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Fuel consumption of global fishing fleets: current understanding and knowledge gaps

Robert W R Parker[1] *& Peter H Tyedmers*[2,3]

[1]Institute for Marine and Antarctic Studies, University of Tasmania, Private Bag 49, Hobart, Tasmania 7001, Australia; [2]School for Resource and Environmental Studies, Dalhousie University, 6100 University Avenue, Suite 5010, PO Box 15000, Halifax, NS B3H 4R2, Canada; [3]College of Sustainability, Dalhousie University, Mona Campbell Building, 1459 LeMarchant St., Suite 1401, PO Box 15000, Halifax, NS B3H 4R2, Canada

Abstract

Compared to a century ago, the world's fishing fleets are larger and more powerful, are travelling further and are producing higher quality products. These developments come largely at a cost of high-fossil fuel energy inputs. Rising energy prices, climate change and consumer demand for 'green' products have placed energy use and emissions among the sustainability criteria of food production systems. We have compiled all available published and unpublished fuel use data for fisheries targeting all species, employing all gears and fishing in all regions of the world into a Fisheries and Energy Use Database (FEUD). Here, we present results of our analysis of the relative energy performance of fisheries since 1990 and provide an overview of the current state of knowledge on fuel inputs to diverse fishing fleets. The median fuel use intensity of global fishery records since 1990 is 639 litres per tonne. Fuel inputs to fisheries vary by several orders of magnitude, with small pelagic fisheries ranking among the world's most efficient forms of animal protein production and crustaceans ranking among the least efficient. Trends in Europe and Australia since the beginning of the 21st century suggest fuel use efficiency is improving, although this has been countered by a more rapid increase in oil prices. Management decisions, technological improvements and behavioural changes can further reduce fuel consumption in the short term, although the most effective improvement to fisheries energy performance will come as a result of rebuilding stocks where they are depressed and reducing over-capacity.

Correspondence:
Robert Parker
IMAS Taroona,
Private Bag 49
Hobart, TAS 7001
Australia
Tel.: +61 3 6227 7250
Fax: +61 3 6227 8035
E-mail: robert.parker@utas.edu.au

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Introduction

Limited availability of conventional energy sources, rising energy prices and the need to reverse the trend of climbing greenhouse gas (GHG) emissions are issues that will shape global economic and socio-political dynamics in the first half of the 21st century. The decade from 2003 to 2013 saw oil commodity prices climb by over 300% (EIA 2012), and it is commonly argued that global oil production has either already peaked or will peak in the near future (Bartlett 2000; Murphy and Hall 2011). Meanwhile, global GHG emissions continue to rise, particularly as large developing and transitional economies become more affluent. Food production, and production of animal protein in particular, has been recognized as placing substantial burden on ecological services such as land and water use, and also contributing heavily to national and global GHG inventories (Steinfeld *et al.* 2006; Garnett 2008). National and global estimates of GHG contributions from food production range from between 10 and 30% of total emissions (Garnett 2011).

Marine capture fisheries represent a major source of food, employment and income globally. Fish products – from both wild fisheries and aquaculture – contribute approximately 17% of global animal protein consumption and are a particularly important source of protein, lipids and micronutrients in poor, undernourished countries (Garcia and Rosenberg 2010; FAO 2013). Fisheries contribute to poverty alleviation and food security via provision of food, raising purchasing power through employment and generation of national revenue through exports, taxes and access fees (Garcia and Rosenberg 2010; Allison 2011). Global employment from marine fisheries has been estimated at 260 million jobs, including some 50 million fishers and 210 million employed indirectly in processing, distribution, trade and other services (Teh and Sumaila 2013). Seafood from fisheries and aquaculture is the most heavily traded food commodity worldwide, with over one-third of global fish production flowing into international trade worth over US$100 billion annually (World Bank 2009; FAO 2013). Despite being a highly valuable and nutritionally critical industry, the marine fishing sector faces multiple challenges including weakened profitability in recent decades, related to increased costs of operation, volatile markets and prices, and depressed fish stocks (World Bank 2009).

