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Fuel use and greenhouse gas emissions of world fisheries

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Food production is responsible for a quarter of anthropogenic greenhouse gas (GHG) emissions globally. Marine fisheries are typically excluded from global assessments of GHGs or are generalized based on a limited number of case studies. Here we quantify fuel inputs and GHG emissions for the global fishing fleet from 1990–2011 and compare emissions from fisheries to those from agriculture and livestock production. We estimate that fisheries consumed 40 billion litres of fuel in 2011 and generated a total of 179 million tonnes of CO_2-equivalent GHGs (4% of global food production). Emissions from the global fishing industry grew by 28% between 1990 and 2011, with little coinciding increase in production (average emissions per tonne landed grew by 21%). Growth in emissions was driven primarily by increased harvests from fuel-intensive crustacean fisheries. The environmental benefit of low-carbon fisheries could be further realized if a greater proportion of landings were directed to human consumption rather than industrial uses.

Production, distribution and consumption of food contribute unequivocally to global climate change, accounting for a quarter of anthropogenic greenhouse gas (GHG) emissions[1,2]. Production of animal protein in particular is a substantial and growing driver of global warming, accounting for approximately half of all food production-related emissions[2–6]. As income and affluence in developing countries increase and diets approach the meat-rich consumption of the developed world, emissions associated with food production are likely to grow at least up until the middle of this century[7–9]. Together, these trends could see an increase in diet-related emissions of over 30% by 2050[9]. Dietary choices, particularly as they relate to animal protein, have pronounced effects on the per capita emissions of food consumption[9–11].

The Paris Agreement adopted by the 2015 United Nations Climate Change Conference, COP21, aims to keep global warming under 2 °C and optimally under 1.5 °C, requiring urgent reduction of GHG emissions from all sectors[12,13]. The proposed efforts of individual countries to limit emissions, in the form of Nationally Determined Contributions, range substantially and intended methods to achieve these proposed reductions include food-production and related industries to varying extents. Given the part that food production, and animal protein production in particular, plays in global emissions, tracking and reducing emissions from these systems will be an important component of national and international initiatives to limit climate change while still meeting the diverse food needs of a growing population. Identifying those countries in which particular food sectors contribute most heavily to overall emissions and present the clearest opportunities for improvement, will assist in domestic efforts to curb emissions. To this end, there is an emerging interest and need to quantify and characterize the drivers of emissions from all important sectors of the global food industry[14,15].

Production by fisheries is a critically important source of nutrition and income around the world, yet it is underrepresented in measurements of GHG emissions from food production. These assessments typically either exclude fisheries entirely[16] or generalize the contribution of fisheries based on small amounts of data[9,17,18], thereby failing to include the vast variation in emissions between fisheries targeting different species and operating different gears in different environments[19]. Fisheries are typically energy-intensive operations that produce the majority of their emissions directly from burning fossil fuels, and exhibit a marked variation both across and within fleets in the amount of fuel that is required[14,19,20]. The extent to which global fisheries rely on fossil fuel inputs was previously assessed[21]; in that study it was estimated that the total fleet consumption was 50 billion litres in 2000[21]. The future of fishery systems and fish production will be heavily influenced by climate change[22], while volatile energy prices and related regulations and policies will affect fishermen, fishing communities and nations whose livelihoods and food security depend on the ocean[23,24].

Here, we synthesize fuel use data from a Fisheries Energy Use Database (FEUD), adapted to account for non-fuel GHG emissions, with a database of global marine fishery landings to estimate annual GHG emissions from the global fishing fleet over two decades. We provide a global breakdown of wild-capture fishery emissions per country, and compare each nation's fishing emissions against those from agriculture and livestock production. We demonstrate that fisheries can contribute substantially to the national emissions of those countries that rely most heavily upon fishing as a source of food and income, and show that overall emissions from the industry have increased while landings have remained relatively constant. Finally, we show that, while some sectors of the industry are associated with high rates of emissions, many fisheries, particularly those targeting small pelagic species, can provide low-carbon sources of animal protein compared to land-based alternatives.

Results

Emissions of national and global fishing fleets. We estimate that the world's fishing fleets in 2011 burned 40 billion litres of fuel and emitted 179 million tonnes of CO_2-equivalent (CO_2-eq)

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GHGs to the atmosphere, or 2.2 kg CO_2-eq per kg of landed fish and invertebrates.

