon runs in Downeast Maine), exacerbate the spread of disease (QPX in quahog leases on Cape Cod), or sap primary productivity (shellfish leases in coastal China). These exceptions are noticeable and can be especially serious in estuaries and protected embayments. Both the positive and negative effects of aquaculture zones as marine protected areas in the open ocean are likely to be vanishingly small.

SIX:

IMPROVING THE SUSTAINABILITY OF AQUACULTURE

There are significant problems with the application of the concept of "economic sustainability" to a specific activity such as the farming of carnivorous marine finfish by aquaculture. The notion of economic sustainability is best applied to a broad cross-section of economic activity in aggregate, since the central question is whether investment in improved knowledge and capital will compensate future generations for the lack of any resources that today's economic activity makes unavailable to them. For example, while the consumption of fossil fuel for automobile propulsion may not be strictly sustainable for the indefinite future, it may be economically sustainable in the context of sufficient general investment, funded from wealth generated by a wide range of economic activity and perhaps tied only peripherally to automobile use, in the technology required for future non-fossil fuel automobiles. Similarly, the possibility that aquaculture may not be practiced (or practicable) the way it is today at some point in the future does not necessarily make it economically unsustainable.

Determining the sustainability of human activity requires making projections of future economic activity, markets, prices, ecological conditions, and human preferences. It is therefore a matter of risk and uncertainty. Therefore, we must think of sustainability in probabilistic and relative terms; that is, one type of human activity may be more or less likely to be more or less sustainable than another. It is also important to specify the scale of economic activity: for example, marine aquaculture may be more sustainable at a modest scale (e.g. five million mt/yr) than at a significantly larger scale (50 million mt/yr).

Achieving an economically optimal level of marine aquaculture production in the United States is complicated because of the numerous links between aquaculture and other activities, such as foreign reduction fisheries, and nonmarket effects, such as the introduction of pollutants to coastal waters. Given that market failures exist in other parts of the economy, it does not necessarily follow that it is best for either the current economy or for the goal of economic sustainability for all of marine aquaculture's market failures to be corrected (Lipsey and Lancaster 1956). To reiterate an earlier example, it may well be less sustainable to continue to overexploit capture fisheries as a source of seafood protein than it would be to develop marine aquaculture and to put up with a certain level of pollution from it. Whether this observation is true depends upon the scales of market failures in the different sectors and whether or not we have the ability and political will to attempt and implement corrections.

In our view, based on the information summarized in this paper, the most significant challenges to the economic sustainability of significantly larger future marine aquaculture production in the United States include:

- Managing disease and parasite problems;
- Managing problems associated with escapes and genetic mixing; and

- Finding alternatives to fishmeal and fish oil inputs to feeds for carnivorous finfish.

Managing pollutant inputs and ecosystem effects from nearshore finfish farms and coastal ponds is also a potential challenge, but neither nearshore farms nor coastal ponds are likely to account for significant future aquaculture production in the United States due to land use conflicts.

Market forces will help resolve some of these challenges. For example, as feed demands exceed the capacity of reduction fishery stocks, prices of fishmeal and fish oil will rise, encouraging feed manufacturers to find alternative constituents. In other cases, market mechanisms can be combined with targeted intervention (such as labeling requirements) to encourage ecologically sound production. Some externalities, such as pollutant releases and escapes/genetic mixing, may be best addressed by the public regulation of operating practices. The following section provides information about institutional approaches to dealing with externalities and encouraging sustainable aquaculture practices.

SEVEN:

INSTITUTIONAL MEASURES FOR ENCOURAGING SUSTANABLE AQUACULTURE

Normally, in the absence of regulation, we expect firms to disregard environmental costs. The challenge to society is to balance the benefits from seafood supply and the social costs of fish production. Regulations and policy instruments should be introduced in a cost-effective way to maximize the net social benefit. In some cases, such as trout farming in West Virginia (Smearman et al. 1997) and net pen operations for salmon in certain locations (Sylvia et al. 1996), discharges from aquaculture production facilities can be monitored and measured. Effluents from these facilities could then be regulated as point sources. One approach is to charge fish farmers a tax equal to the marginal external costs imposed by their farms on the environment at the socially optimal externality level (Smearman et al. 1997).

Waste discharges from many types of aquaculture operations, such as large-scale coastal shrimp ponds, cannot be measured so easily. Consequently, the regulation of these operations as point sources generally is not feasible. Mathis and Baker (2002) argue that in the face of uncertainty about effluent releases, the power of traditional economic instruments such as taxes and tradable permit systems to internalize environmental costs is greatly reduced. Broadly speaking, because of the complexity of production processes and pollutant releases, combinations of market-based and command-and-control instruments may be required (Stanley 2000). Studies by GESAMP (2001) and by Brennan (2002) describe the key factors affecting environmental management in aquaculture, highlighting a range of potentially useful policy instruments (Table 7), such as pollution standards, taxes, legal liability measures, and best management practices (BMPs).[7]

Stanley (2000) suggests that wastewater discharges from coastal shrimp farms are non-point source pollution, because the wastewater may be released at irregular times and levels from large numbers of farms covering large geographic areas. The nature of non-point source pollution implies that the direct regulation of aquaculture operations is not feasible. The shrimp farming industry apparently favors the implementation of BMPs, which would involve the adoption of voluntary pollution controls that are not easily observed or enforced.

Brennan (2002) provides an overview of pollution control options currently practiced in the marine aquaculture industry. First, pollution may be managed through siting decisions that involve a review of the current levels of nutrient loadings at a specific location. Typically, densely populated areas may be eutrophic already, implying that only more remote locations would be available for aquaculture. Second, depending upon the conditions at a particular location, nutrient controls may involve restrictions on the total number and size of individual farms, as well as limits on stocking densities. Further, various technologies may be used to improve the efficiency by which cultured fish convert feed into biomass (i.e., to lower the feed

[7] GESAMP (2001) and Brennan (2002) also discuss strengths and weaknesses of different environmental policy instruments. A theoretical treatment of the issue can be found in Baumol and Oates (1988).

TABLE 7

Management policy instruments.

Instruments	Description
Standards	Effluent standards (i.e., discharge limitations) Receiving water standards Technology-based standards (e.g., regulating feeding schedule and monitoring)
Taxes or Subsidies	Taxes on polluting inputs Taxes on effluent Subsidizing environmentally friendly technologies Charging firms with high input levels above a baseline while subsidizing those with lesser inputs
Liability	Firms are liable for pollution damages
Environmental Assurance Bond (EAB)	Deposit-refund system (refund of surcharge if pollution is avoided)
Emission Trading	Creating markets for pollution trading
Production Management	Best management practice (BMP) initiatives Voluntary codes of practice Cooperative user/owner management of the aquaculture zone, its resources, and facilities Infrastructure provided by government or through cooperatives
Product Certification	Environmental and product quality certification and labeling (e.g., associated with BMPs)
Zoning	Zoning restrictions on location of certain operations
Restrictions	Restrictions on importation and transfer of cultured species Prohibition of specific activities, materials, and technologies

conversion ratio [FCR]), thereby reducing the quantity of unused food in the aquaculture operation. The U.S. Environmental Protection Agency recently has proposed regulations to monitor feed rates and to reduce feed inputs (USEPA 2002). Lastly, different bio-control techniques have been considered. For example, Neori et al. (1996) report that seaweed can be effective as a biofilter in an integrated fish-seaweed culture operation. Similarly, Folke and Kautsky (1992) propose a method for the polyculture of seaweeds, mussels, and salmon.

