9 Energy Use in Fish and Aquacultural Production*

David Pimentel, Roland E. Shanks, and Jason C. Rylander

The oceans and other aquatic ecosystems are vital to the sustainability of all life on Earth. In particular, these aquatic systems provide food for humans and livestock. Overfishing and pollution of fresh and saltwater habitats threaten the continued productivity of aquatic systems.

Worldwide, approximately 95 million metric tons of seafood, including fish, crustaceans, and mollusks, are harvested annually (Figure 9.1). About 90% of all harvested fish are from the marine habitat and the remaining 10% from freshwater habitats. About 28 million tons of fish are fed to livestock, and humans consume an estimated 67 million tons (NOAA, 1991). Nonetheless, fish protein represents less than 5% of the total food protein (387 million tons) consumed annually by the world's human population and less than 1% of the overall caloric intake (FAO, 1991).

As with agricultural food production, harvesting fish requires significant quantities of fossil energy (Pimentel, 1980; Scott, 1982; Bardach, 1982, 1991; Billington, 1988; Mitchell and Cleveland, 1993). Because the United States already imports more than half of its oil at a cost of $120 billion/year and proven U.S. oil reserves are projected to be depleted in 20–30 years, this is an appropriate time to analyze the use of energy in fishery production and to determine which fishery systems are the most energy efficient. Energy shortages and high fuel prices likely will influence future fishery policies and the productive capacity of the industry (Samples, 1983; Mitchell and Cleveland, 1993).

The energy inputs, ecological effects, and relative efficiency of a variety of domestic and international fishery regimes are assessed in this chapter. Also included are effects of different types of vessels and gear on the overall efficiency and sustainability of various methods of catching fish.

ECOLOGICAL ASPECTS OF FISH PRODUCTION

Water covers more than 70% of the Earth, but only about 0.03% of the sunlight reaching an aquatic ecosystem is fixed by aquatic plants, primarily phytoplankton (Odum, 1978). This equates to about 4 million kcal/ha/year or about one-third the energy fixed in terrestrial habitats (Pimentel et al., 1978).

* This chapter appeared in the *Journal of Agricultural and Environmental Ethics*, 9(2), pp. 144–164, 1996.

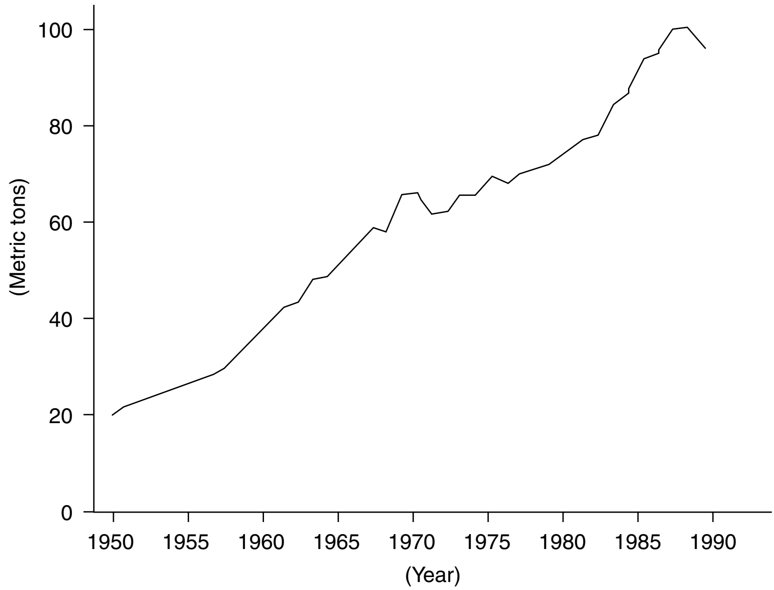

FIGURE 9.1 World fish catch in metric tons per year. (From World Resources Institute, *World Resources 1992–1993*, New York, Oxford University Press, 1992. With permission.)

The phytoplankton that collect light energy in oceans and freshwater are eaten by zooplankton. The light energy passes through four to six links in the food chain before humans harvest it as fish. Energy is dissipated at each link in the food chain, and the final quantity available to humans is much less than that available at the phytoplankton level.

Assuming that each year the ocean ecosystem collects 4 million kcal/ha of light energy and that there are on average four links in the food chain, humans would harvest about 400 kcal/ha/year as fish. Measured in dressed weight of fish, this amounts to only 0.15 kg/ha of harvested fish per year.

If the 115 kg of meat consumed per person per year in the United States were to be supplied by fish from the oceans, and assuming a yield of 0.15 kg/ha of dressed weight (cleaned fish), each person would require nearly 2000 ha of ocean area. Oceans could supply enough fish to meet the needs of only 1.2 billion people. This estimate assumes that the entire fish yield is suitable for human food and that 40% of the catch is edible when cleaned and dressed. Humans actually eat only a few species of fish themselves but feed other fishery products to livestock. Because so many square kilometers of ocean have to be searched for fish, any attempt to increase fish production would be difficult. The farther a vessel must travel from the port, the more energy-intensive the fishing operation.

Overall ecological fishery management will have to be improved, coastal pollution problems solved, and fertilizer nutrient contamination from onshore sources limited if the sea is to remain a viable source of human and livestock food in the future (Bell, 1978; NOAA, 1991).

ENERGY EFFICIENCY OF FISHERY PRODUCTION

The U.S. ocean fishery industry was ranked fifth in the world in 1991 (producing 4.4 million metric tons per year); the former USSR was ranked first (NOAA, 1991). The Alaskan region is the largest U.S. producer, contributing about 56% of the total production by weight; the Gulf of Mexico region is the next largest, providing about 17% of the total (Table 9.1).

Energy expenditures for fishing vary, depending on the distance traveled to harvest and the type of fishing gear used. For example, fishing vessels from Washington state, located relatively near the Alaskan region, use significantly less fuel than do their Japanese counterparts. Wiviott and Mathews (1975) reported that the Washington trawl fleet produced 61.5 kg of fish per liter of fuel, compared with the Japanese production of only 11.4 kg of fish per liter of fuel. They attribute the difference to the fact that the Japanese frequently have to travel long distances for fishing.

Other fishing situations produce different quantities of fish per liter of fuel expended (Table 9.2). For example, Norwegian coastal net fishers produced 13.3 kg

TABLE 9.1
The Total Amounts of Fishery Production in Different Regions of the United States

Region	Thousand Tons	Percentage
Alaska	2450	56
Pacific Coast and Hawaii	300	7
Great Lakes	20	<1
New England	300	7
Mid-Atlantic	90	2
Chesapeake Bay	390	9
South Atlantic	120	3
Gulf	730	17
Total	4400	100

Source: National Oceanic and Atmospheric Administration (NOAA), *Fisheries of the United States 1990*. Washington, D.C., U.S. Government Printing Office, 1991.