The national fishing fleets with the largest overall GHG emissions were based in China, Indonesia, Vietnam, the United States and Japan (Fig. 1). These five countries accounted for 37% of landings and 49% of total emissions in 2011, together producing 81 million tonnes CO_2-eq. The substantial contribution to fishery emissions from Asia reflects the extent of fishing and the scale of fleets based in the region. Fishing fleets based in China alone emitted 50 million tonnes CO_2-eq, approximately one quarter of total global emissions from fisheries, more than the combined impact of all fisheries in Europe and the Americas (Table 1). Countries that disproportionately targeted crustaceans, including Saudi Arabia and Australia, had the most carbon-intensive fleets. The west coast of South America, on the other hand, exhibited the least carbon-intensive production, accounting for 15% of global fishery production in 2011 and just 3% of fishery-sourced emissions, owing to the relatively high percentage of landings from the relatively low-fuel input Peruvian anchovy fishery.

The drivers behind national patterns in emissions are evident when looking at individual countries with diverse fleets. The United States, for example, had the fourth highest total emissions by fisheries in 2011, but, in terms of intensity per unit of landings, had a relatively low-carbon fleet (Fig. 1). The largest fisheries in terms of landings in the United States include two very low-input small-pelagic fisheries targeting Gulf menhaden (*Brevoortia patronus*) and Atlantic menhaden (*Brevoortia tyrannus*), as well as the Alaska pollock (*Gadus chalcogrammus*) trawl fisheries, which consume relatively little fuel compared to similar whitefish fisheries[20,25]. Fisheries for these three species made up over 40% of the total 5.2 million tonnes that were harvested by US fleets in 2011. By contrast, Australian fisheries harvest substantially lower volumes than those of many other countries but disproportionately target high-value crustacean species, including rock lobsters and prawns. The fuel use intensity (FUI) of these fisheries is several orders of magnitude greater than that of many small-pelagic fisheries. As a result, while contributing only 0.5% of overall global emissions, Australian fleets were amongst the most carbon-intensive in 2011, with an average emissions intensity (5.2 kg CO_2-eq per kg) that was several times the average of the US fleet (1.6 kg CO_2-eq per kg).

Emissions by fishing sector. Contribution to overall fishing emissions varies markedly between sectors when national and global fleets are disaggregated by species class (Table 1). Fisheries for pelagic species that are typically under 30 cm in length, which accounted for a fifth of reported landings over the entire period, contributed only 2% of global fishery emissions. Crustacean fisheries, on the other hand, accounted for only 6% of landings but over 22% of emissions. Fisheries for lobster and shrimp harvest relatively low volumes per trip compared to those targeting finfish and, particularly in the case of trawl fisheries that target crustaceans, consume substantial quantities of fuel in the process.

Upwards of a third of reported global marine fishery landings are used for non-food purposes, although the proportion of landings for these purposes has decreased over time[26–28]. Most landings for non-food purposes are directed to meal and oil production for supplying aquaculture and livestock feeds. These reduction fisheries are located primarily in Chile, Peru, Thailand, Europe, China and the USA[29,30]. Non-food fisheries were responsible for 15% of the global emissions by the fishing industry in 2011, with an average emission intensity of approximately 1.1 kg CO_2-eq per landed kg of fish. Reduction fisheries for meal and oil produced only 4% of 2011 fishing emissions, averaging 0.4 kg CO_2-eq per kg landed.

The non-motorized fishing sector was estimated to account for six million tonnes of landed fish and invertebrates in 2011. The vast majority of these landings were in Africa and Asia, based on estimated percentages of non-motorized fishing vessels by country in these regions[31]. Non-motorized vessels are still associated with some

