Report

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Fueling Global Fishing Fleets

Over the course of the 20th century, fossil fuels became the dominant energy input to most of the world's fisheries. Although various analyses have quantified fuel inputs to individual fisheries, to date, no attempt has been made to quantify the global scale and to map the distribution of fuel consumed by fisheries. By integrating data representing more than 250 fisheries from around the world with spatially resolved catch statistics for 2000, we calculate that globally, fisheries burned almost 50 billion L of fuel in the process of landing just over 80 million t of marine fish and invertebrates for an average rate of 620 L t^{-1}. Consequently, fisheries account for about 1.2% of global oil consumption, an amount equivalent to that burned by the Netherlands, the 18th-ranked oil consuming country globally, and directly emit more than 130 million t of CO_2 into the atmosphere. From an efficiency perspective, the energy content of the fuel burned by global fisheries is 12.5 times greater than the edible-protein energy content of the resulting catch.

INTRODUCTION

Marine capture fisheries are the most diverse of the major global food-producing sectors, both in terms of the range of species harvested (1) and harvesting technologies used (2). One characteristic, however, common to nearly all contemporary fisheries, is their dependence on fossil fuels. In a process that began with the launch of the first coal-fired steam trawler in the late 1880s and accelerated through the latter half of the 20th century, fossil fuels have become the dominant energy input to the world's fisheries. Consequently, vessels powered by diesel, and to a lesser degree gasoline and kerosene, now account for the vast majority of global fisheries landings. Indeed, the extent of this dependence has prompted one commentator to observe that "Fishing continues to be the most energy-intensive food production method in the world today…" (3).

Spurred initially by the oil price shocks of the 1970s, analyses have been undertaken of a wide range of fisheries, either to evaluate their energetic performance (4–12) or to assess their economic vulnerability to potential increases in oil prices (13–16). This research indicates that direct fuel inputs typically account for between 75 and 90% of total energy inputs to fishing activities (7, 17, 18). The scale of direct fuel inputs, however, can range widely. Purse seine fisheries for small pelagic species, such as herring and menhaden, that are destined for reduction to fish meal and oil, typically use under 50 L of fuel per tonne of fish landed (11, 17). In contrast, fisheries targeting high value species like shrimp, tuna, or swordfish (*Xiphias gladius*) frequently consume in excess of 2000 L per tonne of landings (8, 11, 12). Where time series data are available, the energy performance of fishing fleets often has declined over time (7, 9, 11, 12), owing to the need for vessels to search longer and to fish deeper in offshore waters as coastal stocks decline (19–21). Despite the importance of fuel inputs to contemporary fishing activities, to date there has been no comprehensive analysis of the scale of fuel inputs to global fisheries, nor is there a clear understanding of the spatial distribution and intensity of where those fuel inputs are being expended.

MATERIALS AND METHODS

For this analysis, we assembled detailed fuel consumption, catch, and vessel/gear characteristic data from a wide range of published and unpublished sources. From these we calculated, in step-wise fashion, species-specific, globally- and where possible, regionally-representative average fuel use values. These values then were integrated with species-specific, spatially resolved catch data for 2000 to provide both estimates of global total and average fuel use intensity and the basis upon which fuel consumption could be mapped.

More specifically, to proceed from individual fuel use case studies to estimates for each reported commercial taxa from each of 18 statistical areas (Fig. 1) used by the Food and Agricultural Organization of the United Nations (FAO) required a process of progressive refinement, where average values were replaced at each step by more specific (with regard to taxa and location) estimates where possible. To provide all combinations of fished commercial taxa and statistical reporting areas with an initial estimate, we started with values based on the average of all case studies within the same broad taxonomic group (for example, "shrimp" or "tuna"), ignoring geographic area. We then repeated the process, but separated the case studies by area and where possible, replaced the more general estimate from the previous step. In this way, if fisheries targeting similar taxa did not have an estimate specific to the area where the landings were reported, then they at least had one for all areas combined. This process was repeated with progressively more specific taxonomic limits for the target of the fishery. Recognizing that in many cases, fisheries land more than one species, a provision also was made to weight averages based on the relative contribution that a given species made to the total landings recorded in a case study. In other words, case studies in which a species was targeted were weighted more heavily than those studies in which the species was taken incidentally. Documentation as to the origin of the estimate was maintained at each step.

