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Food for Thought

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Evaluating the sustainability and environmental impacts of trawling compared to other food production systems

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Mobile bottom contact gear such as trawls is widely considered to have the highest environmental impact of commonly used fishing gears, with concern about impact on benthic communities, bycatch, and carbon footprint frequently highlighted as much higher than other forms of fishing. As a result, the use of such gears has been banned or severely restricted in some countries, and there are many proposals to implement such restrictions elsewhere. In this paper, we review the sustainability of bottom trawling with respect to target-species sustainability, impact on benthic communities, bycatch and discards, carbon footprint from fuel use, and impact on carbon sequestration. We compare the impact to other forms of fishing and other food production systems. We show that bottom-trawl and dredge fisheries have been sustained, and where well managed, stocks are increasing. Benthic sedimentary habitats remain in good condition where fishing pressure is well managed and where VME and species of concern can be protected by spatial management. Bycatch is intrinsically high because of the mixed-species nature of benthic communities. The carbon footprint is on average higher than chicken or pork, but much less than beef, and can be much lower than chicken or pork. The impact on carbon sequestration remains highly uncertain. Overall, the concerns about trawling impacts can be significantly mitigated when existing technical gear and management measures (e.g. gear design changes and spatial controls) are adopted by industry and regulatory bodies and the race-to-fish eliminated. When these management measures are implemented, it appears that bottom trawling would have a lower environmental impact than livestock or fed aquaculture, which would likely replace trawl-caught fish if trawling was banned. A total of 83 bottom-trawl fisheries are currently certified by the Marine Stewardship Council, which is the most widely accepted measure of overall sustainability.

Keywords: Bottom trawling, bycatch, carbon footprint, discards, environmental impacts of fishing.

Introduction

Bottom trawls (such as beam trawls, otter trawls, and shellfish dredges, which we will refer to as bottom trawls) are designed to catch target species that live close to, in, and on the seabed. The use of bottom trawls as a means of catching fish has met with increasing opposition due to its impact on seafloor habitats and biological communities (Watling and Norse, 1998; Watling, 2013), its high bycatch rates (Pérez Roda *et al.*, 2019; Gilman *et al.*, 2020), CO_2 release from fuel use (Tyedmers, 2004; Sala *et al.*, 2022), and, lately, its potential contribution to greenhouse emissions through the release of stored carbon from disturbed seabed sediments (Sala *et al.*, 2021). Although the magnitude of those impacts remains the subject of intense scientific debate (Pitcher *et al.*, 2022), concerns about the environmental impacts of trawling have fueled strong public campaigns, resulting in bottom trawling being demonized (Willer *et al.*, 2022), severely restricted, or effectively banned in some countries and regions (McConnaughey *et al.*, 2020).

However, bottom trawling accounts for 26% of global marine fisheries catches (Steadman *et al.*, 2022), providing food and employment for millions of people at a time when the contributions of marine fisheries towards the United Nations Sustainable Development Goals (United Nations, 2002) and, specifically, to meet the food and nutrient needs of a growing population, are increasingly recognized. While alternative fishing gears and methods may be available and economically viable in some cases, many benthic and demersal target species would be difficult to catch without some form of bottom trawling (Ziegler and Valentinsson, 2008; Suuronen *et al.*, 2012).

From this perspective, bottom trawling needs to be considered as one form of food production, and its sustainability and environmental footprint should be compared to footprints of other ways of producing food, including other capture fisheries, aquaculture, livestock, and crop production.

The purpose of this paper is to summarize the current knowledge about the sustainability and environmental