Advances in fishing and processing technology, as well as globalization of trade and markets, have transformed marine fisheries since the mid 20th century. Fisheries today are targeting previously unharvested species, fishing in new regions and depths, particularly in the high seas, producing higher quality products and distributing products around the world in multiple product forms (Thorpe *et al.* 2007; FAO 2013). These advancements have increased production, expanded fish markets and improved product quality and fisher safety. A consequence of many of these advancements has been the increased reliance of fisheries on larger vessels, the motorization of fishing fleets with more powerful engines and the increased demand by fisheries for fossil fuels to power everything from propulsion and gear operation to onboard processing, refrigeration and ancillary services such as navigational aids (Tyedmers 2004; World Bank 2009). Global marine fisheries have, in essence, followed a similar trend towards highly productive industrialized operations that agricultural production underwent in the 20th century. As a result of this reliance on energy inputs to modern fishing fleets, primarily in the form of fossil fuels, fisheries and their products are increasingly vulnerable to the cost of fuel, regulations on emissions (e.g. carbon taxes) and consumer demands for low-impact, 'green' products.

Expenditures on fuel represent one of the largest costs in modern fishing operations. Globally, between 30 and 50% of fishing expenditure is on fuel, with small-scale fisheries and fisheries in developing countries spending a higher proportion on fuel than those in developed countries (Lam *et al.* 2011; FAO

2013). The increase in fuel costs over the past decade has easily outpaced the growth in fish prices (Tveteras *et al.* 2012), culminating in the temporary shutdown of some energy-intensive fisheries during the price peaks of 2008 (AFP 2008; Kyodo News 2008). Offsetting fuel costs is also the primary purpose of many subsidies to fisheries worldwide, with particularly high levels of government intervention in richer countries (Sumaila *et al.* 2008).

Fuel consumption by fishing vessels is typically the dominant driver of energy demand and GHG emissions from fisheries production, accounting for between 60 and 90% of emissions up to the point of landing (Tyedmers 2004). Additional upstream processes associated with fishing, including vessel construction and maintenance, gear manufacturing and bait provision, also consume energy and produce emissions. When viewed in the context of total life cycle ('cradle to grave') emissions, including post-landing activities such as processing, packaging, transport and food preparation, vessel fuel use remains a primary source of emissions from seafood supply chains (Parker 2012b; Vazquez-Rowe *et al.* 2012).

Relatively little research was published on fuel consumption in fisheries prior to 2000. Some early analyses of energy inputs to fisheries and other food production systems were completed in the wake of the 1970s oil shocks (Leach 1975; Rawitscher 1978; Watanabe and Okubo 1989). Increasing energy prices and concern related to GHG emissions have sparked renewed interest in the topic, and numerous regional and fishery-specific analyses have been undertaken in the past decade. Tyedmers *et al.* (2005) estimated global fuel use intensity (FUI) at 620 L t^{-1} in 2000 and a total industry-wide consumption of 40 billion litres. This value equates to just less than 2 kg of fuel-related GHG emissions per kg of fish caught, before accounting for additional emissions from processing and transportation. A key finding from this set of research was that fisheries, facing relatively low costs of fuel and a growing challenge of over-capacity and declining fish stocks, had been increasing their FUI (typically expressed in terms of the litres of fuel burned per tonne of live weight landings) throughout the 1990s. Furthermore, the extent to which modern fisheries were relying on fuel consumption meant that the energy inputs to many systems far outweighed their energy outputs in terms of edible fish protein.

Since the early 2000s, environmental and economic concerns have resulted in a growing body of research into energy demands and GHG emissions of fisheries, aquaculture and other food production systems. Energy, fuel and GHG-related research in fisheries in the past decade have included efficiency audits of individual vessels and fleets (Thomas *et al.* 2010; Sala *et al.* 2011); assessments of fuel inputs to national or regional fleets (Tyedmers 2001; Thrane 2004; Schau *et al.* 2009); global assessments of fishing sectors (Parker *et al.* 2014); and life cycle assessments (LCA) of fishery-derived products (Parker 2012b; Avadi and Freon 2013).

Here, we draw upon this growing field of analyses to provide an overview of the current state of research into energy use in marine capture fisheries. We present the results of an analytical synthesis of primary and secondary FUI data to identify patterns of fuel use in fisheries targeting different species, employing different gears and operating in different regions. It is our intention that this meta-analysis of energy use in fisheries will provide a broad overview of the status of energy use in fisheries from both an environmental and an economic perspective and highlight significant gaps in our collective understanding of energy use in fisheries. The insights and discussion presented here should be of interest to those directly engaged in the fishing industry, as well as fisheries managers and regulating bodies, non-governmental agencies, consumers and LCA practitioners.

