ENERGY CONSUMED BY NORTH ATLANTIC FISHERIES

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ABSTRACT

As part of the *Sea Around Us* project at the University of British Columbia, research was undertaken to quantify the fuel energy consumed by North Atlantic fisheries. Where possible, this included evaluating both the contemporary situation and changes in direct fuel inputs to fisheries over time. Two distinct methods were employed in estimating both the total fuel consumed and the energy intensity of specific fisheries and fishing fleet sub-sets. The first method involved soliciting relevant data directly from fishing companies. The second technique combined estimates of the generic rates at which fishing vessels consume fuel in relation to their main engine horsepower, as derived from real-world vessel performance data, with detailed catch and fishing effort data. Ultimately, a total of 58 analyses were conducted representing 54 distinct North Atlantic fisheries or fleet sub-sets. Based in five countries, these 54 fisheries together accounted for total annual landings, as of the late 1990s, of over 5.2 million live weight tonnes of fish and/or shellfish, and encompassing a range of fishing gears, vessel sizes and primary target species. Moreover, for almost half of the fisheries analyzed, time series estimates of energy intensity and total fuel consumption were possible for periods ranging up to 21 years. For the most recent years in which data were available, the results indicate that these 54 fisheries together consumed just over 1 billion litres of fuel annually. Amongst the 29 groundfish fisheries analyzed, energy intensities ranged from a low of 230 litres/tonne to just over 2,700 litres/tonne. When taken together, however, these 29 fisheries experienced a mean energy intensity of about 510 litres/tonne of groundfish and associated bycatch species landed. In contrast, amongst the twelve fisheries targeting small pelagic species analyzed, contemporary energy intensities ranged from 19 to 159 litres/tonne of fish landed and averaged just 62 litres/tonne. The single relatively small fishery for large pelagic species analyzed had an energy intensity of 1,740 litres/tonne of tuna and swordfish landed. Amongst the invertebrate fisheries evaluated, the average energy intensity of the eight fisheries targeting shrimp was 918 litres/tonne while the two scallop fisheries had an average energy intensity of just 347 litres/tonne landed, and the single crab fishery evaluated had an energy intensity of about 330 litres/tonne. Finally, the lone fishery for Norway lobster analyzed, had an energy intensity of 1,025 litres/tonne of total landings.

INTRODUCTION

As with all human activities, commercial fishing entails the dissipation of matter and energy in support of their primary activity, the harvesting of aquatic organisms. While these biophysical ‘costs’ are less obvious and consequently receive less attention than the direct impact that fishing has on targeted stocks and associated marine ecosystems, it is precisely the availability of abundant energy that enables most contemporary fisheries to continue even when stocks are in decline. Moreover, the consumption of industrial energy, and in particular fossil energy, has a real, if indirect, ecological impact on marine ecosystems in and of itself through the effects of global climate change. Finally, from a management perspective, industrial energy consumption provides a means of comparing fishing effort between fisheries, and changes in effort over time within fisheries.

Following the oil price shocks of the 1970s, a wave of research was undertaken to evaluate the energy intensity of a variety commercial fisheries (Wiviott and Mathews, 1975; Rochereau, 1976; Leach, 1976; Rawitscher, 1978; Lorentzen, 1978; Ágústsson *et al.,* 1978; Ragnarsson, 1979 & 1985; Nomura, 1980; Brown and Lugo, 1981; Hopper, 1981; Veal *et al.,* 1981; Allen, 1981; Watanabe and Uchida, 1984; Ishikawa *et al.,* 1987; Sato *et al.,* 1989; Watanabe and Okubo, 1989). The results of this and more recent research indicate that:

- Direct fuel energy inputs to fisheries typically account for between 75 and 90% of the total culturally mediated energy inputs. The remaining 10 to 25% of the total is comprised of direct and indirect energy inputs associated with vessel construction and maintenance, providing fishing gear, and labor (Wiviott and Mathews, 1975; Rochereau, 1976; Leach, 1976; Edwardson, 1976; Rawitscher 1978; Lorentzen, 1978; Allen 1981; Watanabe and Uchida, 1984; Watanabe and Okubo, 1989; Tyedmers, 2000);
- Energy intensity can vary considerably depending on the fishing gear used. In general, trawling tends to be more energy intensive than seining, purse seining or more passive techniques such as gillnetting, and trapping. (Wiviott and Mathews, 1975; Leach, 1976; Edwardson, 1976; Lorentzen, 1978; Rawitscher, 1978; Nomura, 1980; Hopper, 1981; Watanabe and Okubo, 1989). An exception to this relative

Zeller, D., R. Watson, and D. Pauly (eds.). Fisheries Impacts on North Atlantic Ecosystems: Catch, Effort and National/Regional Data Sets. Fisheries Centre Research Reports 9(3): 254 pp (2001).

energy intensity pattern occurs with respect to longlining, a passive fish harvesting technology which typically requires relatively large energy inputs relative to the tonnes of fish landed, particularly when used to catch high value pelagic species such as tuna, and billfish (Rawitscher, 1978; Nomura, 1980; Watanabe and Okubo, 1989);

- In many instances, energy intensity has been found to increase with vessel size within a given gear sector and fishery (Wiviott and Mathews, 1975; Rochereau, 1976; Edwardson, 1976, Lorentzen, 1978; Watanabe and Okubo, 1989;). However, exceptions to this have also been found (in particular, see Figure 1 in Edwardson, 1976); and
- The energy intensity of a fishery can change dramatically over time as the abundance of fisheries resources change, fleets expand, the average size of vessels increase, vessels travel further to fish, and become more technologically advanced. For example, Brown and Lugo (1981) estimated that between 1967 and 1975, while the fuel consumed by the U.S. fishing fleet (excluding vessels under 5 GRT) increased from 150 to 319 million gal/year, the catch did not increase accordingly. As a result, the fossil energy input to edible protein energy output ratio for the U.S. fleet increased from 8:1 to almost 14:1 over the same period. Similarly, Mitchell and Cleveland (1993) found that between 1968 and 1988, the fuel energy input to edible protein output ratio of the New Bedford, Massachusetts fleet rose from ~6:1 to over 36:1.

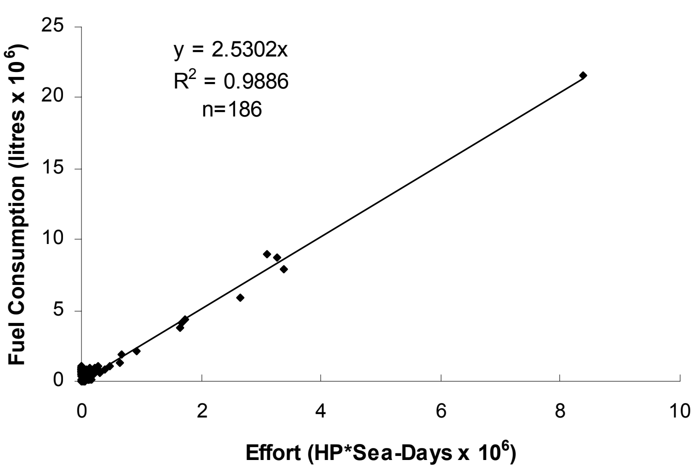

Figure 1. Fuel consumption relationship for all gear types combined.

An analysis of the culturally mediated energy inputs to fisheries would ideally encompass:

- direct fuel energy inputs;
- direct and indirect inputs to build and maintain fishing vessels;
- direct and indirect inputs to provide fishing gear 'consumed' in the process of fishing; and
- the energy required to sustain the fishing labor inputs.

However, because of the large number of fisheries being considered in this analysis, the heterogeneity that exists both between and within the fleets involved, and the general difficulty accessing reliable representative data, this analysis focused exclusively on the direct fuel energy inputs to contemporary North Atlantic fisheries.

When initially undertaken, the objective of this project was to quantify, with as much resolution as possible, the fuel energy consumed by all contemporary North Atlantic fisheries. However, given the limited data available at the time that this part of the *Sea Around Us* project was completed, analyses were only possible for approximately 54 fisheries or fleet sectors representing five countries: Canada, the United States, Iceland, Norway, and Germany. The fisheries for which analyses were conducted, however, together account for over 5.2 million tonnes (live weight) of fish and shellfish landed annually and encompass a range of fishing gears, species, and relative product values. Moreover, for almost half of the fisheries analyzed, time series estimates of energy intensity and total fuel consumption have also been possible for periods ranging up to 21 years.

MATERIALS AND METHODS

For each fishery for which an energy analysis was conducted, the primary output was an estimate of its contemporary energy intensity, or the litres of fuel consumed per round weight tonne of fish and/or shellfish landed. Two techniques were used to estimate energy intensity.

Direct solicitation of data

Annual fuel consumption, landings and temporal fishing effort (both in terms of fishing days and days at sea) data together with the physical characteristics of the associated vessels were solicited from fishing companies actively engaged in North Atlantic fisheries (Table 1).

Table 1. Summary of North Atlantic fishing vessels for which detailed catch, vessel characteristic and performance data were acquired.

Target species and fishery location	Gear type	Vessel size (Tonnage/HP)	Number of vessels represented	Annual catch by vessels (round tonnes)	Fishing seasons represented
Shrimp - NW Atlantic	Trawl	2,290/4,023	1	~4,200	1993 to 1999
Atlantic menhaden - US Atlantic coast	Purse seine	540/1,800 to 750/2,000	13	~175,000	1998 & 1999
Ground fish - NW Atlantic	Trawl	540/1,300 to 802/2,400	8	~10,000	1999
Ground fish - NW Atlantic	Trawl	790/2,400 to 990/2,000	4	~4,000 to ~16,000	1986 to '89 & 1996 to '99
Cod - NW Atlantic	Danish Seine	545/1,250	2	~1,000	1999
Scallops - Georges Bank	Dredge	309/765 to 330/990	5	~5,500	1998 & 1999

From the data provided by fishing companies, energy intensities were calculated using Equation (1).

$$I_i = Q_i / L_i \qquad ...1)$$

Where I_i is the energy intensity of the *i*-th fishery; Q_i is the total quantity of fuel consumed, in litres, by all vessels for which data were available for the *i*-th fishery; and L_i is the total round weight landings of all species, in tonnes, by the vessels for which data were available for the *i*-th fishery.

While soliciting data directly from fishing companies yields accurate estimates of the energy intensity of the vessels from which the data were derived, it has two drawbacks. The vessels represented by the data, and more specifically their fuel performance, may not be representative of the fisheries of which they are a part. Secondly, direct solicitation of data from fishing companies is a slow, labor-intensive process. As a result, a second method was employed to estimate fuel consumption and energy intensity for entire fisheries/fleet sectors.

Inferring fuel consumption from fishing effort data

Based on the rationale that fuel consumption is largely a function of an engine's size and the length of time that it is operated, a methodology was developed that uses fishing effort and catch data to estimate fuel consumption, and ultimately energy intensity, for entire fishing fleets. Specifically, the total fuel consumed by a given fishing fleet was estimated using Equation (2).

$$Q_{ij} = R_{ij} * (H_{ij} * T_{ij}) \qquad ...2)$$

where Q_{ij} is the total quantity of fuel consumed by the *i*-th fleet using the *j*-th type of fishing gear; R_{ij} is the generic rate of fuel consumption, in litres/HP*sea-days, by vessels using the *j*-th type of fishing gear; H_{ij} is the average main engine horsepower of all vessels in the *i*-th fleet using the *j*-th fishing gear; and T_{ij} is the total aggregate effort, in days at sea, expended by the *i*-th fleet using the *j*-th fishing gear.

Once the total fuel consumed by a specific fleet was estimated using the method outlined in Equation (2) and described in detail below, its energy intensity was determined using Equation (1).