The effectiveness of technology-based pollution control measures in Norwegian salmon aquaculture has been examined by Asche et al. (1999) and by Tveteras (2002a, b). Data from Norway between 1980 and 2000 exhibited a declining trend in FCR and in the applications of antibiotics and chemicals, even as production was expanding. Because feed often is the most costly input, constituting around 50 percent of production costs, gains in feed-use efficiency lead to both increased productivity and reduced effluents. Tveteras (2002a) argues that industry growth can be achieved together with pollution reductions by encouraging technological innovations in industry-specific, pollution-reducing inputs. In the case of the salmon aquaculture industry, growth in supply has been associated with reduced environmental problems in both relative and absolute senses.

On the demand side, seafood certification and labeling (i.e., eco-labeling) has been identified as a potentially effective market-based policy instrument for sustainable fisheries. Certification and labeling provides information to consumers who are likely to endorse ecologically friendly products, which, in turn, stimulates supplies of eco-friendly products. Market-based instruments are preferred by policy makers because they are easier to implement and enforce than explicit production site regulations.

The effectiveness of seafood labeling has been documented using empirical data. Teisla et al. (2002) confirm that the implementation of dolphin-safe labeling has affected consumer behavior. Specifically, the dolphin-safe label has increased the market share of canned tuna. In a review of the market impacts from the Marine Stewardship Council (MSC)'s eco-labeling of seafood, Roheim (2003) concludes that the market for MSC-labeled products appears bright. Results of a study of the U.K. seafood market by Jaffry et al. (2004) also indicate that a sustainability certification and labeling program is highly significant in affecting consumer choices. Additional evidence of eco-labeling as an effective policy instrument in other (non-seafood) product markets can be found in Bjørner et al. (2004).

According to Wessells et al. (1999), the design of a successful eco-labeling program for seafood products cannot follow a simple "cookie cutter" approach. Preferences for eco-labled fish will likely differ by species, geographic region, consumer group, and certifying agency. Significant consumer education must take place. With sufficient market research and consumer education, certifying and eco-labeling seafood products may be a feasible long-term approach to promoting sustainable fisheries. However, in the absence of these activities, short-run impacts are likely to be less predictable and more modest. Indeed, the results of Teisla et al. (2002) show that seafood consumers may not respond instantaneously to eco-labeling programs. On the other hand, demand for eco-labeling is reported to be high among European consumers of seafood (Fletcher 2005).

Prominent examples of initiatives in the area of labeling for seafood and nonseafood marine products with potential relevance to marine aquaculture production include the following:

- The Marine Stewardship Council, a nonprofit group advocating for sustainable fisheries, has developed principles and criteria for sustainable fishing (MSC, n.d.) based on FAO's Code of Conduct for Responsible Fisheries (FAO 1995). MSC provides for a third-party certification process by which seafood can be sold with a consumer label certifying its origin from a sustainably managed fishery. As of 2004, the MSC label was carried by more than 220 seafood products marketed in 23 countries, predominantly Switzerland, the United Kingdom, and Germany (Globefish 2005).
- The Marine Aquarium Council has recently developed standards and procedures for third-party certification of sustainability for practices and products in the ornamental fish industry (MAC, no date).
- The Mandatory Country of Origin Labeling (COOL) of Fish and Shellfish regulations were published as an interim final rule (69 Federal Register 59708) by the U.S. Department of Agriculture's Agricultural Marketing Service on October 5, 2004, as mandated by the 2002 Farm Bill (P.L. 107-171). This regulation entered into effect in April 2005 and requires most fish and shellfish sold at retail in the United States to be labeled with country of origin and method of production (wild or farm-raised). The seafood ingredients of processed foods are exempt, as are products sold in food service establishments.
- FAO's (2005b) *Guidelines for the Eco-labeling of Fish and Fishery Products from Marine Capture Fisheries* provide a voluntary framework for public and private labeling schemes to certify and promote fish and fishery products from well-managed capture fisheries.

The effectiveness of these programs in achieving sustainability in related industries will provide valuable lessons to the aquaculture industry.

EIGHT:

CONCLUSIONS

The world demand for seafood products continues to expand. It is unlikely, however, that the annual harvest of fish from wild stocks can be increased significantly. Aquaculture, where practicable, now is recognized as the only means of increasing the supply of protein from seafood.

As the marine aquaculture industry expands, it has been confronted with concerns about its potential impacts on the environment and on other human activities. Questions have also been raised about whether marine aquaculture in its various forms can be considered to be a "sustainable" human activity. The notion of economic sustainability relates to the allocation of scarce resources in a way that generates economic profits, which are available for investments in physical capital, knowledge, and technology. These investments would endow future generations with the capacity to be at least as well off as the current generation.

A key aspect of this definition of sustainability is its emphasis on the welfare of future generations. Economically sustainable aquaculture requires that resources are not overused or wasted in a way that would disadvantage future generations in terms of optimizing their own welfare. As in most decisions about economically optimal allocations of resources, however, economic sustainability entertains the very real possibility that we may need to bear some level of environmental change or resource depletion to optimize societal welfare both now and in the future.

Economic efficiency is a necessary condition for achieving sustainable development because it does not make sense to waste resources without cause. Moreover, efficiency is likely to increase the net benefits that can be shared both within and across generations. In determining whether or not an activity like marine aquaculture is economically efficient, and therefore could be sustainable, a critical issue is to ensure that all costs are accounted for fully.

Studies of market failures and the economic damages associated with pollution from marine aquaculture are few. In this paper, we have identified some of the salient issues relating to the efficiency of marine aquaculture, and, in so doing, we have highlighted areas where economic studies can make a significant contribution to understanding the sustainability of marine aquaculture. We conclude with the following observations:

Future seafood demand. Future seafood demand in the United States will vary with changing consumer tastes and food prices, and it is not clear that U.S. exports of seafood will continue to grow as they have in the past. A careful projection of future aquaculture production and imports and exports would have to be based on projected future demand for particular types and species of seafood, and on assumptions about future prices. These projections are, in turn, linked to global production and to demand in other nations. On balance, it seems likely that the United States will remain a major net importer of seafood, even if domestic aquaculture production can regain the rates of growth it achieved in the early 1990s.

Product markets and sustainability issues. It is appropriate to disaggregate the marine aquaculture sector into individual markets. It is useful to begin to identify markets for marine aquaculture products, because it is likely that issues of sustainability may not be the same across all markets. We present an initial characterization (analogous to a qualitative risk assessment) of the degree to which an array of practices in individual product markets may be deemed unsustainable. Our typology is useful as an example, but we stress that in order to characterize the sustainability of any particular market, it will be important to understand the specific issues faced in that market. Given limited resources for attending to the array of pollution problems presented by marine aquaculture in the United States, this kind of comparison should aid decision makers in allocating these resources as effectively as possible.

