Fisheries and Energy Use

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Glossary

active fishing gear Equipment used for fishing in which the aquatic organisms being targeted encounter the gear primarily through movement of the gear itself. Examples include cast nets, dredges, harpoons, jigs, and all forms of seine and trawl fishing.

animate energy Energy dissipated through the application of human or animal muscles to do work.

artisanal fisheries Small-scale fisheries that are typically executed by members of fishing households (as opposed to commercial companies) in which relatively small amounts of capital and energy and relatively small, if any, fishing vessels are employed.

culturally mediated energy All forms of energy dissipated through the application of technologies in the process of human activities.

energy intensity The amount of culturally mediated energy required to provide a given quantity of a product or service of interest. In the current context, energy intensity is expressed either as the total joules of energy required to land a live weight or "round" tonne of fish or shellfish harvested, or in terms of fuel use intensity, the total liters of fuel burned directly on fishing vessels per tonne of fish or shellfish landed.

energy return on investment (EROI) ratio A dimensionless ratio calculated by dividing the amount of useful energy provided by a given activity by the culturally mediated energy dissipated in providing it. In the case of food production systems, a common energy output used to calculate the EROI is the edible protein energy yield from the system being evaluated.

fishing Any activity that results in the catching, collecting, or harvesting of fish, and or aquatic invertebrates for any purpose other than scientific research. In the current context, the harvesting of aquatic plants and mammals is not considered as fishing, nor is aquaculture.

industrial fisheries Those fisheries typically undertaken by commercial companies in which relatively large quantities of capital and energy are deployed.

net primary productivity (NPP) The difference between the total amount of carbon taken up by plants via photosynthesis and the amount of carbon lost by living plants via respiration.

passive fishing gear Equipment used for fishing in which the aquatic organisms being targeted encounter the gear primarily through their own movement or as a result of the movement of the surrounding waters. Examples include all forms of hook and line gears, drift nets, gillnets, traps, and weirs.

Fishing is one of the most ancient and widespread of human endeavors. Contemporary fisheries harvest an enormous variety of aquatic organisms from virtually every aquatic environment on the planet using a diverse array of technologies. Reflecting the diversity of global fisheries, culturally mediated energy inputs also vary widely in both form and magnitude. At one extreme, traditional artisanal fisheries typically rely on relatively small inputs of exogenous energy, mostly in the form of wind, and animate energy to propel vessels and haul nets. Indeed, among subsistence fisheries in which animate energy inputs predominate, the nutritional value of the catch must routinely exceed the energy expended by the human muscles engaged in the fishery if it is to remain viable. Although such traditional, low-input fisheries persist in many parts of the world, high-input, industrialized fisheries now account for the majority of global landings. Among these fisheries, particularly those targeting high-value species, it is now common for direct fossil fuel energy inputs alone to exceed the nutritional energy embodied in the catch by at least an order of magnitude.

1. INTRODUCTION

As with all human activities, fishing entails the dissipation of energy in support of its primary activity, the harvesting of aquatic organisms. While the energetic cost of fishing is less obvious, and consequently receives much less attention than the direct impact that fishing has on targeted stocks and associated marine ecosystems, it is precisely the availability of abundant energy, in particular fossil energy, that enables many contemporary fisheries to continue even when stocks are in decline. Consequently, analyses of the forms and quantities of energy dissipated in fisheries, and in particular changes in energy use over time, can provide a powerful measure of the biophysical scarcity of exploited populations.

2. OVERVIEW OF GLOBAL FISHERIES

2.1 Scope and Extent

Data compiled by the Food and Agriculture Organization (FAO) of the United Nations indicate that, globally, approximately 90 million tonnes of fish and shellfish, representing more than 130 genera and 750 species, are harvested from the wild each year (Fig. 1). Although in excess of 200 countries report landings of fish and shellfish, the top 10 fishing nations account for over half of the total (Fig. 2). Similarly, while fishing is conducted in virtually every aquatic environment on the planet, over 90% of global landings are derived from marine waters, with most of this coming from highly productive coastal shelf and upwelling ecosystems.

2.2 Importance of Fisheries

One of the oldest forms of food production, fishing currently provides two-thirds of the fish and shellfish consumed by people worldwide, with aquaculture accounting for the balance. As a result, fishing directly contributes approximately 10% of the total animal protein intake by humans. In addition, although wild-caught food fish tend to contain less fat than terrestrial animals, the chemical composition of marine-sourced lipids is of significant nutritional importance. In particular, many species of wild-caught fish are relatively rich sources of Omega-3, or n-3, fatty acids, compounds that are believed to substantially decrease the risk of heart disease, inflammatory processes, and certain cancers.

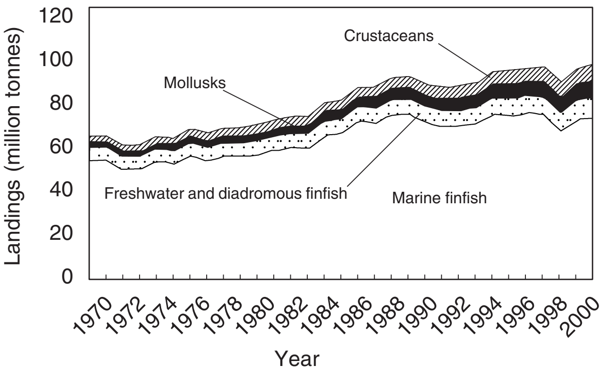

FIGURE 1 Global capture fisheries landings: 1970–2000. Data from FAO statistical database Fishstat+.