Determining generic fuel consumption rates

In applying the technique outlined in Equation (2), it was first necessary to estimate *R*, the standardized rate at which fishing boat engines burn diesel fuel regardless of the species being targeted or the total resulting catch. This was done by first assembling detailed vessel characteristic, fuel consumption and fishing effort data from a variety of sources. In addition to data from the 33 North Atlantic vessels outlined in Table 1, data were also drawn from:

1. two fishing companies engaged in fisheries outside the North Atlantic region;
2. the results of a detailed economic study of 95 pelagic longliners in Hawaii (pers. comm. April, 2000 Dr. Mike Travis, NOAA);
3. and four published sources (Table 2).

For each of the 186 vessels for which detailed performance data were available, an integrated measure of fishing effort was calculated as the product of main engine horsepower and total days at sea. These values were then plotted against the total litres of fuel consumed by each vessel and a best fit line through these points and the origin was determined (Figure 1; note that the best fit line was forced through the origin based on the simplifying

Table 2. Summary of additional sources of data used to establish the relationship between fuel consumption and fishing effort.

Data source	Target species and fishery location	Gear type	Vessel size (Tonnage/HP)	Number of vessels represented	Fishing seasons represented
This research	Gulf menhaden - US Gulf coast	Purse seine	540/1,800 to 750/2,000	40	1998 & 1999
This research	Pollock - Alaska	Trawl	1,600/3,000 to 2,500/8,000	2	1999
Dr. Mike Travis, NOAA (Pers. comm.)	Swordfish & Tuna - Hawaii	Longline	19/145 to 187/1,050	95	1993
Ágústsson *et al.* (1978)	Groundfish - Iceland	Trawl	578/1,800 to 975/2,170	2	1977
Ágústsson *et al.* (1978)	Capelin - Iceland	Purse seine	450/600 to 700/2,100	7	1977
Eiríksson (1978)	Groundfish - Iceland	Trawl	969/2,820	3	1976 & 1977
Veal *et al.* (1982)	Shrimp - US Gulf coast	Trawl	n.a./275 to n.a./520	3	1980
Wiviott and Mathews (1975)	Groundfish - Washington State	Trawl	86/300	1[a)]	1971 & 1972 [a)]

[a)] Data reported for Washington State groundfish trawlers by Wiviott and Mathews (1975) represents the average of 11 vessels.

assumption that without an engine, no fuel will be consumed). The slope of this line provides a first approximation estimate of *R*, the generic rate at which fishing vessels consume fuel per HP*sea-day of effort.

In conducting this part of the analysis it became apparent that fishing gear-specific sub-sets of the vessels for which data were available, have slightly different rates of fuel consumption. In other words, two vessels with the same main engine horsepower operating for the same period of time but deploying markedly different types of fishing gear, say trawl versus purse seine gear consume fuel at different average rates as a result of the relative periods of time that their main engines are operated at various levels of output. This observation, that the rate of fuel consumption is influenced by the ways in which specific fishing gears are deployed, is supported by the analysis of Watanabe and Okubo (1989 and Figure 1). As a result, in order to refine the subsequent energy analyses of various fisheries, fishing gear-specific fuel consumption rates were determined for five sub-sets of vessels:

1. vessels using either trawl or dredge gear (Figure 2);
2. vessels using Danish seine or related mobile seine gear (Figure 3);
3. all purse seiners (Figure 4);
4. only 'standard' purse seiners (Figure 5); and
5. longliners (Figure 6).

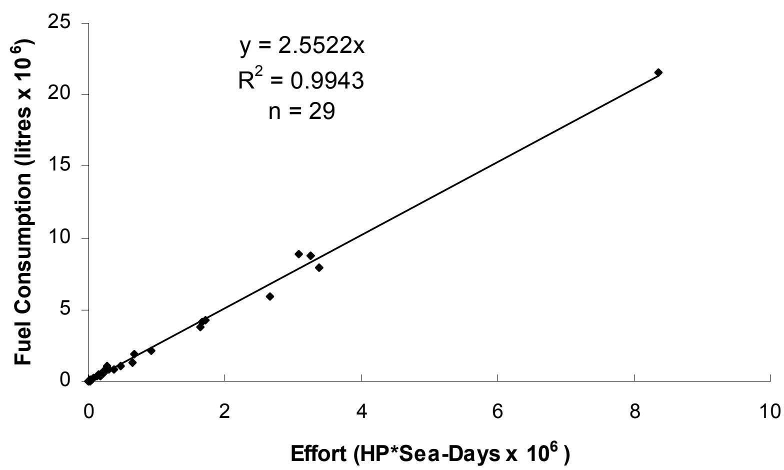

Figure 2. Fuel consumption relationship for trawlers and draggers.

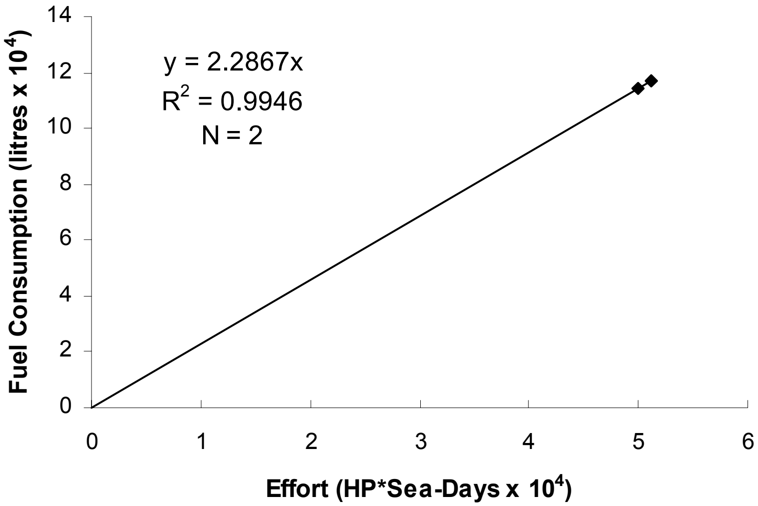

Figure 3. Fuel consumption relationship for vessels using mobile seine gear.

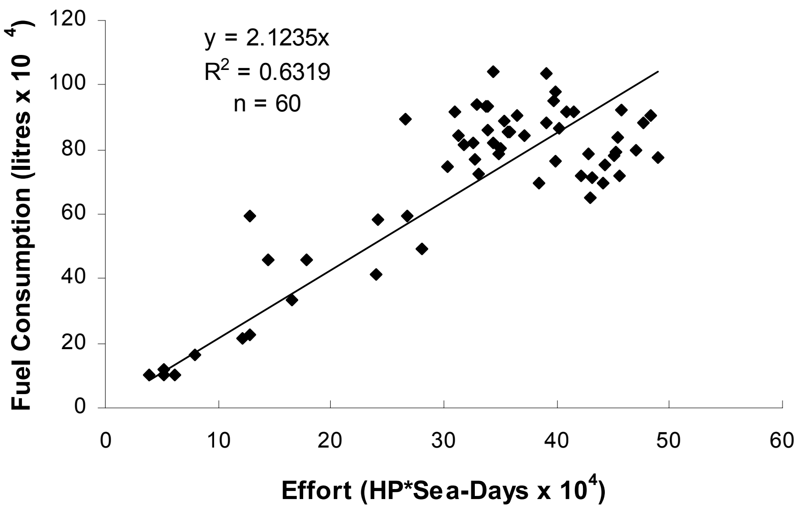

Figure 4. Fuel consumption relationship for all purse seiners.

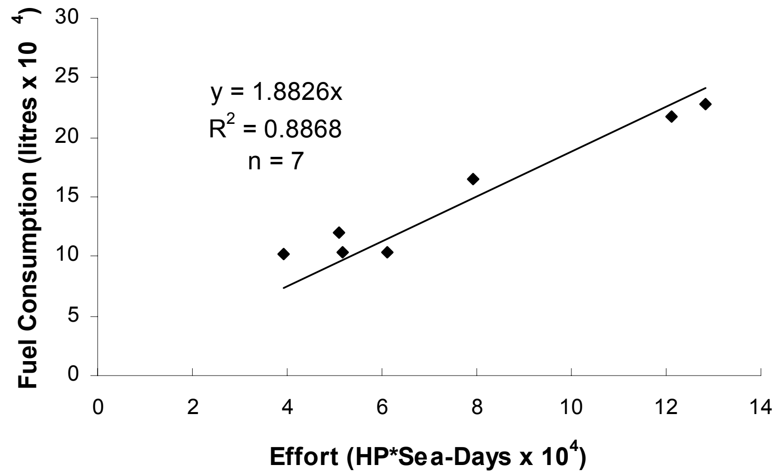

Figure 5. Fuel consumption relationship for 'standard' purse seiners.

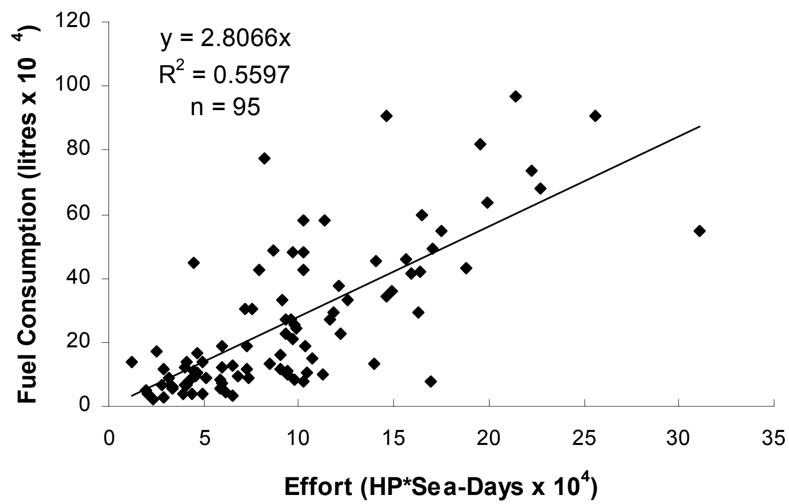

Figure 6. Fuel consumption relationship for longliners.

The estimated rates of fuel consumption per HP*sea-day of effort for all vessels combined and for the five gear-specific sub-sets are summarized in Table 3.

Two fuel consumption rate estimates were made for purse seiners (Table 3). The first represents all vessels deploying purse seine nets while the second represents what may be called 'standard' purse seiners. This distinction was made because 53 of the 60 vessels included in the first estimate (Figure 4) are menhaden (*Brevoortia tyrannus*) fishing vessels that appear to be unique in the way they deploy their nets. Whereas on a standard purse seiner, the vessel's main engine is used to maneuver while the net is deployed from the stern of the vessel, in menhaden boats, their nets are deployed using a pair of independently powered purse boats (Smith, 1991). Functionally, this difference means that menhaden fishing operations will likely burn fuel at a higher rate, relative to the horsepower of the mother ship's main engine, than will a standard purse seiner. This is borne out by the fuel consumption rate estimates in Figures 4 and 5. As a result, throughout the subsequent analyses of energy inputs to purse seine fisheries, I have used the fuel consumption rate associated with standard purse seiners, or 1.88/HP*sea-day, so as to err on the conservative side.

Table 3. Summary of generic fuel consumption rate estimates.

Gear type	Fuel consumption rate (Litres/HP*sea-day)	Sum of squares	Number of vessels represented
All vessels combined	2.53	0.99	186
Vessels deploying trawl or dredge gear	2.55	0.99	29
Vessels deploying mobile seine gear	2.28	0.99	2
All purse seiners	2.12	0.63	60
"Standard" purse seiners	1.88	0.89	7
Longliners	2.81	0.56	95

It should also be noted that for some fishing gears commonly in use in the North Atlantic, including gillnet, handline, and traps, no gear-specific fuel consumption rate estimates were possible, given the vessel performance data available. Consequently, where fuel consumption rate values were required to estimate the energy inputs to a fishery employing one of these gears, the rate associated with all fishing vessels combined was used (Figure 1), or a value of 2.53 l/HP*sea-day of effort.