Using this characterization, we identify several high-priority problems faced by nearshore finfish aquaculture, including organic pollution, disease transmission, escapes, reliance on forage fisheries in fishmeal, and bioaccumulation of toxins. In a comparative sense, nearshore mollusk aquaculture appears relatively benign; its physical side effects may even be beneficial on balance.

Economic literature on external effects. Economic studies of the external costs of marine aquaculture operations are only just beginning to emerge, and only a few can be found in the published literature. One reason for the absence of studies of this type is that the sector is in an early growth phase, particularly in the United States. Another reason is that several forms of marine aquaculture, including nearshore marine shellfish, recirculating system culture, extensive pond culture, and open-ocean aquaculture appear to result in minimal levels of pollution.

Global seafood market. Large-scale U.S. marine aquaculture activities will have to compete in a global market for seafood products with foreign producers, many of whom operate in low-labor cost locations and under less stringent regulatory regimes than those that prevail in the United States. Therefore, U.S. marine aquaculture must either develop extraordinary comparative efficiencies or focus on local or regional niche markets with live or fresh products that cannot be sourced competitively from other parts of the world.

Balance of seafood trade. The ability of increased marine aquaculture production to eliminate or reduce the nation's seafood trade deficit may be limited by species-specific issues. For example, shrimp account for more than half of the U.S. trade deficit in edible seafood, and shrimp consumption has grown strongly in recent years. Most observers consider it unlikely that the United States could develop a large domestic shrimp farming industry because of the significant space requirements of typical shrimp farms, coupled with the high cost of coastal lands, and because of the availability of inexpensive imports. If marine aquaculture is to reduce the overall U.S. seafood trade deficit in this scenario, it will have to produce other species for export, competing with low-cost producers in the global seafood market.

Best prospects for growth in U.S. marine aquaculture. On balance, the best prospects for growth in U.S. marine aquaculture are likely to be in shellfish culture (oysters, mussels) and some species of finfish for high-end, fresh-product markets (including salmon and cod, among others). For species like salmon, for which U.S. producers face a large and competitive global industry, U.S. production will likely succeed best in local or regional niche markets rather than in price competition in the global market.

Opportunity costs of marine aquaculture siting. Most types of marine aquaculture (net pens, longlines, seabed planting) occupy areas of the ocean or seabed for extended periods of time. This physical occupation of ocean space may preclude the conduct of other types of ocean uses, including fishing, navigation, boating, or habitat preservation. Exclusive uses of the ocean will impose opportunity costs in terms of foregone benefits from any excluded alternative uses. Exclusive uses such as marine aquaculture can be considered sustainable as long as the net benefits from these uses exceed the opportunity costs.

With respect to economic sustainability, it should be recognized that an overexploited fishery represents a case where the economic value of an ocean use may be small or nonexistent. Specifically, resource rents may be driven to zero in the stereotypical open-access fishery. In this case, the value of other ocean uses, including marine aquaculture, may well exceed the value of an overexploited fishery. An important question to be addressed is whether the commercial fishery can be managed to optimize yields, and, if so, whether the resource rents from an optimally managed fishery exceed the value of marine aquaculture.

Nutrient pollution. Nutrient emissions from fish farms are considered to be among the most significant environmental effects of marine aquaculture operations, but there are few studies of the economic costs of this kind of pollution. Nutrient loads and settlement of solids from marine aquaculture can be problematic if they exceed the natural assimilative capacity of the local marine environment and lead to adverse changes in the ecosystem. The problem tends to be most significant for intensive coastal shrimp ponds and nearshore finfish farms where waste inputs are concentrated by limited water depth and circulation. The likelihood of negative effects is minimal for open ocean farming operations, and the existence of any effects would depend on both input levels and the assimilative capacity of the surrounding waters.

Antibiotic use. The intensity of antibiotic use in most types of marine aquaculture operations has declined in recent years, and this type of pollution is not likely to constitute a significant threat to the sustainability of marine aquaculture in the United States.

Habitat impacts. No comprehensive estimates exist of the economic losses imposed by habitat and ecosystem modifications due to marine aquaculture. The nature and severity of effects are tied to the scale and nature of the marine aquaculture operation and the flushing/mixing and assimilative capacity characteristics of the local environment.

Escapes. The issue of cultured organisms, such as finfish, escaping to the wild remains unresolved for the marine aquaculture industry. Unintentional releases (escapes) of cultured fish from marine aquaculture operations are a direct cost to the farming operation and can also lead to external economic damages if the escaped fish produce negative consequences in the ecosystem. There are two concerns: direct interaction (interbreeding, genetic mixing) between cultured and wild fish affecting the wild stock gene pool; and indirect interaction (a separate breeding population of escaped cultured fish out-competing wild fish for habitat and food). Economic data on these effects are sparse. Although the economic damages associated with aquatic invasive species have been estimated to be $2.5 billion annually in the United States, these estimates are at best rough and conservative. In particular, these estimates do not include the potential damages associated with escapes from marine aquaculture operations.

Diseases and parasites. Infectious diseases and parasites are a significant economic problem for marine aquaculture producers. Diseases and parasites represent both a direct cost to the farming operations and a potential external cost if diseases or parasites spread from farmed animals to nearby wild stocks. While studies have quantified the direct cost to fish farms and shellfish culture operations from disease and parasites, there are few economic data on the potential economic damages of disease spreading to wild stocks.

Sustainability of reduction fisheries. The majority of the reduction fisheries that traditionally provide feed for marine aquaculture are already fully exploited. As the demands for fishmeal and fish oil increase, these fisheries will come under additional pressures. If these fisheries operate with inadequate or ineffective regulation, they should be considered to be unsustainable. Owing to a combination of scientific uncertainty, implementation conflicts, and natural variability, however, even the well-managed fisheries are at risk of being depleted. The sustainability issue is unquestionably at the level of the wild-harvest fisheries. Nevertheless, as a major consumer of forage fish in aquafeeds, marine aquaculture is likely to be criticized increasingly, but unfairly, as a source of this potential unsustainability.

Fossil fuel externalities. A concern about the sustainability of any economic activity, including marine aquaculture, is the use and correct pricing of hydrocarbon fuels as an input. While automotive fuel is already taxed in most western nations at levels in excess of the total external cost of fossil fuel use, the same may not be true of fuel used by fishing vessels. If there are significant distortions in the pricing of fuel for reduction fishery vessels, the correct pricing of fossil fuels to reflect the true economic cost of its use, combined with proper management of reduction fish stocks, could improve the economic efficiency and prospects for sustainability of marine aquaculture.

Increased seafood supply. Marine aquaculture has produced an expansion in the supply of seafood, particularly of species highly valued by consumers, that would not have been possible from capture fisheries even if they were managed for optimal yield. In addition to increasing total supply, marine aquaculture can in some cases improve the reliability and reduce the seasonality of seafood supply over what is possible from capture fisheries. Marine aquaculture can also, in principle, improve the nutritional value and health effects of seafood by controlling feed constituents.