TABLE 9.2
Fish Production per Liter of Fuel

Fishing Technology	Fish (kg)
Coastal fishing net and longling (northern Norway)	13.3
Longline (Continental Shelf)	7.0
Factory vessels (United States)	3.4

Source: Bardach, J., in *Handbook of Energy Utilization in Agriculture*. Boca Raton, FL, CRC Press, 1982, 431–440.

of fish per liter of fuel (Bardach, 1982). However, using large factory vessels, they produced only 3.4 kg of fish per liter of fuel. But the Norwegian yield/fuel figure only refers to catching fish, whereas the factory-vessel yield/fuel figure includes both catching and processing.

Another problem in comparing figures for fish produced per liter of fuel is the condition of the fish when weighed. The Norway figure, for example, indicates the weight of fish before processing, but the figure reported for the factory vessel was not qualified and could indicate fish either before or after processing. These issues point to some major problems in assessing the productivity and energy efficiency of the fishery industry. Certainly, the energy inputs for various fisheries differ according to the method of fishing, the type of gear used, the type of vessel used, the level of processing on the vessel, and the geographic region (Schaffer et al., 1989).

ENERGY EFFICIENCY OF OCEAN FISHERIES

Harvesting ocean fish requires ships and diverse types of gear used to search for, capture, and transport the fish. Both the construction and operation of this equipment consumes energy. Although fishing vessels also require human power, this energy input is not large, especially on today's new, heavily mechanized fishing vessels.

The energy input in several different fishing systems is examined below, with detailed analysis of the fishery in the northeastern United States.

NORTHEAST U.S. FISHERY

The location of large fish populations along the continental shelf off the northeastern United States has made this one of the world's most productive fishery regions. Like all food production systems, this fishery cannot operate without energy investments in the form of equipment, fuel, and labor.

Two types of fishing take place in this region: (1) inshore pelagic fishing, which utilizes vessels weighing less than 110 gross registered tons (GRT); and (2) offshore fishing, which employs vessels weighing more than 110 GRT. For the inshore pelagic fishery, an input of only 1.03 kcal of fossil fuel is expended to harvest 1 kcal of fish protein (Rochereau and Pimentel, 1978). Offshore fishery requires an input of 3.9 kcal of fossil energy per kcal of fish protein harvested. Thus, small fishing units are nearly four times more efficient than the larger vessels that travel great distances. The inshore fishery's greater efficiency also is due in part to the more productive fish populations of the inshore region. The inshore fish are mainly zooplankton-eating species, and they are about one-third more efficient than the offshore fishes in storing energy per weight of useable biomass (Rochereau and Pimentel, 1978). The offshore fish are primarily carnivorous and are higher up in the food chain than inshore species.

If unused fish are removed from the reported fish yields, the overall efficiency of the Northeast fishery decreases. The average input/output ratio is 4.1 kcal of fossil energy per kcal of fish protein output (Rochereau and Pimentel, 1978). The inshore fishery expends about 2.2 kcal of fossil energy per kcal of fish protein produced, whereas the offshore fishery requires 9.6 kcal of energy per kcal of fish protein output (Rochereau and Pimentel, 1978).

The U.S. Northeast fishery is relatively efficient by comparison with other fishery systems. For the U.S. fishery industry as a whole, Hirst (1974) reported, about 27 kcal of fossil energy input are required to harvest 1 kcal of fish protein. Leach (1976) reported about 20 kcal of fossil energy input per kcal of fish protein output in the United Kingdom, and Edwardson (1975) reported that steel trawlers operating from Scotland use about 21 kcal of energy per kcal of fish protein harvested. However, Edwardson also reported that the wooden vessels used for inshore fishing require only 2.1 kcal fossil energy input per kcal of fish protein output. This agrees favorably with the 2.2 kcal fossil energy input for the inshore U.S. fishery (Rochereau and Pimentel, 1978).

A major reason for the high efficiency of the Northeast fishing system is that about 93% of the fishing fleet comprises vessels weighing less than 5 GRT (Doeringer et al., 1986). The advantage of using small fishing vessels is illustrated by the following example. Assume an annual yield for the Northeast fishery of 7.6×10^{11} kcal of fish protein and an overall regional fishing capacity of 7 GRT, which is typical of the Northeast fleet. If a fleet of 300-GRT vessels were used instead of the usual small vessels, the input/output ratio would rise from the present 4.1 to about 6.7 kcal fossil energy input per kcal of fish protein harvested (Rochereau and Pimentel, 1978). This represents a 63% decline in energy efficiency. All fishing vessels require energy for construction, maintenance, fuel, and onboard processing.

Overall efficiency declines as the size of the fishing vessel increases because a nonlinear relationship exists between vessel size and gross energy requirements (Rochereau and Pimentel, 1978). For example, 22 vessels of 15 GRT have the same capacity as one 330-GRT vessel; yet the smaller vessels are 44% more energy efficient in obtaining the same fish yield. In general, larger vessels travel farther to fish and use more energy than smaller vessels. For all vessel types, the energy inputs for operating the vessel are the largest of the three energy inputs (construction/maintenance, fuel, and operations). In smaller vessels (7–15 GRT), operating needs significantly dominate energy inputs, whereas in larger vessels the energy expended in construction becomes a major input.

U.S. government policies continue to support the trend toward using larger vessels in the rich Northeast fishery grounds (McGoodwin, 1990; Satchell, 1992), even though such vessels are far less efficient than smaller ones in fossil energy use. Surely this is a questionable policy in view of rising fossil fuel prices and unemployment in the fishing industry (McGoodwin, 1990; Bardach, 1991).

The energy efficiency of the Northeast fishing fleet has been declining steadily since the early 1960s, a decline attributed both to the upsurge of international fishing competition on the Northeast fishing grounds (Bell and Hazleton, 1967; Gulland, 1971, 1974) and to the decline in fish stocks in this fishery region (Smith, 1991). Mitchell and Cleveland (1993) document this in their analysis of the New Bedford, Massachusetts, fisheries (Figure 9.2). For instance, in 1966 the ratio of fossil energy to fish protein kcal was 5:1, whereas by 1989 the ratio had dramatically increased to 35:1.