Methods

Fisheries and energy use database

A FEUD was originally developed by P. Tyedmers in Microsoft Access and is currently maintained by both authors to collect and synthesize primary (unpublished analyses or re-analyses by the authors) and secondary (from published articles or reports) records of FUI of fishing vessels or fleets. Database records include, where available, fleet and/or vessel characteristics (e.g. horsepower, gross registered tonnage, etc.), target species, locale of fishing, primary and secondary gears employed, effort (e.g. fishing days) and FUI. To date, FEUD includes over 1600 records covering a wide range of fisheries from all regions of the world, employing all major gears and targeting all species classes, dating back to 1956. Previously, FEUD has been used to estimate fuel inputs to global fisheries in 2000 (Tyedmers *et al.* 2005).

Fuel use intensity analysis

Records of fisheries FUI were extracted from FEUD and aggregated by species, gear and region. Only data referring to fisheries operating in 1990 onwards were included for analysis here. Analysis of FUI by species excluded all records for which species class was unknown. Likewise, analysis of FUI by gear type excluded records for which gear type was unknown. Records were not weighted based on global catch patterns, as the intention here was rather to assess the FUI data available and identify consistent patterns.

Data were imported to R, and summary statistics were generated, including mean, median, quartiles, and maximum and minimum values. This statistical summary was then used to generate graphics and compare the FUI records of fisheries targeting different species, employing different gears and fishing in different regions.

Results

Status of database

An overview of the total number of fisheries records currently collected in FEUD is presented in Table 1. There is a clear pattern of FUI data being more plentiful for fisheries in Europe and those targeting finfish species. In fact, 146 records pertain to European fisheries for Atlantic cod (*Gadus morhua*, Gadidae) alone. The large number of records from Europe and Oceania is the result of recent robust analyses of FUI in fisheries of those regions, particularly for the North Atlantic (Tyedmers 2001), Norway (Schau *et al.* 2009), Denmark (Thrane 2004), the European Union (Anderson and Guillen 2011), New Zealand and Australia (*unpublished analysis*). While some very recent analyses of energy use in Indian and Southeast Asian fisheries have been published (Hua and Wu 2011; Boopendranath and Hameed 2013; Vivekanandan *et al.* 2013), there is a clear lack of fuel use data pertaining to small-scale fisheries in developing countries. African and South American fisheries in particular are grossly under-represented.

Fuel use intensity by species, gear and region

The mean FUI of all fisheries fuel use records since 1990 is 706 L t^{-1}, and the median FUI of all records since 1990 is 639 L t^{-1}. Fuel use intensity varies considerably between fisheries, on the scale of at least three orders of magnitude, but several patterns are clear when comparing fisheries on the basis of target species class and primary gear type (Fig. 1 and Table 2).

The most efficient fisheries are those targeting small pelagic species such as Peruvian anchovy (*Engraulis ringens*, Engraulidae), Atlantic mackerel (*Scomber scombrus*, Scombridae) and Australian sardine (*Sardinops sagax*, Clupeidae). These fisheries make up some of the largest in the world, by volume of landings, but are often directed primarily to the production of animal feeds and other products, rather than for direct human consumption. They are particularly efficient when using purse seine gear or other surrounding nets, averaging 71 L t^{-1}, while small pelagic fisheries employing pelagic trawls average 169 L t^{-1}. The lowest FUI values on record (apart from non-fuel consuming artisanal fisheries) are for fisheries targeting Atlan-

Table 1 Number of records (total and for fisheries operating since 1990) in the Fisheries and Energy use Database, by species class, gear type and region.

Fishery category	All records	Year ≥ 1990
By species class		
Finfish	512	320
Small pelagics	260	188
Crustaceans	372	303
Molluscs	197	94
Large pelagics	113	91
Flatfish	76	68
Salmonids	24	7
Other/unknown	68	55
By gear type		
Bottom trawls	479	347
Hooks and lines	266	110
Surrounding nets	223	145
Pelagic trawls	174	143
Gillnets	114	68
Pots and traps	83	74
Dredges	62	50
Divers	16	16
Other/unknown	205	173
By region		
Europe	866	640
Oceania	323	303
Asia	224	34
North America	159	115
Africa	24	7
Latin America	2	2
Other/unknown	24	24
Total records	1622	1126