Increased economic growth and employment. At present, U.S. aquaculture contributes about $1 billion to gross domestic product and supports an estimated 180,000 jobs. If the industry grows to $5 billion in annual value, NOAA has projected an employment level of 600,000 jobs. These projections are likely to be wildly optimistic. Generally, offshore aquaculture operations are not expected to be labor intensive; and this would certainly have to be true of any competitive marine aquaculture operation based in the United States.

Potential for the relaxation of fishing pressure on wild stocks. In cases where marine aquaculture exhibits marginal costs that are equal to or lower than wild-harvest fisheries, marine aquaculture producers may be able to capture a significant portion of the market for the relevant product. In this case, prices may remain steady or possibly decline, even in the face of expanding demands for seafood. In the case of a price decline, fishermen will cut back on fishing effort, and harvest pressures will be relaxed.

Where commercial fishing clearly is more cost effective than marine aquaculture, it may be useful to think of newly emerging or prospective marine aquaculture technologies as “backstops” for the production of fish from commercial wild fisheries. As wild fishery stocks become depleted, and if demand remains steady or expands, we expect price to rise. This effect will bring marine aquaculture technologies on line, thereby acting as a cap on further depletion of commercial fisheries.

Some economic models have begun to examine the market interactions between marine aquaculture and wild-harvest fisheries. These models suggest that it is possible, but unlikely, that seafood in some markets could be completely supplied by marine aquaculture firms. It is probable that production will come from both commercial fisheries and marine aquaculture for a variety of fish species for the foreseeable future.

Removal of excess nutrients. Several lines of evidence suggest that the propagation and harvesting of bivalve mollusks may be a viable method for removing nitrogen from estuaries, thereby improving coastal water quality. Little is known about the precise economic value of this kind of nutrient removal, but it is a potentially significant positive externality associated with shellfish aquaculture in coastal water bodies affected or threatened by eutrophication. Positive results have been demonstrated in the context of existing shellfish aquaculture operations, including oyster farms in Australia and mussel farms in Sweden.

Marine aquaculture zones as MPAs. The practical extent to which marine aquaculture zones act as marine protected areas is unknown, but we expect that it is only minor. In most cases, marine aquaculture zones are not of sufficient scale to affect the size and population structures of commercially exploited stocks to any significant extent. While marine aquaculture operations may be locally productive, particularly where nutrients are being added to the system, we cannot expect that such effects extend regionally or globally.

Institutional measures. The design and implementation of institutional measures that provide incentives for private growers to account for environmental costs or to increase production where environmental benefits can be realized is needed. Institutional measures may comprise command-and-control regulations, market-based approaches, such as pollution taxes or eco-labeling, or the voluntary adoption of best management practices.

Certification and eco-labeling. Market-based instruments often are easier to implement and enforce than regulations on production activities. For example, the certification and labeling of seafood has been identified as an effective market-based policy instrument for sustainable fisheries. Certification and labeling provides information to consumers who are likely to endorse ecologically friendly products, which, in turn, stimulate production of eco-friendly products. Preferences for eco-labled fish will likely differ by species, geographic region, consumer group, and certifying agency. With sufficient market research and consumer education, certifying and eco-labeling seafood products may be a feasible long-term approach to promoting sustainable fisheries. In the absence of these activities, however, short-run impacts are likely to be less predictable and more modest.

Challenges to the sustainability of marine aquaculture. In our view, based on the information summarized in this paper, the most significant challenges to economic sustainability of significantly larger future marine aquaculture production in the United States include: (1) managing disease and parasite problems; (2) managing problems associated with escapes and genetic mixing; and (3) finding alternatives to fishmeal and fish oil inputs to feeds for carnivorous finfish. We emphasize that the latter issue is not a sustainability issue for marine aquaculture per se. Managing pollutant inputs and ecosystem effects from nearshore finfish farms and coastal ponds also is a potential challenge, but neither nearshore farms nor coastal ponds are likely to account for significant future aquaculture production in the United States due to land use conflicts.

REFERENCES

ADPL (Australia Department of the Parliamentary Library), Information and Research Services. 2001. *Research Note* Number 24 (http://www.aph.gov.au/library/pubs/rn/2000-01/01rn24.pdf).

Agnalt, A.-L., A. Ervik, T.S. Kristiansen, and F. Oppedal. 2004. Aquaculture report 2004. *Fisken og Havet, Saernummer* no. 3.

Asche, F., A.G. Guttormsen and R. Tveteras. 1999. Environmental problems, productivity and innovations in Norwegian salmon aquaculture. *Aquaculture Economics and Management* 3(1):19-29.

Asche, F. and T. Sebulonsen. 1999. Salmon prices in France and the UK: does origin or market place matter? *Aquaculture Economics and Management* 2(1):23-30.

Asche, F. and R. Tveteras. 2004. On the relationship between aquaculture and reduction fisheries. *Journal of Agricultural Economics* 55(2):245-265.

Barbier, E.B, I. Strand and S. Sathirathai. 2002. Do open access conditions affect the valuation of an externality? Estimating the welfare effects of mangrove-fishery linkages in Thailand. *Environmental and Resource Economics* 21(4):343-65.

Baumol, W.J. and W.E. Oates. 1988. *The Theory of Environmental Policy*. Second Edition. Cambridge University Press, New York.

Bjorndal, T. 1990. *The Economics of Salmon Aquaculture*. Blackwell Scientific Publications, Boston, MA.

Bjørner, T.B., L.G. Hansen and C.S. Russell. 2004. Environmental labeling and consumers' choice—an empirical analysis of the effect of the Nordic Swan. *Journal of Environmental Economics and Management* 47(3):411-434.

Bongiorni, L., S. Shafir, and B. Rinkevich. 2003. Effects of particulate matter released by a fish farm (Eilat, Red Sea) on survival and growth of *Stylophora pistillata* coral nubbins. *Marine Pollution Bulletin* 46:1120-1124.

Boshra, H., J. Li, and J.O. Sunyer. 2006. Recent advances on the complement system of teleost fish. *Fish and Shellfish Immunology* 20:239-262.

Brennan, D. 2002. Pollution control options for Australian prawn farms. *Aquaculture Economics and Management* 6(5-6):325-338.

Bricknell, I. and R.A. Dalmo. 2005. The use of immunostimulants in fish larval aquaculture. *Fish and Shellfish Immunology* 19:457-472.

Carpenter, S.M. and J.F. Kitchell. 1988. Consumer control of lake productivity. *Bioscience* 38(11): 764-770.

Caviedes, C. and T.L. Fik. 1992. The Peru-Chile eastern Pacific fisheries and climatic oscillation. Pp. 355-376 in M.H. Glantz, ed., Climate Variability, *Climate Change, and Fisheries*. Cambridge University Press, London and New York

Charbonnier, D. and J.F. Caddy, eds. 1986. *Report of the Technical Consultation of the General Fisheries Council for the Mediterranean on the Methods of Evaluating Small-Scale Fisheries in the Western Mediterranean*, FAO Fish. Rep. No. 362. United Nations Food and Agricultural Organization, Rome.