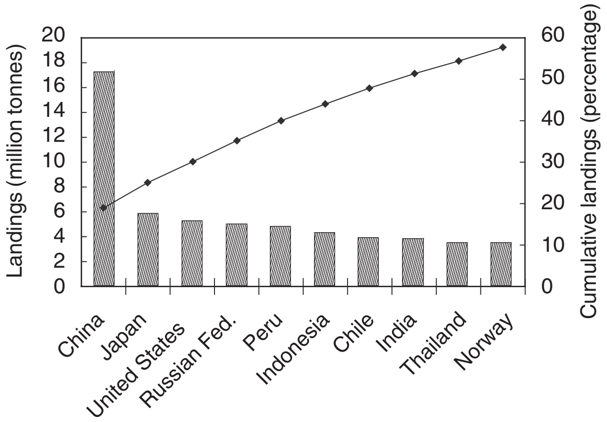

FIGURE 2 Absolute and cumulative fisheries landings by the top 10 fishing nations in 1998. Data from FAO (2000).

It is important to note, however, the role of fish in human diets varies widely among countries and regions (Fig. 3). This variation not only reflects differences in resource availability and cultural preferences with respect to the seafood consumption but also, to a certain extent, development status. Of the 30 countries whose citizens are most dependent on fish as a source of protein, over 80% are less developed countries.

Of the approximately one-third of global landings not consumed directly as human food, the vast majority is destined for reduction to fish meal and oil. Currently, both of these reduction coproducts are directed overwhelmingly to livestock and aquaculture feeds, with smaller volumes of fish oil being consumed directly by people, either as edible oil products or nutritional supplements. Traditionally, however, fish oils have also been used in a wide

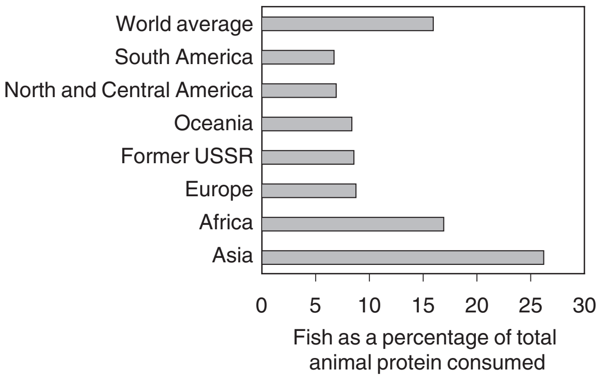

FIGURE 3 Importance of fish and shellfish from all sources to human diets.

range of industrial applications or burned as a source of fuel and illumination. While representing relatively small total landings, other nonfood fisheries are conducted to provide an array of high-value medicinal, decorative, and luxury products including shark cartilage, pearls, and live fish for the aquarium trade.

Reflecting their scale and diversity, it is not surprising that fisheries can play an important role in national and regional economies. Globally, the FAO estimates that as of the late 1990s, fisheries directly employed approximately 25 million people and yielded products whose first sale value exceeded $80US billion annually. The socioeconomic impact of fisheries is most pronounced, however, in many less industrialized countries and rural coastal communities throughout the world, where alternative employment opportunities are often limited.

2.3 Fishing Technologies

Based on archaeological evidence from central Africa, humans have been using dedicated fishing technologies, in this early instance a fishing spear, for at least 90,000 years. As the scope and range of fisheries has expanded over the intervening millennia, so too has the diversity of methods used to harvest fish and shellfish. While it is impractical here to explore the immense range of fishing techniques used around the world, a few broad generalizations are useful: fisheries in which some form of fishing vessel is used account for the vast majority of global landings, and most of the world's catch is taken using active fishing gears, particularly trawling and purse seining techniques in which large nets are respectively either towed behind fishing vessels or used to encircle schools of fish.

3. ENERGY INPUTS TO FISHERIES

Energy flows have been used to evaluate the performance of food production systems for over a hundred years. However, it was not until the first oil price shock of 1973 and the resulting concern regarding the dependency of industrialized food production systems on fossil fuels that systematic analyses were undertaken. One of the first major products of this period of research was Gerald Leach's handbook "Energy and Food Production" published in 1976. While it dealt primarily with agricultural systems, it included, for the first time, data on the major culturally mediated energy inputs to six fisheries from four continents. Since then, a small number of researchers in various parts of the world have continued to evaluate the energetics of fisheries from a variety of perspectives.

From an energetic perspective, fishing is a process in which a variety of culturally mediated forms of energy are dissipated in order to capture edible chemical energy embodied in the carcasses of fish and shellfish. The ultimate source of both the chemical energy embodied in the harvested organisms and most forms of culturally mediated energy is the sun. Consequently, the amount of solar energy required to sustain global landings and fishing activities is enormous. However, to date very few fishery-specific energy analyses have systematically attempted to account for solar energy inputs. As a result, other than a brief discussion of the ecosystem support associated with growing the biomass of animals harvested by global fisheries, solar energy inputs are not a focus of this review. Instead, this work deals primarily with the major forms and quantities of culturally mediated energy inputs to fishing.