Fishing effort and catch data

To estimate the total fuel consumption, and energy intensities for specific fisheries or fleet sectors using the technique outlined in Equation (2), it was also necessary to assemble the following data, in addition to generic gear-specific fuel consumption rates:

- average horsepower of all vessels engaged in a particular fishery;
- total number of days at sea of all vessels engaged in the fishery; and
- total resulting catch of all species, ideally broken down by species, by all vessels engaged in the fishery.

Using the *Sea Around Us* project's network of in-country collaborators and consultants, these types of information were sought for most North Atlantic fishing countries. Ultimately, detailed information in the forms outlined above were obtained from four countries: Canada, Iceland, Norway, and Germany.

Canada

For all Atlantic Canadian fisheries over the period from 1986 to 1999 inclusive, catch and associated effort data, including information on gear type, primary fishery target, vessel size class, average horsepower of vessel class, total fishing days, and total days at sea. These data were compiled by Paul Fanning of the Department of Fisheries and Oceans Canada and Sylvie Guénette of the *Sea Around Us* project. For the purposes of this energy analysis, an output was generated from the resulting database that allowed catch and to be correlated with HP*sea-days of effort for a total of 15 fishing gear and primary fishery target combinations. Unfortunately, in the case of six of the 15 gear type/fishery target combinations, the catch and effort output generated were either incomplete or the resulting energy analyses yielded implausible results. For example, the catch and associated effort data for the Atlantic Canadian lobster (*Homarus americanus*) trap fishery yielded apparent energy intensity values that varied wildly from year to year, spanning at least three orders of magnitude.

Of the nine gear type/fishery target combinations for which data were largely complete and yielded results that were both internally coherent and in general accord with similar fisheries, four targeted groundfish species, three targeted invertebrates, and small and large pelagic species were targeted by one fishery each.

Iceland

Catch along with corresponding effort data, expressed in terms of HP*sea-days, were compiled by Hreidar Valtýsson of the Marine Research Institute of the University of Akureyri, for 23 distinct Icelandic fisheries or fleet segments for the period from 1977 to 1997 inclusive. Of these, four fisheries did not warrant further analysis, either because of their infrequent occurrence or the extremely small landings involved. Of the 19 fisheries for which analyses were ultimately conducted, they together accounted as of 1997 for over 2,000,000 live weight tonnes, or 99% of the total Icelandic fisheries landings that year.

Up to three criteria are used to define these 19 fisheries. The primary basis for differentiation is the size class of the vessels involved. Specifically, the Icelandic fleet is broadly divided into three types of vessels: undecked boats, decked boats and trawlers. The second criteria used to define these fisheries is the fishing gear that is deployed. Finally, the primary species or group of species targeted were used to define each fishery (Table 4).

Table 4. Icelandic fisheries for which energy analysis were conducted.

Vessel class	Gear used	Primary target	Number of vessels	Total landings in 1997[a)] (tonnes)
Undecked boats	Gillnet	Groundfish	95	1,763
Undecked boats	Handline	Groundfish	538	24,031
Undecked boats	Longline	Groundfish	243	12,858
Decked Boats	Gillnet	Groundfish	145	57,864
Decked Boats	Handline	Groundfish	38	3,250
Decked Boats	Longline	Groundfish	136	44,582
Decked Boats	Danish seine	Groundfish	123	46,302
Decked Boats	Bottom trawl	Groundfish	49	38,958
Decked Boats	Bottom trawl	Norway pout	0	0
Decked Boats	Bottom trawl	Shrimp	88	32,614
Decked Boats	Bottom trawl	Lobster	20	5,704
Decked Boats	Mid-water trawl	Pelagic species	5	69,173
Decked Boats	Purse seine	Capelin	40	1,288,693
Decked Boats	Purse seine	Herring	14	249,344
Decked Boats	Driftnet	Herring	0	0
Decked Boats	Dredge	Scallops	13	10,404
Trawlers	Bottom trawl	Groundfish	67	196,241
Trawlers	Bottom trawl	Shrimp	37	42,359
Trawlers	Mid-water trawl	Redfish	9	35,073

a) The last year for which an energy analysis could be conducted.

Norway

Drawing data from the results of a detailed Norwegian government survey of the profitability of its fishing industry in 1998, Gjert Dingsør of the Department of Fisheries and Marine Biology, University of Bergen, compiled catch, effort, and vessel characteristic data for 29 fisheries or distinct fleet subsets representing most Norwegian vessels over 8 meters in length. Unfortunately, both average vessel horsepower and days at sea data were only available for fleet segments comprised of vessels over 13 meters in overall length. As a result, 7 of the 29 fleet segments included in Mr. Dingsør's summary could not be included in the energy analysis. The 22 fleet subsets for which an energy analysis was possible, however, together account for approximately 2,500,000 live weight tonnes, or 86% of the total Norwegian catch of all species by all vessels in 1998.

The first criteria used to differentiate these fisheries and fleet segments is the primary target of the fishery. Next, the fisheries or fleet segments are further defined based on the fishing gear employed. Finally, either vessel size or the location of the fishery may be used to categorize vessels even further. Table 5 summarizes the 22 Norwegian fisheries for which energy analyses were conducted.

Germany

Catch and corresponding fishing effort data, expressed in terms of kW*sea-days (converted to HP*sea-days by multiplying by 1.341), were compiled for German commercial fisheries by Ms. Kristin Kaschner for the years 1995 to 1998 inclusive (Kaschner *et al.*, this volume). Of the eight fleet segments recognized by German fisheries managers as of 1998 (Kaschner *et al.*, this volume), energy analyses were conducted on the five largest, that together account for approximately 95% of all German landings. The five for which analyses were conducted are all trawl based fisheries targeting mainly groundfish, flatfish or small pelagic species (Table 6).

Table 5. Norwegian fisheries for which energy analyses were conducted.

Primary target	Gear used	Vessel size and/or fishery location	Number of vessels	Total landings in 1998 (tonnes)
Gadoid species	Gillnet and Handline	13 to 20.9m in length - North Norway	186	57,177
Gadoid species	Longline	13 to 20.9m in length - North Norway	80	20,698
Gadoid species	Longline	> 28m in length - All counties	58	87,819
Gadoid species	Danish seine	13 to 20.9m in length - North Norway	113	46,990
Gadoid species	Danish seine	21 to 27.9m in length - North Norway	39	41,232
Gadoid species	Unspecified	13 to 20.9m in length - South Norway	100	22,096
Gadoid species	Unspecified	21 to 27.9m in length - All counties	45	49,127
Gadoid species	Unspecified	> 28m in length - All counties	11	10,099
Gadoid species	Trawl	< 250 GRT/500 GT	47	80,843
Gadoid species	Trawl	> 250 GRT/500 GT (freshfish)	39	84,174
Gadoid species	Trawl	> 250 GRT/500 GT (factory trawlers)	21	86,268
Pelagic species	Purse seine	Smaller purse seiners	34	231,794
Pelagic species	Purse seine	Larger purse seiners	16	125,857
Pelagic species plus Blue Whiting	Purse seine	Very large purse seiners	41	863,439
Pelagic species	Mobile seine	13 to 21.34m in length	66	80,310
Pelagic species	Mobile seine	> 21.35m	42	95,637
Pelagic species	Trawl		54	412,873
Shrimp	Trawl	< 50 GRT/80 GT & >13m in length	97	5,185
Shrimp	Trawl and other	< 50 GRT/80 GT & >13m in length	55	7,904
Shrimp	Trawl	Vessels fishing around Greenland with cold storage	9	13,450
Shrimp	Trawl	Vessels fishing in areas other than around Greenland with cold storage	15	22,117
Shrimp	Trawl	> 50 GRT/80 GT without cold storage	31	18,136

Table 6. German fisheries for which energy analyses were conducted.

Gear used	Primary target	Major fishing grounds	Number of vessels	Total landings in 1998 (tonnes)
Beam trawl	Flatfish and crustaceans	Unspecified	306	8,959
Beam trawl	Flatfish	North Sea	7	2,045
Bottom trawl	Groundfish	North & Baltic Seas	133	30,895
Unspecified trawl	Groundfish	NAFO, NEAFC, EU and others	8	61,869
Mid-water trawl	Pelagic species	EU waters	4	109,247

Expressing the results

The primary output of this research are estimates of the energy intensity of various North Atlantic fisheries, expressed in terms of the litres of diesel fuel burned per live weight tonne of fish and/or shellfish landed (see Table 7 for a variety of useful conversions). However, in order to facilitate comparisons with other food production systems and help conceptualize the results, they were also expressed in terms of:

- resulting greenhouse gas emissions;
- the ratio of the edible protein energy output by a fishery divided by the industrial energy input; and
- the energy input relative to the economic value of the catch.

Greenhouse gas emissions

Direct greenhouse gas emissions associated with the routine operation of marine engines amount to the equivalent of 2.66 kg CO_2/litre of fuel burned (calculated from data presented in Lloyd's Register Engineering Services 1995, Table 5, p. 17). In addition, indirect greenhouse gas emissions that result from the production, transmission, refining, distribution and dispensing of diesel fuel amount to the equivalent of an additional 0.50 kg CO_2/litre of fuel consumed (calculated from Delucchi 1997, Table 7, p. 191). Therefore, total greenhouse gas emissions associated with North Atlantic fisheries were estimated by multiplying fuel consumption (in litres) by 3.16 kg CO_2 equiv./litre.

Table 7. Volumetric and other conversion factors for diesel fuel

	US gallons	US Barrels
To convert from 1 litre	= 0.264	= 0.00629
In addition, 1 litre of diesel:	- releases 36.036 MJ of energy upon combustion - has a density of 0.840	

Source: Rose and Cooper 1977.

Edible protein energy return on industrial energy invested ratios

In order to contextualize the performance of fisheries *vis-à-vis* other food production systems, a common basis of comparison is required. 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 industrial energy investment ratio (see for example Wiviott and Mathews, 1975, Pimental and Terhune, 1977; Folke, 1988; Folke and Kautsky, 1992; Ackefors *et al.,* 1993; Mitchell and Cleveland, 1993; Pimentel *et al.,* 1996; Berg *et al.,* 1996; Pimentel, 1997; Tyedmers, 2000).

As the nutritional importance of fish and shellfish is largely a reflection of their protein content, in this analysis edible protein energy output was used as the basis for comparison. Consequently, edible protein energy return on investment ratios ('protein returns') were calculated for each of the fisheries analyzed, for each year in which data were available. In doing so, however, it was first necessary to convert landings data, on a species-specific basis, into estimates of the edible protein output (in tonnes) and edible protein energy yield (in Joules) for each of the fisheries considered. This was done by first assembling published data regarding:

1. the maximum fraction that is generally considered edible for each species. (In the case of finfish, this was assumed to correspond to the fraction of the animal's live weight that is muscle); and
2. the fraction of the edible proportion that is protein.

Where published species-specific values were unavailable, appropriate default values were used. For example, in the case of finfish species, the default maximum edible fraction was assumed to be 55% of live weight. Similarly, in the absence of appropriate species-specific data, it was assumed that protein constituted 19% of the edible portion, regardless of the type of organism. The maximum tonnes of edible protein potentially available from a given fishery was then calculated using Equation (3).

$$M_i = \sum_{k}^{n} (L_{ik} * E_k * P_k) \qquad \ldots 3)$$

where M_i is the maximum edible protein, in tonnes, potentially available from the *i*-th fishery consisting of *n* species; L_{ik} is the landings, in tonnes, of the *k*-th species in the *i*-th fishery; E_k is the maximum potential edible fraction of the *k*-th species; and P_k is the mean protein content of the edible portion, itself expressed as a fraction, of the *k*-th species.

Maximum edible protein energy yield from each fishery was then calculated by multiplying the maximum potential tonnes of edible protein output from the fishery by 17.6 GJ/tonne, the energy content of protein (Wiviott and Mathews, 1975). Finally, edible protein returns for each fishery were calculated by dividing the edible protein energy yield by the fuel energy input, both expressed in Joules.