The majority of case studies used provided fishery-specific fuel use data for a single year, though some also provided several annual estimates (Fig. 1). Though our final global fuel estimate represents the year 2000, this is because the landing statistics (tonnes reported by taxon and area) used to raise average fuel intensity estimates to total annual fuel consumption were from 2000. When case studies included time series data, only values closest to 2000 were used.

When the process of generating representative fuel use values had been completed, some landings were associated with specific case studies, whereas some were best represented by weighted averages calculated for the most specific taxonomic and spatial aggregation applicable.

Total fuel consumption by the world's fishing fleets in 2000 was estimated by summing the products of catches, by species, in each of 18 FAO areas (Fig. 1), and corresponding species-specific fuel use estimates. In order to contextualize the scale of fuel inputs to global fisheries, comparisons were then made with national and global levels of oil consumption in 2000 (22). Resulting CO_2 emissions from fishing vessels were quantified using real-world emission data from vessels (23).

Although for many consumers in industrialized countries, the nutritional importance of seafood has shifted recently to its value as a source of essential fatty acids and micronutrients (24),

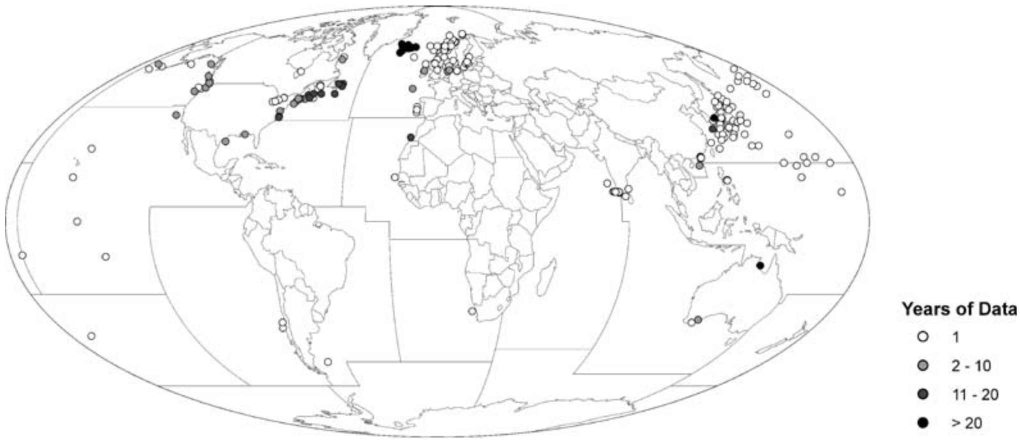

Figure 1. Distribution of case studies from which fisheries-specific estimates of fuel use intensity were derived, covering most of the major fisheries of the world. The straight lines cutting ocean basins demarcate the 18 statistical areas used by the FAO to report on global marine fisheries catches, and used here for geographic stratification.

for most of humanity, seafood remains an important source of animal protein (25). Consequently, the most meaningful basis upon which to compare fisheries with other food-producing sectors is in terms of their edible-protein yield (9–12). We therefore quantified the edible-protein energy efficiency of global fisheries by dividing the maximum edible-protein energy that could be derived from global catches in 2000 by the energy content of the fuel burned (26). The maximum edible-protein yield from catches in 2000 was estimated by first multiplying species-specific values for the maximum edible fraction of the animals landed, assumed to be equivalent to the muscle content of the animal (4, 27–29), by species-specific protein content of muscle values (1, 28–30). The resulting species-specific edible-protein fractions were multiplied then by corresponding catches in 2000, were summed, and then were converted to an energetic equivalent (4).

As the 2000 global catch statistics used to calculate total fuel consumption were available by ½ degree latitude and longitude cells, and are therefore mappable using a rule-based algorithm (19, 31), we also generated a global map of fuel consumption by fisheries, the first of its kind.