3.1 Ecosystem Support of Fisheries

While not a direct measure of the solar energy flux underpinning fish and shellfish harvests, estimates have been made of the scale of ecosystem support appropriated by global fisheries. Typically, this is done by estimating the fraction of global aquatic net primary productivity (NPP)—or the amount of carbon fixed by plants via photosynthesis minus that lost through respiration—required to sustain the mass of fish and shellfish harvested. In 1995, Daniel Pauly and Villy Christensen, fisheries scientists currently based at the University of British Columbia, provided the most robust analysis of this measure to date. Their work indicates that as of the mid-1990s, global fisheries landings and discards appropriated approximately 8% of the total NPP available in the world's aquatic ecosystems. More striking, however, were their findings regarding those highly productive freshwater and near-shore marine ecosystems that sustain nearly 85% of total fisheries landings yet spatially represent less than 10% of the planet's total aquatic environment. Within the context of these most productive aquatic ecosystems, fisheries alone appropriate between 24 and 35% of the NPP available.

3.2 Forms of Direct Energy Inputs

Culturally mediated energy inputs to fishing activities can be categorized into direct and indirect types. Common indirect inputs, often referred to as embodied energy inputs, are those associated with building and maintaining fishing vessels and providing fishing gear, bait, and ice. In contrast, in most fisheries, direct energy inputs are typically those required to propel fishing vessels and deploy fishing gears. The three dominant forms of energy dissipated to these ends include animate, wind, and fossil fuel energy, each of which are briefly described next.

3.2.1 Animate Energy

Animate energy is the one form of culturally mediated energy common to all of the world's fisheries regardless of their technological sophistication. In many traditional artisanal fisheries, human muscles still provide the bulk of the energy used to deploy gears, handle the catch, and, where they are employed, propel vessels. However, while animate energy inputs may represent the dominant form of energy applied in a fishery, in absolute terms, the quantities involved are typically small. For example, among subsistence fisheries in which animate energy inputs predominate, the nutritional value of the catch must routinely exceed the energy expended by the human muscles engaged in the fishery if it is to remain viable. In the case of most contemporary fisheries, however, while human animate energy inputs remain part of the production equation, they are generally dwarfed by the inputs of wind or fossil fuel energy.

Unlike preindustrial agriculture wherein a wide variety of animals were domesticated to provide important secondary sources of animate energy, relatively few fisheries have systematically employed animals. Examples, however, include the traditional use of trained fishing cormorants in parts of China and Japan and the now largely outmoded European practice of using otters and diving ducks to drive fish into traps.

3.2.2 Wind

For as long as people have sailed, it is likely that wind energy has been used to support fishing activities. The integration of wind energy into fisheries not only allowed fishing vessels to be propelled farther and faster than would otherwise be possible, it facilitated the development of fishing techniques that would otherwise have been impractical, if not impossible, to conduct from a rowed boat. Specifically, various trawl or dragger fisheries in which nets or dredges are towed either through the water or along the seafloor were almost all first developed within the context of sail fisheries.

Although little if any research has been conducted to quantify the wind energy inputs to sail-assisted fisheries, prior to the introduction of fossil fuels, it likely accounted for a large proportion of the culturally mediated energy inputs to global fisheries.

3.2.3 Fossil Fuels

As with most other food production sectors, fossil fuels have become the dominant form of energy used in fishing in a relatively short period of time. The process began in England in the late 1800s, when coal-fired steam engines were first installed on trawl fishing vessels to provide power for both propulsion and net hauling. With the advantages of increased speed and power, together with the ability to operate regardless of the wind, steam trawling expanded rapidly. Although coal- and oil-fired steam engines remained in use on fishing vessels throughout much of the 20th century, their significance was ultimately eclipsed by internal combustion engines.

Gasoline- and diesel-fueled internal combustion engines were first adapted for use on fishing boats in the early 1900s. Technological advances made during and after the Second World War, however, greatly accelerated their integration into fisheries. Consequently, over the past 50 years not only has the size of the global fishing fleet increased but so has its power. The trend to larger, more powerful fishing vessels is exemplified by the emergence of so-called supertrawlers, vessels that can exceed 100 m in length with propulsive engines well in excess of 10,000 horsepower. At the same time, more and more relatively small engines are introduced annually into small-scale fisheries around the world. Given these twin trends of increasing prevalence and size of engines, it is not surprising that the bulk of the world's catch is now harvested using vessels propelled by fossil fuels.

3.3 The Relative Importance of Direct and Indirect Energy Inputs

Among modern industrial fisheries in which the major direct and indirect culturally mediated energy inputs have been systematically analyzed using either process analysis or input-output techniques, a consistent pattern has emerged. Direct fuel energy inputs typically account for between 75 and 90% of the total culturally mediated energy inputs, regardless of the fishing gear used or the species targeted (Fig. 4). Depending on the character of the fishery and the scope of the analysis conducted, the remaining 10 to 25% is generally composed of energy inputs associated with vessel construction and maintenance, and the provision of labor, fishing gear, bait, and ice if used.