RESULTS

Energy intensity of fisheries as of the late 1990s

Using either the direct solicitation method or the technique in which fuel consumption and energy intensity is inferred using generic fuel consumption rates together with catch and effort data, a total of 58 energy analyses were conducted representing 54 unique North Atlantic fisheries or fleet subsets. When considering the most recent year for which analyses were possible in each of these fisheries (either 1997, 1998 or 1999), they together accounted for just over 5.2 million tonnes of total annual landings and consumed slightly more than 1 billion litres of diesel fuel. In doing so, they released greenhouse gases equivalent to approximately 3.2 million tonnes of CO_2 into the atmosphere.

In order to facilitate comparison amongst these fisheries, the most recent year's results have been arranged in the following four primary target groups: groundfish, small pelagic species, large pelagic species, and invertebrates.

Fisheries targeting groundfish

A total of 31 energy analyses were conducted representing 29 distinct fisheries in which groundfish species were targeted (Table 8). When taken together, the annual landings by these 29 fisheries, in the most recent year for which data were available, amount to just over 1.2 million tonnes. Of this total, Atlantic cod (*Gadus morhua*) accounted for approximately 36%, saithe (*Pollachius virens*) 14%, haddock (*Melanogrammus aeglefinus*) 10%, redfish species (*Sebastes* spp.) 10%, herring (*Clupea harengus*) 8%, and Greenland halibut (*Reinhardtius hippoglossoides*) 3%. The remaining approximately 19% for the total catch by these 29 fisheries was comprised of almost two dozen species.

In landing these 1.2 million tonnes of fish, these 29 fisheries consumed a total of approximately 615 million litres of diesel resulting in an overall weighed average energy intensity of approximately 510 litres/tonne or 18.4 GJ/tonne. Consequently, their mean greenhouse gas emission intensity was 1.6 tonnes CO_2 equiv./tonne.

When considered individually, the energy intensity of these fisheries varied from a low of 230 litres/tonne, for a Canadian mobile seine fishery for cod, to a high of 2,724 litres/tonne for a German trawl fishery targeting flatfish species (Table 8). In the case of two-thirds of the North Atlantic groundfish fisheries analyzed, however, the resulting energy intensity fell between 400 and 700 litres/tonne.

On a country-specific basis, the eleven Norwegian fisheries represented in Table 8 landed a total of 587,000 live weight tonnes in 1998 and consumed approximately 266 million litres of fuel, for a weighted average energy intensity of 453 litres/tonne (16.3 GJ/t) - the lowest combined average of the four countries represented. Next most efficient are the ten Icelandic fisheries that together accounted for approximately 461,000 tonnes in 1997 and consumed about 233 million litres of fuel, for a weighted average energy intensity of 505 litres/tonne (18.2 GJ/t). The four Canadian fisheries, with combined landings of only 63,000 tonnes and fuel consumption of approximately 38 million litres in 1999, had the second highest weighted average energy intensity at approximately 600 litres/tonne (21.6 GJ/t). Finally, the four German fisheries that together landed 104,000 tonnes and consumed an estimated 78 million litres of fuel had an average energy intensity of approximately 750 litres/tonne (27.0 GJ/t).

Amongst those fisheries in Table 8 for which only a single fishing gear is specified, the three gillnet fisheries had the highest weighted average energy intensity at almost 640 litres/tonne (23.1 GJ/t). When considered together, the two handline fisheries had the next best average energy intensity at approximately 580 litres/tonne (20.9 GJ/t) while the eleven dedicated trawl fisheries had an average energy intensity of about 530 litres/tonne (19.1 GJ/t). The five-longline fisheries in combination enjoyed the second lowest gear-specific energy intensity at approximately 490 litres/tonne (17.6 GJ/t) while the four fisheries in which mobile seine gear was used performed the best with an average energy intensity of approximately 440 litres/tonne (15.9 GJ/t).

With respect to the relatively poor energy performance of gillnet and handline fisheries, it should be kept in mind that these are both gears for which the non-gear-specific overall generic fuel consumption rate had to be used when calculating the total fuel consumed in these fisheries. In other words, when inferring the amount of fuel consumed based on the horsepower*sea-days of effort expended in these fisheries, the generic fuel consumption rate associated with all vessels was employed (Figure 1).

Fisheries targeting small pelagic species

Energy analyses were conducted on twelve North Atlantic fisheries, encompassing five countries, in which small pelagic species were targeted (Table 9). For the most recent years in which analyses were possible, these fisheries together accounted for total annual landings of approximately 3.8 million live weight tonnes. While the catch composition varied widely between fisheries, when taken together, capelin (*Mallotus villosus*) accounted for approximately 37% of the total, herring 27%, blue whiting (*Micromesistius poutassou*) 15%, sandeels (*Ammodytes* spp.) 8%, mackerel sp. (*Scomber* sp.) 5%, and Atlantic menhaden 4%. In catching these 3.8 million tonnes, these 12 fisheries together consumed a total of almost 234 million litres of fuel for an overall average energy intensity of 62 litres/tonne or 2.2 GJ/tonne. The resulting average greenhouse gas emission intensity amounted to the equivalent of only about 200 kg CO_2/tonne of fish landed.

When considered individually, the massive Icelandic purse seine fishery targeting capelin had the lowest overall energy intensity at just 19 litres/tonne. At the other extreme, the Norwegian mobile seine fishery targeting herring experienced an energy intensity of 159 litres/tonne (Table 9).

On a country-specific basis, the comparatively small Canadian fishery for small pelagic species caught a total of just under 120,000 tonnes in 1999 and burned just 2.39 million litres of fuel for an energy intensity of just 20 litres or 0.72 GJ per tonne (Table 9). Almost as efficient, however, are the three very

Table 8. Summary of energy analyses of North Atlantic fisheries targeting groundfish. (All but the first two cases relied on indirect methods (see text).)

Country	Year	No. of vessels	Average GRT	Average length (m)	Gear type	Top four species landed (by weight)				Total landings (tonnes)	Fuel burned (litres)	Energy intensity (l/t)	Edible protein return
Canada	1999	12	724	44.5	Trawl	Redfish	Flatfish	Cod	Gr. Halibut	17,340	6,424,177	370	0.130
Canada	1999	2	544	38	Mobile seine	Cod	-	-	-	1,005	231,326	230	0.250
Canada	1999	n/a	n/a	n/a	Gillnet	Cod	Saithe	Gr. Halibut	White hake	9,164	13,102,592	1,430	0.031
Canada	1999	n/a	n/a	n/a	Mobile seine	Plaice	Witch	Cod	-	3,154	1,198,277	380	0.120
Canada	1999	n/a	n/a	n/a	Longline	Cod	Haddock	White hake	Tusk	14,652	7,168,053	489	0.093
Canada	1999	n/a	n/a	n/a	Trawl	Silver hake	Haddock	Saithe	Cod	36,168	16,404,779	454	0.110
Norway	1998	186	28	15.4	GN & HL	Cod	Herring	Saithe	Haddock	57,177	24,580,276	430	0.110
Norway	1998	113	44	17.8	Mobile seine	Cod	Herring	Haddock	Saithe	46,990	22,470,664	478	0.099
Norway	1998	39	105	23.9	Mobile seine	Herring	Cod	Saithe	Haddock	41,232	12,275,447	298	0.170
Norway	1998	80	24	15.1	Longline	Cod	Haddock	Herring	Gr. Halibut	20,698	11,830,644	572	0.079
Norway	1998	58	243	37.7	Longline	Cod	Ling	Tusk	Catfishes	87,819	33,504,939	382	0.130
Norway	1998	100	25	14.9	n/a	Cod	Herring	Saithe	Mackerel	22,096	13,009,412	589	0.085
Norway	1998	45	119	23.8	n/a	Herring	Cod	Saithe	Ling	49,127	12,206,742	248	0.220
Norway	1998	11	172	34.4	n/a	Cod	Saithe	Herring	Ling	10,099	4,111,744	407	0.120
Norway	1998	47	214	33.8	Trawl	Saithe	Cod	Herring	Haddock	80,843	35,072,904	434	0.110
Norway	1998	39	330	46.9	Trawl	Cod	Saithe	Haddock	Shrimp	84,174	41,696,137	495	0.088
Norway	1998	21	754	60.7	Trawl	Cod	Saithe	Redfish	Haddock	86,268	55,206,428	640	0.070
Iceland	1997	95	6	n/a	Gillnet	Cod	Plaice	Haddock	Redfish	1,763	2,701,121	1,532	0.029
Iceland	1997	145	53	n/a	Gillnet	Cod	Saithe	Haddock	Porbeagle	57,864	27,931,125	483	0.093
Iceland	1997	538	5	n/a	Handline	Cod	Saithe	Redfish	Haddock	24,031	13,692,120	570	0.078
Iceland	1997	38	7	n/a	Handline	Cod	Saithe	Catfish	Redfish	3,250	2,115,994	651	0.069
Iceland	1997	243	6	n/a	Longline	Cod	Haddock	Catfish	Tusk	12,858	6,918,738	538	0.084
Iceland	1997	136	63	n/a	Longline	Cod	Catfish	Haddock	Tusk	44,582	29,182,739	655	0.071
Iceland	1997	123	6366	n/a	Mobile seine	Cod	Dab	Plaice	Haddock	46,302	24,425,833	528	0.086
Iceland	1997	49	164	n/a	Trawl	Cod	Haddock	Saithe	Redfish	38,958	18,909,242	485	0.092
Iceland	1997	67	602	n/a	Trawl	Cod	Redfish	Saithe	Haddock	196,241	91,825,793	468	0.092
Iceland	1997	9	930	n/a	Trawl	Redfish	-	-	-	35,073	15,496,059	442	0.093
Germany	1998	306	n/a	n/a	Trawl	Cod	Plaice	Haddock	Sole	8,958	24,404,930	2,724	0.016
Germany	1998	7	n/a	n/a	Trawl	Plaice	Sole	Cod	-	2,045	4,741,768	2,319	0.018
Germany	1998	133	n/a	n/a	Trawl	Cod	Saithe	Sprat	Flounder	30,894	23,513,788	761	0.060
Germany	1998	8	n/a	n/a	Trawl	Redfish	Bl Whiting	Herring	Capelin	61,869	25,559,345	413	0.110

much larger Icelandic fisheries that together landed approximately 1.607 million tonnes in 1997 and consumed just over 32.2 million litres of fuel for a weighted average energy intensity of only 24 litres/tonne (0.86 GJ/t). The United States, represented by the Atlantic menhaden fishery with an energy intensity of 32 litres/tonne, had the next most energy efficient national fishery for small pelagic species.

The six Norwegian fisheries for which analyses were conducted had the second worst national average energy intensity. Together they landed a total of 1.81 million tonnes in 1998 and burned approximately 176 million litres of fuel for an average energy intensity of 97 litres/tonne (3.5 GJ/t). Finally, Germany's trawl fishery for small pelagics had the highest national average energy intensity at 112 litres/tonne (4.0 GJ/t).

Amongst the fisheries analyzed, only three fishing gears were used to target small pelagic species (Table 9). Of these, purse seining accounted for the lion's share of total landings at just over 3 million tonnes and enjoyed the lowest average gear-specific energy intensity at 50 litres/tonne (1.8 GJ/t). The three trawl fisheries for small pelagic species together accounted for about 590,000 tonnes and experienced an average energy intensity of 97 litres/tonne (3.5 GJ/t). Finally, the two mobile seine fisheries landed a total of approximately 176,000 tonnes and had the highest average energy intensity at 145 litres/tonne (5.2 GJ/t).

Fisheries targeting large pelagic species

Only one North Atlantic fishery targeting large pelagic species was analyzed (Table 9). The 1999 Canadian longline fishery for swordfish (*Xiphias gladius*) and tuna required almost 2.1 million litres of fuel to land approximately 1,200 tonnes of fish for an energy intensity of 1,740 litres/tonne or the resulting equivalent of about 63 GJ/tonne. This fishery's greenhouse gas emission intensity amounts to the equivalent of approximately 5.5 tonnes of CO_2/tonne landed.