Clayton, P.L. and D.V. Gordon. 1999. From Atlantic to Pacific: price links in the U.S. wild and farmed salmon market. *Aquaculture Economics and Management* 3(2):93-104.

Cloern, J.E. 1982. Does the benthos control phytoplankton biomass in South San Francisco Bay? *Marine Ecology Progress Series* 9(2):191-202.

Costanzo, S.D., M.J. O'Donohue, and W.C. Dennison. 2004. Assessing the influence and distribution of shrimp pond effluent in a tidal mangrove creek in north-east Australia. *Marine Pollution Bulletin* 48:514-525.

Costello, C. and C. McAusland. 2001. Protectionism, trade, and measures of damage from exotic species introductions. Bren School of Environmental Science and Management. University of California at Santa Barbara, CA.

Dame, R.F., J.D. Spurrier, and T.G. Wolaver. 1989. Carbon, nitrogen, and phosphorous processing by an intertidal oyster reef *Marine Ecology Progress Series* 54:249-256.

Dame R.F. and S.L. Libes. 1993. The role of bivalve filter feeder material fluxes in estuarine ecosystems. Pp. 245-249 in R.F. Dame, ed., *Bivalve Filter Feeders in Estuarine and Coastal Ecosystem Processes.* Springer-Verlag, Heidelberg.

Delgado, C.L, N. Wada, M.W. Rosegrant, S. Meijer, and M. Ahmed. 2003. Fish to 2020: *Supply and demand in changing global markets.* International Food Policy Research Institute, Washington, DC.

Doksroed, T. 1996. Short history of coastal zone planning in Norway, with emphasis on the municipality of Vega. Pp. 35-40 in *Reconciling Pressures on the Coastal Zone: Fisheries and Aquaculture.* Organisation for Economic Co-operation and Development, Paris.

Doroshov, S.I. 2000. The escape of cultured sturgeon and the interbreeding with wild stocks. Pp. 25-32 in *Proceedings of the Florida Sturgeon Culture Risk Assessment Workshop.*

Drakeford, B. and S. Pascoe. 2006. Substitutability of fishmeal in diets for salmon: an optimisation by simulation approach. *Proc. International Institute for Fisheries Economics and Trade.* Portsmouth, UK (August).

Dumas, C.F. and S. Horton. 2002. The potential impact of summer flounder (*Paralichthys dentatus*) aquaculture on regional flounder price. Aquaculture Economics and Management 6(1-2):39-54

Fast, A.W. and P. Menasveta. 2003. Mangrove forest recovery in Thailand. *World Aquaculture* 34(3):6-9.

Fletcher, A. 2005. "Consumers demand better seafood labeling." Food Navigator.com/Europe. 15 December 2005; last accessed 14 May 2006.

Folke C. and N. Kautsky. 1992. Aquaculture with its environment: prospects for sustainability. *Ocean and Coastal Management* 17:5-24.

Food and Agricultural Organization (FAO) 1995. *Code of Conduct for Responsible Fisheries.* FAO, Rome.

Food and Agricultural Organization (FAO). 2005a. *State of World Fisheries and Aquaculture – 2004.* FAO, Rome.

Food and Agricultural Organization (FAO). 2005b. *Guidelines for the Ecolabeling of Fish and Fishery Products from Marine Capture Fisheries.* FAO, Rome. ftp://ftp.fao.org/docrep/fao/008/a0116t/a0116t00.pdf

Food and Agriculture Organization (FAO). 2005c. FISHSTAT Plus: universal software for fishery statistical time series. Data and Statistics Unit, FOA Fisheries Department [as cited in Tacon 2005], Rome.

Forster, J. 1999. Halibut Farming: Its development and Likely Impact on the Market for Wild Alaska Halibut. Report to Alaska Department of Commerce and Economic Development. Juneau, AK.

Galbreath, P.F. and G.H. Thorgaard. 1995. Sexual maturation and fertility of diploid and tiploid Atlantic salmon x brown trout hybrids. *Aquaculture* 137(1-4):299-311.

Garant, D., I.A. Fleming, S. Einum, an dL. Bernatchez. 2003. Alternative male life-history tactics as potential vehicles for speeding introgression of farm salmon traits into wild populations. *Ecology Letters* 6(6):541-549.

Garcia, A.F. and J.P. Massam. 2005. Elimination of antibiotics in hatcheries while improving production levels by use of probiotics. *World Aquaculture* 36(1):57-60.

GESAMP (Joint Group of Experts on the Scientific Aspects of Marine Pollution). 1990. State of the Marine Environment. Reports and Studies No. 39. Joint Group of Experts on the Scientific Aspects of Marine Pollution. United Nations Environment Program.

GESAMP (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection [formerly Marine Pollution]). 2001. *Planning and Management for Sustainable Coastal Aquaculture Development*. Food and Agriculture Organization of the United Nations, Rome.

Gifford, S., H. Dunstan, W. O'Connor, and G.R. Macfarlane. 2005. Quantification of in situ nutrient and heavy metal remediation by a small pearl oyster (*Pinctada imbricate*) farm at Port Stephens, Australia. *Marine Pollution Bulletin* 50:417-422.

Globefish. 2005. Increasing interest in ecolabelling by European retail chains. http://www.globefish.org/index.php?id=2495&easysitestatid=1726553922. Last accessed 14 May 2006.

Goldburg, R.J., M.S. Elliot and R.L Naylor. 2001. Marine aquaculture in the United States: environmental impacts and policy options. Pew Oceans Commission, Arlington, VA.

Gozlan, R.E., S. St-Hilaire, S.W. Feist, P. Martin, and M.L. Kent. 2005. Biodiversity: disease threat to European fish. *Nature* 435(7045):1046.

Graeslund, S. and B.-E. Bengtsson. 2001. Chemicals and biological products used in south-east Asian shrimp farming, and their potential impact on the environment – a review. *Science of the Total Environment* 280(1-3):93-131.

Gustafson, L., S. Ellis, P. Merrill, T. Robinson, and D. MacPhee. 2005. Mortality rates predict apparent prevalence of infectious salmon anemia (ISA) at two infected salmon farms in Maine. *Bulletin of the European Association of Fish Pathologists* 25(5):212-220.

Haldrup, N., P. Mollgaard and C.K. Nielsen. 2005. Sequential versus simultaneous market delineation: The relevant antitrust market for salmon. Wkg. Pap. 23. Department of Economics, University of Aarhus, Aarhus, Denmark.

Hawkins, C.D. and J.B. Jones. 2002. Larval escape through abalone culture effluent systems: an analysis of the risk. *Journal of Shellfish Research* 21(2):805-809.

Heath, M.R. 2005. Changes in the structure and function of the North Sea fish food-web, 1973-2000. *ICES Journal of Marine Science* 62(6):1202.