RESULTS

In total, data representing more than 250 distinct fisheries or fleet subsets, based in 20 countries, were assembled (Fig. 1) (32). Although it is impossible to know exactly where the vessels represented in this data set actually fished, most either targeted species caught over large geographic ranges (e.g. fisheries for various tuna, billfish, or squid) or produced very large catches of major species. Hence, we believe our data set to be broadly representative of world fisheries. Similarly, although a number of small-scale fisheries employing small outboard engines are represented, most are larger industrialized fisheries in which average vessel engine outputs are in the range of many tens to thousands of kilowatts — a pattern generally reflective of global catches.

In 2000, global fisheries reported landings of 80.4 million t of fish and invertebrates from marine waters (33). In the process of catching these, the world's fleets burned approximately 50 billion L of fuel, yielding a global average fuel use intensity of 620 L per live weight tonnes of fish and shellfish landed. Applying an average diesel fuel density of 0.85 (26), global fisheries landed approximately 1.9 t of fish and invertebrates for each tonne of fuel consumed directly in their capture.

As a consequence of burning almost 42.4 million t of fuel in 2000, representing approximately 1.2% of total global oil consumption, fishing boats released approximately 134 million t of CO_2 into the atmosphere at an average rate of 1.7 t of CO_2 per tonne of live-weight landed product.

Note that although our estimates of average fuel consumption and resulting emissions per landed tonne should be reliable, the above estimates of absolute fuel consumption and CO_2 emissions by the world's fishing fleets are likely serious underestimates, given that we did not account for freshwater fisheries nor the tens of millions of tonnes of fish caught by illegal, unreported, or unregulated (IUU) marine fisheries (20). Moreover, although direct fuel inputs represent the lion's share of industrial energy inputs to fisheries, our analysis does not account for the indirect or "embodied" energy inputs associated with the provision of fishing vessels, gear, labor, or the fuel itself.

In terms of their energy efficiency, fisheries globally dissipated 12.5 times the amount of fuel energy as they provided in the form of edible-protein energy. Whereas an 8% edible-protein energy return on fuel energy investment ratio is disturbingly low, it is higher than many other animal protein production systems (Table 1), including many of the intensive

Table 1. Edible-protein energy return on investment (EROI) values for various animal protein production systems.

Production system (locale)	Edible-protein EROI (%)
Carp — extensive pond culture (various)	100–11
Chicken (US)	25
Tilapia — extensive pond culture (Indonesia)	13
Mussel — longline culture (Scandinavia)	10–5
Turkey (US)	10
Carp — unspecified culture system (Israel)	8.4
Global fisheries	**8.0**
Milk (US)	7.1
Swine (US)	7.1
Tilapia — unspecific culture system (Israel)	6.6
Tilapia — pond culture (Zimbabwe)	6.0
Beef — pasture-based (US)	5.0
Catfish — intensive pond culture (US)	4.0
Eggs (US)	2.5
Beef — feedlot (US)	2.5
Tilapia — intensive cage culture (Zimbabwe)	2.5
Atlantic salmon — intensive cage culture (Canada)	2.5
Shrimp — semi-intensive culture (Ecuador)	2.5
Chinook salmon – intensive cage culture (Canada)	2.0
Atlantic salmon – intensive cage culture (Sweden)	2.0
Lamb (US)	1.8
Sea bass – intensive culture (Thailand)	1.5
Shrimp – intensive culture (Thailand)	1.4

Sources: aquaculture data (34), livestock data (39).

Note: Range of values for some culture systems reflects differences in production practices.