Fisheries targeting invertebrates

A total of fourteen energy analyses were conducted representing twelve distinct fisheries or fleet sectors in which invertebrate species were targeted (Table 10). Given the peculiarities of these fisheries, aggregating them, either on a country or gear specific basis (beyond the principal species targeted), was not warranted.

Of the twelve invertebrate fisheries analyzed, eight were directed at shrimp and/or prawn (Table 10). When taken together, these fisheries landed a total of approximately 166,000 tonnes of shrimp along with an additional 17,000 tonnes of fish bycatch, and burned just over 168 million litres of diesel resulting in an average energy intensity of 918 litres/tonne (33.1 GJ/t). Interestingly, because almost all of the fish bycatch associated with these eight fisheries was concentrated in just three of the five Norwegian fleet subsets that targeted shrimp, it was also possible to evaluate the energy intensity of a typical contemporary 'clean' shrimp fishery. Accordingly, of the five directed shrimp fisheries in which fish bycatch accounted for less than 20% of the reported landings, a total of approximately 136 million litres of fuel was burned in the process of landing 149,000 tonnes of shrimp. The resulting energy intensity of 913 litres/tonne (32.9 GJ/t) associated with these 'clean' shrimp fisheries turns out to be essentially the same as the average of all eight fisheries taken together. In terms of greenhouse gas emissions, these eight fisheries released, on average, the equivalent of 2.9 tonnes of CO_2/tonne of shrimp and bycatch landed.

After shrimp, the next largest tonnage of invertebrates represented in the fisheries analyzed are those for scallops (Table 10). Specifically, two dredge/plough fisheries, one Icelandic and one Canadian, were analyzed. Of the two, the 1997 Icelandic fishery had the lower energy intensity at 293 litres or 10.6 GJ per live weight tonne landed. In contrast, the 1999 Canadian scallop fishery experienced an energy intensity of 358 litres/tonne (12.9 GJ/t). When taken together these two fisheries accounted for a combined total of almost 70,000 tonnes of scallops and burned approximately 24.3 million litres of fuel for a weighted average energy intensity of 347 litres/tonne (12.5 GJ/t) and a greenhouse gas emission intensity of 1.1 tonnes CO_2 equiv./tonne.

The next largest invertebrate fishery for which data were available was the 1999 Canadian crab trap fishery. In this case, approximately 6.8 million litres of fuel were consumed in the process of catching 20,600 live weight tonnes of various crab species. The resulting energy intensity of this fishery was 331 litres or the equivalent of 11.9 GJ per tonne. Consequently it released the equivalent of just over one tonne of CO_2 per tonne of crabs landed. The final invertebrate fishery for which data were available was the relatively small 1997 Icelandic trawl fishery for Norway lobster (*Nephrops norvegicus*; Table 10). This fishery, in which only 1,200 tonnes of lobster were taken together with approximately 4,500 tonnes of various species of fish, consumed a total of almost 5.85 million litres of fuel for an energy intensity of 1,025 litres/tonne (36.9 GJ/t) and a greenhouse gas emission intensity of approximately 3.2 tonnes of CO_2 equiv./tonne of all fish and shellfish landed.

Table 9. Summary of energy analysis of North Atlantic fisheries targeting small pelagic species (first 12 cases) and large pelagics (13th case). (All but the first case relied on indirect methods (see text).)

Country	Year	No. of vessels	Average GRT	Average length (m)	Gear type	Top four species landed (by weight)				Total landings (tonnes)	Fuel burned (litres)	Energy intensity (l/t)	Edible protein return
U.S	1999	13	595	52.4	Purse seine	Menhaden	-	-	-	153,717	4,980,822	32	1.67
Canada	1999	n/a	n/a	n/a	Purse seine	Herring	Capelin	Mackerel	-	119,877	2,378,611	20	2.66
Norway	1998	66	67	18.8	Mobile seine	Herring	Saithe	Mackerel	Cod	80,310	12,801,082	159	0.33
Norway	1998	42	110	25.1	Mobile seine	Herring	Saithe	Mackerel	Cod	95,637	12,761,887	133	0.40
Norway	1998	54	199	35.2	Trawl	Sandeels	Herring	Blue whiting	Norway pout	412,873	39,358,284	95	0.54
Norway	1998	34	396	46.7	Purse seine	Herring	Sandeels	Mackerel	Capelin	231,794	22,244,150	96	0.56
Norway	1998	16	668	59	Purse seine	Herring	Mackerel	Capelin	Sprat	125,857	15,819,770	126	0.42
Norway	1998	41	1,427	64.1	Purse seine	Blue whiting	Herring	Mackerel	Capelin	863,439	73,168,078	85	0.59
Iceland	1997	5	656	n/a	Trawl	Capelin	Herring	Blue whiting	-	69,173	5,636,814	81	0.60
Iceland	1997	14	480	n/a	Purse seine	Herring	Capelin	-	-	249,344	7,995,359	32	1.66
Iceland	1997	40	551	n/a	Purse seine	Capelin	Herring	-	-	1,288,693	24,575,780	19	2.24
Germany	1998	4	n/a	n/a	Trawl	Mackerel	Herring	Rnd Sardine	Pilchard	109,247	12,259,706	112	0.51
Canada	1999	n/a	n/a	n/a	Longline	Swordfish	Bigeyetuna	Bluefin tuna	-	1,204	2,095,406	1,740	0.034

Table 10. Summary of energy analysis of North Atlantic fisheries targeting invertebrates. (All but the first two cases relied on indirect methods (see text).)

Country	Year	No. of vessels	Average GRT	Average length (m)	Gear type	Top four species landed (by weight)				Total landings (tonnes)	Fuel burned (litres)	Energy intensity (l/t)	Edible protein EROI
Canada	1999	1	2,290	60.0	Trawl	Shrimp	-	-	-	4,281	3,100,598	724	0.041
Canada	1999	5	298	34.0	Dredge	Scallops	-	-	-	5,462	1,852,298	339	0.025
Canada	1999	n/a	n/a	n/a	Trawl	Nrthn prawn	Aesop shrimp	-	-	55,158	29,299,017	531	0.057
Canada	1999	n/a	n/a	n/a	Dredge	Sea scallop	Surf clam	-	-	59,331	21,234,021	358	0.027
Canada	1999	n/a	n/a	n/a	Trap	Queen crab	Rock crab	Jonah crab	-	20,601	6,814,461	331	0.057
Norway	1998	97	27	15.5	Trawl	Shrimp	-	-	-	5,185	12,142,597	2,342	0.014
Norway	1998	55	27	15.7	Trawl	Shrimp	Herring	Mackerel	Cod	7,904	11,853,363	1,500	0.031
Norway	1998	31	97	23.9	Trawl	Herring	Shrimp	Cod	Saithe	18,136	6,840,203	377	0.127
Norway	1998	15	387	39.8	Trawl	Shrimp	Cod	Saithe	Haddock	22,117	13,826,120	625	0.059
Norway	1998	9	699	54.0	Trawl	Shrimp	-	-	-	13,450	17,608,722	1,309	0.023
Iceland	1997	88	129	n/a	Trawl	Shrimp	-	-	-	32,614	29,415,952	902	0.033
Iceland	1997	37	552	n/a	Trawl	Shrimp	-	-	-	42,359	47,363,491	1,118	0.027
Iceland	1997	13	59	n/a	Dredge	Scallops	-	-	-	10,404	3,044,429	293	0.035
Iceland	1997	20	98	n/a	Trawl	Cod	Nrwy Lobster	Redfish	Witch	5,704	5,845,099	1,025	0.039

Changes in energy intensity over time

It was possible to evaluate changes in energy intensity through time for the nine Atlantic Canadian and 19 Icelandic fisheries for which data were available. Specifically, 14 years of data, spanning 1986 to 1999 inclusive, were available in the case of the nine Canadian fisheries, and 21 years of data, spanning 1977 to 1997 inclusive, were available for each of the 19 Icelandic fisheries.

Canadian fisheries

Changes in the energy intensity of the four Canadian groundfish fisheries analyzed are plotted in Figure 7. While there is a great deal of inter-annual variability in the energy intensity of three of the four Canadian groundfish fisheries illustrated in Figure 7, in general the energy intensity of all four has increased over the period from 1986 to 1999. Interestingly, and perhaps not surprisingly, the period of greatest variability in energy intensity for most of these fisheries coincides with the years immediately prior to, and during the collapse of Canada's northern cod stock. Finally, it is worth noting that for almost the entire interval analyzed, the mobile seine fishery experiences the lowest energy intensity of the four fisheries illustrated in Figure 7.

Changes in the energy intensity of the three Canadian invertebrate fisheries analyzed are plotted in Figure 8. Over the period from 1986 to 1999, the Atlantic Canadian shrimp fishery experienced marked changes in its energy intensity (Figure 8). After a period of steady decline through the late 1980s, its energy intensity increased rapidly from approximately 600 litres/tonne in 1989 to over 1,800 litres/tonne just four years later. Through the late 1990s, however, the trend again reversed itself to the point that by 1998, the fishery was once again consuming less than 600 litres of fuel per tonne of shrimp landed. In contrast, both the Atlantic Canadian crab and scallop fisheries have displayed much less dramatic changes in energy intensity over the period from 1986 to 1999 (Figure 8). Specifically, through the first half of the interval, the crab fishery enjoyed a general reduction in its energy intensity reaching a low of just under 200 litres/tonne in 1993. Since then, however, this fishery's energy intensity has been slowing trending upwards once again. Finally, while the scallop fishery's energy intensity has been the least volatile of the three Atlantic Canadian invertebrate fisheries considered, it has been slowly trending upwards, with only a few minor reversals, throughout the period from 1986 to 1999 (Figure 8).

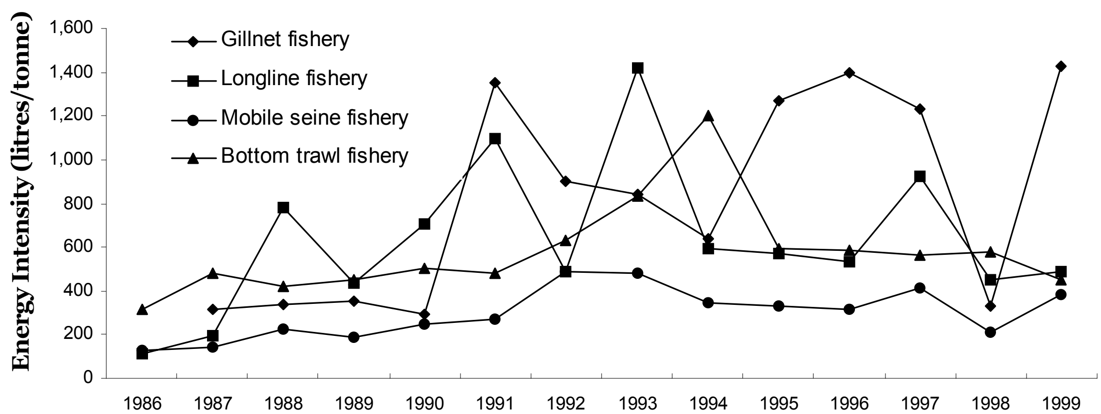

Figure 7. Changes in the energy intensity of Atlantic Canadian groundfish fisheries from 1986 to 1999.