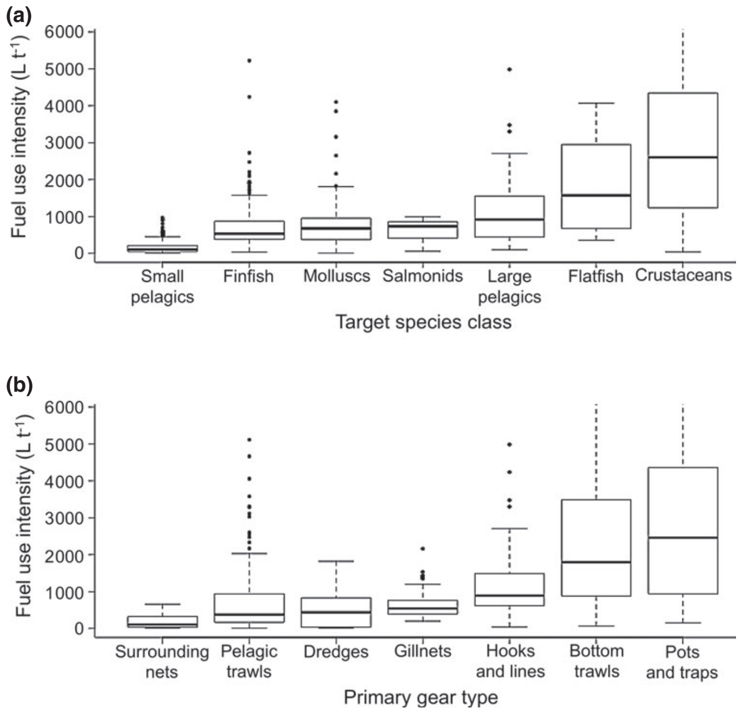

Figure 1 Median and range of fishery fuel use intensity (FUI) records by (a) species class and (b) gear type. Boxes represent 25th and 75th percentiles, while dots denote outliers. Note that, while the *y*-axis is truncated at 6000 L $t^{-1}$for graphical purposes, some FUI values for crustacean fisheries, pots and traps, and bottom trawls are higher.

tic herring (*Clupea harengus*, Clupeidae) in Iceland (Tyedmers 2001) and Peruvian anchovy in Chile (P. Trujillo, UBC Fisheries Centre, personal communication); FUI values for these and similar fisheries are typically under 100 L t^{-1}, with some reported values as low as 8 and 10 L t^{-1}.

The least energy-efficient fisheries globally are those targeting crustaceans, particularly species of shrimps and lobsters, using either bottom trawls or pots and traps. Many of these fisheries have recorded FUI values of up to, and even over, 10 000 L t^{-1}. Among the most fuel-intensive fisheries in the world are those targeting Tiger prawns (*Penaeus esculentus*, Penaeidae) with bottom trawls in Australia and Norway lobster (*Nephrops norvegicus*, Nephropidae) with bottom trawls in Sweden, with reported maximum FUI values higher than 11 000 and 17 000 L t^{-1}, respectively. Overall, crustacean fishery records in FEUD have an average value of 2923 L t^{-1}. Other fuel-intensive forms of fishing include flatfish bottom trawls, averaging 2827 L t^{-1}, and large pelagic (primarily tuna) fisheries using longlines and other forms of hooks and lines (e.g. trolling), averaging 1612 L t^{-1}.

Variations in FUI between regions are less clear than those between species class and gear type. One evident regional pattern is the relatively high FUI of records from Oceania, which have a mean value of 2183 L t^{-1}. This is driven primarily by the high occurrence of fuel-intensive crustacean fisheries in Australia and by the large number of FUI records pertaining to those fisheries. Average FUI values for records from North America (432 L t^{-1}) and Europe (859 L t^{-1}), meanwhile, are lower as a result of the prevalence of fisheries for finfish and small pelagic species. Regional variations within fishery categories have been reported elsewhere, although inconsistently. Purse seine fisheries for skipjack tuna, for example, are reported as more efficient in the Indian Ocean by Hospido and Tyedmers (2005) and more efficient in the Pacific Ocean by Parker *et al.* (2014) although these apparent differences may be a function of sample size or a genuine change in FUI over time. Fisheries for lobster species vary dramatically between regions, with the difference in fuel consumption between American lobster (*Homarus americanus*) and Norway lobster (*Nephrops norvegicus*)

Table 2 Average fuel use intensity (FUI) of fishery records with known target species, gear type and region, since 1990.