The development of new integrated fishing technologies (i.e., stern-trawling hydraulic systems and electronic detection systems) has increased fishing efficiency but not the energy efficiency of the vessel (Captiva, 1968; DeFever, 1968; FAO, 1972a; Gulland, 1974; Margetts, 1974). From 1960 to 1964, both the total GRT and the total gross energy expenditures for the Northeast fishery increased (Rochereau

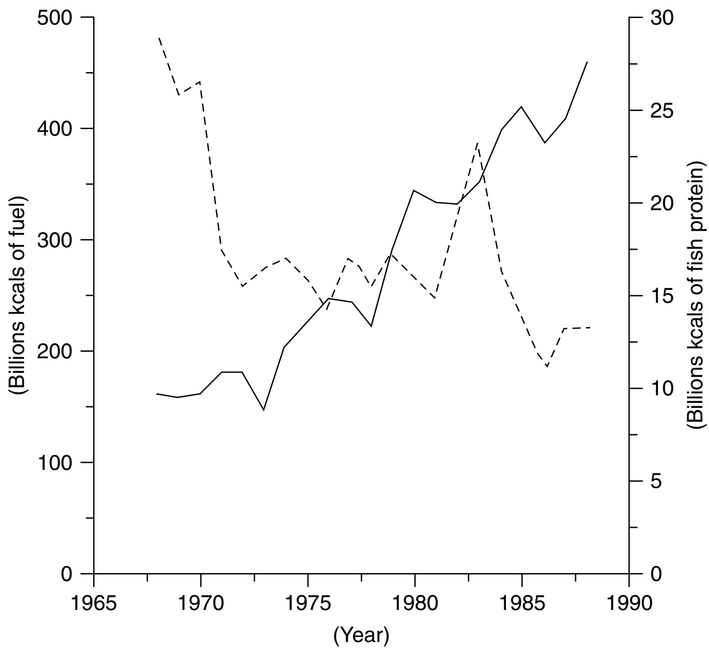

FIGURE 9.2 The total kcal of fish protein caught by the New Bedford, Massachusetts, fleet based on the total amount of fuel used. Fish protein (---) and fuel (——). (From Mitchell, C. and Cleveland, C.J., *Environmental Management*, 17, 305–317, 1993. With permission.)

and Pimentel, 1978). Since 1964 total gross energy expenditures have remained relatively steady, but total GRT has declined sharply. The constancy in total gross energy requirements reflects the replacement of numerous smaller vessels with fewer larger vessels that require more energy both to construct and to operate. Therefore, increasing energy inputs and increasing vessel size have caused deterioration in the energy efficiency of the Northeast fishery industry.

Another major factor contributing to the deterioration of the Northeast fishery is the continued overfishing of the coastal water zone. That is, the yearly harvests are well above the area's maximum sustainable yield level (NOAA, 1992). Of the 49 fishery stocks monitored in the Northeast, 27 have been identified as overexploited (Table 9.3). Large harvests continue because the fishing system in this region is overcapitalized and requires a high level of exploitation to remain profitable (Bell and Hazleton, 1967; Henry, 1971; Gulland, 1971; FAO, 1972b; USDC, 1974). Many scientists believe there is no extra biological stock available to act as a buffer against heavy overfishing (WRI, 1992; NOAA, 1992).

As early as the period from 1967 to 1974, the decline in fish protein production and the increase in fossil energy input reduced the investment return of a typical 50-GRT trawler (Rochereau, 1976). Based on the annual operating cost, which reflects the level of seasonal activity, an inverse relationship exists between the return on the investment and the intensity of fishing in the Northeast (Bell and Hazleton, 1967). That is, as the amount of fishing increases, the return in money

TABLE 9.3
The Exploitation and Status of Monitored Fishery Stocks in the U.S. Northeast

Exploitation Status	Number of Stocks
Overexploited	27
Fully exploited	9
Underexploited	10
Variable exploitation	2
Protected (closed to exploitation)	10

Source: National Oceanic and Atmospheric Administration (NOAA), *Status of Fishery Resources off the Northeastern United States for 1992*. Technical Memorandum NMFS-F/NEC–95. Washington, D.C., U.S. Department of Commerce, 1992.

decreases (Bardach, 1991). Indeed, the Northeast fishery system appears to be approaching the point where the value of the catch will cover only the operating costs; some operations will run in the red. This is beginning to happen, as evidenced by return-on-investment indices. In 1973 the return-on-investment index was more than five times lower than in 1968 for a similar level of effort (Rochereau, 1976). The combined effects of overfishing, rising operating costs, and variable earnings account for the economic instability and the gradual deterioration of the Northeast fishing industry.

U.S. Fishery

Rawitscher and Mayer (1977) analyzed energy inputs for several types of seafood and estimated that from 2 to 192 kcal of energy were expended per kcal of fish protein produced (Table 9.4). As previously stated, the average for all fish produced for the U.S. market was about 27 kcal of fossil energy per kcal of fish protein produced (Hirst, 1974).

The most efficiently harvested fish is herring, with only 2 kcal of fossil energy expended to produce 1 kcal of herring protein (Table 9.4). A common fish such as haddock requires an input of 23 kcal of fossil energy per protein kcal produced. Lobster requires the largest input—192 kcal of fossil energy per kcal of protein produced. This high energy cost is not surprising considering the relative scarcity of lobsters and the extensive fishing effort that goes into harvesting these animals.

Peru

The anchovy fishing grounds off Peru are one of the most productive fisheries in the world (WRI, 1992). Anchovies are consumed fresh, canned, and as fish meal. In particular, Europe and the United States import large amounts of anchovy fish meal for use in poultry and other livestock production systems.

TABLE 9.4
Energy Input for Production of Various Fish Species in the United States

Seafood Type	Fossil Energy Input/Protein Output (kcal)
Herring	2:1
Perch, ocean	4:1
Salmon, pink	8:1
Cod	20:1
Tuna	20:1
Haddock	23:1
Halibut	23:1
Salmon, king	40:1
Shrimp	150:1
Lobster	192:1

Source: Calculated from Rawitscher, M. and Mayer, J., *Science* 198, 261–264, 1977. With permission.

Leach (1976) gathered data on anchovy and fish meal production in Peru and reported that about 2 kcal of fossil fuel are expended to produce 1 kcal of fish protein. This input is nearly twice the 1.03 kcal of fossil energy needed to produce a kcal of inshore fish protein in the Northeast fishery (Rochereau and Pimentel, 1978). In addition, Leach did not include energy inputs for construction of the vessels, equipment, and fishing gear. As the data from the Northeast fishery system indicate, these inputs are substantial and often represent about half of the total energy used in the system (Rochereau and Pimentel, 1978). If these additional energy costs were included in the Peruvian fish production data, the inshore Northeast fishery would be as much as six times more efficient than Peruvian anchovy fishing.