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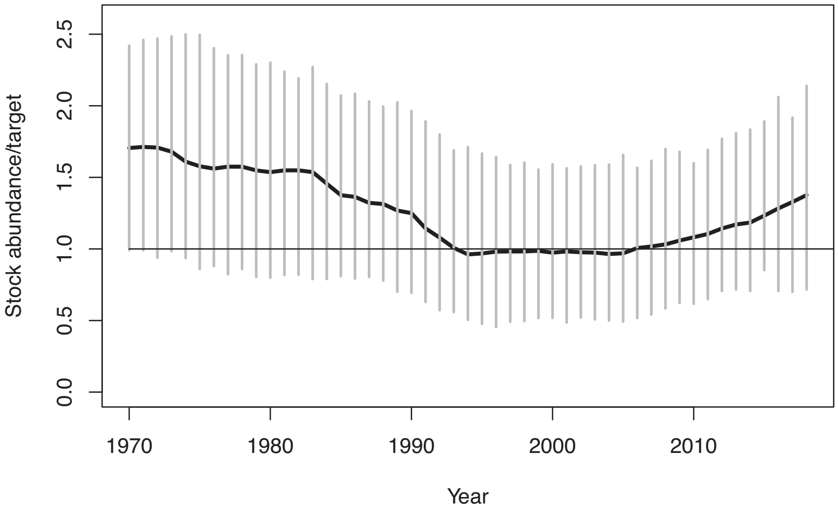

Figure 1. The abundance trend in global groundfish stocks relative to management targets (solid black line). In most cases, management targets are based on achieving maximum sustainable yield. Vertical bars show the range of 50% of the stocks, with 25% being below and 25% above. The thin grey horizontal line shows where the stock abundance is equal to the management target. Redrawn from Hilborn *et al.* (2021).

impacts of bottom trawling, to compare trawling impacts to other forms of food production, to identify important information gaps, and to suggest the best ways to minimize the environmental impacts of trawling.

Certifications as sustainable

At present, 83 bottom-trawl fisheries representing 252 bottom-trawl-caught species/fisheries combinations have been certified by the Marine Stewardship Council (personal communication, Mike Melnychuk, MSC staff) as sustainable. These include 122 units of certification from Europe, 63 from the United States, 19 from Canada, 15 from Australia, 12 each from Chile and New Zealand, 5 from Africa, and 2 from Argentina. Many are recommended by the Seafood Watch programme of the Monterey Bay Aquarium (www.seafoodwatch.org). These are the two best-known international standards for fisheries sustainability, and the fact that bottom-trawl fisheries meet their standards is evidence that bottom-trawl fishing can be sustainable. These sustainability evaluations consider not only the status of the target stock but also the marine environmental impacts of the fishing method and have specific criteria regarding the management of bottom-trawl impacts on benthic communities (Monterey Bay Aquarium, 2023) (Marine Stewardship Council, 2023).

Sustainability of target species

Bottom trawling is the primary method used to harvest many demersal species known as groundfish, which include cod, haddock, pollock, hake, and multiple species of flatfish and rockfish. Globally, almost all the catch of groundfish comes from fish stocks whose trends in abundance are scientifically assessed (Hilborn *et al.*, 2021). Groundfish populations are increasing overall and above the target levels for sustainable exploitation (Figure 1) (Hilborn *et al.*, 2021). Arguments that bottom trawling is incompatible with sustaining a fishery for the target species are contradicted by the trends in the abundance of groundfish stocks. The mixed-stock nature of all bottom fishing methods (trawl, longline, Danish seine, gillnet) poses challenges to sustainable exploitation of mixed species of differential productivity, but the increasing trend of groundfish in many regions of the world shows that even in mixed-species fisheries, good management can lead to sustainability (Fernandes and Cook, 2013; Zimmermann and Werner, 2019).

There are of course many stocks that are overexploited with bottom trawls, but this is a failure of fisheries management to control fishing pressure rather than a direct consequence of the fishing gear used, as it has been clearly demonstrated that well-regulated bottom-trawl fisheries can avoid overfishing (Hilborn *et al.*, 2021). Bottom trawling and related mobile bottom-contact gear like dredges are also commonly used for many invertebrates, but there has been no global summary of the trends in abundance of these species.