On most fishing vessels, direct fuel inputs are used primarily for vessel propulsion. In some fisheries, however, secondary energy-consuming activities, including onboard processing, refrigeration, and freezing, can account for a nontrivial portion of the fuel burned. Squid jig fisheries are interesting and fairly extreme examples of fisheries in which a relatively large proportion of fuel inputs are used for activities other than vessel propulsion. In these fisheries, vessels typically employ batteries of high-intensity lamps, automated jigging machines, and freezers, all powered by diesel-fuelled generators to attract, hook, and preserve the catch while at sea. As a result, these nonpropulsion energy demands can, in combination, account for a much as 40% of the total fuel burned (Fig. 5).

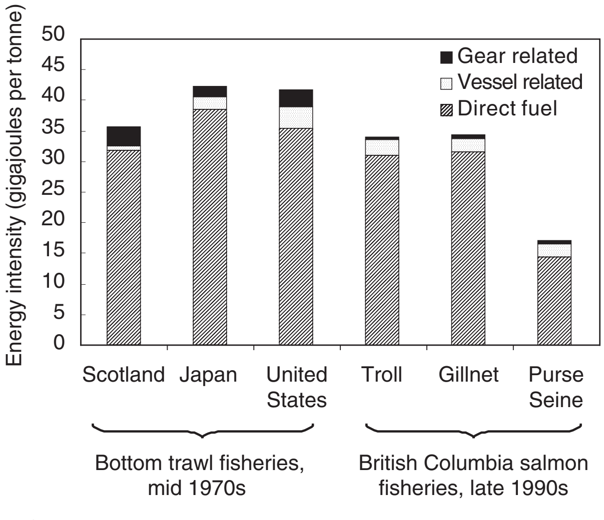

FIGURE 4 Relative contribution of direct and indirect energy to various fisheries. Data sources: Scotland: Edwardson, W. (1976). The energy cost of fishing. *Fishing News Intl.* **15**(2), p. 36–39. Japan: Watanabe and Uchida (1984); United States: Rawitscher (1978); British Columbia salmon fisheries: Tyedmers (2000).

Among indirect energy inputs, those associated with building and maintaining the fishing vessels themselves regularly account for the largest fraction (Fig. 4). This is particularly the case when a vessel's major components (i.e., its hull, superstructure, decks, and holds) are fabricated primarily from relatively energy-intensive materials such as aluminum and steel as opposed to wood or fiberglass. For example, an analysis of the direct fabrication and major embodied energy inputs to build and equip two equivalent 10 m long salmon gillnet fishing vessels, one constructed largely of fiberglass and wood and the other of aluminum, found that the embodied energy inputs were over 50% higher in the case of the aluminum-hulled vessel (Table I). Moreover, when the electricity required to fabricate the aluminum-hulled vessel is included in the analysis, the total embodied energy costs of this vessel rise to 2.5 times that of its fiberglass counterpart.

3.4 Comparing the Energy Performance of Fisheries

Most energy analyses of fisheries have focused largely, if not exclusively, on evaluating the direct fuel inputs to fishing. This relatively narrow focus

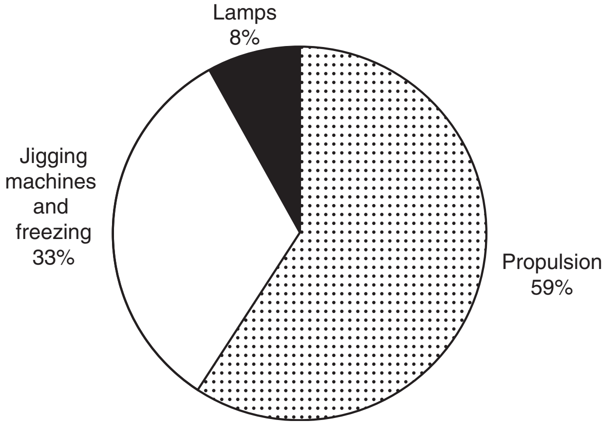

FIGURE 5 Functional fuel utilization on a Japanese long-distance squid fishing vessel. Data from Ishikawa, *et al.* (1987). A case study of energy analysis of long distance squid angling. *Bull. Jap. Soc. Sci. Fish.* **53**(9), 1525–1531.

TABLE I

Direct and Indirect Energy Inputs to Build a 10-Meter-Long Salmon Gillnet Fishing Vessel Fabricated from Either Fiberglass or Aluminum

	Material and embodied energy inputs			
	Fiberglass hull		Aluminum hull	
Inputs	kg	GJ	kg	GJ
Glass				
Matting	1500	15		
Sheet	100	1	100	1
Wood (m^3)	5	21		
Fiberglass resin	1200	90		
Steel				
Engine and transmission	1110	28	1110	28
Fishing equipment	400	10	400	10
Anchor, winch and chain	200	5	200	5
Hardware and other	1050	26	550	14
Lead (batteries)	100	2	100	2
Mixed metals (controls, etc.)	390	10	390	10
Aluminum				
Fuel and water tanks	540	75	540	75
Fishing equipment	330	46	330	46
Hull, decks, holds, and cabin			2250	315
Total embodied energy		329		506
Electricity to weld hull, etc.				324
Total		329		830

not only reflects the fact that these inputs dominate the energy profile of fishing, but detailed analyses of indirect inputs tend to be labor intensive and time consuming. Therefore, in order to facilitate the comparison of as wide a range of fisheries as possible, throughout the balance of this review only the direct fuel energy inputs to various fisheries is considered. Consequently, the energy intensities of various fisheries is expressed in terms of the liters of fuel burned per "round" or live weight tonne of fish or shellfish landed.