Gulf of Mexico and Australia

In comparison with herring, haddock, and anchovies, the production of shrimp in the Gulf of Mexico requires large inputs of energy—about 206 kcal of fossil energy per kcal of shrimp protein produced (Leach, 1976). This ratio is higher than the U.S. average of 150 kcal energy input per kcal of shrimp protein produced (Table 9.4).

Although producing shrimp in the Gulf of Mexico is energy intensive, the investment is profitable at present. Shrimp is considered an extremely choice seafood, and the dollar return is currently high enough to offset the cost of energy expended and other production costs. However, shrimp imported from Asian and South American aquaculture is putting severe economic pressure on the U.S. wild shrimp industry (Coastwatch, 1990; Matherne, 1990).

In the Australian wild shrimp industry, only 22 kcal of fossil energy input are expended to produce 1 kcal of shrimp protein (Leach, 1976). This is significantly less than the U.S. average of 150 kcal and the Gulf of Mexico average of 206 kcal fossil energy input per kcal of shrimp protein harvested.

Malta

The Malta fishing industry reported an input of 25 kcal of fossil energy per kcal of fish protein produced (Leach, 1976). This input/output ratio of 25:1 is similar to the 27:1 reported for the U.S. fishery and the 20:1 for the U.K. fishery (Hirst, 1974; Leach, 1976).

Adriatic

Fish production in the Adriatic region is energy intensive. When small vessels capable of harvesting 50 tons of fish per year were used, the average energy input was about 68 kcal of energy per kcal of fish protein produced (Leach, 1976). However, when large vessels capable of harvesting 150 tons of fish per year were used, the average energy input increased to about 100 kcal of energy per kcal of protein produced.

MARINE FISHERIES AND THE ENVIRONMENT

Serious overfishing of the common species already is a serious problem in many parts of the world, and increased pressure on all kinds of fish populations appears to be the worldwide trend (Satchell, 1992; Worldwatch Institute, 1992). Additional threats to fishery sustainability include: coastal development; loss of coastal wetlands; pollution of bays and estuaries; and bycatch (unintended catch) (Worldwatch Institute, 1992). Consider that almost 50% of the U.S. population now lives within 50 miles of the coastline (Satchell, 1992). Urban development along the coast has infringed on piscatorial breeding grounds and caused massive changes in coastal ecology. For example, Louisiana loses 50 square miles of fish breeding ground each year to development, and only 9% remains of California's original 3.5 million acres of wetlands (Satchell, 1992). Although some attempt has been made to protect U.S. wetlands, nearly half of them have been drained and used for agricultural or urban development (Satchell, 1992).

All nations, including the United States, have sought ways to protect their fisheries from foreign exploitation. In 1976 the United States asserted an exclusive claim to the sea's resources within 200 miles of the coast (Sullivan, 1981). The Magnuson Fisheries Conservation and Management Act of 1976 marked the dawning of a new era in fisheries management and eventually decreased the foreign fish catch. Currently, less than 1% of the fish landed from U.S. waters are caught under foreign flags (Park, 2005).

The Magnuson Act created regional committees to implement management programs. Further, it required that fisheries be managed for optimum sustainable yield (OSY), a new concept that is difficult to define. OSY is intended to combine social, economic, ecological, and biological factors into one standard—an extremely difficult task, to say the least (Weber, 1987).

Along with these legal steps has come the use of larger and more modern ships. Concurrently, the number of harbor facilities, processing plants, and fish-handling systems also has increased. Overcapitalization and overcapacity now plague the U.S. fishery industry (Satchell, 1992).

The 1982 Law of the Sea Convention represented the culmination of a series of unilateral declarations of sovereignty over the oceans in the post–World War II era. However, the United States has never signed this agreement. Although some nations were more concerned about oil and mineral rights than fishing, protection of fish from foreign exploitation was a major concern for many nations.

Management of Fishery Systems

Worldwide, small-scale fishing employs about 100 million people, either directly or in supporting industries (McGoodwin, 1990). Large-scale fishing, by contrast, employs only about 500,000 people. The economic contribution of small-scale fishing is increasing (McGoodwin, 1990; Bardach, 1991).

Small-scale fishing is more effective in other ways. For example, its capital cost per job averages 100 times less than that of large-scale fishing (McGoodwin, 1990; Bardach, 1991). It is less likely to be overcapitalized, which is the major problem with many large-scale fisheries today. Small-scale fishing consumes only about 11% of the fuel oil used in commercial fishing, but it produces nearly five times as much fish per unit of fuel oil consumed as the large-scale fishing sector (McGoodwin, 1990; Bardach, 1991).

Most experts agree that the best way to halt overfishing and save the troubled fisheries is to ban all fishing in overexploited areas for 5–10 years. This step has been taken with the cod fishery in Newfoundland, Canada, which recently shut down for 2 years (Worldwatch Institute, 1993). Concurrently, all those who depend on the fishery for their livelihood were placed on welfare (Worldwatch Institute, 1993). This approach works for individual nations' fisheries, but it is doubtful that such a ban would prove effective globally.

The Newfoundland approach is drastic, but the situation is critical. Most fishery management policies have two components: conservation (determining the level of harvest that will ensure the sustainability of the fishery) and allocation (determining who fishes). McGoodwin (1990) identifies seven basic management strategies to achieve sustainability. These include: (1) closing overfished areas for a period of years, as in Newfoundland, to allow the fish populations to come back; (2) establishing closed seasons within each year; (3) establishing aggregate quotas or total allowable catch; (4) restricting gear and technology; (5) using monetary measures such as taxes and subsidies to control fishing; (6) limiting entry in the fishery area; and (7) instituting various forms of property rights over the fishery area.

Gear restrictions and seasonal closings are the traditional methods used to manage fisheries. Many economists dislike these policies because they claim it creates economic inefficiency. However, in certain regions this approach has reduced overfishing and helped maintain the long-term productivity of the fishery (Anderson, 1985). For example, gear restrictions forced New England clam diggers to work only with hand rakes and to harvest only clams above a certain size (Townsend, 1985, 1990; Koppleman and Davies, 1987). As a result, more clam diggers are employed and, more important, the clam population has not been overexploited in New England. These strategies may not be effective in pelagic fisheries unless the number of people fishing in the area is limited as well.

One of the most effective ways to prevent overfishing is to limit access to the fishery. The four major strategies for this are (1) licensing, which limits the number of fishing boats or fishers per area; (2) allocation of quotas by auction to fishers; (3) implementing restrictive taxes or fees that indirectly limit fishing; and (4) establishing a system of catching rights (McGoodwin, 1990; Townsend, 1990; Waters, 1991). A combination of gear restrictions and limited entry has the greatest potential for maintaining the viability of the fishery industry.

