QUANTIFYING THE ENERGY CONSUMED BY NORTH ATLANTIC FISHERIES

Peter Tyedmers[1]

Fisheries Centre,
The University of British Columbia,
Vancouver, Canada V6T 1Z4

ABSTRACT

As part of the *Sea Around Us Project* at the University of British Columbia, an analysis is being conducted of the fuel energy consumed by contemporary North Atlantic fisheries. Where possible, this will include evaluating changes in energy consumption over time for specific fisheries. The purpose of this paper is to describe the methods that will be used to achieve these ends. After reviewing the major findings of the published fisheries energy analysis literature, this paper introduces the two major thrusts of the planned research, and describes the techniques that will be used to address them. Specifically, there is a need to broadly apportion basin-wide catch data on a fishing gear- and vessel class-specific basis, along with a need to update fuel consumption estimates for a wide range of fisheries and fishing gear types. In support of the latter task, this paper summarizes my efforts to date acquiring detailed fuel consumption, catch, effort, and associated vessel description data for a variety of contemporary North Atlantic fisheries. Using two examples, I illustrate how data gathered in this way will be used directly to estimate the total fuel inputs to the associated fisheries. This is followed by a discussion and a further example of how generic fuel consumption rates based on vessel characteristics and fishing effort will be generated for specific gear sectors and applied to indirectly estimate the total fuel consumed in other fisheries. The paper ends by describing and providing examples of the ways in which fishery-specific and North Atlantic-wide fuel consumption estimates will ultimately be presented that facilitate comparison both amongst the fisheries evaluated and between fisheries and other food production sectors.

[1] Resource Management and Environmental Studies, 2206 East Mall, University of British Columbia, Vancouver, B.C. Canada V6T 1Z3 and *Sea Around Us Project*, Fisheries Centre, UBC (E-mail address: tyedmers@interchange.ubc.ca).

INTRODUCTION

The purpose of this paper is to describe the methods that will be used to quantify the major culturally mediated energy inputs to contemporary North Atlantic fisheries. In addition, examples will be provided that illustrate some of the techniques that will be used along with the forms in which the results will be expressed.

Key Terms Defined

Culturally mediated energy: fossil fuel and electrical energy dissipated in the process of human activities.

Energy intensity: the amount of direct and indirect culturally mediated energy required to provide a given quantity of a product or service of interest. In the current context, energy intensity is expressed in terms of the MJ of energy required to yield a round or live weight mass of fish or shellfish harvested.

Ecological Footprint: the area of land and/or water required to produce the resources consumed and to assimilate the wastes generated by a given population or activity on a continuous basis, wherever on Earth that land/water occurs.

Energy Return on Investment (EROI) ratio: a dimensionless ratio calculated by dividing the amount of useful energy produced 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 days: the number of complete or partial days in which a fishing vessel engages in fishing activities.

Sea days: the number of complete or partial days in which a fishing vessel is away from port on fishing related activities. Note, for a given fishing trip fishing days are always less than or equal to sea days.

As with all human activities, commercial fishing entails the consumption (or more accurately the dissipation) of matter and energy in support of their primary activity, the catching and killing 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, research indicates that they can be substantial. Moreover, they have real, if indirect, ecological impacts in and of themselves.

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, Nomura 1980, Brown and Lugo, 1981, Hopper, 1981, Veal et al. 1981). 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 fish gear, and labour (Wiviott and Mathews, 1975, Rochereau 1976, Leach 1976, Edwardson, 1976, Rawitscher 1978, Lorentzen 1978, Tyedmers, forthcoming dissertation).
- Energy intensity can vary considerably between fishing gears 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)[2].
- In many cases, energy intensity was found to increase with vessel size within a given gear sector and fishery (Wiviott and Mathews, 1975, Rochereau 1976, Edwardson, 1976, Lorentzen 1978). However, exceptions to this have also been found (in particular, see Figure 1 in Edwardson, 1976).
- The energy intensity of a given fishery can increase dramatically over time as fisheries resources become scarcer, fleets expand, the average size of vessels increase, vessels travel further to fish, and become more technologically advanced (Brown and Lugo, 1981, Mitchell and Cleveland 1993)[3].

As part of the *Sea Around Us Project* at the University of British Columbia, I am undertaking an energy analysis of the fisheries of the North Atlantic. Ideally, such an analysis would 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 labour inputs.

However, because of the large number of fisheries to be considered, the heterogeneity that exists both between and within the fleets involved[4], and the general difficulty accessing reliable representative data the analysis will focus exclusively on estimating the direct fuel energy inputs to contemporary North Atlantic fisheries. Notwithstanding the above, in order to explore recent trends in energy use in commercial fisheries, fuel consumption time series estimates will be constructed for selected North Atlantic fisheries where necessary data are available.

METHODS TO BE USED

Estimating the total fuel energy inputs to as diverse a range of fisheries as currently occur in the North Atlantic presents two main challenges:

1. the catch must be broadly apportioned between fishing gears and sizes of vessels used; and
2. there is a need to update energy intensity estimates to better reflect contemporary North Atlantic fisheries.