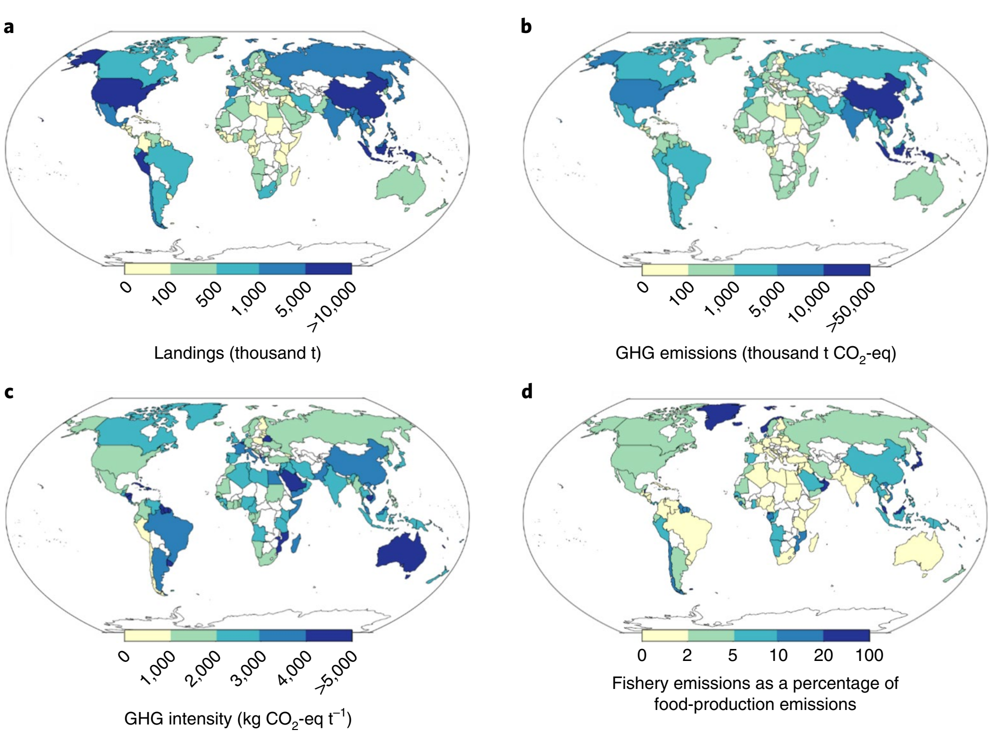

Fig. 1 | Production and GHG emissions by fisheries for each country. a, Landings by national fishing fleets in 2011 in millions of tonnes. **b** Aggregate GHG emissions by national fishing fleets, up to the point of landing in thousands of tonnes CO_2-eq. **c**, Emission intensity of fishery landings in kg CO_2-eq per tonne. **d**, GHG emissions from fisheries as a percentage of emissions from agricultural production.

Table 1 | Fishery GHG emissions by sector in 2011

Industry sector	Landings (million tonnes)	Fuel use intensity (l t^{-1})	Emissions intensity (kg CO_2-eq per kg)	Total emissions (million t CO_2-eq)
Global fisheries	81	489	2.2	179
By vessel type				
Motorized	74	532	2.3	174
Non-motorized	6	0	0.7	5
By product type				
Human consumption	57	592	2.7	152
Non-food products	24	246	1.1	27
Meal and oil	18	82	0.4	7
By species group				
Pelagic fish <30 cm	17	42	0.2	3
Pelagic fish >30 cm	21	430	1.9	41
Demersal molluscs	3	523	2.4	7
Demersal fish	31	539	2.4	75
Cephalopods	4	613	2.8	10
Crustaceans	5	1,739	7.9	43
By region				
Latin America	16	235	1.0	16
North America	6	380	1.7	10
Europe	12	390	1.7	20
Africa	5	385	1.8	9
Asia (excluding China)	28	554	2.5	71
Oceania	1	636	2.8	3
China	13	809	3.7	50

non-fuel emissions, but contribute less than 2% to overall atmospheric emissions from the sector as a whole. A potential source of concern for fishery management in developing countries is the expected increase in reliance on fossil fuels as fleets shift from traditional methods to energy-intensive industrialized operations[32]. Fuel use in these regions already accounts for a relatively larger portion of fishing costs[33] and increased costs could potentially threaten the capacity of subsistence and small-scale operators to fish.

Trends in emissions from 1990 to 2011. Total landings from the world's fishing fleets remained relatively unchanged over the period from 1990 to 2011 (Fig. 2). Fluctuations throughout the period were driven primarily by varying harvests of small pelagic species, particularly from the Peruvian anchovy fisheries off the coast of Peru and Chile (see for example, the drop in landings corresponding to the El Niño event in 1998).