However, as food fisheries can also be thought of as food energy "producing" systems, it is also useful to calculate their energy efficiency. Traditionally within analyses of agriculture, aquaculture, and fisheries systems, this has been done by calculating either their industrial energy input to edible food energy output ratio or its inverse, the edible energy return on investment (EROI) ratio. As the nutritional importance of fish and shellfish is primarily a function of their protein content, edible protein energy output is the most meaningful basis of comparison. Therefore, edible protein energy return on investment (protein EROI) ratios for various fisheries are also presented.

4. ENERGY PERFORMANCE OF FISHERIES FOR HUMAN CONSUMPTION

To date, most energy analyses of fisheries for human consumption have concentrated on relatively large-scale industrial fisheries that are conducted for commercial gain. Moreover, few analyses have been undertaken on fisheries based in the Southern Hemisphere. As a result, much of the discussion that follows reflects these biases.

Given the diversity of fisheries for human consumption, both in terms of species harvested and fishing gears used, it is helpful to focus on broad subsets when considering their energy performance. Consequently, the following discussion is organized into four major divisions: fisheries for demersal species, or those fish that spend much of their life on or near the ocean floor; fisheries for pelagic species, or those fish that spend most of their life swimming in the water column; fisheries for invertebrates; and subsistence fisheries.

4.1 Fisheries for Demersal Species

Fisheries for demersal finfish species are some of the largest, most economically important fisheries in the world. Each year, upwards of a hundred species of demersal finfish may be harvested in fisheries globally. Of these, the most important include the various gadoid, or codlike species, and flatfish species. Given that, by definition, demersal species live on or near the ocean floor, fisheries for these species are undertaken in waters ranging from under 10 m to many hundreds of meters deep. As a result, many different types of fishing gears are used in their capture. By far the largest tonnages, however, are harvested each year using trawl and to a lesser extent, long-line fishing gear.

As a result of their importance, fisheries for demersal species have been the subject of numerous energy analyses over the last three decades (Table II). Some of the most recent work to systematically evaluate the fuel consumption of a wide variety of demersal finfish fisheries examined 29 fisheries involving more than 3000 vessels based in Atlantic Canada, Iceland, Norway, and Germany. As of the late 1990s, these fisheries together harvested approximately 1.2 million tonnes of fish annually from ecosystems around the North Atlantic. While fuel use intensities varied by an order of magnitude among these 29 fisheries, from lows of just under 300 l/t to more than 2000 l/t, on average they consumed just over 500 liters of diesel per tonne of fish landed.

TABLE II

Energy Performance of Industrial Fisheries for Direct Human Consumption

Main fishery targets	Gear	Time frame	Location of fishery	Fuel use intensity (liters/tonne)	Edible protein EROI
Demersal fisheries					
Redfish spp.	Trawl	Late 1990s	North Atlantic	420[a]	0.11
Cod/flatfish spp.	Danish seine	Late 1990s	North Atlantic	440[a]	0.10
Cod/haddock	Longline	Late 1990s	North Atlantic	490[a]	0.091
Cod/saithe	Trawl	Late 1990s	North Atlantic	530[a]	0.084
Alaskan pollock	Trawl	Early 1980s	North Pacific	600[b]	0.052
Flatfish spp.	Trawl	Early 1980s	NW Pacific	750[b]	0.066
Croakers	Trawl	Early 1980s	NW Pacific	1500[b]	0.029
Flatfish spp.	Trawl	Late 1990s	NE Atlantic	2300[a]	0.019
Pelagic fisheries					
Herring/mackerel	Purse seine	Late 1990s	NE Atlantic	100[a]	0.56
Herring	Purse seine	Early 1990s	NE Pacific	140[c]	0.36
Herring/saithe	Danish Seine	Late 1990s	NE Atlantic	140[a]	0.35
Salmon spp.	Purse seine	1990s	NE Pacific	360[c]	0.15
Salmon spp.	Trap	Early 1980s	NW Pacific	780[b]	0.072
Salmon spp.	Gillnet	1990s	NE Pacific	810[c]	0.068
Salmon spp.	Troll	1990s	NE Pacific	830[c]	0.067
Herring	Purse seine	Early 1980s	NW Pacific	1000[b]	0.051
Skipjack/tuna	Pole and line	Early 1980s	Pacific	1400[b]	0.053
Skipjack/tuna	Purse seine	Early 1980s	Pacific	1500[b]	0.049
Swordfish/tuna	Longline	Late 1990s	NW Atlantic	1740[a]	0.042
Salmon spp.	Gillnet	Early 1980s	NW Pacific	1800[b]	0.031
Swordfish/tuna	Longline	Early 1990s	Central Pacific	2200[d]	0.027
Tuna/billfish	Longline	Early 1980s	Pacific	3400[b]	0.022
Shellfish fisheries					
Abalone/clams	Hand gathering	Early 1980s	NW Pacific	300[b]	0.11
Crab	Trap	Late 1990s	NW Atlantic	330[a]	0.057
Scallop	Dredge	Late 1990s	North Atlantic	350[a]	0.027
Shrimp	Trawl	Late 1990s	North Atlantic	920[a]	0.058
Shrimp	Trawl	Early 1980s	North Pacific	960[b]	0.056
Norway lobster	Trawl	Late 1990s	NE Atlantic	1030[a]	0.026
Crab	Trap	Early 1980s	NW Pacific	1300[b]	0.014
Spiny lobster	Trawl	Early 1980s	NW Pacific	1600[b]	0.017
Squid	Jig	Early 1980s	NW Pacific	1700[b]	0.033
Shrimp	Trawl	Late 1990s	SW Pacific	3000[d]	0.019