Apportioning the Catch Amongst Fishing Gears and Vessel Classes

An important step in the process of estimating the total fuel energy consumed by contemporary North Atlantic fisheries will be to allocate the catch based on both the type of fishing gear used and the typical size class of vessel employed. This

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[2] An exception to this relative energy intensity pattern occurs with respect to longlining, a passive fish harvesting technology which typically requires relatively large energy inputs relative to the amount of fish landed (Rawitscher 1978, Nomura, 1980).

[3] For example, Brown and Lugo (1981) estimated that between 1967 and 1975, while the fuel consumed by the entire 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, but on a smaller scale, Mitchell and Cleveland (1993) found 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.

[4] With respect to the types of gears used, the size of vessels within each fleet, and the complex material composition of fishing vessels and gears.

is because energy inputs vary with respect to both of these parameters.

In the case of some species, this will be a fairly straightforward process. For example, most contemporary Atlantic menhaden (*Brevoortia tyrannus*) landings are made using relatively large (over 500 gross ton) purse seiners. Similarly, trawling accounts for the majority of contemporary North Atlantic shrimp and prawn landings, while lobsters (*Homarus* spp.) are caught using traps deployed from relatively small vessels and scallops are harvested by dredging.

In other cases, however, where a given species of fish or shellfish is typically harvested using more than one type of fishing gear[5], or vessels of dramatically different sizes, the North Atlantic-wide landings of these species will have to be apportioned accordingly[6]. This will be done using detailed catch statistics that relate landings to fishing gear and size of vessel employed. To this end, *Sea Around Us Project* team members are assembling statistics of catch by gear and vessel size from a variety of sources (see Watson et al. 2000 for a description of this process). For example, unpublished data sets that relate landings to fishing gear used, vessel size, and horsepower, and total fleet effort (measured either in terms of fishing days or days at sea) have been received and are currently being processed by the team for both Canadian and foreign fishing vessels operating in Canada's Atlantic Exclusive Economic Zone. Similar data sets are currently on order for U.S. North Atlantic fisheries.

However, complete detailed coverage of all North Atlantic fisheries will not be possible given the limitations of the data available. It will therefore be necessary to apply the proportion of the gear- and vessel size-specific catch of each major species from the countries and regions of the North Atlantic for which data are available to the landings of the entire North Atlantic. In the final report of this project, the extent of this extrapolation from known to total catch of the major species will be presented and the uncertainties that result will be discussed.

Estimating the Fuel Energy Inputs to Contemporary Fisheries and Gear Sectors

While many of the published commercial fishery energy analyses were conducted on North Atlantic fisheries, virtually all are based on primary data collected during the 1970's (Appendix). Because of changes that have been likely to occur over the last 25 to 30 years[7], I am reluctant to directly apply energy intensity estimates from fisheries of the 1970s to those of the late 1990s unless absolutely necessary. Consequently, I am actively updating estimates of fuel energy inputs to a wide range of contemporary fisheries and gear types using two main approaches.

Direct Solicitation of Fuel Consumption Data

I have begun to solicit annual fuel consumption, landings and temporal fishing effort (both fishing days and sea days) data together with the physical characteristics of the associated vessels from companies and individuals currently engaged in North Atlantic fisheries. Table 1 summarizes the fisheries, gear types, and vessel characteristics represented by this data collection effort to date[8] and presents preliminary estimates of the resulting fuel consumption per live weight tonne of fish or shellfish harvested.

To illustrate how fuel consumption and landings data will be used to estimate total fuel energy inputs to specific contemporary North Atlantic fisheries, preliminary estimates were made of the total direct fuel consumption associated with the 1997 Atlantic menhaden fishery (below) and the 1997 North Atlantic-wide scallop fisheries (adjacent).

Although by the end of the project I intend to have acquired data representing many more vessels and fisheries than are outlined in Table 1,

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[5] For example, Atlantic cod (*Gadus morhua*) are harvested using bottom trawls, seines, gillnets, traps, and longlines while bluefin tuna (*Thunnus thynnus*) are harvested using purse seines, seines, gillnets, traps, hook and line and harpoon.

[6] While apportioning the catch based on gear type used will be straightforward, because fishing vessel size, either measured in terms of vessel length, gross tonnage or horsepower varies over a continuum, for simplicity it will be necessary to establish some arbitrary size classes. For example, appropriate size classes that might be used are as follows: under 5 gross tonnes (GT), from 5 to 50 GT, from 50 to 150 GT, from 150 to 500 GT, from 500 to 1000 GT, from 1000 to 2000 GT, and over 2000 GT (Ruttan, et al. 2000).

[7] Particularly with respect to: stock abundance, fleet size, average fishing trip length, average vessel size and horsepower, engine fuel efficiency and types of fuel used, etc. (see Brown and Lugo (1981) and Mitchell and Cleveland (1993) for examples of how fuel energy inputs to fisheries can change over time).

[8] Other fisheries for which fuel consumption inquiries have been initiated include the English groundfish trawl and longline fishery in the English Channel, and the Icelandic capelin trawl and purse seine fisheries and groundfish trawl fisheries.

the extent of data coverage will vary widely between fisheries. In some cases, vessels for which I have data will represent a relatively large proportion (>50%) of the total annual basin-wide catch of a given species. In these cases, the extrapolated

Table 1. Fisheries, Gears and Vessels for Which Fuel Consumption Data has been Acquired.