Emissions from world fisheries increased by 28% from 1990 levels over the two decades analysed, contributing 39 million tonnes CO_2-eq more GHGs to the atmosphere in 2011 than in 1990 (Fig. 2). Average emissions intensity per tonne of landings increased by 21% over the same period. Much of the overall increase in emissions over this time period can be attributed to catch composition. In particular, landings from high-input crustacean fisheries increased by 60%. GHG emissions from global fishing fleets increased with increasing catch rates of crustaceans ($P<0.001$) and demersal and reef fish ($P=0.001$) (multiple regression, $r^2=0.96$). Trends in some species groupings were also influenced by increasing fuel inputs to fisheries through the 1990s and early 2000s observed in European waters[34,35], the North Atlantic[36] and around Australia[37], although these trends have reversed in some sectors in recent years. Trends in emissions were significantly correlated to FUI for large pelagic fishes ($r^2=0.71$, $P<0.001$), demersal fishes ($r^2=0.67$, $P<0.001$), and crustaceans ($r^2=0.33$, $P=0.005$), suggesting that changing FUI estimates, rather than variable landings alone, contributed to the variation in emissions in these sectors.

Comparison to agriculture and livestock. Global emissions from agriculture and livestock production in the FAOSTAT database, excluding those associated with burning savannah and cropland, amounted to 5 billion tonnes CO_2-eq in 2011[17]. Emissions from fisheries, at 179 million tonnes, account for approximately 4% of combined fishery, agriculture and livestock emissions. In approximately half of the world's countries, including almost all industrialized nations, fisheries account for less than 5% of domestic food production emissions (Fig. 2). However, in some coastal and island countries, including Kiribati, the Marshall Islands and the Maldives, where agriculture is limited and most domestically produced protein comes from the ocean, fisheries account for almost all food-production emissions. Among industrialized countries and regions, fishing fleets from Iceland (80%), Greenland (72%), Taiwan (50%), Norway (38%), Japan (21%) and Denmark (12%) contribute substantially to domestic food production-related emissions, reflecting the relative role that fisheries have in the economies, diets and cultures in these countries.

Compared to other sources of animal protein, products derived from marine fisheries and destined for human consumption produce relatively low GHG emissions (Fig. 3). Over half of fishery-derived products for consumption were estimated to produce fewer GHGs than the low end of emission ranges for pork, beef and lamb. Average fisheries had a carbon footprint similar to the range reported for poultry production. Previous estimates have suggested that fisheries are emission-intensive sources of protein[9], but were seemingly skewed by over-reliance on case studies of highly fuel-intensive fisheries. The comparisons made here and shown in Fig. 3 present only those fisheries that fish for human consumption; if fish landed for non-food uses were also directed to consumption, their products would be associated with lower emissions than every other major source of animal protein. This, of course, would require increased market demand for products of anchovies and sardines, and would necessitate the substitution of non-fishery feed inputs to aquaculture systems as farm-based fish production continues to grow—potentially increasing emissions from that industry as a result[38].

Reducing emissions from fisheries. Strategies to improve the short- and long-term performance of the industry should include behavioural, technological and managerial efforts. The relative effect of these efforts has been assessed for different fisheries with mixed results. Identifying those factors that influence fuel use most, and that can therefore yield potential for improvement, is difficult: both the direction and magnitude of relationships between fuel use and variables such as vessel size and engine horsepower vary from fishery to fishery[35,39,40]. Behavioural changes, such as reducing vessel speed while steaming and using more selective fishing times and locations, are often suggested as short-term adaptations to increased fuel prices that are easily implemented by fishermen[23]. Indeed, the skill and experience of skippers can help to explain variation in efficiency within fleets[41,42].

Fishery management efforts aimed at reducing overcapacity and rebuilding stocks may have a particular benefit in reducing fuel use and emissions. Fuel use reductions were observed, for example, after government vessel buy-backs in Australia's Northern Prawn Fishery[37,43], as well as following capacity reduction in Taiwanese fishing fleets in 2005[44]. The reduction in fuel use in European fisheries has been attributed at least partially to increased stock biomass

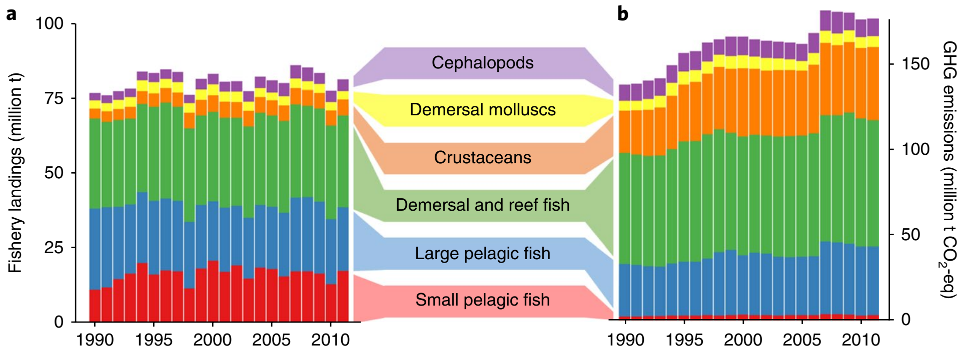

Fig. 2 | Global marine fishery landings and GHG emissions for 1990–2011 categorized by species groups. a, Global marine fishery landings. **b**, Global GHG emissions from marine fisheries.