With attention and action devoted to preserving the sustainability of fish production, increased quantities of fish could become available for human consumption at decreased energy expense. Certainly, inaction will leave the world fishery in a condition as critical as that now plaguing Newfoundland. Perhaps by more effectively using unexploited fish, implementing sound management of fish populations based on the knowledge of their population ecology, and reducing pollution, the world harvest of fishery products could be improved. However, if the global population doubles in about 47 years, as expected, the percentage of world food calories provided by fish will decline below the present level of less than 1%.

AQUACULTURE

Aquaculture is the farming of fish, shellfish, and other aquatic animals for food (Bardach, 1980). In many regions of the United States, commercial catfish aquaculture is practiced. Catfish is an excellent eating fish, and its popularity has spread throughout the United States.

The largest energy input in catfish aquaculture is the feed. Westoby and Kase (1974) and Mack (1971) reported that catfish required 5.9 tons/ha of feed over the 1.5 years it took them to reach the marketable weight of 0.5 kg per fish. The annual catfish yield was 2783 kg/ha (Table 9.5). The total annual fossil energy input for the

TABLE 9.5
Energy Inputs for Commercial Catfish Production in 1 ha Ponds in Louisiana

	Quantity/ha	kcal/ha
Inputs		
Labor	120 h	63,250
Equipment	9,500,000 kcal	9,500,000
Pumping	1667 kWh	4,343,250
Fertilizer and other chemicals	3.3 kg	60,000
Feed	5925 kg	39,000,000
Total		52,500,500
Outputs		
Catfish yield	2783 kg	
Protein yield[a]	384 kg	1,536,000
Input/Output ratio		34.2:1

[a] Assuming a dressed weight of 60% and 23% protein content.

Source: After Westoby, M. and Kase, R.T., Catfish farming and its economic feasibility in New York state. Unpublished manuscript, Ithaca, NY, 1974; Mack, J., *Catfish Farming Handbook*, San Angelo, TX, Educator Books, 1971. With permission.

production of catfish feed is estimated to be 39 million kcal. The other major energy input for this system is 9.5 million kcal/ha/year for production and maintenance of equipment. An additional 4.3 million kcal is expended to pump and circulate the water in the 1-ha pond. The pumping and circulation of water is necessary to remove wastes and protect the fish from diseases, which are a problem when fish are raised in dense populations. A significant environmental problem is the treatment of the wastewater from catfish production. The U.S. Environmental Protection Agency recently adopted new regulations dealing with wastewater from aquacultural systems, and this will increase the cost of production.

Producing the yield of about 2783 kg/ha/year of catfish requires an input of 52.5 million kcal of fossil energy. Assuming that dressed weight equals 60% of total weight and that protein equals 23% of dressed weight, the total production of catfish protein is 384 kg/ha, equivalent to 1.5 million kcal of food energy. Thus, the input/output ratio is about 34 kcal of fossil energy input per kcal of catfish protein produced. This ratio is identical to that of another U.S. catfish production system (Pimentel et al., 1975) and that of U.S. beef production (Pimentel et al., 1980).

Although catfish are cold-blooded and use no energy in heating their bodies, they are not particularly efficient in converting feed into protein. They are much less efficient than chickens but more efficient than hogs, shrimp, and lobster (Figure 9.3).

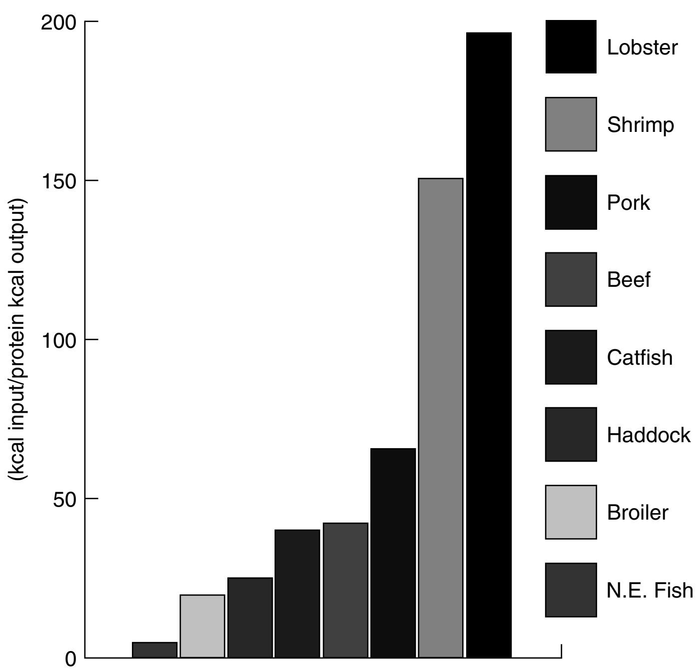

FIGURE 9.3 Fossil energy inputs per protein output for various fisheries and several livestock systems.

TABLE 9.6
Farm Production of Malaysian Prawn (*Macrobrachium rosenbergi*) on Oahu, Hawaii

Item	Amount	kcal
Inputs, fixed		
Pond construction	3.5 ha of land	
Tractor grader	27.5 days/year	1,922,291
Pipes	350 m 6 in. pipe 125 psi	36,120
Cement flumes	120 ft^2 (8 flumes)	238,286
Wooden building	2000 ft^2	217,143
Labor	122 days/year	—
Inputs, annual operating		
Water	130 L/ha/min	—
Labor; manual/miscellaneous	72 days/year	—
Machinery use		
Running maintenance	—	—
Harvesting (50-HP tractor)	91 days/year on 3.5 ha	10,102,698
Materials		
Net	4-cm mesh, 135- × 2-m nylon	7,000
Fertilizer		
Sodium nitrate	14 kg/ha	17,250
Triplesuperphosphate	5 kg/ha	9000
Feed (chicken mash)	4500 kg/ha	9,000,000
Larva for planting (seed)	50,000 larva/ton of production	19,333
Total inputs		21,569,092
Output		
Live Malaysian prawns[a]	3000 kg/ha	3,240,000
kcal input/g protein output		328.3:1
kcal input/kcal output		66.6:1
kcal output/labor hour		129.6:1

[a] Edible portion about 45%; caloric content 720 kcal/kg; protein content in prawn flesh 14.6% (65.7 kg protein from 450 kg of prawn that is edible in 1 metric ton).

Source: Bardach, J., in *Handbook of Energy Utilization in Agriculture*, Boca Raton, FL, CRC Press, 1980, 431–440.