Notes to sources: [a]Tyedmers (2001); [b]Watanabe and Okubo (1989); [c]Tyedmers (2000); [d]unpublished data.

Much of the variability in fuel use intensity among the 29 North Atlantic fisheries appears to be a function of two factors. Not surprisingly, the relative abundance and catchability of various targeted species has a major influence on resulting energy performance. Evidence of this is can be seen by comparing average fuel use intensities of various trawl fisheries targeting very different species assemblages in different parts of the North Atlantic (Table II). Specifically, Canadian and Icelandic trawl fisheries targeting redfish species experienced average fuel use intensities of just over 400 l/t while trawl fisheries for cod and related species from across the North Atlantic averaged 530 l/t. At the other extreme, German trawl fisheries targeting high value flatfish species in the North Sea consumed approximately 2300 liters of diesel per tonne of fish landed.

A second factor that affects the energy performance of fisheries is the type of fishing gear employed. This can be illustrated by focussing on those North Atlantic fisheries that targeted Atlantic cod and related species (Table II). On average, cod fisheries in which Danish seine nets were used burned approximately 440 liters per tonne of fish landed. In contrast, long-line fisheries averaged 490 l/t, while trawl fisheries for cod averaged 530 l/t.

Looking beyond the North Atlantic, a comprehensive analysis of the fuel use intensity of all Japanese fisheries as of the early 1980s suggests that North Pacific fisheries for demersal species may be more energy intensive than many of their North Atlantic counterparts (Table II). Specifically, Japanese trawl fisheries targeting either Alaskan pollock, various flatfish species or yellow croaker burned, respectively 600, 750, and 1500 liters of diesel per tonne of fish landed. It is important to keep in mind, however, when comparing the performance of these Japanese fisheries with those described previously from the North Atlantic, that almost 20 years has elapsed between when the two data sets were acquired. Over that period of time much can have changed that might influence the energy performance of any specific fishery. As we shall see, however, evidence from a variety of fisheries suggests that there has been a general tendency for the energy performance of industrial fisheries to decline over time.

From an energy efficiency perspective, the performance of fisheries targeting demersal species also ranges widely. As measured in terms of their edible protein EROI, the 29 North Atlantic fisheries discussed previously together averaged 0.095. This means that the edible protein energy content of all the fish that they landed amounted to just under 10% of the fuel energy that they burned. More generally, edible protein EROI values for individual fisheries targeting demersal species can range from approximately 0.02 to over 0.1 (Table II). While efficiencies in this range may seem low, they are broadly in keeping with the energy performance of other industrial fisheries and, in fact, compare favorably with other animal protein production systems (Table III).

4.2 Fisheries for Pelagic Species

Pelagic fish species harvested for human consumption encompass a diverse variety of animals. They range from the small, densely schooling, largely planktivorous herrings, to large, top-level carnivores including various tuna and billfish species. What they generally have in common, however, is that all are typically harvested using fishing gears deployed at or near the ocean's surface.

TABLE III

Edible Protein EROI values from Livestock and Aquaculture Production Systems

Production system (locale)	Edible protein EROI
Carp—unspecified culture system (Indonesia)	0.70
Tilapia—unspecified culture system (Africa)	0.11
Mussel—longline culture (Scandinavia)	0.10
Carp—unspecified culture system (Israel)	0.084
Turkey (United States)	0.077
Milk (United States)	0.071
Tilapia—unspecific culture (Israel)	0.066
Tilapia—pond culture (Zimbabwe)	0.060
Swine (United States)	0.056
Eggs (United States)	0.038
Catfish—intensive pond culture (United States)	0.030
Chicken (United States)	0.029
Tilapia—intensive cage culture (Zimbabwe)	0.025
Atlantic salmon—intensive cage culture (Canada)	0.025
Shrimp—semi-intensive culture (Colombia)	0.020
Chinook salmon—intensive cage culture (Canada)	0.020
Lamb (United States)	0.020
Atlantic salmon—intensive cage culture (Sweden)	0.020
Beef—feedlot (United States)	0.019
Seabass—intensive culture (Thailand)	0.015
Shrimp—intensive culture (Thailand)	0.014

For sources, see Tyedmers (2001).