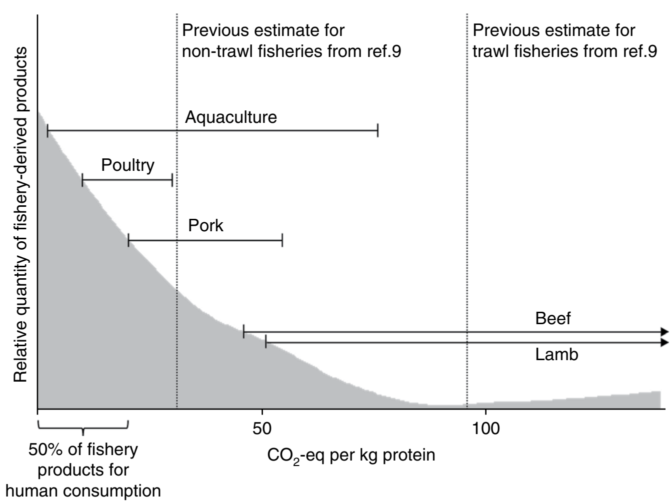

Fig. 3 | Carbon footprint of fishery-derived products for human consumption in 2011 compared to other sources of animal protein. Truncated for display purposes to include 98% of landings. Vertical partitions indicate previous generalized estimates for trawl and non-trawl fisheries[9], showing the percentage of global fisheries below (59%), within (32%) and above (9%) those estimates[9]. Ranges for livestock systems have been previously published[15]: aquaculture, 4–75 kg CO_2 per kg protein; poultry, 10–30 kg CO_2 per kg protein; pork, 20–55 kg CO_2 per kg protein; beef, 45–640 kg CO_2 per kg protein; lamb, 51–750 kg CO_2 kg protein[15].

in recent years[35,39,45]. Even when management measures are not constructed around the rebuilding of stocks or reduction of fleet capacity, substantial changes in FUI can occur[46]. Overall, the potential for management efforts to reduce fuel consumption varies substantially between fisheries with estimates ranging from 20 to 80% in a report by the Organization for Economic Cooperation and Development[45].

Although the results were presented here per fishing country, the management of fisheries, consumption of the fish and the policies that relate to the fisheries, energy and climate change transcend borders and jurisdictions. Many European fisheries, for example, are managed through the European Union rather than by individual states, and so decisions influencing fishing efficiency would be made at an international level. Furthermore, the life cycle of fishery products extends well beyond the point of landing. Emissions from seafood up to the point of consumption are influenced by a number of factors, not least of which is the role of international trade and transport. Over two-fifths of the world's seafood products are traded between countries, and large flows of products originating in the exclusive economic zones of developing countries are imported to markets in the European Union, United States and Japan[26,47]. As a result, fishery-derived products may travel thousands of kilometres from their origin to their point of processing and ultimately to the market, in some cases passing through multiple national borders in the process[28,48]. This transport is a key source of emissions for some products when flown fresh or live by air freight, whereas ship-based transport of frozen or otherwise preserved products does not contribute as much to overall seafood emissions[49]. The extent of seafood trade, the demand for species from distant origins and the desire for fresh products may make transport particularly important for fishery-derived products compared to meat products.

Findings here will help to inform global and regional GHG emissions models as well as food and climate policies both nationally and internationally, helping to illuminate the role that fisheries have in the environmental cost of global food-production systems. As more data are gathered, particularly from small-scale fisheries and from fisheries in developing nations, as well as non-fuel and post-harvest sources of emissions, the patterns provided here will become better informed and more dynamic in highlighting the contribution of diverse seafood production systems to climate change.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available at https://doi.org/10.1038/s41558-018-0117-x.