Fishery	Gear Type	Vessel Size (Tonnage/HP)	Vessel(s) Represented	Annual Catch by Vessel(s) (round tonnes)	Fishing Seasons Represented[a]	Fuel Consumption[b] (litres/tonne)
Shrimp - NW Atlantic	Trawl	2,290/4,023	1 Freezer Trawler	~4,200	1993 to 1999 inclusive	850
Atlantic menhaden - US	Purse seine	540/1,800 to 750/2,000	13 Purse Seiners	~175,000	1998 & 1999	31.5
Gulf menhaden - US [c]	Purse seine	540/1,800 to 750/2,000	37 Purse Seiners	~400,000	1998 & 1999	39.2
Ground fish - NW Atlantic	Trawl	540/1,300 to 802/2,400	8 Trawlers	~10,000	1999	347
Cod - NW Atlantic	Norwegian Seine	545/1,250	2 Seiners	~1,000	1999	230
Scallops - Georges Bank	Dredge	309/765 to 330/990	5 Draggers	~5,500	1998 & 1999	350

Notes:

a. Data represents all fishing trips undertaken during the years indicated.

b. Calculated by dividing the total fuel consumed in litres for all vessels and seasons represented by the total resulting landings in round or live weight tonnes.

c. For the purposes of our project, the Gulf of Mexico is not considered part of the North Atlantic. However, data from the Gulf menhaden fishery may be used to help characterise purse seine fisheries generally.

estimates of the total fuel consumed by the basin-wide fishery will be relatively robust. In other instances, however, the data coverage may only amount to the equivalent of few percent of the total annual catch. Consequently, the resulting extrapolated estimates of total fuel consumed will be less accurate. As part of the final report, the uncertainties that result from extrapolating from sample sets of various sizes will be discussed.

Because acquiring fuel consumption data directly from fishers and fishing companies is a slow, labour intensive process and at best only a small fraction of all the fishing vessels active in the North Atlantic can be canvassed[9] I am

Example 1 - Fuel Inputs to All North Atlantic Atlantic Menhaden Fisheries in 1997

Omega Protein Limited, of Hammond, Louisiana, provided two years (1998 and 1999) of detailed catch and fuel consumption data from their fleet of 13 purse seiners based in Reedville, Virginia. From these data, representing a two year total catch of over 368,600 wet tonnes, I estimate that the Atlantic menhaden fishery consumed an average of 31.5 litres of diesel per tonne of fish landed (Table 1).

Multiplying this rate of fuel consumption by 322,239 tonnes, the total 1997 North Atlantic-wide Atlantic menhaden landings (as reported by the Food and Agriculture Organization (FAO) of the United Nations), I estimate that a total of 10 million litres of diesel were consumed in this fishery.

Example 2 - Fuel Inputs to All North Atlantic Scallop Fisheries in 1997

Anonymous sources provided a total of ten vessel-years of detailed catch and fuel consumption data representing five scallop draggers active in the North Atlantic during the late 1990's. From these data, representing a total catch of almost 11,000 live weight tonnes, I have estimated that the North Atlantic scallop fishery consumed an average of 350 litres of diesel per live weight tonne of scallops landed (Table 1).

Multiplying this rate of fuel consumption by 171,013 tonnes, the total 1997 North Atlantic-wide scallop catch (as reported by the FAO), I estimate that this fishery consumed a total of 60 million litres of diesel in 1997.

[9] While the data acquisition efforts to date have been reasonably successful, given the sensitivity that many individuals and companies can display regarding the release of information that could be perceived to be at variance with their interests, it is possible that

concentrating my efforts on fisheries and gear sectors that either: 1) account for relatively large proportions of the total North Atlantic catch of all species, or 2) use inherently energy intensive fishing gears. In this way, I hope to reduce the degree of error in the final estimate of the total energy inputs to North Atlantic fisheries. As a result, the large tonnage fisheries for small pelagic species such as herring, capelin and menhaden using purse seine, trawl, and seine gears are of particular interest as are trawl, and longline fisheries generally. However, where opportunities arise to acquire data representing smaller tonnage fisheries and less 'productive' gears, these will be pursued.

Inferring Fuel Consumption for Specific Gear Sectors Using Fleet Effort and Horsepower Characteristics

Based on a preliminary analysis of the fuel consumption and vessel data collected to date, it appears that for at least some gear sectors the *rate* of fuel consumption under normal operating conditions has relatively little to do with either the species being targeted or the resulting size of the catch. Instead, average fuel consumption rates seem to depend more on the size/power of the fishing vessels themselves together with the unique characteristics associated with deploying, fishing and retrieving the specific gear being used.

By way of example, a regression analysis was conducted of the relationship between average fuel consumption per day and main engine horsepower for the nine trawlers and two seiners (described in Table 1), representing a total of 17 vessel-seasons in which the number of sea days per season varied from 24 to 333 and averaged 178.

The results of the analysis, which was forced through the intercept based on the assumption that no fuel will be burned by a vessel without an engine, indicate that 2.56 litres of diesel are consumed per horsepower•sea-day (s.e. 0.054, r^2 0.965) (Figure 1).