Hickman, R.W. 1996. The fisheries-aquaculture relationship in New Zealand: is it competitive or complementary? Pp. 451-454 in D.A. Hancock, D.C. Smith, A. Grant and J.P. Buemer, eds., *Developing and Sustaining World Fisheries Resources: The State of Science and Management,* Commonwealth Scientific and Industrial Research Organisation, Brisbane, New Zealand.

Hites, R.A., J.A. Foran, D.O. Carpenter, M.C. Hamilton, B.A. Knuth, and S.J. Schwager. 2004. Global assessment of organic contaminants in farmed salmon. *Science* 203:226-229.

Hoagland, P., D. Jin and H.L. Kite-Powell. 2003. The optimal allocation of ocean space: aquaculture and wild harvest fisheries. *Marine Resource Economics* 18(2):129-147.

Horan, R.D., C. Perrings, F. Lupi and E.H. Bulte. 2002. Biological pollution prevention strategies under ignorance: the case of invasive species. *American Journal of Agricultural Economics* 84(5):1303-1310.

Howarth R., D. Anderson, J. Cloern, C. Elfring, C. Hopkinson, B. Lapointe, T. Malone, N. Marcus, K. McGlathery, A.N. Sharpley, and D. Walker. 2000. Nutrient pollution of coastal rivers, bays, and seas. *Issues in Ecology* 7:1-17.

Huang, C.-H. 1997. Aquaculture and the endogenous damage cost of water pollution: the case of Taiwan. *Aquaculture Economics and Management* 1(1-2):99-108.

International Aquafeed. 2005. Volume 8, Issue 4, pages 38-40.

International Council for the Exploration of the Sea (ICES). 2003. *Report of the ICES Advisory Committee on Fishery Management and Advisory Committee on Ecosystems*, 2004. ICES, Copenhagen.

Islam, M.S. 2005. Nitrogen and phosphorus budget in coastal and marine cage aquaculture and impacts of effluent loading on ecosystem: review and analysis towards model development. *Marine Pollution Bulletin* 50:48-61.

Íslandbanki (ISB). 2005. ISB Seafood Industry Report—South America. (December). ISB website at http://www2.isb.is/Docs/Pdf/ISB_Seafood_Report_S_America_Dec_2005.pdf

Jackson, C., N. Preston, and P.J. Thompson. 2004. Intake and sicharge nutrient loads at three intensive shrimp farms. *Aquaculture Research* 35(11):1053-1061.

Jaffrey, S.,S. *Pascoe, G. Taylor and U. Zabala*. 2000. Price Interactions between salmon and wild caught fish species on the Spanish market. *Aquaculture Economics and Management* 4(3-4):157-67

Jaffry, S., H. Pickering, Y. Ghulam, D. Whitmarsh and P. Wattage. 2004. Consumer choices for quality and sustainability labeled seafood products in the UK. *Food Policy* 29(3):215-228.

Jin, D., H.L. Kite-Powell, and P. Hoagland. 2005. Future growth of the U.S. aquaculture industry and associated environmental quality issues. *Proceedings of Socio-Economic Causes and Consequences of Future Environmental Changes Workshop*. Nov. 16, U.S. EPA, San Francisco, California.

Kam, L.E., P.S. Leung and A.C. Ostrowski. 2003. Economics of offshore aquaculture of Pacific threadfin (*Polydactylus sexfilis*) in Hawaii. *Aquaculture* 223:63-87.

Katz, L.S. 2005. The sustainability of reduction fisheries in light of a growing aquaculture industry. Marine Policy Center, Woods Hole Oceanographic Institution, Woods Hole, MA.

Krkosek, M., M.A. Lewis, and J.P. Volpe. 2005. Transmission dynamics of parasitic sea lice from farm to wild salmon. *Proceedings of the Royal Society of London, Series B: Biological Sciences* 272(1564):689-696.

Kristofersson, D., G.L. Shamshack and J.L. Anderson. 2006. The relationship between fisheries and farming. Proc. *International Institute for Fisheries Economics and Trade*. Portsmouth, UK.

LaMontagne, M.G., V. Astorga, A.E. Giblin, and I. Valiela. 2002. Denitrification and the stoichiometry of nutrient regeneration in Waquoit Bay, Massachusetts. *Estuaries* 25(2):272-281.

Le, T.X. and Y. Munekage. 2004. Residues of selected antibiotics in water and mud from shrimp ponds in mangrove areas in Vietnam. *Marine Pollution Bulleting* 49(11-12):922-929.

Lindahl, O., R. Hart, B. Hernroth, S. Kollberg, L.-O. Loo, L. Olrog, A.-S. Rehnstam-Holm, J. Svensson, S. Sevensson, and U. Syversen. 2005. Improving marine water quality by mussel farming: a profitable solution for Swedish society. *Ambio* 34(2):131-138.

Lipsey, R.G. and K. Lancaster. 1956. The general theory of second best. *Review of Economic Studies* 24(1):11-32.

MacDougall, N. A. (1999). The tradeoff between ecosystem services and location of production: The case of shrimp aquaculture in an Ecuadorian mangrove ecosystem. *DAI* 61(04A):1530.

Machias, A., I. Karakassis, M. Labropoulou, S. Somarakis, K.N. Papadopoulou, and C. Papaconstantinou. 2004. Changes in wild fish assemblages after the establishment of a fish farming zone in an oligotrophic marine ecosystem. *Estuarine, Coastal and Shelf Science* 60:771-779.

Marine Aquarium Council (MAC). No date. "MAC Certification - from reef to retail." http://www.aquariumcouncil.org/ subpage.asp?section=13. Last accessed 14 May 2006.

Marine Stewardship Council (MSC). No date. "MSC standards - Ps and Cs." http://www.msc.org/html/content_504.htm. Last accessed 14 May 2006.

Mathis, M.L. and P.B. Baker. 2002. Assurance bonds: a tool for managing environmental costs in aquaculture. *Aquaculture Economics and Management* 6(1-2):1-17.

McGinnity, P., P. Prodoehl, A. Ferguson, R. Hynes, N.O. Maoileidigh, N. Baker, D. Cotter, B. O'Hea, D. Cooke, G. Rogan, J. Taggart, and T. Cross. 2003. Fitness reduction and potential extinction of wild populations of Atlantic salmon, *Salmo salar*, as a result of interactions with excaped farm salmon. *Proceedings of the Royal Society of London, Series B: Biological Sciences* 270(1532):2443-2450.

McGinnity, P., P. Prodoeh, N.O. Maoileidigh, R. Hynes, D. Cotter, N. baker, B. O'Hea, and A. Ferguson. 2004. Differential lifetime success and performance of native and non-native Atlantic salmon examined under communal natural conditions. *Journal of Fish Biology* 65(Suppl. 1):173-187.

Melroy, B. 2002. Aquaculture [salmon culture statistics – 2001]. *Pacific Fishing* 23(3):33-43.

Metcalfe, N.B., S.K. Valdimarsson, and I.J. Morgan. 2003. The relative roles of domestication, rearing environment, prior residence and body size in deciding territorial contests between hatchery and wild juvenile salmon. *Journal of Applied Ecology* 40(3):535-544.