	Fishery category			Fuel use intensity (L t^{-1})		
Species class	Gear type	Region	*n*	Mean	Min	Max
Crustaceans	Bottom trawls	Oceania	88	4125	1165	10 886
Crustaceans	Pots and traps	Oceania	53	3803	846	9474
Crustaceans	Bottom trawls	Europe	117	3083	377	17 300
Flatfish	Bottom trawls	Europe	32	2851	631	4062
Molluscs	Bottom trawls	Europe	7	2618	1205	4103
Crustaceans	Bottom trawls	Africa	1	2600	2600	2600
Molluscs	Gillnets	Europe	1	2162	2162	2162
Crustaceans	Pelagic trawls	Asia	1	2028	2028	2028
Large pelagics	Hooks and lines	Asia	3	1925	106	4985
Large pelagics	Hooks and lines	Europe	12	1745	570	3478
Large pelagics	Hooks and lines	Oceania	20	1676	937	3300
Large pelagics	Hooks and lines	North America	4	1495	385	2678
Finfish	Pelagic trawls	Europe	2	1444	413	2475
Crustaceans	Bottom trawls	North America	12	1231	531	2262
Molluscs	Pelagic trawls	Oceania	2	1097	406	1787
Flatfish	Pelagic trawls	Oceania	4	1086	918	1480
Flatfish	Bottom trawls	North America	3	1084	957	1338
Crustaceans	Hooks and lines	Europe	2	1031	47	2015
Molluscs	Divers	Oceania	16	951	585	1472
Finfish	Hooks and lines	Europe	42	927	125	4238
Small pelagics	Bottom trawls	Asia	1	922	922	922
Salmonids	Gillnets	North America	2	886	785	986
Molluscs	Bottom trawls	North America	2	859	313	1405
Salmonids	Hooks and lines	North America	2	835	735	935
Crustaceans	Pots and traps	Europe	8	834	334	2156
Large pelagics	Bottom trawls	North America	1	824	824	824
Crustaceans	Pots and traps	North America	3	783	331	1026
Finfish	Bottom trawls	Asia	3	766	671	874
Finfish	Bottom trawls	Europe	55	756	236	2724
Large pelagics	Gillnets	Oceania	9	751	397	1352
Finfish	Gillnets	North America	37	686	300	1532
Large pelagics	Gillnets	Asia	1	683	683	683
Finfish	Bottom trawls	North America	15	682	65	1457
Finfish	Pelagic trawls	Oceania	40	675	207	1495
Crustaceans	Pelagic trawls	Europe	2	634	232	1035
Crustaceans	Gillnets	Africa	1	630	630	630
Large pelagics	Pelagic trawls	Oceania	6	627	151	1649
Small pelagics	Gillnets	Europe	1	602	602	602
Flatfish	Gillnets	Europe	1	598	598	598
Flatfish	Hooks and lines	North America	1	570	570	570
Flatfish	Bottom trawls	Asia	1	549	549	549
Finfish	Hooks and lines	Oceania	1	549	549	549
Finfish	Bottom trawls	Oceania	3	538	363	665
Molluscs	Bottom trawls	Oceania	1	533	533	533
Molluscs	Dredges	Europe	44	525	15	1822
Flatfish	Gillnets	North America	3	517	492	566
Molluscs	Pots and traps	Europe	7	513	392	641
Finfish	Surrounding nets	Europe	13	466	104	659
Large pelagics	Surrounding nets	Europe	3	447	373	527
Finfish	Dredges	North America	1	445	445	445
Finfish	Gillnets	North America	8	443	297	1430
Small pelagics	Bottom trawls	North America	2	431	230	631

Table 2 (Continued).

	Fishery category			Fuel use intensity (L t^{-1})		
Species class	Gear type	Region	*n*	Mean	Min	Max
Finfish	Hooks and lines	North America	7	411	396	489
Flatfish	Surrounding nets	North America	1	380	380	380
Finfish	Surrounding nets	Oceania	18	346	62	497
Small pelagics	Hooks and lines	Europe	2	323	60	585
Molluscs	Dredges	North America	5	295	71	361
Salmonids	Surrounding nets	North America	3	291	56	513
Small pelagics	Pelagic trawls	Oceania	7	234	141	354
Finfish	Surrounding nets	North America	1	230	230	230
Large pelagics	Gillnets	North America	1	199	199	199
Large pelagics	Surrounding nets	Oceania	1	195	195	195
Small pelagics	Pelagic trawls	Europe	28	168	45	565
Finfish	Surrounding nets	Asia	1	162	162	162
Large pelagics	Surrounding nets	Asia	2	156	149	162
Small pelagics	Surrounding nets	Asia	2	152	142	162
Crustaceans	Pelagic trawls	North America	1	132	132	132
Small pelagics	Pelagic trawls	North America	6	101	49	147
Small pelagics	Surrounding nets	Oceania	17	89	29	217
Small pelagics	Surrounding nets	Europe	36	84	8	506
Small pelagics	Bottom trawls	Europe	3	83	65	94
Finfish	Pelagic trawls	North America	8	66	36	73
Small pelagics	Surrounding nets	North America	20	42	20	160
Small pelagics	Surrounding nets	Africa	6	31	16	46
Small pelagics	Surrounding nets	Latin America	2	10	10	10

being a full order of magnitude. Additional regional trends are likely to exist, such as differences in FUI between small-scale fleets using outboard motors and larger vessels with inboard engines in developing countries; however, a lack of publicly available data to date makes these assertions impossible to test.