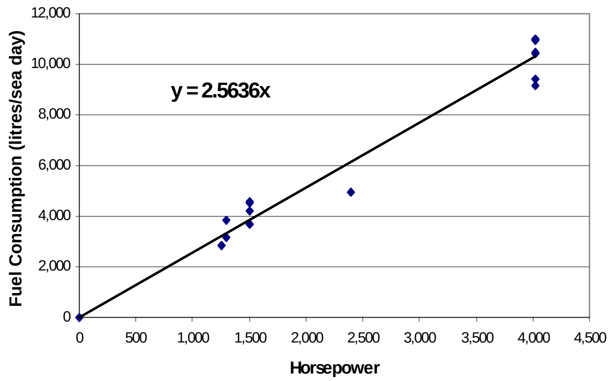

Figure 1. Daily Fuel Consumption Versus Propulsive Horsepower Relationship for Contemporary Trawlers and Seiners (17 vessel-seasons represented)

From this and other gear-specific relationships that I have yet to quantify but am confident will emerge, either derived from fishing effort and main engine horsepower data alone or a combination of vessel characteristics[10], estimates will be made of total fuel consumption and resulting energy intensity for some fisheries for which I have been unable to directly acquire fuel consumption data. Specifically, this will be possible in situations in which catch data can be related to vessel characteristics and total days at sea for a given gear sector. For example, by multiplying the product of average fleet horsepower and total days at sea by the gear-specific fuel consumption rate derived above (2.56 litres per horsepower•sea-day) an estimate of total fuel input to a trawl fishery can be made[11].

For many fisheries, days at sea data together with the physical characteristic of the vessels engaged in a fishery - this typically includes vessel tonnage and/or horsepower - are available from national fisheries management agencies. For example, the *Sea Around Us Project* team has already acquired Canadian and foreign vessel catch, gross tonnage, horsepower and temporal fishing effort data for all fisheries that occur within Canada's Atlantic Exclusive Economic Zone from Fisheries and Oceans Canada (see Watson et al. 2000). At the time of writing, this data set was being re-formatted into a form that could be easily used by all team members. We are also in the process of ordering a comparable data set for all U.S.

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additional direct fuel consumption data may be difficult to acquire.

[10] In the preliminary example given, the regression analysis was conducted using only fuel consumption per sea day and main propulsive horsepower. However, as more data becomes available representing a wider range of vessels and gear types, I will also perform multiple regression analyses in which average fuel consumption per sea day will be regressed against gross vessel tonnage, vessel length, the presence or absence of auxiliary engines in addition to main propulsive horsepower.

[11] This is the technique that Brown and Lugo (1981) employed to estimate the energy inputs to all U.S. fisheries over the period from 1967 to 1975. In doing so they derived generic fuel consumption rates for three gear sectors - trawlers, purse seiners and all other gears combined.

Atlantic fisheries from the National Marine Fisheries Service and are in the process of tracking down similar data from other North Atlantic fishing countries.

In situations in which fisheries agencies only report temporal fleet effort in terms of fishing days and not total days at sea, a fishery-appropriate correction factor will have to be applied. This is because not only do fishing vessels often burn fuel at higher rates when steaming than they do when actively fishing but the transit time to and from fishing grounds can account for a substantial portion of a vessel's total operating time and hence its fuel consumption. For example, amongst the groundfish trawlers and seiners for which I have acquired data, fully 23% of their time at sea during the 1999 fishing season was spent in transit to and from fishing grounds. As a result, for any comparable groundfish trawl fisheries I would apply a 1.3 times correction factor[12] to any temporal effort data that are reported only in terms of fishing days[13].

Where only the gross tonnage of vessels engaged in a fishery is available in conjunction with catch and temporal effort data, estimates of total fleet horsepower will be made using published fishing vessel descriptions and databases. For example, *Fishing Vessels of Britain and Ireland 2000*[14] will be used to construct gear-specific horsepower profiles for British and/or Irish fleets as needed while fleet characteristic data files are being solicited from both Fisheries and Oceans Canada and the National Marine Fisheries Service in the U.S. Finally, the project may acquire a database from Lloyd's Maritime Information Service in London that provides the physical characteristics, including engine power, of most of the world's fishing vessels over 100 GT.

As a simple illustration of the techniques described above, I have made a preliminary estimate of the fuel consumed by foreign vessels fishing for turbot (*Reinhardtius hippoglossoides*) in the Canadian Atlantic EEZ during 1996 (next page).

[12] The 1.3 correction factor was determined by taking the inverse of 0.77, the proportion of the total days at sea that eight trawlers and two seiners spent actively fishing for groundfish in 1999 in the NW Atlantic.

[13] However, in other fisheries, particularly those conducted in nearshore waters, no correction factor would be applied because transit times are negligible.

[14] *Fishing Vessels of Britain and Ireland 2000,* published by Fishing News, London, provides descriptions of all British and Irish fishing vessels over 12m in length including gross and net tonnage, main engine power, and type of fishing gear deployed.