Reflecting the diversity of their quarry, fisheries for pelagic species display the widest range of energy intensities of fisheries for human consumption (Table II). At one extreme are those that target herring and associated species using purse seine or Danish seine nets. For example, recent analyses of herring fisheries from both the Atlantic and Pacific oceans indicate that they typically consume between 100 and 150 liters of diesel per tonne of fish landed. It is interesting to note, however, that an analysis of a herring fishery based in Japan, conducted in the early 1980s, reported a fuel use intensity of 1000 l/t. It is unclear from the data available why such a large difference should exist between this fishery and comparable fisheries in other parts of the world.

In sharp contrast, analyses of fisheries for relatively high value, large pelagic species like tuna and billfish report fuel use intensities ranging from 1400 to 3400 l/t (Table II). Among these fisheries, those that use long-line fishing gear are often the most energy intensive.

Between these two energy performance extremes, lie fisheries for Pacific salmon. Reported fuel use intensities of salmon fisheries range from just under 400 l/t to 1800 l/t (Table II). In a comparative analysis of the three fishing gears used to harvest salmon in British Columbia, Canada, it was found that purse seiners burned, on average, just under half the amount of fuel, per tonne of salmon landed, than did either gillnet or troll fishing boats.

Largely as a result of the major differences in the amount of fuel that they burn, the energy efficiency of fisheries for pelagic species, measured in terms of their edible protein EROI ratios, range from as low as 0.02 (or 2%) to over 0.5 (or 50%).

4.3 Invertebrate Fisheries

While fisheries for invertebrates account for a relatively small proportion of global landings (Fig. 1), they are some of the most lucrative fisheries in the world. It is not surprising therefore that in many instances they can be highly energy intensive. For example, fisheries targeting various species of shrimp and lobster often burn upwards of 1000 liters of fuel per tonne of landings (Table II). Interestingly, however, not all relatively high value invertebrate fisheries are this energy intensive. Some, including the valuable North Atlantic scallop and crab fisheries, consume between 300 and 350 liters of fuel per tonne of shellfish landed.

As measured in terms of their edible protein EROI ratios, many invertebrate fisheries are relatively energy inefficient. This not only reflects rather high fuel use intensities, but the fact that many species of invertebrates yield relatively small quantities of edible meat. For example, the adductor muscle in scallops generally only represents 10 to 12% of the live weight of the animal. Similarly, the edible portion of many crab and lobster species normally does not exceed 30% of their live weight. In contrast, edible muscle usually constitutes between 50 and 60% of most finfish species.

4.4 Subsistence Fisheries

To date, little attention has been paid to the energy performance of small-scale fisheries. However, an analysis of a northern Canadian aboriginal subsistence fishery targeting primarily pike and pickerel in rivers and lakes provides some intriguing and potentially worrying insights into their performance. From data collected through the late-1970s, human ecologist Fikret Berkes estimated that Cree fishermen, based in the community of Fort George, Quebec, burned, on average, approximately 1400 liters of gasoline per tonne of fish landed in the course of tending their fishing nets. Remarkably, this level of fuel use intensity is on the same scale as some of the most energy intensive industrial fisheries for human consumption in the world. It also highlights the extraordinary vulnerability of fossil fuel-dependent artisanal fisheries, and ultimately the communities that depend on them, to disruptions in the supply or increases in the price of fuel.

4.5 Temporal Trends in Energy Performance

Numerous analyses have been undertaken to evaluate how the energy performance of fisheries for human consumption has changed through time. Although the time periods and types of fisheries analyzed differ, when their results are expressed in a consistent format, say in terms of their edible protein EROI ratios, a regular and troubling pattern emerges (Fig. 6). Over time, the energy performance of virtually every fishery analyzed has declined, and in some cases quite dramatically. For example, the edible protein EROI ratio of the entire New Bedford, Massachusetts-based fishing fleet experienced a five-fold declined from just over 0.15 (or 15%) to under 0.03 (or 3%) over the period from 1968 to 1988 (Fig. 6A). Similarly, over the course of a decade, beginning in the late 1960s, the edible protein EROI

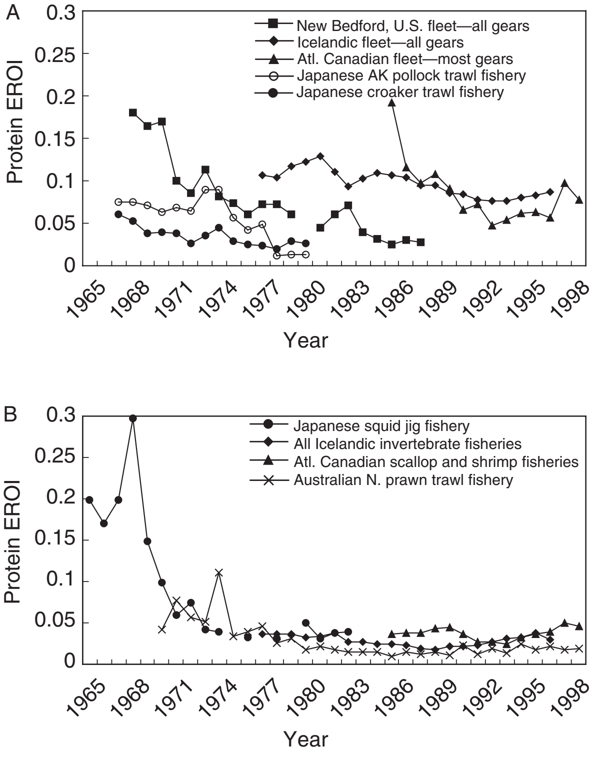

FIGURE 6 Changes in edible protein EROI ratios of fisheries for human consumption: 1965–1999. (A) Demersal finfish fisheries. (B) Shellfish fisheries. Data compiled from Watanabe and Uchida. (1984); Sato, K. *et al.* (1989). Chronological change of energy input for squid angling in Japan 1956–1983. *Bull. Jap. Soc. Sci. Fish* **55**(**11**), 1941–1945; Mitchell and Cleveland (1993). Resource scarcity, energy use and environmental impact: A case study of the New Bedford, Massachusetts, USA Fisheries. *Environ. Management* **17**(**3**), 305–317; Tyedmers (2001); and unpublished data.