Mississippi State University. 2006. U.S. Aquaculture Production. http://www.msstate.edu/dept/crec/aquaprod.html.

Morton, A., R.D. Routledge, and R. Williams. 2005. Temporal patterns of sea louse infestation on wild Pacific salmon in relation to the fallowing of Atlantic salmon farms. *North American Journal of Fisheries Management* 25(3):811-821.

Nash, C.E. 2003. Interactions of Atlantic salmon in the Pacific Northwest. VI. A synopsis of the risk and uncertainty. *Fisheries Research (Amsterdam)* 62(3):339-347.

Nash, C.E. 2004. Achieving policy objectives to increase the value of the seafood industry in the United States: the technical feasibility and associated constraints. *Food Policy* 29:621-641.

Nash, C.E., .R. Burbridge, and J.K. Volkmann (editors). 2005. *Guidelines for ecological risk assessment of marine fish aquaculture.* U.S. Department of Commerce, NOAA Technical Memo NMFS-NWFSC-71.

Nash, C.E. and F.W. Waknitz. 2003. Interactions of Atlantic salmon in the Pacific Northwest. I. Salmon enhancement and the net-pen farming industry. *Fisheries Research (Amsterdam)* 62(3):237-254.

National Marine Fisheries Service (NOAA NMFS). 2005. *Fisheries of the United States 2004.* http://www.st.nmfs.gov/st1/fus/fus04/ index.html.

National Oceanic and Atmospheric Administration (NOAA). 2005. Seafood supply and U.S. trade. NOAA website at http://www.nmfs.noaa.gov/ocs/tradecommercial/documents/ustrade2004F.ppt

National Oceanic and Atmospheric Administration (NOAA). 2004. LME 13: Humboldt Current. Large Marine Ecosystems research website of the NOAA Fisheries Northeast Fisheries Science Center, Narragansett Laboratory. Accessible at <<http:/na.nefsc.noaa.gov/lme/text/ lme13.htm>>

National Research Council (NRC). 1994. *Priorities for Coastal Science*. National Academy Press, Washington, DC.

Naylor, R.L., R.J. Goldburg, J.H. Primavera, N. Kautsky, M.C.M. Beveridge, J. Clay, C. Folke, J. Lubchenco, H. Mooney and M. Troell. 2000. Effect of aquaculture on world fish supplies. *Nature* 405:1017-1024.

Naylor, R.L., K. Hindar, I.A. Fleming, R. Goldburg, S. Williams, J. Volpe, F. Whoriskey, J. Eagle, D. Kelso, and M. Mangel. 2005. Fugitive salmon: assessing the risks of escaped fish from net-pen aquaculture. *Bioscience* 55(5):427-37.

Neori, A., T. Chopin, M. Troell, A.H. Buschmann, G.P. Kraemer, C. Halling, M. Shpigel, and C. Yarish. 2004. Interated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. *Aquaculture* 231:361-391.

Neori, A., M.D. Kromb, S.P. Ellnerc, C.E. Boydd, D. Poppera, R. Rabinovitcha, P.J. Davisonb, O. Dvira, D. Zubera, M. Uckoa, D. Angela and H. Gordin. 1996. Seaweed biofilters as regulators of water quality in integrated fish-seaweed culture units. *Aquaculture* 141:183-199.

Newell, R.I.E. 1988. Ecological changes in Chesapeake Bay: Are they a result of overharvesting the American oyster, *Crassostrea virginica? In Understanding the Estuary: Advances in Chesapeake Bay Research.* Proceedings of a conference. Chesapeake Bay Research Consortium Baltimore, MD.

Newell, R.I.E., J.C. Cornwell, and M.S. Owens. 2002. Influence of simulated bivalve biodeposition and microphytobenthos on sediment nitrogen dynamics: A laboratory study. *Limnology and Oceanography,* 47(5), 2002, 1367–1379.

National Marine Fisheries Service (NOAA NMFS). 2005. *Fisheries of the United States 2004*. - http://www.st.nmfs.gov/st1/fus/ fus04/index.html.

Oakes, J.D. 1996. Assessment of the potential threat posed by escaped farmed Atlantic Salmon (*Salmo Salar*) on British Columbia's indigenous salmonid stocks and the economic feasibility of the use of all-female triploid Atlantic Salmon. MAI 35(5):1273.

Officer, C.B., T.J. Smayda, and R. Mann. 1982. Benthic filter feeding: a natural eutrophication control *Marine Ecology Progress Series* 9:203-210.

O'Hara, F. et al. 2003. *Economic Impact of Aquaculture in Maine*. Planning Decisions, Hallowell, ME.

Olivier, G. 2002. Disease interactions between wild and cultured fish – perspectives from the American northeast (Atlantic provinces). *Bulletin of the European Association of Fish Pathologists* 22(2):103-109.

Papatryphon, E., J. Petit, S.J. Kaushik, and H.M.G. van der Werf. 2004. Environmental impact assessment of salmonid feeds using life cycle assessment (LCA). *Ambio* 33(6):316-323.

Parry, I.W.H. 2005. Should fuel taxes be scrapped in favor of per-mile charges? RFF Discussion Paper 05-36 (August). Resources for the Future, Washington, DC.

Phuong, D.M. and C. Gopalakrishnan. 2004. Optimal management of water for sustainable fisheries and aquaculture. *Water Resources Development* 20(4):493-506.

Pimentel, D., L. Lach, R. Zuniga and D. Morrison. 2000. Environmental and economic costs of nonindigenous species in the United States. *BioScience* 50(1):53-65.

Pimentel, D., R. Zuniga and D. Morrison. 2005. Update on the environmental and economic costs associated with alien-invasive species in the United States. *Ecol. Econ.* 52:273-288

Posadas, B.C. and C.J. Bridger. 2003. Economic feasibility of offshore aquaculture in the Gulf of Mexico. Pages 307-317 in C.J. Bridger and B.A. Costa-Pierce, eds. *Open Ocean Aquaculture: From Research to Commercial Reality.* The World Aquaculture Society, Baton Rouge, LA.

Price, J. 2005. Review of spawning stock finds menhaden being managed to death. *Chesapeake Bay Journal* 15(3):22.

Primavera, J. 1997. Socio-economic impacts of shrimp culture. *Aquaculture Research* 28(10):815-827.

Rembold, C.M. 2004. The health benefits of eating salmon. *Science* 305:475.

Rice, M.A. 2000. A review of shellfish restoration as a tool for coastal water quality management. *Environment Cape Cod* 3(2):1-8.

Roberts, R.J. and M.D. Pearson. 2005. Clinical review: infectious pancreatic necrosis in Atlantic salmon, *Salmo salar L. Journal of Fish Diseases* 28(7):383-390.

Roheim, C.A. 2003. Early indications of market impacts from the Marine Stewardship Council's ecolabeling of seafood. *Marine Resource Economics* 18(1): 95-104.

Roheim, C.A., E. Gudmundsson, F. Asche and J-S Lee. 2003. Market information and fisheries management. NOAA/CMER Award No. #NA07FE0188. App. XVIII: Amendment 13 to the Northeast Multispecies Fishery Management Plan. New England Fishery Management Council, Newburyport, MA.