In addition to the catfish system described in detail above, five other aquaculture systems have been analyzed. The first is Malaysian prawn production on Oahu, Hawaii. The fossil energy input per kcal of protein output for this system was about 67:1, or nearly twice that for catfish (Tables 9.5 and 9.6). Prawns, however, have a much higher market value than catfish, and this makes the prawn system profitable.

Oysters were produced through aquaculture on Oahu, Hawaii (Table 9.7). The energy input/output ratio for this system was 89:1, or about one-third higher than that for shrimp production (Table 9.6). The major U.S. oyster-producing regions include Virginia, Maryland, New York, and Connecticut.

TABLE 9.7
Annual Oyster Production on Land in Oahu, Hawaii

Item	Amount	kcal
Water area under production	0.45 ha	
Inputs, fixed		
Farm construction	2,884,436	
Machinery (tractor, grader, dredger)	5 days	
Labor	26 days	72,200
Pipes and cement flumes	3 level, 30 m^3, 1000 m, 6 in. and 4 in. PVC	34,700,000
Plastic trays for oysters	3400 kg	129,956
Inputs, operating		
Seed oysters	—	—
Labor	1095 days	—
Electricity, water pumping	10,000 kWh/month	343,560,000
Fertilizer		
Triplesuperphosphate	5 kg/day/ha	7,391,250
sodium nitrate	20 kg/day/ha	109,500,000
Total inputs		498,237,842
Output		
Oysters[a] (*Grassostrea gigas*)	13,636 kg/ha	5,583,760
kcal input/kcal output		89.2:1
kcal input/g protein output		766.5
kcal output/labor hour		619.9

[a] Edible weight (flesh) 45%; 910 kcal/kg oyster flesh; protein content 10.6%.

Source: Bardach, J., in *Handbook of Energy Utilization in Agriculture*, Boca Raton, FL, CRC Press, 1980, 431–440.

An aquaculture system for lake perch production in Wisconsin proved to be highly energy intensive, with an energy input/output ratio of 189:1 (Table 9.8). It is doubtful that this system will prove economically feasible unless ways are found to reduce energy costs. However, it may become more economical if the fish are raised for sport fishing, because sport fish might have a relatively high market value.

In contrast to U.S. perch production, fish polyculture in Israel has proven to be energy efficient (Table 9.9). Producing an array of species, including the common carp, silver carp, tilapia, and mullet, the polyculture system had an energy input/output ratio of 10:1, making it one of the most efficient aquaculture systems for which data are available. The energy advantage of polyculture is mainly due to its fish-herbivore component—that is, having fish types that feed directly on the plants in the system.

The energetics of an aquacultural system for sea bass and shrimp in Thailand was calculated from data presented by Pillay (1990) and Shang (1992), respectively. The energy input/output ratios for these high-value fishery systems were about 65:1

TABLE 9.8
Experimental Production of Lake Perch (*Perca flavescens*) in Wisconsin

Item	Amount	kcal
Inputs, fixed		
Land	2.08 ha (0.2 ha/ton)	—
Containment structures		
Machinery 50 HP	15.3 days	596,277
Pipes, conduits	1200 m 4 in. PVC, 125 psi	765,217
Buildings	Estimated	1,200,000
Water	3400 m^3/ton	—
Labor	16 days	—
Inputs, operating		
Labor		
Maintenance	250 days	—
Operation	1095 days/year	—
Harvest (for farm)	95 days	—
Nets, pails, etc.	30 × 1 m seine, about 20 kg; dip nets (for farm), 10/20; 1 plastic pail	
Stocking material (fingerlings)	50 kg/ha	4,634,200
Fertilizer	200 kg/ha	3440
Medication	5 kg/ha	350,000
Feed (40% protein dry pellets)	1750 kg/ton of fish	5,250,000
Direct energy inputs	2862-L fuel oil	32,666,868
Pumping	20,190 kWh	57,803,970
Total inputs		103,280,922
Output		
Lake (yellow perch)[a]	per ton	546,000
Protein (19.3%)	115.8 kg protein/ton	891.9
kcal input/kcal output		189.2:1
kcal output/labor hour		181.4

[a] Edible portion 60%; 910 kcal/kg.
Source: Bardach, J., in *Handbook of Energy Utilization in Agriculture*, Boca Raton, FL, CRC Press, 1980, 431–440.

and 70:1, respectively (Tables 9.10 and 9.11). These values are significantly higher than that of the Israeli fish polyculture system and the Louisiana catfish operation (Tables 9.5, 9.9 through 9.11).

In contrast to pond-type aquaculture, marine aquaculture has been tried along the coasts of Norway and Sweden. Atlantic salmon, mass produced in cages, are fed pellets made from fish by-products. These fish pellets represent the consolidation of solar energy fixed by phytoplankton from a sea surface estimated to be 40,000–50,000 times larger than the area of the cages housing the salmon (Folke and Kautsky, 1989, 1992). Low-value fish living over vast areas of the sea are harvested and

TABLE 9.9
Pond Polyculture in Israel

Item	Amount	kcal
Inputs, fixed		
Pond construction	Moving 3000 m^3 of soil	610,000
Pond inlet (steel pipe)	100 m, 20 cm diameter (4100 kg)	2,150,000
Pond outlet		
Asbestos-cement pipe	20 m, 35 cm diameter (35 kg)	3500
Cement base (Monk)	40 kg	3000
Machinery (used on 100 ha for 10 years)	Jeep, tractors, etc., tank cars (22,800 kg of steel)	705,200
Nets (used on 100 ha for 5 years)	200 kg nylon	16,000
Inputs, operating		
Labor	27 days/year	
Machinery operation	Fuel for jeeps, trucks, tractors, aerators, pumping	21,744,000
Fertilizer		
Liquid ammonia	600 L (494 kg N_2)	7,200,000
Superphosphate	600 kg	1,800,000
Herbicide	About 2 kg	99,000
Feed		
Sorghum	4.14 tons	9,108,000
Pellets (25% crude protein)	3.38 tons	6,216,000
Seed production	Prorated from grow-out figs	15,000
Total Inputs		49,670,000
Output		
Production total	4150 kg	4,772,500
Common carp	65.5%	
Silver carp	15.7%	
Tilapia	15.1%	
Mullet	3.7%	
kcal input/kcal output		10.4:1
kcal input/g protein output (unprocessed)		64.7

Source: Bardach, J., in *Handbook of Energy Utilization in Agriculture*, Boca Raton, FL, CRC Press, 1980, 431–440.

concentrated into pellets to feed the high-value caged salmon. This system requires about 50 kcal of fossil energy per kcal of fish protein produced (Folke and Kautsky, 1989, 1992), a figure that compares extremely well with the energy expenditures of other aquacultural systems.