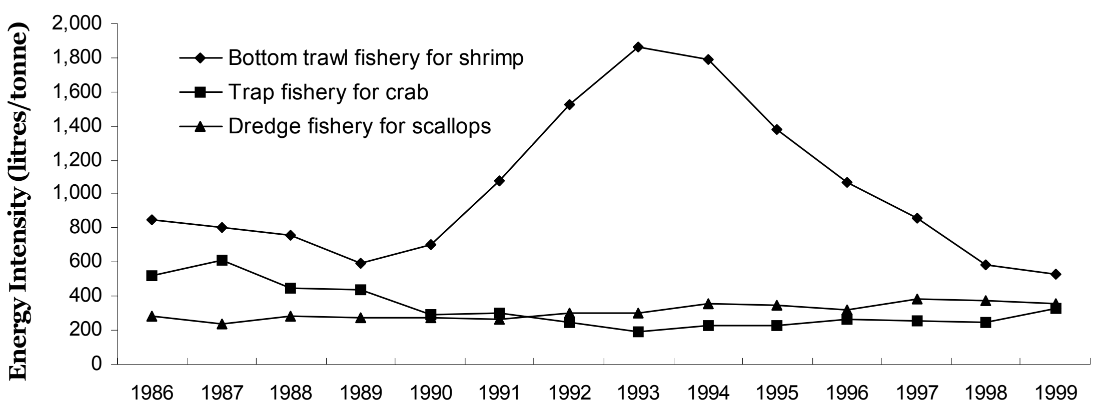

Figure 8. Changes in the energy intensity of Atlantic Canadian invertebrate fisheries from 1986 to 1999.

Changes in the energy intensity of Atlantic Canada's purse seine fishery for small pelagic species are illustrated in Figure 9. Although this fishery for small pelagic species is consistently the least energy intensive of all the Atlantic Canadian fisheries considered, it experienced approximately a doubling of its energy intensity over the period from 1986 to 1999 (Figure 9).

Changes in the energy intensity of Atlantic Canada's longline fishery for large pelagic species are illustrated in Figure 10. In addition to being the smallest fishery analyzed, with annual landings of typically under 2,000 tonnes, the longline fishery for large pelagic species is not only the most energy intensive of all the Canadian fisheries analyzed in most years, it also has the dubious distinction of achieving the highest one time energy intensity of any fishery considered in this analysis of just over 3,800 litres/tonne in 1996 (Figure 10).

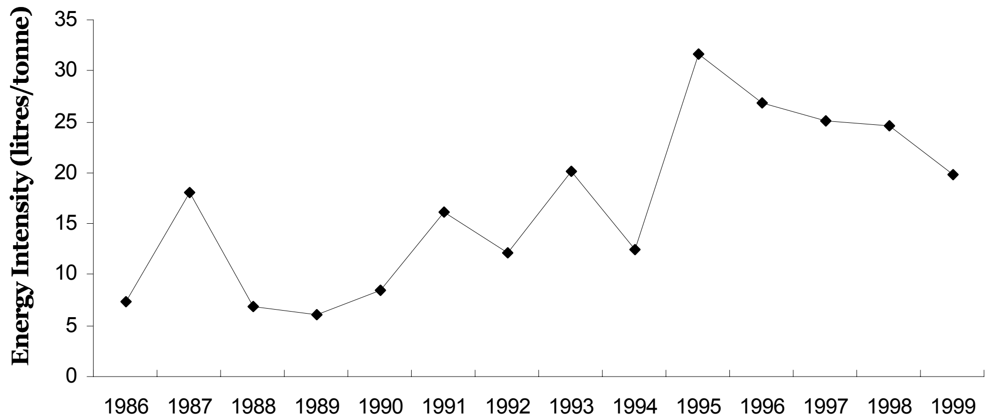

Figure 9. Changes in the energy intensity of Atlantic Canada's purse seine fishery for small pelagic species from 1986 to 1999.

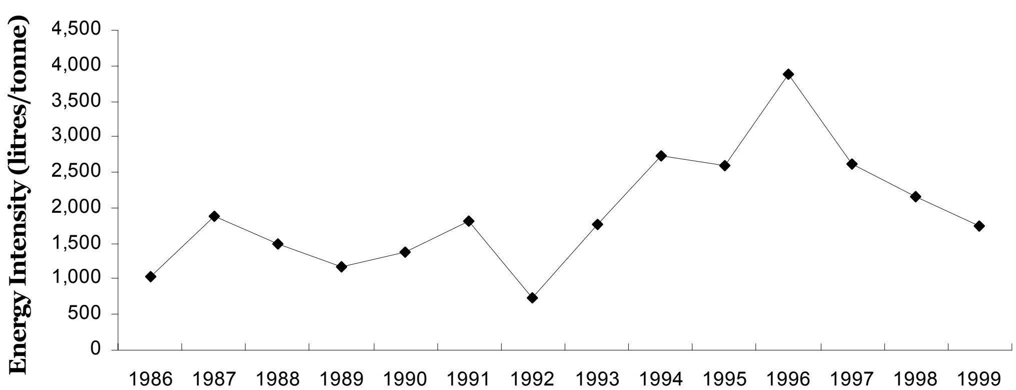

Figure 10. Changes in the energy intensity of Atlantic Canada's longline fishery for large pelagic species from 1986 to 1999.

Finally, changes in the total amount of fuel consumed annually by the nine Atlantic Canadian fisheries analyzed are illustrated in Figure 11.

What is most striking about the temporal changes in the total fuel consumed by the nine Atlantic Canadian fisheries considered, is the dramatic reduction that has occurred since 1991, coinciding with the collapse of the Northern cod stock (Figure 11). From a peak annual consumption of over 400 million litres of fuel in 1991, of which groundfish fisheries accounted for fully 80%, total fuel consumption has dropped to just 100 million litres in 1999.

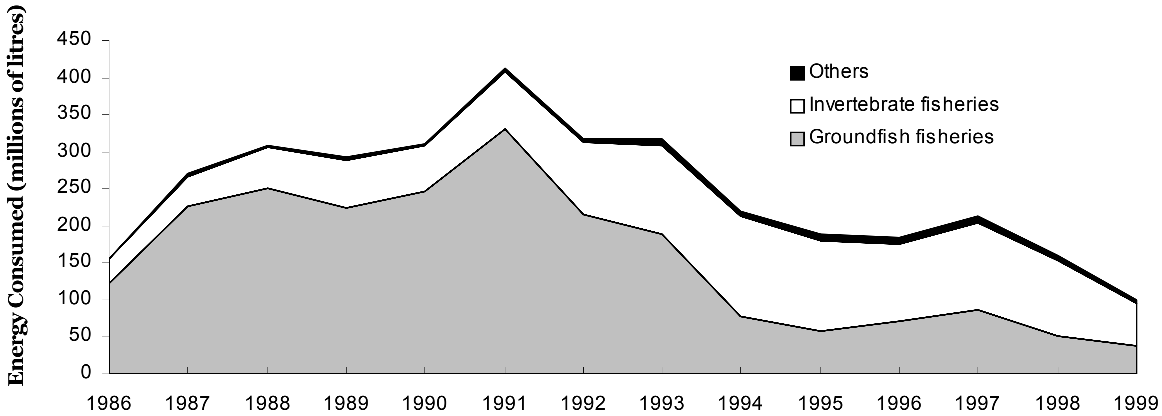

Figure 11. Changes in the total fuel consumed by nine Atlantic Canadian fisheries from 1986 to 1999.

Icelandic fisheries

Changes in energy intensity through time of nine Icelandic fisheries targeting groundfish species are illustrated in Figure 12.

Upon close inspection, a number of very interesting patterns emerge from the data presented in Figure 12. First, after an initial period of general decline through the late 1970s, the energy intensity of almost all of the groundfish fleet subsets illustrated in Figure 12 increased throughout much of the 1980s and early 1990s. Since then, however, all fleet subsets except one, the undecked boats deploying gillnet gear, have undergone a more or less pronounced decrease in their energy intensity. Second, the three fleet subsets composed of the smallest fishing vessels in the Icelandic groundfish fleet (i.e., undecked boats that are all demarcated by dashed lines in Figure 12) which were the least energy intensive at the beginning of the period illustrated in Figure 12, became the most energy intensive fleet segments throughout the 1990s. In contrast, trawlers, the fleet segment composed of the largest groundfish fishing vessels used in Iceland (demarcated by the heavy solid line in Figure 12), experienced a mid-range energy intensity through the late 1970s and early 1980s. However, since 1983 they have consistently been one of, if not the least energy intensive groundfish fleet subsets in operation in Iceland. Finally, many of the fleet subsets illustrated in Figure 12 display a sharp increase in their energy intensity in 1983. Interestingly, this was the last year before an individual transferable quota (ITQ) system was introduced by Icelandic management authorities to better manage its groundfish stocks (Hreidar Valtýsson, University of Akureyri, Iceland, pers. comm.) and it is possible that the marked energy intensity increases in 1983 reflect the extra lengths that fishers were willing to go to in trying to secure a larger fraction of the total quota allocation under the ITQ system starting in 1984.

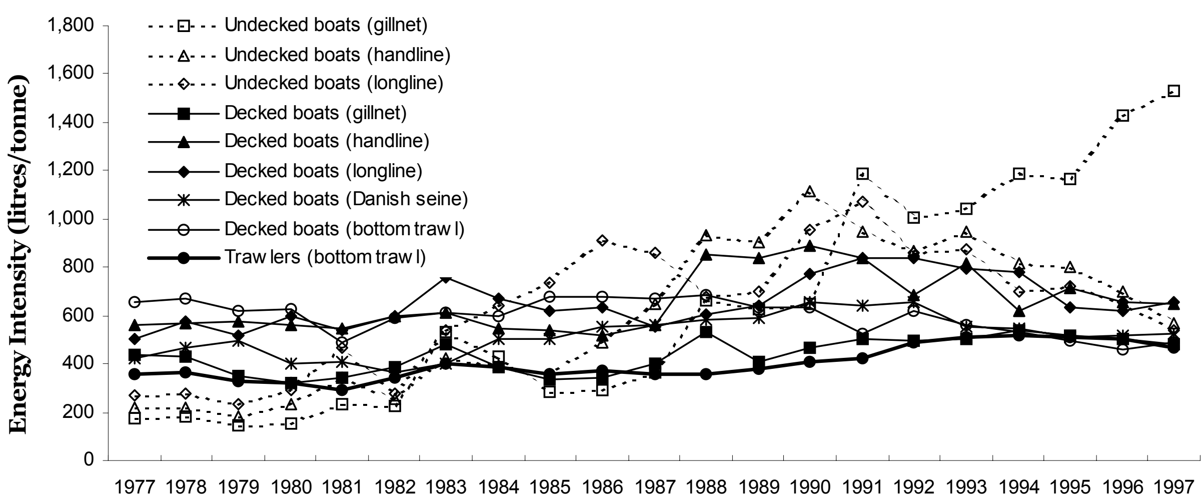

Figure 12. Changes in the energy intensity of Icelandic groundfish fisheries from 1977 to 1997.

Changes in the energy intensity of the three Icelandic fisheries targeting small pelagic species are illustrated in Figure 13. In years in which it has been conducted, the mid-water trawl fishery is not only the smallest, in terms of tonnes landed, of the three Icelandic fisheries directed at small pelagic species, it is typically the most energy intensive (Figure 13). Of the two fisheries for small pelagic species conducted continuously through the period from 1977 to 1997, the purse seine fishery for herring has been markedly more energy intensive in most years than the purse seine fishery for capelin. What is most remarkable about this latter fishery has been its consistently low energy intensity through time. Specifically, only once in the 21 years for which data were available has the purse seine fishery for capelin experienced an energy intensity of over 30 litres/tonne.

Changes in the energy intensity through time of the four Icelandic fisheries targeting invertebrates are illustrated in Figure 14. Of these Icelandic invertebrate fisheries, the two bottom trawl fisheries for shrimp employing either decked boats or trawlers, are typically the most energy intensive (Figure 14). Interestingly, while there were often large differences in the energy intensity experienced by these two size classes of vessels fishing for shrimp prior to 1988, since then their energy intensities have both been very similar and have largely declined over time. Over the period for which data were available, the relatively small tonnage fishery for Norwegian lobster has experienced a relatively consistent though generally high-energy intensity of between 800 and 1,300 litres/tonne (Figure 14). As was the case in the Canadian scallop fishery, the energy intensity of the Icelandic scallop fishery varied little from year to year but generally trended upward over the period from 1977 to 1994.