Saarni, K. et al. 2003. An overview of salmon trout aquaculture in Finland. *Aquaculture Economics and Management* 7(5-6):335-343.

Samocha, T.M., I.M. Lopez, E.R. Jones, S. Jackson, and A.L. Lawrence. 2004. Characterization of intake and effluent waters from intensive and semi-intensive shrimp farms in Texas. *Aquaculture Research* 35(4):321-339.

Sandweiss, D.H., K.A. Maasch, F. Chai, C. Andrus, and E.J. Reitz. 2004. Geoarchaeological evidence for multidecadal natural climatic variability and ancient Peruvian fisheries. *Quaternary Research* 61(3):330-334.

Smearman, S.C., G.E. D'Souza and V.J. Norton. 1997. External cost of aquaculture production in West Virginia. *Environmental and Resource Economics* 10(2):167-175.

Stanley, D.L. 2000. The economics of the adoption of BMPs: the case of mariculture water management. *Ecological Economics* 35: 145-155.

Steins, N.A. 1997. The "black box" in collective action research: incentives from outside the management system (a case study of an Irish aquaculture cooperative), Wkg. Pap. in Coastal Zone Mgmt. No. 22. Centre for Coastal Zone Management, University of Portsmouth, Portsmouth, UK.

Stephens, W.W. and J.L. Farris. 2004. Instream community assessment of aquaculture effluents. *Aquaculture* 231:149-162.

Stokesbury, M.J. and G.L. Lacroix. 1997. High incidence of hatchery origin Atlantic salmon in the smolt output of a Canadian river. In: Interactions between Salmon Culture and Wild Stocks of Atlantic Salmon: The Scientific and Management Issues. Proceedings of an ICES/NASCO Symposium held in Bath, England, April 1997. *ICES Journal of Marine Science* 54(6):1074-1081.

Sumaila, U.R., J. Volpe and Y. Liu. 2006. Potential economic benefits from sablefish farming in British Columbia. *Marine Policy* [available online].

Sutherland, R.M. 2001. Organic salmon production: a preliminary analysis of the economics. *Aquaculture Economics and Management* 5(3-4):191-210.

Sylvia, G., J.L. Anderson and D. Cai. 1996. A multilevel, multiobjective policy model: the case of marine aquaculture development. *American Journal of Agricultural Economics* 78(1):79-88.

Tacon, A.G.J. 2005. State of information on salmon aquaculture feed and the environment. Prepared for the WWF Salmon Aquaculture Dialogue. http://www.worldwildlife.org/cci/dialogues/salmon.cfm

Tacon, A.G.J. and I.P. Forster. 2003. Aquafeeds and the environment: policy implications. *Aquaculture* 226:181-189.

Teichert-Coddington, D.R., D. Martinez and E. Ramirez. 2000. Partial nutrient budgets for semi-intensive shrimp farms in Honduras. *Aquaculture* 190:139-154.

Teisla, MF, B. Roe and R.L. Hicks 2002. Can Eco-Labels Tune a Market? Evidence from Dolphin-Safe Labeling. *Journal of Environmental Economics and Management* 43(3):339-359.

Thacker, S.G. 1994. *The Economic Impact of Marine Aquaculture on Virginia's Eastern Shore.* Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA.

Tilman, D., G. Cassman Kenneth, A. Matson Pamela, R. Naylor, and S. Polasky. 2002. Agricultural sustainability and intensive production practices. *Nature* 418:671-677.

Troell, M., A. Neori, T. Chopin, and A.H. Buschmann. 2005. Biological wastewater treatment in aquaculture – more than just bacteria. *World Aquaculture* 36(1):27-29.

Tveteras, R. 2002a. Industrial agglomeration and production costs in Norwegian salmon aquaculture. *Marine Resource Economics* 17(1):1-22.

Tveteras, R. 2002b. Norwegian salmon aquaculture and sustainability: the relationship between environmental quality and industrial growth. *Marine Resource Economics* 17(2):121-132.

Tyedmers, P.H. 2000. Salmon and sustainability: the biophysical cost of producing salmon through the commercial salmon fishery and the intensive salmon aquaculture industry. Ph.D. dissertation, Resource Management and Environmental Studies, University of British Columbia.

Tyedmers, P.H., R. Watson, and D. Pauly. 2005. Fueling global fishing fleets. *Ambio* 34(8):635-638.

US Department of Commerce (USDOC). 1999. Aquaculture policy. U.S. Department of Commerce, Washington, DC.

US Environmental Protection Agency (USEPA). 2002. *Development Document for Proposed Effluent Limitations Guidelines and Standards for the Concentrated Aquatic Animal Production Industry Point Source Category.* EPA-821-R-02-016. Office of Water, USEPA, Washington, DC.

US Joint Subcommittee on Aquaculture. 2001. *Aquaculture Economics and Statistics Report.* http://aquanic.org/jsa/statistics/index.htm.

Valiela, I., G. Collins, J. Kremer, K. Lajtha, M. Geist, B. Seely, J. Brawley and C.H. Sham. 1997. Nitrogen loading from coastal watersheds to receiving estuaries: new method and application. *Ecological Applications* 7(2):358-380.

Valiela, I., M. Geist, J. McClelland and G. Tomasky. 1999. Nitrogen loading from watersheds to estuaries: verification of the Waquoit Bay nitrogen loading model. *Biogeochemistry* 49:277-293.

Washington Post. 2006. "A Fish Called Menhaden." Sunday, February 5, 2006, p. B-6.

Weir, L.K., J.A. Hutchings, I.A. Fleming, and S. Einum. 2005. Spawning behavious and success of mature male Atlantic salmon (*Salmo salar*) parr of farmed and wild origin. *Canadian Journal of Fisheries and Aquatic Sciences* 62(5):1153-1160.

Weir, L.K., J.A. Hutchings, I.A. Fleming, and E. Sigurd. 2004. Dominance relationships and behavioural correlates of individual spawning success in farmed and wild male Atlantic salmon, *Salmo salar*. 2004. *Journal of Animal Ecology* 73(6):1069-1079.

Wessells, C. R., R.J. Johnston and H. Donath. 1999. Assessing consumer preferences for ecolabeled seafood: the influence of species, certifier, and household attributes. *American Journal of Agricultural Economics* 81(5): 1084-1089.

Westport Scalloping Corporation (WSC). 1998. Sea scallop enhancement and sustainable harvesting: the Seastead Project, Final Rep. for NOAA Award No. NA66FD0027. Coonamessett Farm, North Falmouth, MA.

Wolk, A, S.C. Larsson, J.-E. Johansson, P. Ekman. 2006. Long-term fatty fish consumption and renal cell carcinoma incidence in women. *Journal of the American Medical Association* 296:1371-1376.

Young, J.A., C. Brugere and J.F. Muir. 1999. Green grow the fishes—oh? Environmental attributes in marketing aquaculture products. *Aquaculture Economics and Management* 3(1):7-17.

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