Discussion

Comparison to previous findings

This is the first broad global overview and classification of FUI of fisheries relative to species, gear and region. Results, however, reflect findings of previous national or regional fleet assessments in many ways. The lower fuel demand of small pelagic fisheries has been highlighted previously in analyses of North Atlantic, European and Australian fisheries (Tyedmers 2001; Schau *et al.* 2009). Likewise, the lower FUI of purse seines and surrounding nets has also been demonstrated previously on smaller scales (Tyedmers 2001; Schau *et al.* 2009).

Estimates of FUI presented here, while averaged across FUI records and unweighted by relative catch, resemble previous findings for fisheries in fleet- and vessel-specific analyses, suggesting a relative degree of consistency across fuel use studies of different fleets, different regions or different years. Median FUI for large pelagics caught using hooks and lines (1485 L t^{-1}), and surrounding nets (434 L t^{-1}), for example, are close to global tuna FUI assessment findings for 2009 (Tyedmers and Parker 2012; Parker *et al.* 2014). Likewise, the median FUI of finfish fisheries (519 L t^{-1}) is very close to the FUI values previously reported for Atlantic cod fisheries in Europe and the North Atlantic, taking into consideration variation between gear types (Tyedmers 2001; Ziegler *et al.* 2003; Svanes *et al.* 2011).

Tyedmers *et al.* (2005) estimated global FUI of fisheries to be 620 L t^{-1} for the year 2000. This very closely corresponds to the median value of FUI records of 639 L t^{-1} found here. While this is not particularly surprising as both studies analysed data from FEUD, the current study benefitted from a much larger set of recent data points; the similarity in results, then, reinforces the previous estimate. The mean FUI of records in FEUD, 1188 L t^{-1}, is positively skewed by high FUI values for crustacean and flatfish fisheries and by a lower FUI truncation at 0 L t^{-1}.

Knowledge gaps and need for additional data

It is clear from the data presented here that research into the fuel performance of fisheries has been largely limited to modernized commercial fleets in developed countries, particularly those operating in Europe. There is a stark absence of meaningful data from developing countries, and relatively few assessments have been undertaken on small-scale and artisanal fisheries, exceptions include Ziegler *et al.* (2011), Vivekanandan *et al.* (2013) and Boopendranath and Hameed (2013). In fact, while African and Asian fleets account for over 50% of landings by global fisheries (FAO 2011), they represent only a small fraction of available FUI data. This bias of fuel use data towards developed country fisheries, and particularly European fleets, was previously identified by Tyedmers *et al.* (2005) and Parker (2012b) in assessing carbon footprint studies of fisheries and aquaculture. The lack of data pertaining to fuel inputs to developing country fleets is particularly worrisome in the context of food security: Those countries for which the least data are available, including Africa and southeast Asia, are often those which rely most heavily on fisheries as a source of food and employment and which in turn are more vulnerable to impacts from energy price increases (Pelletier *et al.* 2014).

Inferring fuel use of small-scale and artisanal fisheries from the current breadth of data is difficult. The dependence of many communities in developing countries, particularly in coastal Africa, on fisheries for small pelagic species and coastal fisheries suggests that fuel inputs may be low. Furthermore, the prevalence in some areas of non-motorized vessels and the use of coast-based gears would support the idea that these fisheries are less fuel intensive than their larger, more industrialized counterparts. However, fishing cost data from the FAO (2007) show that fisheries in developing countries spend a substantial amount on fuel when compared to those in developed countries, as a percentage of total fishing costs (Lam *et al.* 2011; FAO 2013); while this reflects, to some degree, lower costs of labour in these countries, it also suggests the possibility of higher input of, and therefore expenditure on, fuel.

Addressing this lack of data related to developing country fisheries is paramount in identifying the potential impact of rising fuel costs on fishery-dependent communities and countries. Moreover, understanding current fuel consumption in small-scale artisanal fisheries can provide a baseline from which to evaluate and ideally inform any process of fishery industrialization. Such a transition has already been identified in India as having had a substantial effect on the fuel use of fisheries there, increasing consumption tenfold between 1961 and 2010 (Vivekanandan *et al.* 2013).