Inferring Fuel Consumption When Only Catch Data are Available

For those fisheries in which only catch data are available and I have been unable to directly acquire fuel consumption data from one or more vessels active in the fishery, I will assign an energy intensity value based on the analyses of similar fisheries from other parts of the North Atlantic[15]. Factors to be considered when identifying a comparable fishery include: species caught, fishing gear used (if known), proximity to the fishing grounds, whether the fisheries are conducted on the same or similar populations of fish, and the known or probable purpose to which the catch is put.

To illustrate how this last factor may be useful in helping to constrain the energy intensity of a given fishery, consider the example of a fishery in which the catch is used entirely for reduction to fishmeal and oil. In this situation, the catch has a very low unit economic value and hence the costs of conducting the fishery must also be relatively low. As a result, the energy intensity of that fishery would likely be quite low since in most contemporary fisheries fuel costs represent a fairly large portion of total operating costs.

Finally, in rare instances, I may have to apply published energy intensity values from the same or a comparable fishery from the 1970s. Fortunately, by applying energy intensity values from 25 year ago to comparable contemporary fisheries should result in relatively conservative estimates of contemporary energy use given the changes in both stock, vessel and fleet sizes that have been likely to occur in the interim.

Using Total Fuel Consumption by a Given Region or Nation's Fisheries to Constrain The Results

I hope to identify data from which an estimate of the total annual fuel inputs to all fisheries within a given geographic region or political jurisdiction bordering the North Atlantic can be made. For example, for some countries it may be possible to quantify total fuel consumption by all commercial fisheries using fuel tax rebate data. While such an approach will not provide gear- or fishery-specific energy intensity estimates, it will help to confirm/constrain the estimates of the energy inputs to those fisheries.

[15] This is essentially the process that Hammer (1991) used to estimate the total fuel energy inputs associated with all domestic Swedish fisheries and the other fisheries whose products are traded by Sweden.

Example 3- Fuel Inputs to Foreign Vessels Fishing for Turbot in Canada's EEZ in 1996

In this example, fishing effort data for four size classes of trawlers, as recorded by NAFO (see Watson et al 2000), was used to estimate the total horsepower•sea-days required to land a given catch of turbot in 1996 (Table 2).

Table 2. Turbot Catch, Effort and Average Horsepower of Foreign Vessels Fishing in Canadian Waters in 1996

Trawler Size Class (GT)	Catch (tonnes)[a]	Fishing Days[a]	Sea Days[b]	Average Horsepower[c]	HP-Days
150 to 499	2,917	77	100.1	1,000	100,100
500 to 999	6,694	546	709.8	2,000	1,419,600
1000 to 1999	4,175	39	50.7	3,000	152,100
>2000	1,327	20	26.0	4,500	117,000
TOTALS:	15,113				1,788,800

Notes: a. Catch and corresponding fishing effort data for four classes of trawlers provided by Fisheries and Oceans Canada.
b. Sea-days calculated by multiplying fishing days by 1.3 based on the fishing-days to sea-days relationship that we have established for Canadian trawlers (see text above).
c. Preliminary estimates of the average horsepower of trawlers in these four size classes based on gross tonnage and horsepower data for 180 British fishing vessels (all gear types) as reported in the latest edition of *Olsen's Fisherman's Nautical Almanack* (Simpson, 2000).

Multiplying the total horsepower•days of effort (Table 2) by the generic trawler fuel consumption rate of 2.56 litre/horsepower•sea-day (see text above), I estimate that this fishery consumed approximately 4,580,000 litres of diesel in the process of catching 15,113 tonnes of turbot. This indicates an average fuel consumption rate of about 300 litres/tonne for this fishery.

Constructing Energy Consumption Time-Series

Where data are available, I will also construct fisheries specific fuel consumption time-series. The most appropriate method of doing this will be to use time series temporal fishing effort and fleet characteristic data together with the fishing gear specific fuel consumption rates that will be generated for late 1990s fisheries. Using this approach, the results will better reflect changes in total fleet effort and stock abundance over time. In addition, for those North Atlantic fisheries covered by energy analyses conducted during the 1970s, I will be able to evaluate energy intensity changes that have occurred over the last 25 to 30 years.

EXPRESSING THE RESULTS

Once fuel input estimates are generated for specific fisheries and for the entire North Atlantic, it will be possible to re-express the results in a variety of forms that either:

- facilitate comparisons both amongst fisheries and between fisheries and other food producing activities; or
- provide additional insights into the potential impacts of contemporary fisheries.

Specifically, energy intensities (MJ/tonne landed), and edible protein EROI ratios will be calculated for individual fisheries and as a weighted average of all North Atlantic fisheries. Employing both of these measures is useful because they provide different perspectives on the efficiency of fisheries (and food production activities generally), reflecting the often dramatic differences in the edible yield and protein contents of fish and shellfish. In addition, edible protein EROI ratios, or its inverse the energy cost of providing edible protein, have been shown to be particularly useful for analysing changes in fisheries over time (Brown and Lugo, 1981, Mitchell and Cleveland, 1993) and as a basis for comparing diverse food producing systems or technologies (Folke and Kautsky, 1991, Larsson et al, 1994, Pimentel, et al, 1996, Pimentel, 1997). Table 3 presents preliminary estimates of the energy intensity and edible protein EROI ratio for the three Examples provided above.