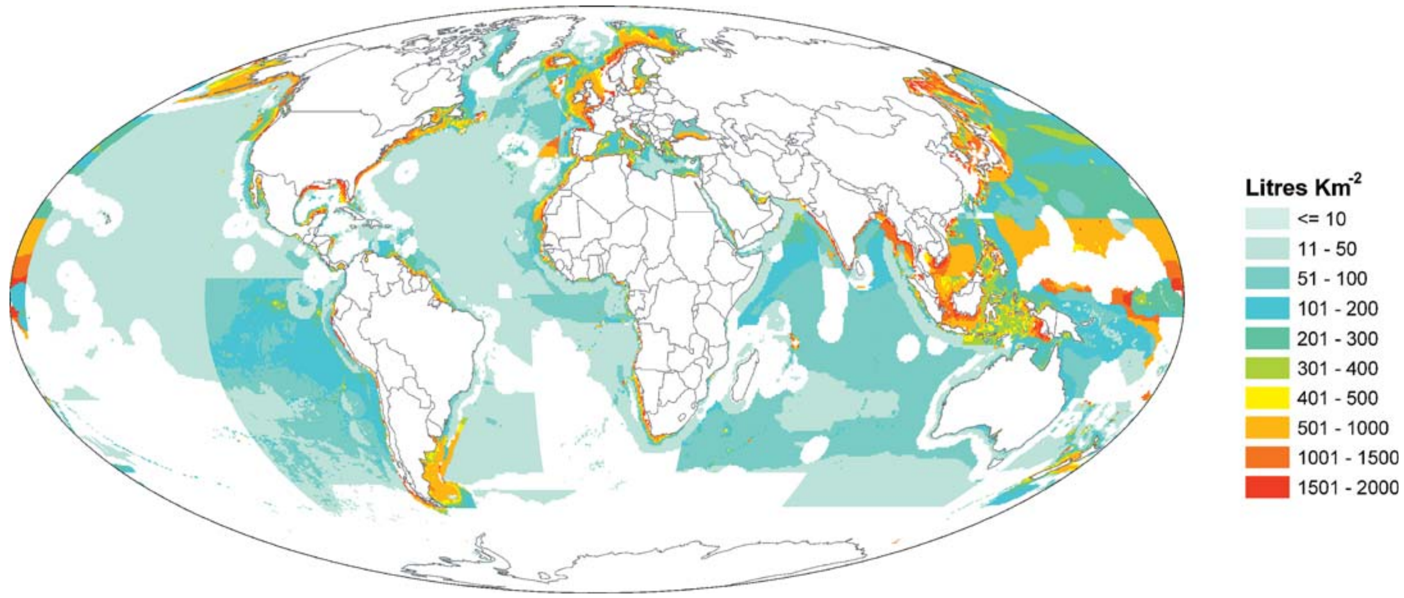

Figure 2. Distribution and intensity of fuel consumption by marine fisheries in 2000. Total fuel inputs amount to 50 billion L, with most of this being expended in nearshore fishing grounds of the Northern Hemisphere.

aquaculture systems (34) that compete directly with and have been proposed as alternatives to capture fisheries (35).

Reflecting, in part, that the world's oceans are not uniformly productive (31, 36), the spatial distribution of fuel use by the world's fishing fleets is highly variable (Fig. 2). Whereas large areas of the world's oceans experience relatively low levels of fishing effort, as measured in terms of spatially distributed fuel use, more productive (largely coastal) fishing areas experience annual effort levels exceeding 1000 Lkm^{-2}. Fishing grounds in which heavy fuel use is particularly widespread in 2000 include the western Pacific and adjacent seas, the Bering Sea, and coastal waters of the northeastern and southwestern Atlantic and northern Indian Ocean (Fig. 2).

DISCUSSION

Our results document for the first time the extent to which global fisheries have become dependent upon large inputs of nonrenewable, petroleum-derived fuels (37, 38) and illustrate the scale and intensity of arguably the largest direct industrial use of the world's oceans. At a conservative 1.2% of global oil consumption, this sector turns out to be a far from trivial player when it comes to the consumption of this important resource, a detail that should not be overlooked despite the fact that most of its activities occur far from shore and far from the thoughts of most of the public. Indeed, the scale of the industry's fuel consumption places it on a par with the total amount of oil consumed annually by the Netherlands, the 18th-ranked oil consuming country globally.

Interestingly, although the fishing sector consumes a substantial amount of fuel, its use of energy is far more efficient than many other contemporary food production systems, a finding that flies in the face of some widely held perceptions of capture fisheries in general (3). This seeming incongruity between perception and reality may, in part, result from the relatively high proportion of total energy inputs, and resulting energy-related costs that accrue at the level of the fishing enterprise itself. In contrast, in the case of many other animal protein production systems, the majority of energy inputs tend to occur farther back in the production chain (34, 39).