Within modern industrialized fleets, it is easier to draw conclusions from available fuel use data, even where data for a particular region are lacking. Analysis of our database shows that variation in FUI is more closely associated with species class and gear type than with region. While variations between regions certainly exist, the combination of species and gear can be considered a relatively reliable predictor. Fisheries in North America where less data are available, for example, can be expected to follow similar patterns to those in Europe. Likewise, South American purse seine fisheries for small pelagic species, which are among the largest in the world, can be expected to have a FUI similar to that of other purse seine fisheries targeting large aggregations of small pelagics (generally under 100 L t^{-1}). Thus, large gaps in the database can, to some degree, be estimated with a reasonable degree of confidence. Region-specific and even fishery-specific energy assessments, however, are always preferable to estimates based on similar fisheries, as these broader generalizations fail to incorporate local effects such as stock abundance, environmental conditions, gear and related technological choice, and management regime.

Improving FUI

Recent analyses of fuel inputs to European and Australian fisheries (Anderson and Guillen 2011; Cheilari *et al.* 2013) suggest that FUI of fisheries has been decreasing over the past decade. This is particularly the case in some fuel-intensive fisheries in Australia, including those targeting prawns and tuna (unpublished analyses). This trend of improvement has also been identified for specific fisheries in Sweden (Ziegler and Hornborg 2014) and for some major tuna fisheries (Tyedmers and

Parker 2012). Importantly, lower rates of fuel consumption observed in many fisheries have not completely counteracted the increase in the cost of fuel, and these fisheries are facing consistent increases in their overall expenditure on fuel.

Recent trends of declining FUI in some fisheries suggest a reversal of trends observed throughout the 1990s and early 2000s (Tyedmers 2004). This could be the result of increased awareness of fuel expenditure related to higher oil prices, improvements in technology, rebuilding of previously overfished stocks or changes in fishing capacity and management. Evidence from Sweden suggests that improved stocks are more likely to explain improvements in fuel performance than are technological improvements (Ziegler and Hornborg 2014). Supporting this, a decrease in stock biomass and an increase in fishing capacity led to a substantial increase in FUI of New England fisheries in the 1970s and 1980s (Mitchell and Cleveland 1993). Recent improvement in fuel consumption of some Australia fisheries is likely linked with decreased fishing capacity: the Northern prawn fishery in particular has experienced a marked drop in fuel use rates since a broad government vessel buyout starting in 2005 (Pascoe *et al.* 2012; unpublished analyses). Evidence of rebuilding stocks in Europe, coinciding with reductions in over-capacity (Cardinale *et al.* 2013), may explain the apparent improvement in fuel performance of European fisheries in recent years and hints that this improvement may continue.

Technological innovation, vessel size and power, and fishing behaviour have also been suggested as potential drivers of changes (both positive and negative) in fuel consumption of fishing fleets (Mitchell and Cleveland 1993; Schau *et al.* 2009; Vazquez-Rowe and Tyedmers 2013). However, evidence of the impact of technology and vessel characteristics seems to be mixed. Larger vessels, for example, have been found to be associated with higher fuel consumption in Danish fisheries (Thrane 2004) and global tuna fisheries (Tyedmers and Parker 2012), lower fuel consumption in the Portuguese sardine fishery (Almeida *et al.* 2013) and mixed influence in some Baltic fisheries (Ziegler and Hornborg 2014). While there are certainly improvement opportunities for fisheries relating to new technologies and fuel-efficient practices, stock abundance and capacity are more likely drivers. Furthermore, small improvements resulting from technological developments are likely to be overshadowed by the greater influence of species and gear. In this regard, management decision-making that intentionally or unintentionally re-allocates harvest between gear sectors can have a surprising impact on resulting fleet-wide FUI either positively or negatively. This was demonstrated by Driscoll and Tyedmers (2010), who found that a management-related shift from mid-water trawlers to purse seines in the Atlantic herring (*Clupea harengus*) fishery could easily result in reductions in total fuel combustion of at least two-thirds.

Potential applications

The FEUD database, and the breadth of literature and analyses that comprise it, offers a number of application opportunities. First and foremost is the ability to compare the relative energy performance – and related carbon footprint – of fisheries and their derived products. The ability to quickly assess an individual fishery or a range of products on the basis of energy use and emissions has application for industry, regulators, environmental non-governmental organizations and consumer groups. The Sea Fish Industry Authority in the United Kingdom, for example, has been developing industry tools for the past several years to readily provide energy and carbon performance information to industry (Tyedmers *et al.* 2007; Parker 2012b). Similarly, Seafood Watch in the United States is exploring opportunities to incorporate metrics of energy use in their consumer-oriented assessments of fisheries and aquaculture products (Parker 2012a).