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Author contributions

R.W.R.P. co-manages FEUD, conducted analyses and wrote the manuscript. J.L.B., C.G. and B.S.G. assisted with projected development and manuscript preparation. K.H. assisted with data analysis and manuscript preparation. P.H.T. developed and co-manages FEUD and assisted with manuscript preparation. R.A.W. provided global fishery landing data and assisted with data analysis and manuscript preparation.

Competing interests

The authors declare no competing interests.

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Methods

Estimates of fishing effort were sourced from a global database based on estimates of total vessel engine size and number of fishing days in a year, assembled from FAO, the European Union, regional tuna-management bodies and other sources[50,51]. The number of fishing vessels, gross registered tonnage and gear type were sourced from the FAO Fishing Fleet database. The EUROPA Fishing Fleet Register online database provided detailed data about vessel characteristics for country members of the European Union. These data sources were augmented by data from regional tuna associations and various online sources to provide in depth information about fleet sizes and characteristics, and also, importantly, by information about the number of days that this fishing capacity was used each year.

For gear types that could be operated by non-motorized vessels, estimates of non-motorized landings were made based on the reported number of non-motorized vessels in each country's fleet according to the FAO[31]. Because of limited data, non-motorized landing rates for many countries were estimated from neighbouring countries and/or countries with similar socio-economic and fishing conditions.

Fuel consumption rates were extracted from FEUD[19], which contains over 1,600 records of FUI (in litres per round weight tonne of landings), vessel characteristics and fishing operations at various scales (individual vessels, national fleets and global sectors). Records of fisheries operating before 1985 were excluded from analysis, as were any records for which target species group or gear type could not be determined.

Each record from the global landings database was matched to a subset of FEUD records based on a hierarchy of match criteria. All records were matched to gear type, which has a marked influence on fuel consumption rates[15,19]. In cases for which species-specific FUI estimates were not available, matches were based on a set of 30 target groups of species sharing similar characteristics and habitats (for example, pelagic species of <30 cm). First attempts to match records identified FEUD records that matched the target species, gear and fishing country of the landings record. In lieu of successful matches, second attempts matched target species and gear, regardless of fishing country. Third attempts matched target species group, gear and fishing country. Fourth attempts matched target species group and gear, regardless of fishing country. If no fuel use records matched the combination of species target group and gear for a given fishery, an average FUI value across all records was applied.

To generate fuel use estimates for each fishery, all FEUD records matching the above criteria were weighted based on three variables: the number of vessels reporting data, the number of FUI estimates originating from the same data source, and the difference in years between the fishing record and the fuel record. Records reporting data from multiple vessels were attributed a weight equal to the log of the number of vessels plus one, considering that a direct weighting would have given undue influence to records with a large number of reported vessels. If multiple records were derived from the same source material, log weighting was also applied, such that the total relative influence of a data source was equal to the log of the number of data points provided plus one. Finally, record weights were decreased by 10% for each year of difference between the fishing year of interest and the fishing year in the FEUD record. Fuel consumption estimates were thus generated following equation (1)

$$F_{f,y} = \sum \left(F_r \frac{w_r}{\sum (w_r)} \right) \quad (1)$$

where $F_{f,y}$ is the FUI estimate generated for fishery f in year y, F_r is the FUI of record r matching fishery f, w_r is the weighting factor applied to record r using the weighting method in equation (2)

$$w_r = \log (v_r + 1) \frac{\log (s_r + 1)}{s_r} 0.9^{|y_f - y_r|} \quad (2)$$

where v_r is the number of vessels reporting data in record r, s_r is the number of data points coming from the same source as record r, y_f is the year of fishing in fishery f and y_r is the year of fishing of record r.

Average fuel density was assumed to be 0.9 kg l^{-1} with an average carbon content of 860 g kg^{-1}. Total direct emissions from burning fuel were calculated to be 2.8 kg CO_2-eq per litre of fuel based on chemical content of marine fuels and using IPCC 2013 characterization factors[1,52]. Upstream emissions associated with mining, refining and distributing diesel fuel were extracted from the ecoinvent 3.0 life cycle inventory database[53]. Average rates of upstream emissions of 0.5 kg CO_2-eq per litre were applied across all fisheries, although actual upstream emissions vary according to production method, processing location and transport distance.

The combined rate of emissions was 3.3 kg CO_2-eq GHG per litre of fuel combusted.