Impact of trawling on benthic ecosystems

The magnitude of the effect of the trawl disturbance on benthic communities depends on the frequency of trawling, the impact (or depletion rate) per trawl pass, and the individual recovery rates of biota exposed to trawling (Hiddink *et al.*, 2017). The effects of trawling on the commonly fished sedimentary habitats, such as muddy and sandy seabeds, are much less severe than on the more sensitive habitats, such as oyster reefs in shallow waters and vulnerable marine ecosystems (VMEs) (Parker *et al.*, 2009), such as sponge gardens or cold-water coral reefs (Clark and Rowden, 2009; Clark *et al.*, 2015; Kaiser *et al.*, 2018), in deeper waters. For sedimentary habitats, average depletion rates (the percentage of benthic invertebrates killed per passage of the gear) range from 4.7 to 26.1% depending on trawl type, gear penetration depth, and habitat type, with otter trawls causing the lowest depletion, followed by beam trawls and towed dredges causing the most impact (Sciberras *et al.*, 2018). Depletion rates are lower in sand than in gravel and mud (Collie *et al.*, 2017; Pitcher *et al.*, 2022). Recovery rates are related to the longevity of the affected species (Hiddink *et al.*, 2019). Meta-analysis of studies reporting how the biomass of the benthic community declines with increasing trawling intensity produced estimates of recovery rates that ranged from 29 to 68% per year along a gravel-to-mud continuum (Pitcher *et al.*, 2022). Slower recovery with increasing gravel reflects the greater proportions of longer-lived species found in more stable gravel habitats. Epibenthic megafauna and biogenic habitats are the most sensitive to all forms of trawling, and recovery rates are often measured in decades (Kaiser *et al.*, 2018). However, complex habitats like coral reefs and rocky bottoms are generally avoided by trawlers because of the threats to their nets. When these habitats are trawled, they are heavily impacted (Parker *et al.*, 2009; Williams *et al.*, 2020), and a consensus is growing that the best practise is to close such areas to mobile bottom contact gear (McConnaughey *et al.*, 2020).

A global modelling assessment of trawl impacts on macro epifauna and infauna in sedimentary habitats showed that the status of benthic populations relative to an untrawled state differs greatly among regions and was related to the total amount of trawling (Pitcher *et al.*, 2022). The model included 24 regions worldwide and used fine-scale data on the frequency of trawling and recovery rates of biota estimated from meta-analysis (Figure 2). The measure used, relative benthic status (RBS), reflects the extent to which the macrofauna have been numerically reduced and is an aggregated measure across many species (Pitcher *et al.*, 2017). A status of 0.9, for instance, would mean that the abundance of benthic macrofauna averaged across taxa would be 90% of the abundance in the absence of trawling. Even with a RBS of 0.9, some more sensitive species would be reduced more than that and more resilient species less. The RBS for a region will reflect the average across untrawled, lightly trawled, and heavily trawled areas in the region, weighted by the area of each level of trawl intensity. Mazor *et al.* (2021) were able to look at the impacts on specific species where data were available. There are no established targets for this index, and as in discussions of changes in biodiversity, multiple measures are potentially usable. RBS allows us to compare widely across benthic habitats in many different regions.

Overall impacts are low in most regions examined, and much of the seabed is untrawled in many regions. Regional average status relative to an untrawled state (status = 1.0) was high (>0.9) in 15 regions (mostly outside Europe) but <0.7 in three European regions and only 0.25 in the Adriatic Sea. Across all regions, 66% of the seabed area was not trawled, 1.5% was depleted (status = 0), and 93% had status >0.8 (Figure 2) (Pitcher *et al.*, 2022).

The RBS is calculated for each region in the most recent range of years where trawl effort data were available (mostly 2010–2014), and reflects the expected status of benthos at that intensity of trawling. RBS depends on habitat type (reflecting both the taxa found and the sensitivity to trawling) and the intensity of trawling. In most areas where we have trawl-effort data, there is declining fishing pressure (see a later section on trends in trawl footprint), so we would expect that in general RBS would be improving.

Mazor *et al.* (2021) provide more detail on impacts within different taxonomic groups. The status of populations of benthic-invertebrate groups was examined for 13 of the 24 regions for which suitable invertebrate distribution data were available and ranged between 0.86 and 1 (mean = 0.99), with 78% of benthos-groups having a status >0.95 (Mazor *et al.*, 2021). Again, mean benthos status was lower in European regions than regions elsewhere, which accords with the intensity and history of fishing in Europe.