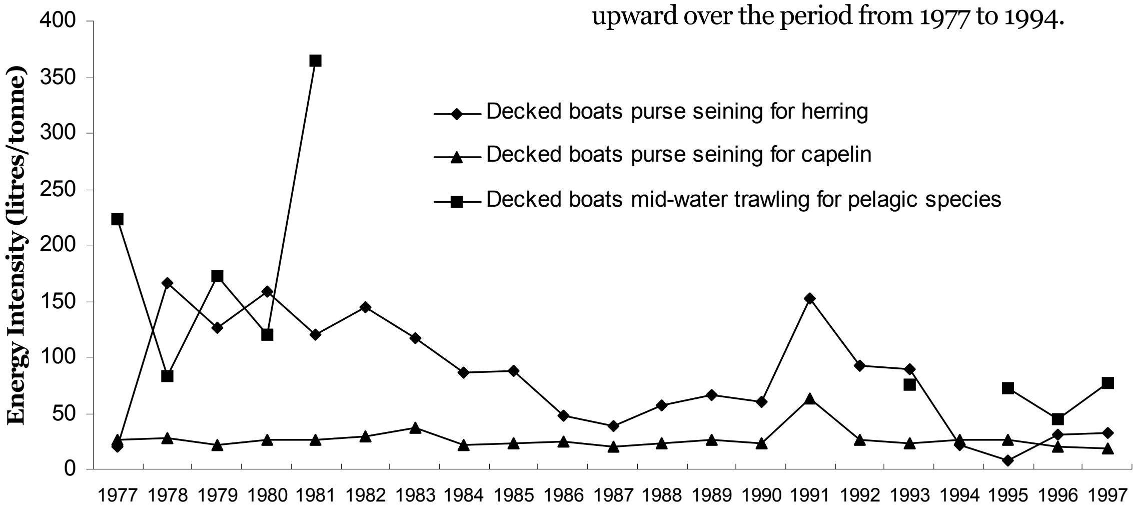

Figure 13. Changes in the energy intensity of Icelandic fisheries for small pelagic species from 1977 to 1997.

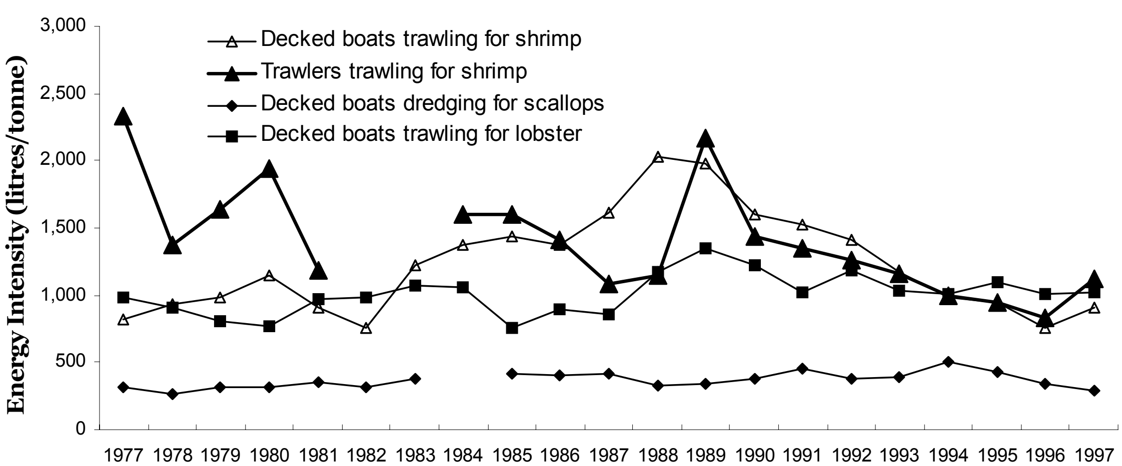

Figure 14. Changes in the energy intensity of Icelandic invertebrate fisheries from 1977 to 1997.

Finally, changes in the total amount of fuel consumed annually by the entire Icelandic commercial fishing industry are illustrated in Figure 15. Except for a minor reversal in 1984-85, the total amount of fuel consumed annually by all Icelandic fisheries increased steadily through the period from 1977 to 1991 when it peaked at almost 450 million litres. Between 1991 and 1996, however, the total annual energy inputs to Icelandic fisheries declined steadily, only to increase once again in 1997. On a broad sectoral basis, the combined Icelandic groundfish fisheries account for the lion's share of total fuel inputs in any given year. Interestingly, however, since 1982, when groundfish fisheries accounted for 90% of the total fuel consumed, their proportion of the total has slowly been reduced over time to the point that in 1997, they only represented 65% of the total. The one broad fishing sector whose total annual energy inputs have consistently increased over the period from 1977 to 1997 has been the invertebrate fisheries.

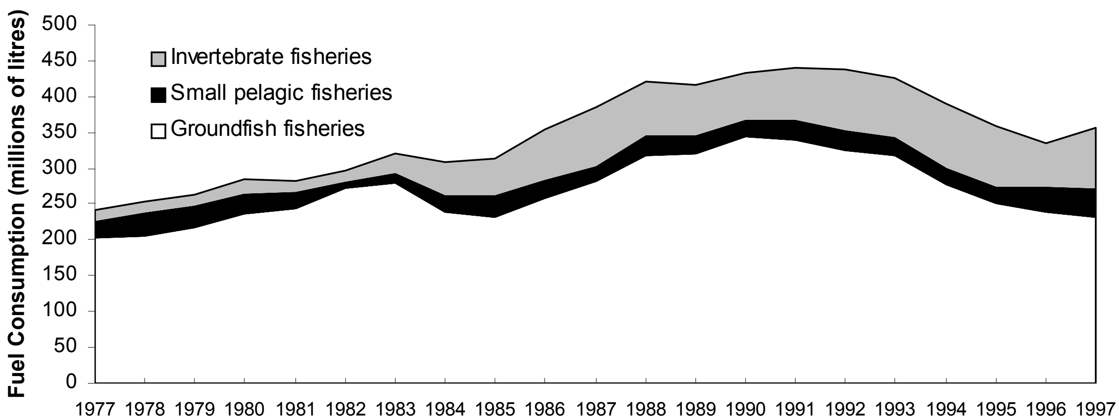

Figure 15. Changes in the total fuel consumed by Icelandic fisheries from 1977 to 1997.

Edible protein energy returns on investments

Of the four major types of fisheries analyzed, those targeting small pelagic species consistently had the highest edible protein returns, ranging from 0.33 to over 2.6 (Table 9). Taken together, the overall mean edible protein returns of these 12 fisheries was about 1.3. In other words, contemporary North Atlantic fisheries for small pelagic species yield, on average, 1.3 times as much potentially edible protein energy than is contained in the fossil fuel consumed for catching it. A very important point to note, however, is that the vast majority of the landings by these fisheries is destined for reduction to fishmeal and oil and not for direct human consumption. As a result, only a tiny fraction of the edible protein that they yield is ultimately available for human consumption.

Amongst fisheries whose catches are destined for direct human consumption, those targeting groundfish had protein returns ranging from just under 0.02 to a high of 0.25 (Table 8). Taken together, the mean edible protein return of all 29 groundfish fisheries, in the most recent years for which data were available, was 0.095. In contrast, the mean edible protein return of all invertebrate fisheries considered was 0.039. However, between individual fisheries, values varied from 0.014 to almost 0.13 (Table 10).

Recent temporal changes in the edible protein returns of Icelandic and Canadian groundfish and invertebrate fisheries are illustrated in Figures 16 and 17 respectively. Of note, there has been a more or less steady decline in the edible protein return of both country's groundfish fishing sector over the periods for which data were available. In contrast, although the mean edible protein returns of invertebrate fisheries in both Iceland and Canada are markedly lower than those of the groundfish sector, they have remained much more consistent over time, and in recent years have improved in both countries.

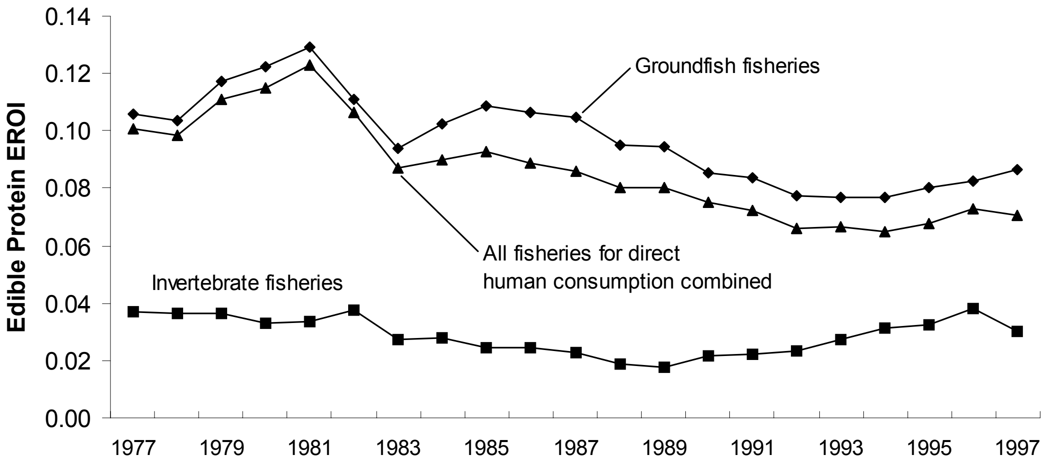

Figure 16. Changes in the edible protein returns of Icelandic groundfish and invertebrate fisheries from 1977 to 1997.

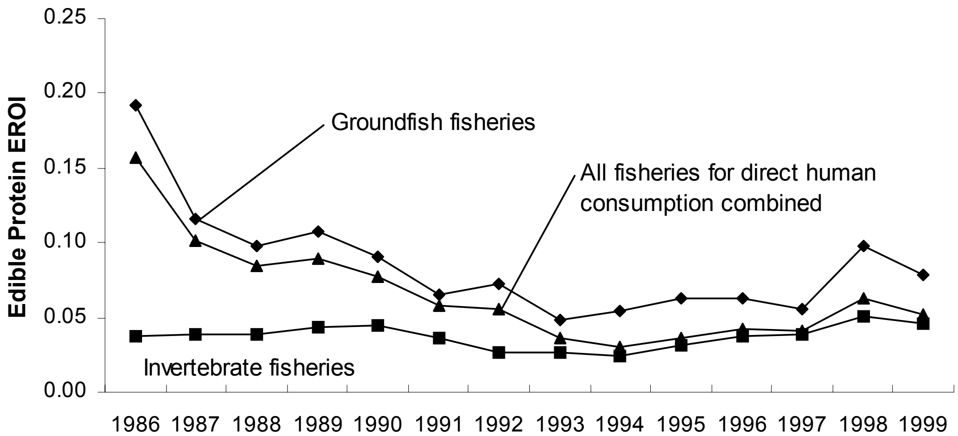

Figure 17. Changes in the edible protein returns of Canadian groundfish and invertebrate fisheries from 1986 to 1999.

DISCUSSION

Validating the methods used

Given the novelty of the technique used to quantify energy inputs to most of the fisheries analyzed (as outlined in Equation 2), I was anxious to confirm or 'ground truth' my results where possible. Such an opportunity arose within the context of the energy inputs to Icelandic trawlers. In a report prepared for the Fisheries Association of Iceland and the Icelandic Ministry of Fisheries, Ragnarsson (1985) provides estimates of the total litres of fuel consumed annually by Icelandic side and stern trawlers over the period from 1972 to 1984. By summing these estimates and plotting them beside the total annual energy input estimates that I derived for all Icelandic trawlers, regardless of the species group targeted, I found an extremely good agreement for all the years in which the two time series overlap (Figure 18).

Thus, the methods used in this analysis appear appropriate, particularly when:

- there are sufficient real world vessel performance data from which gear-specific fuel consumption rate estimates can be based; and
- data are available that accurately reflects average vessel horsepower and total days at sea for any fleet or fleet sub-set of interest.