Norway produces more than 40 tons of salmon each year (Folke and Kautsky, 1992). This highly productive system has many economic advantages, but it creates two major environmental problems. The caged Atlantic salmon are not as fit

TABLE 9.10
Energy Inputs and Outputs for Sea Bass Production in Thailand

	Quantity/ha	10^3 kcal/ha
Inputs		
Labor	80 h	47.4
Ponds and operation	50×10^6 kcal	50,000
Fuel and lubrication	1890 L	18,900
Feed	35,000 kg	231,000
Total		299,947.4
Outputs		
Sea bass yield	14,000 kg	—
Protein yield	1848 kg	4,600
kcal input/kcal output		65.2:1

Source: Calculated from data presented in Pillay, T.V.R., *Aquaculture Principles and Practices*, Oxford, UK, Fishing New Books, 1990. With permission.

TABLE 9.11
The Energy Inputs in Shrimp Production in Thailand

	Quantity/ha	kcal/ha
Inputs[a]		
Labor	70 h	41,475
Electricity and fuel	31,000,000 kcal	31,000,000
Seed	250 kg	125,000
Feed	6000 kg	24,000,000
Maintenance	14,000,000 kcal	14,000,000
Total		69,500,000
Outputs		
Shrimp yield	2135 kg	
Protein yield	427 kg	1,067,500
kcal input/kcal output		69.5:1

[a] The inputs were calculated from the economic data of Shang Y.C., in *Marine Shrimp Culture: Principles and Practices*, Amsterdam, Elsevier, 1992, 589–604.

for survival in the open sea as the wild Atlantic salmon, and escaped caged salmon sometimes mate with wild salmon, with a negative impact on the overall population. In addition, the heavy concentration of caged salmon along the Norway coast pollutes some of the fjords with fish wastes (T. Edland, personal communication, Ås, Norway, 1992).

CONCLUSION

The Northeast fishery system is generally economical both in terms of energy inputs and dollar returns. By contrast, fishery production systems in the northeastern United States and Gulf of Mexico, such as the lobster and shrimp fisheries, are expensive and require extremely high energy inputs. At present the high market value of these species makes them profitable despite the high costs of harvesting, but these costs make it impractical to treat such fish as a common and abundant food source. Some fish production systems, particularly those in some coastal regions, compare favorably to livestock production systems in terms of energy inputs and efficiency, but others require more energy inputs per kcal of protein produced than livestock systems do.

Small-scale fishing systems are generally more energy efficient than large-scale systems. Especially for developing countries, small-scale fishery systems provide a number of benefits, including increased employment and low fuel costs. Large-scale vessels are inefficient, usually requiring government subsidies for their operation (McGoodwin, 1990). In addition, the high costs of large vessels contribute to overcapitalization and overfishing of fishery resources.

Policymakers have at their disposal a wide range of management techniques to improve fishery production in the future. Gear and season restrictions and limited-access regimes seem to have the greatest potential to protect the biotic stability of the world's fisheries, upon which the future of fish as a food source depends. Long-term sustainability must be the first priority of fishery managers and policymakers.

In the near future, overfishing is more likely to cause fish scarcity than fossil fuel shortages and high energy prices. The causes and seriousness of overfishing and poor management are known. However, at the international and national levels, needed priorities have not been established to deal with the problems. Studies should focus on the breeding habits, population dynamics, and optimal yields of major fish species as well as the effects of pollution on fish habitats to help ensure the sustainability of the major fishery regions. Finding ways to protect wetlands, estuaries, and other aquatic areas will help maintain healthy ecosystems for fish populations.

Concurrently, policymakers need to identify the most efficient type of vessel for each specific region, to encourage development of more energy-effective technologies, and to control harvests. Developing techniques to make effective use of currently unexploited fish will increase the total food harvested from aquatic systems.

However, even if fish production is improved, the rapid growth of the human population will tend to negate the contribution of increased yields. In all probability, the world's fishery industry will not be able to supply more than 1% of the world's food energy in the future. It should be emphasized that fish provide high-quality protein, and thus this 1% is extremely valuable to society.

REFERENCES

Anderson, L.G. 1985. Potential economic benefits from gear restrictions and license limitation in fisheries regulation. *Land Economics* 61: 409–418.

Bardach, J. 1980. Aquaculture. In D. Pimentel (ed.), *Handbook of Energy Utilization in Agriculture*, pp. 431–440. Boca Raton, FL: CRC Press.

Bardach., J. 1982. Oil, fish, and the sun and the wind. In R.C. May, I.R. Smith, and D.B. Thomson (eds.), *Appropriate Technology for Alternative Energy Sources in Fisheries*, pp. 1–6. Manila: International Center for Living Aquatic Resources Management.

Bardach., J. 1991. Sustainable development of fisheries. In International Ocean Institute (ed.), *Ocean Yearbook 9*, pp. 57–72. Chicago, IL: University of Chicago Press.

Bell, F.W. 1978. *Food from the Sea: The Economics and Politics of Ocean Fisheries*. Boulder, CO: Westview Press.

Bell, F.W. and J.E. Hazleton. 1967. *Recent Developments and Research in Fisheries Economics*. New York: Oceana Publications.

Billington, G. 1988. Fuel use control in the fishing industry. In S.G. Fox and J. Huntington (eds.), *World Symposium on Fishing gear and Fishing Vessel Design*, pp. 112–115. St. John's, Canada: Marine Institute.

Captiva, F.J. 1968. Modern U.S. shrimp vessels design, construction, current trends and future developments. In G. DeWitt (ed.), *The Future of the Fishing Industry of the United States*, pp. 141–148. Seattle, WA: University of Washington, Publications in Fisheries, New Series.

Coastwatch. 1990. Shrimping: a fishery in trouble? *Coastwatch* 10: 1–2.

Defever, A. 1968. Modern U.S. tuna vessel construction, design and future trends. In G. DeWitt (ed.), *The Future of the Fishing Industry of the United States*, pp. 134–140. Seattle, WA: University of Washington, Publications in Fisheries, New Series.

Doeringer, P.B., P.I. Moss, and D.G. Terkla. 1986. *The New England Fishing Economy: Jobs, Income, and Kinship*. Amherst, MA: University of Massachusetts Press.

Edwardson, W. 1975. *Energy Analysis and the Fishing Industry*. A Report of the Energy Analysis Unit. Glasgow: University of Strathclyde.

Folke, C. and N. Kautsky. 1989. The role of ecosystems for a sustainable development aquaculture. *Ambio* 18: 234–243.

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

Food and Agriculture Organization (FAO). 1972a. *FAO Catalogue of Fishing Gear Designs*. London: Fishing News (Books) Ltd.