Assessing the status of sedimentary habitats (the habitat types where most trawling occurs) is critical to ensuring the integrity of the seabed ecosystems because sedimentary habitats constitute most of the continental shelves. Nevertheless, much concern surrounds rarer, more sensitive habitat types that can characterize VMEs and biogenic habitats (FAO, 2009). These habitats are not well mapped over large scales in most regions, and while impact rates are known to be high in many cases, there are few quantitative estimates of the impact that bottom trawling has on them because few studies have been carried out because it is hard to justify trawling over such sensitive habitats for a scientific experiment (Hall-Spencer and Moore, 2000). Even the most resilient of these VMEs cannot withstand trawling more than once every three years (Thompson *et al.*, 2016). A preliminary assessment conducted by Pitcher *et al.* (2022) calculated the percentage of each of the 24 regions in their study where trawl intensity exceeded that frequency, which was used as a local extinction threshold for highly sensitive biota. The percentage of seabed trawled at least once every three years ranged from 0.2% in southern Chile to 82% in the Adriatic Sea and was >20% for 10 regions (all European regions and northern Benguela) (Pitcher *et al.*, 2022). In those regions, we would expect the sensitive species in VMEs to be eliminated in proportion to the amount of area trawled three times or more. Because of the high sensitivity of the habitat-forming biota types that characterize VMEs, fisheries management should seek to prevent significant adverse impacts on them, according to the Deep-Sea Fisheries Guidelines (FAO, 2009).

The data on trawl intensity in Pitcher *et al.* (2022) covers almost all European waters, Australia, New Zealand, South Africa, Namibia, Argentina, Chile, the western US, and Alaska. There is no coverage of Asia, where trawling is thought to be quite intense (Suuronen *et al.*, 2020), and Africa with the exception of Namibia and South Africa.

Indirect impact of trawling on productivity of target species

Intense bottom trawling causes a high level of local mortality to benthic fauna, and for fish species that depend on benthic fauna for food, shelter, productivity, and hence sustainable harvest may decline with increasing levels of bottom fishing disturbance. Indirect effects of bottom fishing have been demonstrated experimentally and with dynamic models in which trawling affects the target species, their benthic prey, and the habitat-forming epifauna (Collie *et al.*, 2017; Pitcher *et al.*, 2022). Ultimately, the response of fish productivity to bottom fishing depends on the interplay between reduced benthic prey abundance and reduced competition for benthic food as fish density declines (Hiddink *et al.*, 2011; 2016). Historically, trawling may have modified habitat and reduced the carrying capacity of fish stocks, but these effects are difficult to distinguish empirically because fishing and other factors may impact the abundance of target species. Over large areas of the continental shelf with sandy sediments, these indirect effects are estimated to be small compared with the direct mortality caused by fishing target species (Collie *et al.*, 2017; Pitcher *et al.*, 2022). A possible explanation for this small effect is that the distribution of fishing effort is very patchy—small fractions of fishing grounds are heavily fished, while large fractions are lightly fished or unfished (Amoroso *et al.*, 2018). Therefore, the indirect effects of