The spatial distribution of fuel use intensity illustrated in Figure 2 provides, to our knowledge, the first comprehensive picture of global fishing effort. In addition, because the scale of fuel inputs to fisheries are broadly proportional to the value of the resulting catch (8), the spatial distribution of fuel use intensity provides a partial indication of the relative extractive-use value of the world's oceans. Reflecting the relative importance of vessel-sourced operational inputs of oil to the world's oceans (40), our map of fuel inputs to fishing vessels also provides a basis upon which future oil pollution monitoring programs can be tailored.

Given the absolute and relative scales of fuel consumed by fishing fleets globally, it is essential that it be considered explicitly in future policy planning (21), both with regard to the fuel subsidies from which fishing fleets usually benefit and the needless climate impact of fossil fuels burned by overcapitalized fisheries.

References and Notes

1. Froese, R. and Pauly, D. (eds.). 2000. *FishBase 2000: Concepts, Design and Data Sources*. ICLARM, Los Baños, Philippines, 346 pp. (Distributed with four CD-ROMs; updates available at http://www.fishbase.org)
2. von Brandt, A. 1984. *Fish Catching Methods of the World*. Avon Litho, Stratford-upon-Avon, Warwickshire, 240 pp.
3. Wilson, J.D.K. 1999. *Fuel and Financial Savings for Operators of Small Fishing Vessels*. FAO Fisheries Technical Paper 383, FAO, Rome, pp. 46 at 1.
4. Wiviott, D.J. and Mathews, S.B. 1975. Energy efficiency comparison between the Washington and Japanese otter trawl fisheries of the northeast Pacific. *Mar. Fish. Rev. 37*, (4), 21–24.
5. Rawitscher, M. and Mayer, J. 1977. Nutritional outputs and energy inputs in seafood. *Science 198*, 261–264.
6. Lorentzen, G. 1978. Energy account of the Norwegian fishing sector. *Meldingen SSF M2*, 5–9. (In Norwegian).
7. Watanabe, H. and Uchida, J. 1984. An estimation of direct and indirect energy input in catching fish for fish paste products. *Bull. Jpn. Soc. Sci. Fish./Nippon Suisan Gakkaishi 50*, 417–423.
8. Watanabe, H. and Okubo, M. 1989. Energy Input in Marine Fisheries of Japan. *Bull. Jpn. Soc. Sci. Fish./Nippon Suisan Gakkaishi 53*, 1525–1531.
9. Mitchell, C. and Cleveland, C.J. 1993. Resource scarcity, energy use and environmental impact: a case study of the New Bedford, Massachusetts, USA Fisheries. *Environ. Manage. 17*, 305–317.
10. Pimentel, D., Shanks, R.E. and Rylander, J.C. 1996. Bioethics of fish production: energy and the environment. *J. Agric. Environ. Ethics 9*, 144–164.
11. Tyedmers, P. 2001. Energy consumed by North Atlantic fisheries. In: *Fisheries' Impacts on North Atlantic Ecosystems: Catch, Effort and National/Regional Datasets*. Zeller, D., Watson, R. and Pauly, D. (eds.). Fisheries Centre, University of British Columbia, Vancouver, pp. 12–34. http://www.seaaroundus.org/report/method/tyedmers10.pdf
12. Tyedmers, P. 2004. Fisheries and energy use. In: *Encyclopaedia of Energy*. Cleveland, C. (ed.). Elsevier, San Diego, vol. 2. pp. 683–693.
13. Scott, W.G. 1981. *Energy and Fish Harvesting: Conference Proceedings*. Fisheries and Oceans Canada, Ottawa, 166 pp.
14. Samples, K.C. 1983. An economic appraisal of sail-assisted commercial fishing vessels in Hawaiian waters. *Mar. Fish. Rev. 45*, (7–9), 50–55.
15. George, V.C., Vijayan, V., Varghese, M.D., Radhalakshmi, K., Thomas, S.N. and Joseph, J. (eds). 1993. *Proceedings of the National Workshop on Low Energy Fishing, 8–9 August, 1991*. Society of Fisheries Technologists (India), Cochin, 286 pp.
16. Senthilathiban, R., Venkataramanujam, K., Selvaraj, P. and Sanjeeviraj, G. 1997. Costs and earnings of trawlers operating at Tuticorin, Tamilnadu. *Fish. Technol. 34*, (2), 31–34.
17. Rawitscher, M. A. 1978. *Energy Cost of Nutrients in the American Diet*. PhD Thesis, University of Connecticut, Storrs, Connecticutt.