Life cycle assessments (LCAs) of fisheries over the past decade have estimated non-fuel related inputs to account for between 10 and 40% of total emissions up to the point of landing[54–57]. This includes emissions from vessel construction and maintenance, gear manufacture, loss of refrigerants and other activities. Refrigerant loss in particular has been identified as a key source of emissions in some fisheries[12,13]. Fishery LCAs have primarily reported data for large, industrial fleets in developed countries, and relatively little data are available on rates of emissions from artisanal or small-scale fisheries or for those in developing countries, although data availability for the latter is increasing[55,58,59]. Non-fuel-related emissions vary between fisheries, but the limited coverage of studies providing data for different fisheries to date did not allow for the incorporation of that variation in the analysis presented here. Instead, an average of 25% was assumed across the industry. No additional emissions were attributed to the use of bait, a key source of GHG emissions in some fisheries, such as those for American lobster (*Homarus americanus*),[60] in order to avoid double-counting, assuming that bait was sourced either from the fishing vessels themselves or from other fisheries already accounted for. Non-fuel-related emissions for non-motorized vessels were considered to be equivalent to the non-fuel-related emissions of their motorized counterparts, in order to account for emissions associated with vessels, gear and other inputs to those fisheries. Total fuel and non-fuel emission intensity of each fishing record were then calculated using equation (3)

$$G_{f,y} = \frac{3.3 F_{f,y} t_{\mathrm{m}} + 1.1 F_{f,y} (t_{\mathrm{m}} + t_{\mathrm{n}})}{(t_{\mathrm{m}} + t_{\mathrm{n}})} \quad (3)$$

where $G_{f,y}$ is the total emissions from fishery f in year y, t_{m} is the tonnage landed by motorized vessels, t_{n} is the tonnage landed by non-motorized vessels.

National fishery GHG emissions were compared against agriculture and livestock emissions at a country level using data reported in the FAOSTAT Emissions Database[17]. All emissions associated with direct food production from agricultural and livestock production were included. Major sources of emissions included enteric fermentation (34% in 2011), application and management of manure (23%), on-farm energy use (13%) and use of synthetic fertilizers (11%). Emissions associated with the burning of savannah and shrubland (4%) were excluded as their primary function was not considered to be directly related to food production, and because their inclusion would have greatly expanded agricultural emissions in some countries in which burning is required for multiple reasons, such as fire prevention and forest regeneration. Important to note is that emissions associated with land use change are not included in the FAO dataset, so values here do not consider, for example, emissions that result from deforestation of land for soy or palm oil production.

For further investigation of the role of different sectors, species were grouped into six categories and then trends in catch, modelled GHG intensity and contribution to overall GHGs from the industry were assessed. Linear models within each category identified the extent to which overall emissions were influenced by changes in modelled FUI, rather than variation in the harvest alone. Multiple regression of global aggregate emissions relative to landings from each species category identified the effect of global catch composition on the overall emission estimate. Fishery landings by non-food sectors (for example, fishmeal, nutraceuticals and so on) were separated from fishery landings intended for human consumption, assuming 75% of non-food landings originated from fisheries targeting pelagic species under 60 cm in length. Reduction fisheries for meal and oil, in particular, were assumed to be sourced from fisheries targeting pelagic species under 60 cm in length, with the majority of products coming from small pelagic species such as Peruvian anchovy (*Engraulis ringens*), South American pilchard (*Sardinops sagax*), Gulf menhaden (*Brevoortia patronus*) and Atlantic herring (*Clupea harengus*). Country of origin for reduction fisheries was based on global fishmeal production data from the US Department of Agriculture[29] and production in Europe was further disaggregated based on the relative rate of small-pelagic harvests in European countries.

Comparisons of fishery emissions to livestock production systems were made on the basis of kg CO_2-eq emissions per kg of edible protein, including only those fisheries whose products were destined for human consumption in 2011. Landed weight of fish was translated to values per kg protein based on species-specific edible yields and protein content of flesh, with average values of 40 and 20%, respectively. An additional 0.5 kg CO_2-eq per kg of landed fish was added across all fisheries to account for post-landing emissions, including inputs to processing, packaging and transportation[15]. The resulting distribution of fishery-derived products by GHG emissions intensity was compared to the range of emissions from livestock LCAs[15], as well as values previously calculated for global trawl and non-trawl fisheries[9].

Data availability. The data that support the findings of this study are available from the corresponding author upon request. The global fisheries catch database used in this study is available from ref. [51].

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