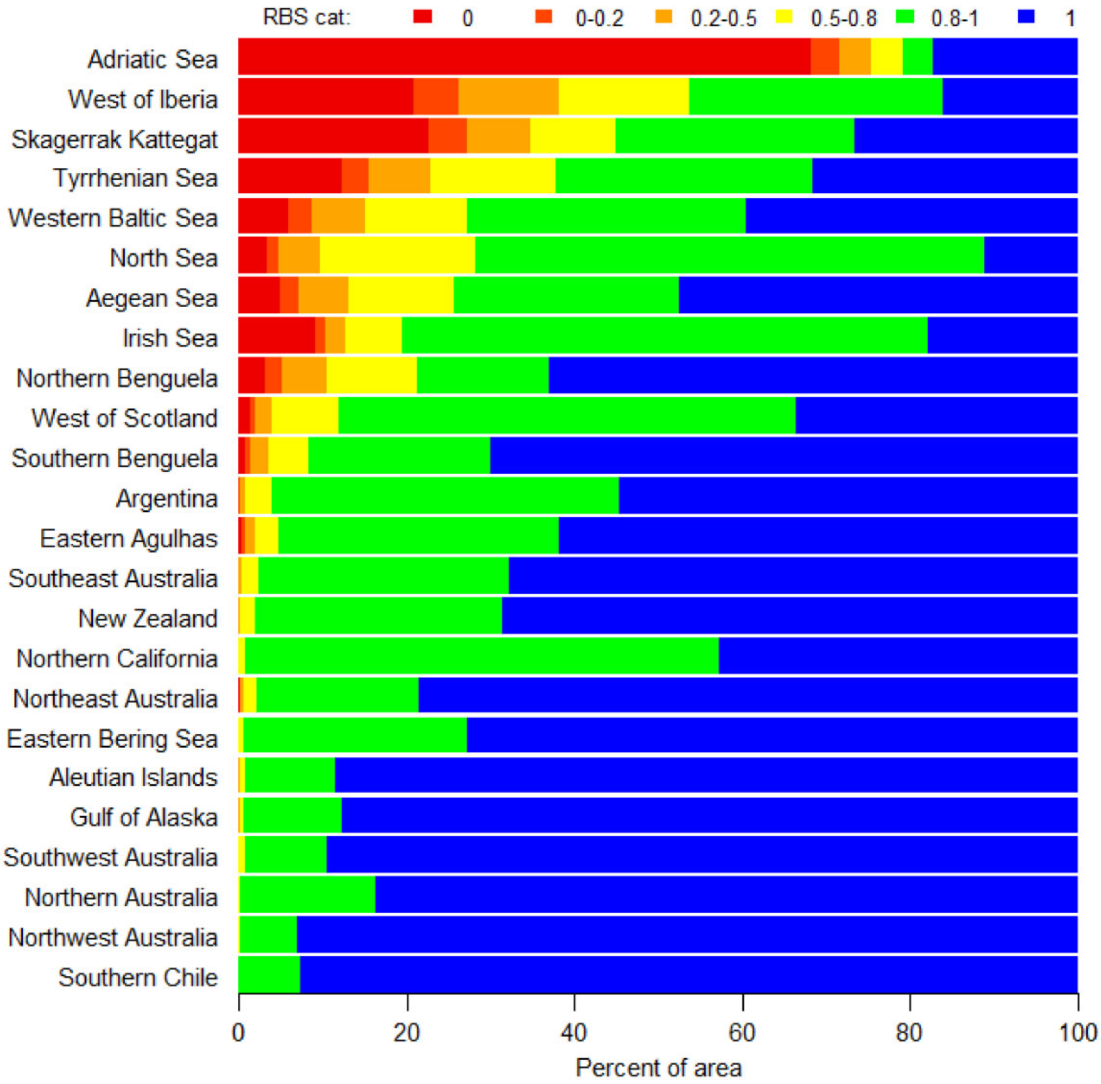

Figure 2. Depletion level (RBS) of benthic flora and fauna in different regions of the world where data on trawl effort and sediment type are available. Data from Pitcher *et al.* (2022).

bottom fishing are also likely to be localized, for example, where target species live on vulnerable habitats.

Bycatch and discards

Bycatch is generally defined as the "unintended, non-targeted organisms caught while fishing for particular species (or sizes of species)," including "landed bycatch," which is retained to be eaten or sold (Pérez Roda *et al.*, 2019). Discards are the portion of the catch that are returned to the sea whole, alive or dead. Fishers are discarding in response to numerous and continuously changing factors, including market conditions, regulations, and the size and quality of the catch.

Using Food and Agriculture Organization (FAO) databases on country-specific landings, Pérez Roda *et al.* (2019) estimated the discard rate and magnitude for the period 2010–2014 for global marine capture fisheries using fishery-specific discard rates derived from direct observations and global gear-specific discard rates. Discard rates for trawl fisheries and selected other gear types are shown in Table 1.

Table 1 shows that the dominant determinant of discard rate is whether the fishing occurs on the bottom or surface or

Table 1. Mean discard rates and 95% confidence bound (CI) for different fishing gears from Pérez Roda *et al.*, 2019 (Table B1).