Table 3. Re-Expressing the Results of the Three Examples Provided

	Total 1997 Atlantic Menhaden Landings	Total 1997 Scallop Landings	1996 Foreign Fleet Turbot Landings in Canada's EEZ
Landings (round tonnes)[a]	322,239	171,013	15,113
Diesel consumed (litres)[a]	10,163,400	59,854,550	4,580,000
Rate of fuel consumption (l/t)[b]	31.5	350	300
Energy intensity (MJ/t)[c]	1,135	12,600	10,800
Edible protein EROI[d]	n/a	2.5%	16%
CO_2 emission intensity (kg/t)[e]	84	932	806
Total CO_2 emissions (tonnes)[e]	27,000	159,400	12,200
Ecological footprint (hectares of CO_2 assimilation forest)[f]	4,100	24,200	1,850

Notes:
a. Landings and total fuel consumption from Examples above.
b. Average fuel consumption rates from Table 1.
c. Calculated by multiplying the fuel consumption rate (litres/tonne of shell/fish harvested) by 36.036 MJ/litre, diesel fuel's net energy release upon combustion (calculated from data in Rose and Cooper, 1977, Tables 5.24 and 5.25).
c. Edible protein EROI was not calculated for menhaden as the bulk are not used for direct human consumption. For other species, protein EROI was calculated by dividing the edible protein energy content of a tonne of seafood (in MJ) by the fossil fuel energy consumed to harvest a round tonne. Protein energy content determined by multiplying 1000kg by the maximum edible meat yield rate (12.5% for scallops (Dominion Bureau of Statistics, 1931) and 56% for turbot (Bykov, 1983)), by the average protein energy content of the meat (scallops assumed to be the same as oysters at 10.6% (Pimentel et al, 1996) and 13% for turbot (Bykov, 1983)), by the nutritional energy of protein: 23.6 MJ/kg.
d. Calculated by multiplying the diesel fuel consumed (in MJ) by 73.9 gm CO_2/MJ, the average rate of CO_2 emissions from a variety of vessels under normal operating conditions (calculated from Lloyd's Register Engineering Services, 1995, Table 5, p. 17).
e. Calculated by dividing tonnes of carbon emitted (CO_2 emissions divided by 3.66) by 1.8 t C/ha•yr, a conservative estimate of the global average rate of carbon assimilation by the world's forests (Wackernagel and Rees, 1996).

To illustrate the potential contribution that North Atlantic fisheries make to global climate change, energy use related CO_2 emission intensities will be calculated for individual fisheries (e.g. tonnes CO_2 /tonne landed) along with the total CO_2 emissions for all fisheries (Table 3). Finally, to help place the scale of these emissions in context, the notional fossil fuel consumption-related ecological footprint will be calculated for specific fisheries (e.g. ha of CO_2 assimilation forest required/tonne landed) and all North Atlantic fisheries combined (Table 3). While this latter measure is a relatively new pedagogical tool (see Rees and Wackernagel, Wackernagel and Rees, 1996,) and the methods used to 'footprint' energy use are still undergoing refinement[16], it has been applied in the analyses of other fish producing systems (Larsson et al, 1994, Tyedmers, forthcoming dissertation) in addition to a range of other activities (Wackernagel and Rees, 1996, Folke et al, 1997). Finally, the results can then be combined with estimates of the marine primary productivity directly appropriated by the fisheries themselves (see Christensen and Walters, 2000) to produce a more complete picture of the ecological footprint of contemporary North Atlantic commercial fisheries.

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[16] Most ecological footprint analyses have employed one of two methods when estimating the ecosystem support area associated with fossil fuel use. The first is to calculate the area of ecosystem required to produce a contemporary biologically sourced liquid fossil fuel substitute such as ethanol, methanol, soydiesel, or fish oil. The second, and the one that will used in this analysis, is to estimate the area of forest ecosystem required to sequester the CO_2 produced through the combustion of fossil fuels (see Wackernagel and Rees, 1996 for a review of these approaches).