18. Tyedmers, P. 2000. Salmon and Sustainability: The Biophysical Cost of Producing Salmon Through the Commercial Salmon Fishery and the Intensive Salmon Culture Industry. PhD Thesis, University of British Columbia, Vancouver, Canada.
19. Watson, R. and Pauly, D. 2001. Systematic distortions in world fisheries catch trends. *Nature 414*, 534–536.
20. Pauly, D., Christensen, V., Guénette, S., Pitcher, T.J., Sumaila, U.R., Walters, C.J., Watson, R. and Zeller, D. 2002. Toward sustainability in world fisheries. *Nature 418*, 689–695.
21. Pauly, D., Alder, J., Bennett, E., Christensen, V., Tyedmers, P. and Watson, R. 2003. The future for fisheries. *Science 302*, 1359–1361.
22. British Petroleum (BP). 2003. *BP Statistical Review of World Energy 2003*. BP, London, 40 pp.
23. Engineering Services Group. 1995. *Marine Exhaust Emissions Research Programme*. Lloyd's Register of Shipping, London, 63 pp.
24. Valdimarsson, G. and James, D. 2001. World fisheries — utilization of catches. *Ocean Coast. Manage. 44*, 619–633.
25. FAO. 2002. The State of World Fisheries and Aquaculture. FAO, Rome, 150 pp.
26. Rose, J.W. and Cooper, J.R. (eds). 1977. *Technical Data on Fuel (* 7th ed.). Scottish Academic Press, Edinburgh. 343 pp.
27. Crapo, C., Paust, B. and Babbitt, J. 1993. *Recoveries and Yields from Pacific Fish and Shellfish*. Alaska Sea Grant College Program, University of Alaska Fairbanks, Fairbanks, 36 pp.
28. Bykov, V.P. 1986. Marine Fishes: Chemical Composition and Processing Properties. A.A. Balkema, Rotterdam, 322 pp.
29. Torry Research Station. 1989. *Yield and Nutritional Value of the Commercially More Important Fish Species*. FAO Fisheries Technical Paper No. 309. FAO, Rome, 187 pp.
30. Wheaton, F.W. and Lawson, T.B. 1985. *Processing Aquatic Food Products*. John Wiley, New York, 518 pp.
31. Watson, R., Kitchingman, A., Gelchu, A. and Pauly, D. 2004. Mapping global fisheries: sharpening our focus. *Fish Fish. 5*, 168–177.
32. A summary of the fisheries represented in this dataset and their sources is available from P.T.
33. Detailed annual species-specific catches based in large measure on data in FAO 2003 FishStat Plus statistical database. (http://www.fao.org/fi/statist/FISOFT/FISHPLUS.asp)
34. Troell, M., Tyedmers, P., Kautsky, N. and Rönnbäck, P. 2004. Aquaculture and energy use. In: *Encyclopaedia of Energy*. Cleveland, C. (ed.). Elsevier, San Diego, vol. 1, pp. 97–108.
35. Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C.M., Clay, J., Folke, C., Lubchenco, J., et al. 2000. Effect of aquaculture on world fish supplies. *Nature 405*, 1017–1024.
36. Pauly, D. and Christensen, V. 1995. Primary production required to sustain global fisheries. *Nature 374*, 255–257.
37. Deffeyes, K.S. 2001. *Hubbert's Peak: The Impending World Oil Shortage*. Princeton University Press, Princeton, 208 pp.
38. Heinberg, R. 2003. *The Party's Over: Oil, War and the Fate of Industrial Societies*. New Society, Gabriola Island, BC, Canada, 275 pp.
39. Pimentel, D. 2004. Livestock production and energy use. In: *Encyclopaedia of Energy*. Cleveland, C. (ed.). Elsevier, San Diego, vol. 3, pp. 671–676.
40. Committee on Oil in the Sea. 2003. *Oil in the Sea III: Inputs, Fates, and Effects*. National Academies Press, Washington, DC, 280 pp.

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