Gear Category	Mean percent discarded	95% CI
Purse seine	5%	3.9–5.6%
Longline, pelagic	7%	5.8–9.4%
Pole-and-line	9%	6.4–14.4%
Handline	10%	1.9–44.2%
Gillnet, pelagic (driftnet)	12%	7.4–19.0%
Otter trawl, midwater	12%	8.2–18.2%
Longline, bottom and pelagic	13%	11.0–16.4%
Pots	17%	12.1–22.2%
Gillnet, surface and bottom	17%	8.8–32.9%
Trawl, pair, midwater	19%	3.3–73.0%
Trolling lines	20%	6.8–49.8%
Longline, bottom	24%	18.0–31.1%
Gillnet, bottom	26%	19.8–33.8%
Otter trawl, bottom	31%	28.5–60.0%
Trawl, otter twin	44%	28.5–60.0%
Trawl, beam	46%	37.7–53.8%
Trawl, pair, bottom	48%	14.1–87.8%
Trawl, shrimp	55%	50.0–59.6%

Table 2. The average, minimum, and maximum amount of fuel used to capture one MT (litres per MT) of fish for different gear types and the amount of carbon released per kilogramme (Kg) of fish wet weight landed (Kg CO_2 per kg landed).

	Liters of fuel per MT landed			Kg CO2 per Kg landed		
Gear	**Average**	**Minimum**	**Maximum**	**Average**	**Minimum**	**Maximum**
Surrounding nets	252	8	659	0.68	0.02	1.78
Dredges	506	15	1 822	1.37	0.04	4.92
Pelagic trawls	667	36	2 475	1.80	0.10	6.68
Gillnets	604	199	2 162	1.63	0.54	5.84
Divers	951	585	1 472	2.57	1.58	3.97
Hooks and lines	1 032	47	4 985	2.79	0.13	13.46
Bottom trawls	1 722	65	17 300	4.65	0.18	46.71
Pots and traps	3 014	331	9 474	8.14	0.89	25.58

Data source is Parker and Tyedmers (2015).

midwater. Bottom trawls generally have the highest discard rate and account for an estimated 46% of all discards, with shrimp trawls having particularly high discards (Pérez Roda *et al.*, 2019). In many trawl fisheries (and most other fisheries), most of the discarded catch will not survive, but this depends largely on species, size of organisms, handling practises (e.g. sorting time), environmental conditions (e.g. air temperature), and haul duration and depth (Broadhurst *et al.*, 2006). For instance, many crustaceans typically incur <50% discard mortalities, whereas small pelagic fish may suffer very high mortality (reviewed by Broadhurst *et al.*, 2006).

When comparing the FAO discard estimates covering four decades (Alverson *et al.*, 1994; Kelleher, 2005; Pérez Roda *et al.*, 2019), it is obvious that there has been a declining trend from the late 1980s, as the latest discard estimate is less than half of the initial estimate. The estimates from the current assessment are consistent with the findings of Zeller *et al.* (2018), who found that annual discards peaked at around 19 million tonnes in 1989 and gradually declined to under 10 million tonnes by 2014.

Improved gear selectivity and reduction of fishing effort have contributed to the reduction of discards in many trawl fisheries in Europe, North America, and Australia (Kennelly and Broadhurst, 2021). A major change has also been the increased utilization of all species in trawl fisheries of SE Asia, where trawling has been largely non-selective and thus has resulted in large volumes of juvenile fish, small-sized fish species, and other organisms in the landings (Funge-Smith *et al.*, 2012; Suuronen *et al.*, 2020). Most of these fish are now used in SE Asia both for local markets and for aquaculture feed, and discarding is uncommon. Increased use of trawl "bycatch" is also growing in Africa and Latin America, leading to reduced discards.

The capture of endangered, threatened, or protected species, such as rays, sharks, and sea turtles, as well as juveniles of target species, remains a cause of concern in some trawl fisheries (Gray and Kennelly, 2018). They estimated that 19% of sea turtles discarded globally at sea were taken by trawls (both pelagic and bottom), that the extensive Alaska bottom-trawl fishery annually discarded 534 seabirds, the Argentine factory trawl fleet discarded 8500 seabirds and suggest that the global trawl impact on seabirds may be on the same order as the longline fleets.

Table 3. Kg CO_2 per kg of processed product from life cycle analysis.