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APPENDIX

Summary of Published Fisheries Energy Analysis

Reference	Data From	Based	Fishing Ground	Gear Used	Species Targeted	Annual Landings per vessel (t)	Length (m)	Tonnage	Main HP	Total Energy Inputs (GJ/t)	Total Energy Inputs (GJ/year)	Includes*
		----------------Fishery Characteristics------------					--------Vessel Characteristics--------					
Leach, 1976	1969	England	Various	Various	Various					34.6		unknown
Leach, 1976	?	Peru	coastal?	n/a	Anchoveta					0.5		F
Leach, 1976	1972	U.S.	Gulf of Mexico	various	Shrimp					358.0		F
Leach, 1976	1974	Australia	n/a	trawlers	Shrimp		>17			38.1		F,V
Leach, 1976	1972	Malta	n/a	Various	Various					40.3		F
Wiviott and Mathews, 1975	1971-72	Washington State	NE Pacific	Bottom Trawl	Various	449	24.4	86	300	9.6	4,306	F,O,V
Wiviott and Mathews, 1975	1971-72	Japan	NE Pacific	Bottom Trawl	Various	2,440	n/a	1,947	2,648	51.5	125,699	F,O,V
Rochereau, 1976	1972	NE, USA		Various	Various			5-9			237	F,G,O,V
Rochereau, 1976	1972	NE, USA		Various	Various			10-19			336	F,G,O,V
Rochereau, 1976	1972	NE, USA		Various	Various			20-29			484	F,G,O,V
Rochereau, 1976	1972	NE, USA		Various	Various			30-39			631	F,G,O,V
Rochereau, 1976	1972	NE, USA		Various	Various			40-59			777	F,G,O,V
Rochereau, 1976	1972	NE, USA		Various	Various			60-79			1,167	F,G,O,V
Rochereau, 1976	1972	NE, USA		Various	Various			80-99			1,556	F,G,O,V
Rochereau, 1976	1972	NE, USA		Various	Various			100-119			1,973	F,G,O,V
Rochereau, 1976	1972	NE, USA		Various	Various			120-139			2,390	F,G,O,V
Rochereau, 1976	1972	NE, USA		Various	Various			140-159			2,956	F,G,O,V
Rochereau, 1976	1972	NE, USA		Various	Various			160-169			3,522	F,G,O,V
Rochereau, 1976	1972	NE, USA		Various	Various			170-179			4,255	F,G,O,V
Rochereau, 1976	1972	NE, USA		Various	Various			180-199			4,988	F,G,O,V
Rochereau, 1976	1972	NE, USA		Various	Various			220-239			6,512	F,G,O,V
Rochereau, 1976	1972	NE, USA		Various	Various			250-299			7,832	F,G,O,V
Rochereau, 1976	1972	NE, USA		Various	Various			300-319			9,274	F,G,O,V
Rochereau, 1976	1972	NE, USA		Various	Various			320-339			10,592	F,G,O,V
Edwardson, 1976	1973	Scotland	Unknown	Pair trawl	Pelagic species	357	16.8			10.8	3,854	F,G,O,V
Edwardson, 1976	1973	Scotland	Unknown	Purse seine	Pelagic species	3,976	24.4			2.7	10,611	F,G,O,V
Edwardson, 1976	1973	Scotland	Unknown	Seine	Demersal species	294	19.8			15.3	4,512	F,G,O,V
Edwardson, 1976	1973	Scotland	Unknown	Trawl	Demersal species	628	24.4			19.7	12,376	F,G,O,V
Edwardson, 1976	1973	Scotland	Unknown	Trawl	Demersal species	697	36.6			35.8	24,923	F,G,O,V
Edwardson, 1976	1973	Unknown	Unknown	Trawl	Demersal species	1,869	64			56.3	105,225	F,G,O,V

Note: *: F = fuel, G = gear and/or bait, O = other operating inputs (including labour), V = Vessel building and maintenance

		----------------Fishery Characteristics--------------				Annual	--------Vessel Characteristics--------			Total Energy Inputs		
Reference	Data From	Based	Fishing Ground	Gear Used	Species Targeted	Landings per vessel (t)	Length (m)	Tonnage	Main HP	(GJ/t)	(GJ/year)	Includes*
Rawitscher, 1978	1973	California	Central Pacific	Purse Seine	Tuna					31.6		F,G,O,V
Rawitscher, 1978	1974	California	Central Pacific	Purse Seine	Tuna					31.0		F,G,O,V
Rawitscher, 1978	1975	California	Central Pacific	Purse Seine	Tuna	1,570				62.3	97,692	F,O,V
Rawitscher, 1978	1973	Maine	Coastal Maine	Purse Seine	Herring					2.3		F,G,O,V
Rawitscher, 1978	1974	Maine	Coastal Maine	Purse Seine	Herring					2.4		F,G,O,V
Rawitscher, 1978	1974	Maine	Coastal Maine	Purse Seine	Herring	18.3				2.2	40	F,G,V
Rawitscher, 1978	1973	Washington	North Pacific	Troll	Chinook Salmon					87.3		F,O,V
Rawitscher, 1978	1974	Washington	North Pacific	Troll	Chinook Salmon					82.5		F,O,V
Rawitscher, 1978	1973	Washington	Coastal Washingon	Gillnet	Pink Salmon					13.4		F,O,V
Rawitscher, 1978	1974	Washington	Coastal Washingon	Gillnet	Pink Salmon					19.0		F,O,V
Rawitscher, 1978	1973	Maine		Trawl	Perch					7.9		F,O,V
Rawitscher, 1978	1974	Maine		Trawl	Perch					5.5		F,O,V
Rawitscher, 1978	1973	Pacific		Longline	Halibut					50.9		F,G,O,V
Rawitscher, 1978	1974	Pacific		Longline	Halibut					48.1		F,G,O,V
Rawitscher, 1978	1973	Rhode Is.	Offshore New England	Trawl	Flounder					22.1		F,O,V
Rawitscher, 1978	1974	Rhode Is.	Offshore New England	Trawl	Flounder					21.8		F,O,V
Rawitscher, 1978	1974	Rhode Is.	Offshore New England	Trawl	Flounder	62				20.2	1,248	F,O,V
Rawitscher, 1978	1973	Mass.		Trawl	Cod					19.7		F,O,V
Rawitscher, 1978	1974	Mass.		Trawl	Cod					17.9		F,O,V
Rawitscher, 1978	1973	Mass.		Trawl	Haddock					41.6		F,O,V
Rawitscher, 1978	1974	Mass.		Trawl	Haddock					33.7		F,O,V
Rawitscher, 1978	1973	Maine		Traps	Lobster					145.1		F,G,V
Rawitscher, 1978	1974	Maine		Traps	Lobster					141.0		F,G,V
Rawitscher, 1978	1973	Texas		Trawl	Shrimp					269.4		F,G,O,V
Rawitscher, 1978	1974	Texas		Trawl	Shrimp					311.8		F,G,O,V
Rawitscher, 1978	1973	Maryland		Traps	Crab					7.9		F,G,V
Rawitscher, 1978	1974	Maryland		Traps	Crab					9.5		F,G,V