Comparing contemporary North Atlantic fisheries with other commercial fisheries

Gear-specific mean energy intensities for each major targeted groups were calculated and tabulated along with the results of previous energy analyses for comparison of the energy performance of contemporary North Atlantic fisheries with those in other parts of the world (Table 11). In general, the energy intensities of contemporary North Atlantic fisheries are broadly consistent with those of similar fisheries conducted elsewhere in the world.

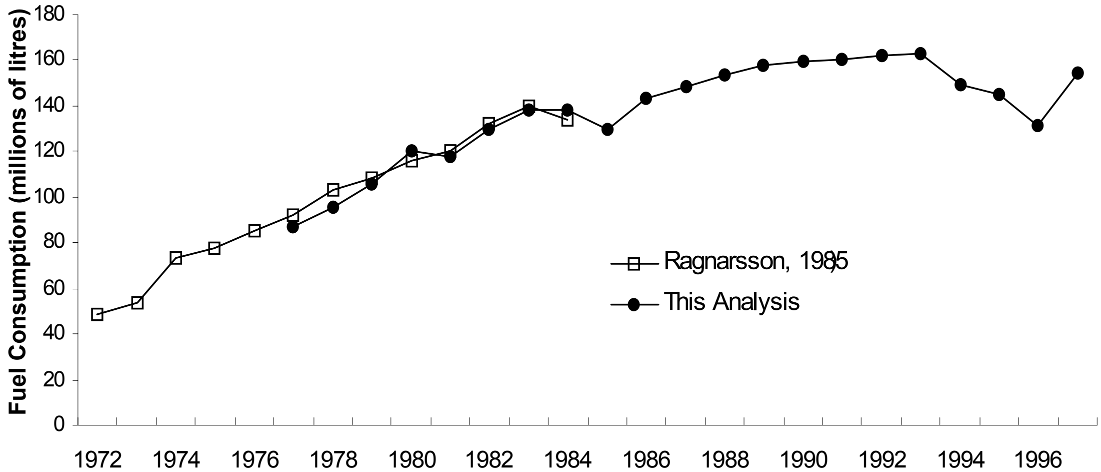

Figure 18. Total fuel consumed annually by Icelandic trawlers as determined by Ragnarsson (1985) and in the present study.

Comparing contemporary North Atlantic fisheries with other protein producing sectors

Using mean edible protein returns, it is possible to compare the energy performance of contemporary North Atlantic fisheries with other protein producing sectors (Table 12). While the protein energy output of contemporary North Atlantic fisheries for direct human consumption is only a small fraction of the fossil fuel energy that they consume, they fall well within the range of other protein producing sectors. In fact, even the two poorest performing North Atlantic fishing sectors, those targeting invertebrates and large pelagic species, have better protein returns than many livestock and intensive aquaculture systems.

Reflecting both their size and highly industrialized character, contemporary North Atlantic fisheries are major consumers of energy and emitters of greenhouse gasses. The relative significance, however, of fisheries as energy consuming sectors within economies, varies widely amongst North Atlantic countries. For example, Iceland's fishing industry accounts for fully one third of the entire nation's fossil fuel consumption and greenhouse gas emissions (Árnason and Sigfússon, 2000). This contrasts with larger, highly diversified economies such as the United States and Germany, where fishing accounts for only a small fraction of total national energy consumption and greenhouse gas emissions.

Of much greater significance and concern, however, than the relative scale of commercial fishing as an energy consuming sector within North Atlantic economies, is the fact that for many fisheries there are very clear signs of ever increasing dependence on fossil fuels and decreasing yields per unit of energy expended. Amongst those North Atlantic fisheries analyzed, this trend is particularly evident in both Icelandic and Canadian groundfish and scallop fisheries, and Canadian fisheries targeting small and large pelagic species. Even though this general pattern has been documented previously in other fisheries, in other parts of the world (Brown and Lugo 1981, Watanabe and Uchida 1984, Sato *et al.,* 1989, Mitchell and Cleveland 1993), it is deeply troubling given the state of many of the world's fish stocks, the finite nature of fossil energy resources (Duncan and Youngquist, 1999, 2001) and the ever increasing scarcity of industrial energy availability per capita globally (Duncan, 1993).

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Table 11. Comparison of commercial fishery energy intensities.

Fishery (home base or location)	**Energy intensity (GJ/t)**	**Analysis includes energy inputs to**	**Source**
Purse seining for capelin (Iceland)	0.7	Fuel	Ágústsson (1978)
Purse seining for small pelagics (N. Atl.)	**1.8**	**Fuel**	**This study**
Purse seining for herring (Maine, U.S.)	2.2 to 2.4	Fuel, gear, vessels	Rawitscher (1978)
Set nets for various species (Japan)	2.9	Fuel	Nomura (1980)
Trawling for small pelagics (N. Atlantic)	**3.5**	**Fuel**	**This study**
Mobile seining for small pelagics (N. Atl.)	**5.2**	**Fuel**	**This study**
Purse seining for herring (B.C., Canada)	5.8	Fuel, vessels	Tyedmers (2000)
Trawling for pollock (Japan)	7.5	Fuel	Nomura (1980)
Trawling for perch (Maine, U.S.)	6 to 8	Fuel, gear, vessels	Rawitscher (1978)
Jigging for squid (Japan)	7.2 to 72	Fuel	Sato *et al.* (1989)
Trapping crabs (Maryland, U.S.)	8 to 10	Fuel, gear, vessels	Rawitscher (1978)
Purse seining for pelagics (Japan)	10	Fuel	Nomura (1980)
Trawling for groundfish (Wash. U.S.)	10	Fuel, vessels and other	Wiviott and Mathews (1975)
Trapping crabs (N. Atlantic)	**12**	**Fuel**	**This study**
Dredging for scallops (N. Atlantic)	**13**	**Fuel**	**This study**
Gillnetting pink salmon (Washington, U.S.)	13 to 19	Fuel, gear, vessels	Rawitscher (1978)
Mobile seine for groundfish (N. Atlantic)	**16**	**Fuel**	**This study**
Purse seining for salmon (B.C., Canada)	17	Fuel, gear, vessels	Tyedmers (2000)
Longlining for groundfish (N. Atlantic)	**18**	**Fuel**	**This study**
Trawling for cod (Massachusetts, U.S.)	18 to 20	Fuel, gear, vessels	Rawitscher (1978)
Trawling for groundfish (N. Atlantic)	**19**	**Fuel**	**This study**
Trawling for flounder (Rhode Island, U.S.)	20 to 22	Fuel, gear, vessels	Rawitscher (1978)
Jigging for squid (Japan)	20 to 44	Fuel	Nomura (1980)
Handlining for groundfish (N. Atlantic)	**21**	**Fuel**	**This study**
Trawling for pollock (Japan)	21 to 84	Fuel and other	Watanabe and Uchida (1984)
Gillnetting for groundfish (N. Atlantic)	**23**	**Fuel**	**This study**
Purse seining for tuna (California, U.S.)	31 to 62	Fuel, gear, vessels	Rawitscher (1978)
Trawling for shrimp (N. Atlantic)	**33**	**Fuel**	**This study**
Trawling for croaker (Japan)	33 to 75	Fuel and other	Watanabe and Uchida (1984)
Gillnetting for salmon (B.C., Canada)	34	Fuel, gear, vessels	Tyedmers (2000)
Trolling for salmon (B.C., Canada)	34	Fuel, gear, vessels	Tyedmers (2000)
Trawling for Norway lobster (N. Atlantic)	**37**	**Fuel**	**This study**
Trawling for shrimp (Australia)	38	Fuel, vessels	(Leach 1976)
Trawling for groundfish (Japan)	38	Fuel	Nomura (1980)
Trawling for haddock (Massachusetts, U.S.)	34 to 42	Fuel, gear, vessels	Rawitscher (1978)
Pole & line for skipjack (Japan)	42	Fuel	Nomura (1980)
Driftnetting for salmon (Japan)	44 to 68	Fuel	Nomura (1980)
Longlining for halibut (U.S.)	48 to 51	Fuel, gear, vessels	Rawitscher (1978)
Trawling for groundfish (Japan)	52	Fuel, vessels and other	Wiviott and Mathews (1975)
Longlining for swordfish/tuna (N. Atlantic)	**63**	**Fuel**	**This study**
Trolling for chinook salmon (Washington, U.S.)	82 to 87	Fuel, gear, vessels	Rawitscher (1978)
Longlining for tuna (Japan)	84 to 134	Fuel	Nomura (1980)
Trapping lobster (Maine, U.S.)	141 to 145	Fuel, gear, vessels	Rawitscher (1978)
Trawling for shrimp (Texas, U.S.)	270 to 312	Fuel, gear, vessels	Rawitscher (1978)
Trawling for shrimp (U.S.)	358	Fuel	Leach (1976)

Table 12. Protein returns for various food production systems

Food production system	Edible Protein EROI	Source
Carp farming (Indonesia)	0.70	Ackefors *et al.* (1993)[a)]
Kapenta fishery (Zimbabwe)	0.25	Michélsen (1995)[b)]
Groundfish trawl fishery (Washington State - 1970's)	0.17	Wiviott and Mathews (1975)
All commercial fishing (New Bedford Mass., 1968 to 1988)	0.17 declining to 0.03	Mitchell and Cleveland (1993)
Salmon purse seine fishery (British Columbia)	0.14	Tyedmers (2000)
Tilapia farming (Africa)	0.11	Ackefors *et al.* (1993)[a)]
Mussel farming (Scandinavia)	0.10	Folke and Kautsky (1992)[b)]
Contemporary North Atlantic groundfish fisheries	**0.095**	**This study**
Carp farming (Israel)	0.084	Ackefors *et al.* (1993)[a)]
Sea ranched Atlantic salmon (Sweden)	0.083	Folke and Kautsky (1992)[b)]
Turkey (USA)	0.077	Pimentel (1997)[c)]
Milk (USA)	0.071	Pimentel (1997)[c)]
Salmon gillnet fishery (British Columbia)	0.068	Tyedmers (2000)
Salmon troll fishery (British Columbia)	0.068	Tyedmers (2000)
Tilapia farming (Israel)	0.066	Ackefors *et al.* (1993)[a)]
Tilapia semi-intensive pond culture (Zimbabwe)	0.060	Berg *et al.* (1996)
Swine (USA)	0.056	Pimentel (1997)[c)]
Cod fishery (USA - 1970's)	0.050	Folke and Kautsky (1992)[b)]
Contemporary North Atlantic invertebrate fisheries	**0.039**	**This study**
Egg production (USA)	0.038	Pimentel (1997)[c)]
Contemporary North Atlantic longline fishery (large pelagics)	**0.034**	**This study**
Catfish - intensive pond culture (USA)	0.030	Pimentel *et al.* (1996)
Chicken (USA)	0.029	Ackefors *et al.* (1993)[a)]
Tilapia - intensive cage culture (Zimbabwe)	0.025	Berg *et al.* (1996)
Atlantic salmon - intensive cage culture (British Columbia)	0.025	Tyedmers (2000)
Shrimp- semi-intensive culture (Colombia)	0.020	Larsson *et al.* (1994)
Chinook salmon - intensive cage culture (British Columbia)	0.020	Tyedmers (2000)
Lamb	0.020	Pimentel (1997)[c)]
Atlantic salmon - intensive cage culture (Sweden)	0.020	Folke and Kautsky (1992)[b)]
Beef (USA)	0.019	Pimentel (1997)[c)]
Seabass - intensive culture (Thailand)	0.015	Pimentel *et al.* (1996)
Shrimp - intensive culture (Thailand)	0.014	Pimentel *et al.* (1996)

Note: a.) Ackefors *et al.* (1993) do not cite the original sources of these data. In addition, as they only provide energy inputs per gram of protein produced, these were converted to protein return ratios based on protein's energy density of 17.9 kJ/gram;
b.) As cited in Berg *et al.* (1996);
c.) Energy inputs to contemporary US livestock production systems as reported by Pimentel (1997) only include the energy needed to provide feed inputs (Dr. David Pimentel, pers. comm. 1999).

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