Food type	Kg CO2/kg
Corn	0.10
Wheat	0.23
Rice	0.33
Tofu	0.60
Potatoes	0.80
Alaska pollock fishery	0.83
Alaska bottom-trawl fishery	1.17
Isle of Man scallop fishery	1.73
New Zealand hoki and ling	2.24
Chicken	2.28
Pork	2.92
Impossible Burger	3.50
Bottom-trawl fisheries average	4.65
Farmed Salmon Norway	5.50
Beef	19.20

Data sources: crops and livestock from Poore and Nemecek (2018); Pollock from Zhang *et al.* (2022); Alaska bottom trawl converted by ratio of fuel used in pollock fishery (Fissel *et al.*, 2016); scallop fishery (Bloor *et al.*, 2021); Impossible Burger (Khan *et al.*, 2019); New Zealand (Mazzetto and Ledgard 2023,); Norwegian farmed salmon (Ziegler and Hilborn, 2023).

Carbon footprint of fuel use

The majority of the carbon footprint of capture fisheries comes from the fuel used, and Parker and Tyedmers (2015) assembled an impressive collection of 878 studies of fuel use in fisheries since 1990, measured as litres of fuel used per metric tonne (MT) landed. The data are predominantly from Europe, North America, and Oceania, with few studies from Africa or Asia. For bottom trawl gear, Europe had a fuel consumption per MT landed that was 1.8 times as high as North America and Oceania. Table 2 shows the fuel use and carbon released by fuel use for different fishing gears.

The most important feature of these data is the high variability within and among different fisheries, indicating that almost any fishing gear type can catch fish with a much lower carbon footprint than the average, and no method is consistently best. Nevertheless, bottom trawls are among the least fuel-efficient gear types. Two-thirds of the bottom trawl data set is from Europe, and many of the data are from the 1990s, a time of low stock status and highly competitive fisheries (i.e. greater fishing effort was required to catch the same amount of fish relative to when stock status was more abundant). In contrast, trawl fisheries for stocks at high abundance and where the race-to-fish has been eliminated by the allocation of quota to cooperatives have much lower fuel use and carbon footprint (Fissel *et al.*, 2016). Two Alaskan trawl fisheries have quite low carbon footprint per unit of edible product (0.83 and 1.17 kg CO_2/kg; see Table 3) and exemplify how the carbon footprint of trawling can be reduced by maintaining high stock size and eliminating the race-to-fish and sets a standard for other trawl fisheries to aspire to. The New Zealand deep-water trawl fleet has a carbon footprint of 2.24 kg CO_2/kg (Mazzetto and Ledgard, 2023). Similarly, a well-managed territorial use rights-based scallop dredge fishery in the Isle of Man (Irish Sea) resulted in emissions of 1.73 kg CO_2/kg of scallop meat, compared with up to 4.07–13.61 kg CO_2/kg scallop meat in the adjacent open access scallop fishery (Bloor *et al.*, 2021). At present, both the Alaskan and Isle of Man fisheries are dominated by older vessels, and it would be expected that newer, more fuel-efficient vessels could reduce the carbon footprint further.

Impact of trawling on carbon sequestration

Carbon stocks in seabed sediments are a large natural asset (e.g. 0.52 Pg of organic and 2 Pg of inorganic carbon in UK waters) (Parker *et al.*, 2020; Smeaton and Austin, 2022), and bottom-trawl fishing is the most extensive anthropogenic physical disturbance to these sediments (Legge *et al.*, 2020). The impacts of fishing on carbon stocks are currently unquantified and unregulated. The available evidence suggests that the seabed disturbance could result in greenhouse gas release (CO_2, CH_4, and others) from the seabed into the water column (Epstein *et al.*, 2022). A global extrapolation by Sala *et al.* (2021) suggested that seabed disturbance with mobile fishing gears releases 0.16–0.4 Pg carbon per year to the ocean, but this estimate has been widely criticized and is likely to be two orders of magnitude too high (Epstein *et al.*, 2022) (Hiddink *et al.*, 2023), meaning that mineralization of benthic carbon stores comes primarily from natural processes.