ratio of the entire Japanese-based squid fishing fleet declined from over 0.20 (or 20%) to consistently below 0.04 (or 4%) (Fig. 6B).

While their relative importance may vary between fisheries, the two factors that likely contribute most to the general trend to poorer energy performance over time include decreases in relative abundance or proximity of targeted fisheries resources, and increases in the size, power, and technical sophistication of both fishing vessels and fleets.

5. ENERGY PERFORMANCE OF FISHERIES FOR REDUCTION

As many as 50 countries routinely report some production of fish meal and oil. However, less than a dozen account for the lion's share of total annual global output. The most significant of these include Peru, Chile, Iceland, Norway, Denmark, Japan, the United Kingdom, the United States, and the countries of the former Soviet Union.

TABLE IV

Fuel Energy Intensities of Reduction Fisheries as of the Late 1990s

Main fishery targets	Gear	Location of fishery	Fuel use intensity (liters/tonne)
Capelin/herring	Purse seine	NE Atlantic	20
Menhaden	Purse seine	NW Atlantic	32
Capelin/herring	Trawl	NE Atlantic	80
Blue Whiting	Purse seine	NE Atlantic	85
Sand Eels/herring	Trawl	NE Atlantic	95
Herring/sand Eels	Purse seine	NE Atlantic	100
Herring/mackerel	Trawl	NE Atlantic	110

Data source: Tyedmers (2001).

Although they account for 30% of global landings, most of the world's fish meal and oil production is derived from large tonnage landings of a relatively small number of species. In the waters off Peru and Chile the major species harvested for reduction include the Peruvian anchoveta, Inca scad, and the South American pilchard. In the northeast Atlantic, the main species destined for reduction include capelin, blue whiting, Norway pout, European sprat, various species of sand eel together with smaller quantities of Atlantic herring and Atlantic mackerel. In U.S. waters, Atlantic and Gulf menhaden account for virtually 100% of landings destined entirely to reduction.

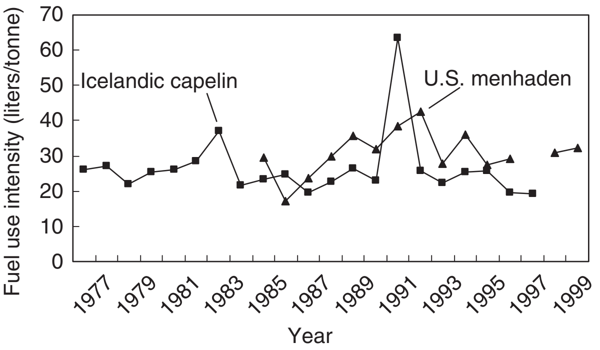

FIGURE 7 Changes in fuel use intensity of fisheries for reduction, 1977 to 1999. Data from Tyedmers, 2001, and unpublished data.

Recent analyses of various North Atlantic fisheries for reduction indicate that in most instances, they consume less than 100 liters of diesel per tonne of fish landed (Table IV). Remarkably, it is not unusual for some of the largest of these fisheries to routinely burn well below this mark. For example, time series data from both the Icelandic and American purse seine fisheries, targeting capelin and menhaden respectively, indicate that in recent decades, they have seldom consumed more than 40 liters of fuel per tonne of fish landed (Fig. 7). Such low and seemingly stable fuel use intensities would seem to suggest that in both instances, fish stocks and fleet effort are being carefully managed.

While the data available do not support direct head-to-head comparisons, from the spectrum of fuel use intensities associated with various North Atlantic fisheries for reduction, it would appear as if those employing purse seine nets are routinely less energy intense than those using trawl fishing gear (Table IV).

6. CONCLUSIONS

Global fisheries are highly varied. They harvest an enormous diversity of aquatic animals using a variety of mostly vessel-based fishing gears. Not surprisingly, therefore, the major forms and absolute quantities of culturally mediated energy inputs dissipated in their execution also vary widely. However, in the case of most fisheries, particularly large-scale industrial fisheries over the past half-century, fossil fuel inputs have come to dominate their energy profile.

Of concern, though, is evidence from a number of fisheries from around the world of a general tendency to poorer energetic performance over time. This pattern of ever-increasing apparent biophysical scarcity reinforces the oft expressed concerns regarding both the declining status of many of the world's fish stocks and the growing size and power of the global fishing fleet. In spite of the ongoing declines in their energy performance, however, many industrial fisheries for human consumption remain energetically competitive with other animal protein–producing systems.

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