As fuel can be used as a coarse proxy for the relative carbon footprint of fisheries-derived products, comparisons between fisheries and other food production systems are also possible. Figure 2 presents a comparison of fisheries from FEUD to other forms of protein production, on the basis of carbon footprint prior to processing and transport. It is clear that FUI greatly impacts how fish products compare to other forms of protein production. Fuel-intensive crustacean fisheries are among the least fuel-efficient forms of protein production, while lower fuel input fisheries targeting small pelagics rank among the most efficient. It is important to note, however, that in developed countries, landings from these highly efficient small pelagic fisheries are more often used for production of livestock and aquaculture feed than for direct human consumption.

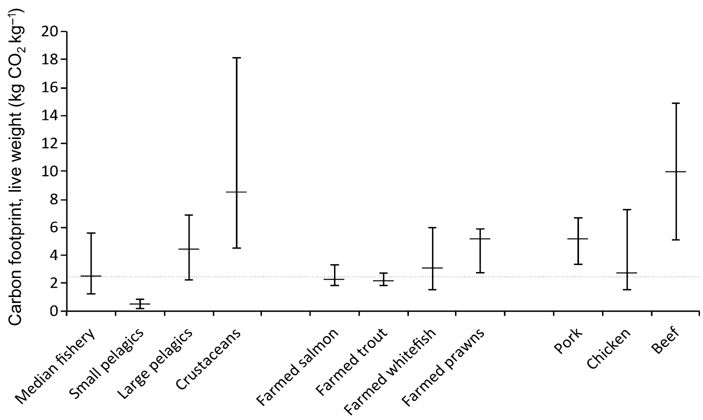

Figure 2 Median expected greenhouse gas (GHG) emissions of different forms of fisheries, aquaculture, pork and chicken, showing median and range of results (reflecting 25th and 75th percentiles of observed fisheries fuel use intensity (FUI) from the current study and range of reported carbon footprints for other sources). Sources of data for aquaculture and agriculture: Sonesson *et al.* (2010), Pelletier *et al.* (2009), Ayer and Tyedmers (2009), Boissy *et al.* (2011), Aubin *et al.* (2009), Baruthio *et al.* (2008), Cao *et al.* (2011), Papatryphon *et al.* (2004), Sun (2009), Nijdam *et al.* (2012).

With fuel's important role in the financial performance of many fisheries around the globe, the collection and analysis of FUI data is an essential component for economic analyses. Fuel analyses help inform indicators of economic health of individual fisheries and allow for the tracking of economic performance over time. Perhaps, more pertinent to policy makers, analyses of fuel consumption and costs can also provide insight into the relative impacts expected to be felt by fishers in response to fuel taxes, carbon taxes, emission regulations and energy price increases.

Conclusions

Many fisheries, particularly those targeting small pelagic species, are among the most energy- and carbon-efficient forms of protein production. However, high-value crustacean fisheries rank among the more energy- and carbon-intensive forms of protein production, with the exception of ruminant livestock production systems. Furthermore, small pelagic fisheries, while an important source of food in some developing countries, are often overlooked as a food option in developed countries and instead used as an intermediate product in aquaculture and livestock production, foregoing the potential energy and carbon benefits of these fisheries as a food source.

European and Australian fisheries exhibited signs of improvement in their energy consumption during the first decade of the 21st century. This reversal of previous trends suggests that fishers may be adapting – via behavioural changes or technological innovation – to rising fuel costs. It may also be an indication that fleets are fishing more efficiently as a result of management efforts to rebuild stocks and counter the challenge of over-capacity. While the trend in FUI is encouraging, particularly if viewed as a proxy for management effectiveness, fuel subsidies to fisheries risk delaying adaption to rising costs and contributing to unsustainable fishing practices.

The role of fisheries as a source of income, employment and food in developing countries necessitates further research into the energy performance of their fisheries. Little research is available on the performance of small-scale fisheries, coastal fisheries and artisanal fisheries. Research will need to be undertaken to assess the economic role of fuel in developing country fisheries that are transitioning to motorized fleets, facing high relative fuel costs of fishing and switching to more energy-intensive seafood choices as their populations become more affluent.

Fisheries are likely to face continued pressure on their profitability by rising fuel costs and carbon-related regulations in coming years. Technological innovations, behavioural changes and consideration of the energy-related effects of management decisions may be necessary to help fisheries adapt in the short term. However, the most effective way to improve the energy performance of fisheries facing these challenges will be to rebuild stocks and manage capacity effectively.

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