Note: *: F = fuel, G = gear and/or bait, O = other operating inputs (including labour), V = Vessel building and maintenance

Reference	Data From	Based	Fishing Ground	Gear Used	Species Targeted	Annual Landings per vessel (t)	Length (m)	Tonnage	Main HP	Total Energy Inputs (GJ/t)	Total Energy Inputs (GJ/year)	Includes*
		----------------Fishery Characteristics-----------------					--------Vessel Characteristics--------					
Nomura, 1980	1975	Japan	distant water/high seas?	Longline	Tuna			192			21,622	F
Nomura, 1980	1975	Japan	distant water/high seas?	Longline	Tuna	259		229		133.5	34,595	F
Nomura, 1980	1975	Japan	distant water/high seas?	Longline	Tuna			344			37,838	F
Nomura, 1980	1975	Japan	offshore	Longline	Tuna	168		69		83.8	14,054	F
Nomura, 1980	1975	Japan	distant water/high seas?	Pole and line	Skipjack	1,290		284		41.9	54,054	F
Nomura, 1980	1975	Japan	distant water/high seas?	Pole and line	Skipjack			374			43,243	F
Nomura, 1980	1975	Japan	offshore	Pole and line	Skipjack			59			14,414	F
Nomura, 1980	1975	Japan	high seas?	Drift net - 'Mother boat'	Salmon	117		96		68	7,928	F
Nomura, 1980	1975	Japan	offshore?	Drift net - 'Catcher boat'	Salmon	214		65		43.8	9,369	F
Nomura, 1980	1975	Japan	high seas?	Angling/ jigging	Squid	542		300		43.9	23,784	F
Nomura, 1980	1975	Japan	offshore?	Angling/ jigging	Squid	580		99		20	11,604	F
Nomura, 1980	1975	Japan	East China Sea	Bottom trawl?	Various demersal	1,153		114		37.5	43,243	F
Nomura, 1980	1975	Japan	North Pacific	Trawl	Pollack	13,453		349		7.5	100,900	F
Nomura, 1980	1975	Japan	unspecified	Purse Seine	Various pelagic	11,171		111		10	111,712	F
Nomura, 1980	1975	Japan	coastal	Set net- (large)	Various	250		n/a		2.9	721	F

Note: *: F = fuel, G = gear and/or bait, O = other operating inputs (including labour), V = Vessel building and maintenance

		----------------Fishery Characteristics----------------				Annual	--------Vessel Characteristics--------					
Reference	Data From	Based	Fishing Ground	Gear Used	Species Targeted	Landings per vessel (t)	Length (m)	Tonnage	Main HP	Total Energy Inputs (GJ/t)	(GJ/year)	Includes*
Hopper, 1981	1970's	Unknown	North Sea	Trawl (beam)	Flat fish		20			51.5		F
Hopper, 1981	1970's	UK	Unknown	Trawl	Unknown		<24			34.3		F
Hopper, 1981	1970's	Norway	Unknown	Trawl (stern)	Unknown			>200		25.8		F
Hopper, 1981	1970's	Norway	South Norway	Longline	Unknown		>18			12.9		F
Hopper, 1981	1970's	Scotland	West Scottish coast	Gillnet	Unknown		20			8.6		F
Hopper, 1981	1970's	Norway	North Norway continental shelf	Longline	Unknown		>21			6.9		F
Hopper, 1981	1970's	Norway	Coastal Troms and Finnmark	Longline	Unknown		12.2			5.6		F
Hopper, 1981	1970's	Norway	Coastal Troms and Finnmark	Gillnet & Seine	Unknown					4.3		F
Hopper, 1981	1970's	Norway	Unknown	Purse Seine	Unknown					2.6		F
											(GJ/day)	
Veal et al, 1981	1980	US Gulf coast	Gulf of Mexico	Trawl	Shrimp		19.2		275		19.6	F
Veal et al, 1981	1980	US Gulf coast	Gulf of Mexico	Trawl	Shrimp		25.9		520		53.1	F
Veal et al, 1981	1980	US Gulf coast	Gulf of Mexico	Trawl	Shrimp		22.9		365		36	F

Note: *: F = fuel, G = gear and/or bait, O = other operating inputs (including labour), V = Vessel building and maintenance