Food and Agriculture Organization (FAO). 1972b. *Atlas of the Living Resources of the Seas*. Rome: Food and Agriculture Organization of the United Nations, Department of Fisheries.

Food and Agriculture Organization (FAO). 1991. *Food Balance Sheets*. Rome: Food and Agriculture Organization of the United Nations.

Gulland, J.A. 1971. *The Fish Resources of the Ocean*. London: Fishing News (Books) Ltd. (for FAO of UN).

Gulland, J.A. 1974. *The Management of Marine Fisheries*. Seattle, WA: University of Washington Press.

Henry, K.A. 1971. *Atlantic Menhaden (Brevoortia tyrannus) Resource and Fishery—Analysis of Decline*. Technical Report, Seattle, WA: National Marine Fisheries Service.

Hirst, E. 1974. Food-related energy requirements. *Science* 184: 134–139.

Koppleman, L.E. and D.S. Davies. 1987. *Strategies and Recommendations for Revitalizing the Hard Clam Fisheries in Suffolk County*. Hauppauge, NY: Suffolk County Planning Department.

Leach, G. 1976. *Energy and Food Production*. Guildford, Surrey, UK: IPC Science and Technology Press Ltd.

Mack, J. 1971. *Catfish Farming Handbook*. San Angelo, TX: Educator Books.

Margetts, A.R. 1974. Modern development of fishing gear. In F.R.H. Jones (ed.), *Sea Fisheries Research*, pp. 243–260. New York: John Wiley & Sons.

Matherne, R. 1990. *Testimony of Concerned Shrimpers of America*. Washington, D.C.: Fisheries and Wildlife Conservation and the Environment Subcommittee of the House of Representative Merchant Marine and Fisheries Committee, U.S. Congress. May 1, 1990.

McGoodwin, J.R. 1990. *Crisis in the World's Fisheries*. Stanford, CA: Stanford University Press.

Mitchell, C. and C.J. Cleveland. 1993. Resource scarcity, energy use and environmental impact: A case study of the New Bedford, Massachusetts, USA, fisheries. *Environmental Management* 17: 305–317.

National Oceanic and Atmospheric Administration (NOAA). 1991. *Fisheries of the United States 1990*. Washington, D.C.: U.S. Government Printing Office.

National Oceanic and Atmospheric Administration (NOAA). 1992. *Status of Fishery Resources off the Northeastern United States for 1992*. Technical Memorandum NMFS-F/NEC–95. Washington, D.C.: U.S. Department of Commerce.

Odum, E.P. 1978. *Fundamentals of Ecology*. New York: Saunders.

Park, J.W. 2005. *Surimi and Surimi Seafood*. Boca Raton, FL: CRC Press.

Pillay, T.V.R. 1990. *Aquaculture Principles and Practices*. Oxford, UK: Fishing New Books.

Pimentel, D. (ed.). 1980. *Handbook of Energy Utilization in Agriculture*. Boca Raton, FL: CRC Press.

Pimentel, D., W. Dritchillo, J. Krummel, et al. 1975. Energy and land constraints in food-protein production. *Science* 190: 754–761.

Pimentel, D., D. Nafus, W. Vergara, et al. 1978. Biological solar energy conversion and U.S. energy policy. *BioScience* 28: 376–382.

Pimentel, D., P.A. Oltenacu, M.C. Nesheim, et al. 1980. The potential for grass-fed livestock: Resource constraints. *Science* 207: 843–848.

Rawitscher, M. and J. Mayer. 1977. Nutritional outputs and energy inputs in seafoods. *Science* 198: 261–264.

Rochereau, S. 1976. Energy analysis and coastal shelf resource management; Nuclear power generation vs. seafood protein production in the Northeast region of the U.S. Ph.D. thesis. Cornell University, Ithaca, NY.

Rochereau, S. and D. Pimentel. 1978. Energy tradeoffs between Northeast fishery production and coastal power reactors. *Journal of Energy* 3: 545–589.

Samples, K.C. 1983. An economic appraisal of sail-assisted commercial fishing vessels in Hawaiian waters. *Marine Fisheries Review* 45: 50–55.

Satchell, M. 1992. The rape of the oceans. *U.S. News and World Report* (June 22): 64–75.

Schaffer, H.C., L.E. Barger, and H.E. Kumpf. 1989. The driftnet fishery in the Fort Pierce–Port Salerno area off southeast Florida. *Marine Fisheries Review* 51: 44–49.

Scott, W.G. 1982. Energy and fish harvesting. In *Proceedings of the Fishing Industry Energy Conservation Conference*, pp. 1–34. New York: Society of Naval Architects and Marine Engineers.

Shang, Y.C. 1992. Penaeid markets and economics. In A.W. Fast and L.J. Lester (eds.), *Marine Shrimp Culture: Principles and Practices*, pp. 589–604. Amsterdam: Elsevier.

Smith, J.W. 1991. The Atlantic and Gulf menhaden purse seine fisheries: Origins, forecasting. *Marine Fisheries Review* 53(4): 20–41.

Sullivan, K. 1981. Overfishing and the new Law of the Sea. *OECD Observer* 129 (July 1991): 16–19.

Townsend, R.E. 1985. An economic evaluation of restricted entry in Maine's soft shell clam industry. *North American Journal of Fisheries Management* 5: 57–64.

Townsend, R.E. 1990. Entry restrictions in the fishery: A survey of the evidence. *Land Economics* 66: 359–378.

U.S. Department of Commerce (USDC). 1974. *Basic Economic Indicators: Atlantic and Pacific Groundfish*. U.S. Department of Commerce, National Atmospheric and Oceanic Administration, National Marine Fisheries Service, Current Fish. Stat. No. 6271.

Waters, J.R. 1991. Restricted access methods of management: Toward more effective regulation of fishing effort. *Marine Review* 53: 1–10.

Weber, M. 1987. Federal marine fisheries management. In R. DiSilvestri (ed.), *Audubon Wildlife Report 1987*, pp. 131–145. San Diego, CA: Academic Press.

Westoby, M. and R.T. Kase. 1974. Catfish farming and its economic feasibility in New York state. Unpublished manuscript, Ithaca, NY.

Wiviott, D.J. and S.B. Mathews. 1975. Energy efficiency comparison between the Washington and Japanese otter trawl fisheries of the Northeast Pacific. *Marine Fisheries Review* 37(4): 21–24.

Worldwatch Institute. 1992. *State of the World 1992*. Washington, D.C.: Worldwatch Institute.

Worldwatch Institute. 1993. *State of the World 1993*. Washington, D.C.: Worldwatch Institute.

World Resources Institute (WRI). 1992. *World Resources 1992–1993*. New York: Oxford University Press.