This controversy has highlighted major uncertainties in the magnitude and even the direction of the response of sediment carbon stores due to sediment mixing, resuspension, and a reduction in the bioturbation activity as a result of the loss of benthic fauna following trawling disturbance (Smeaton *et al.*, 2021; Epstein *et al.*, 2022). Knowledge about how these effects translate into changes in carbon storage and fluxes into or out of seabed sediments and across the air-sea interface showed that of 49 investigations reporting the effect of bottom trawling on seabed carbon, 61% of studies showed no significant effect, 29% reported lower organic carbon after fishing, and 10% reported higher seabed organic carbon after fishing (Epstein *et al.*, 2022). Only five studies have estimated changes in carbon mineralization and O_2 uptake, and the majority of these recorded a decrease rather than an increase in CO_2 production with trawling (e.g. Polymenakou *et al.*, 2005). With respect to potential impacts on climate change, even if trawling does significantly increase the mineralization of seabed carbon, only a fraction of it would make it into the atmosphere (Collins *et al.*, 2022). We conclude that there is little evidence that trawling increases sediment carbon mineralization significantly, even less that it impacts atmospheric CO_2 levels, but uncertainty certainly remains.

Interaction of bottom trawling and hypoxia

Marine benthic habitats in continental shelf regions are increasingly impacted by hypoxia [dissolved oxygen (DO) $\leq$2 mg L^{-1}] caused by the combination of eutrophication and climate warming. Environmental hypoxia has been documented in over 400 marine systems globally and affects >240000 km^2 of coastal habitat (Diaz and Rosenberg, 2008; Breitburg *et al.*, 2018). The combined effects of trawling and hypoxia on benthic community biomass and seabed processes may be synergistic and disproportionally impact benthic fauna, or trawl impacts may be smaller in hypoxic areas. Despite the high annual trawling intensities in the southern Baltic Sea (each square metre of bottom is trawled seven times per year on average), van Denderen *et al.* (2022) found that the benthic community was predominantly impacted by low oxygen concentrations (DO at sites studied ranged between 0.8 and 5.8 ml O_2 L^{-1}) and found neither an effect of trawling nor a synergistic effect of trawling and hypoxia. In such cases, benthic communities may be expected to benefit most from management actions targeting reductions of nutrient loads and reversing eutrophication and hypoxia. Conversely, management efforts for regulating trawling are better targeted to regions that are not in a prolonged state of hypoxia.

Hypoxia has also been demonstrated to alter catch and effort patterns. Purcell *et al.* (2017) showed that hypoxia-induced changes in the distribution of shrimp also alter the spatial dynamics of the Gulf of Mexico shrimp fleet, with potential consequences for harvest interactions and the economic condition of the fishery. Bio-economic simulations of the Gulf shrimp trawl fishery suggest that hypoxia can lead to both short-term increases or decreases in catch, depending on the effects of hypoxia on components of shrimp production (e.g. growth, mortality) and the behaviour of the fishery (e.g. catchability) (Smith *et al.*, 2014).

Is the trawl footprint expanding?

A common perception of trawling is that it is expanding worldwide and new areas are being impacted each year. Some have compared trawling to forest clear cutting and stated that the area trawled each year, estimated from trawl effort, speed, and width of trawl nets, is 150 times the area of forest clearcut (Watling and Norse, 1998). The obvious flaw in this analogy is that, for the most part, the same areas are trawled each year, and indeed, in some cases, many times each year, but you cannot clearcut the same area twice.

Amoroso *et al.* (2018, SM) calculated the increase in the cumulative area impacted by trawling as a function of the number of years considered using data from 32 regions of the continental shelf. They found that the trawling footprint tended to be rather stable, especially in mid-to-highly impacted regions. For example, in regions where >30% of grid cells were annually impacted by trawling, the cumulative number of cells impacted over a three-year period was at most 40% larger than the annual impact, indicating a substantial overlap in fishing areas from year to year. Using detailed tow-by-tow data by individual vessel in the British Columbia bottom trawl fleet, Branch *et al.* (2005) showed that each vessel fished over a limited number of standard locations (an average of 26 per vessel), where the vessel had previously fished, and exploration of new fishing grounds was uncommon.

Certainly some new areas have been explored, particularly in deeper waters as gear technology has permitted deeper tows, and as species distributions shift fishing effort may also shift. For the major bottom-trawl fisheries on groundfish (cod, pollock, haddock, hake, and flatfish), the annual harvest rates and catches have been declining, the total effort declining, and hence the area trawled is presumably also declining (Hilborn *et al.*, 2021). However, without a longer time series of spatial data on trawl effort, it is difficult to determine if the extent of bottom trawl footprints is expanding.

Conflicts with other fishing gears and ocean uses

Bottom-trawl fisheries have a long history of conflict with static fishing gears that lie on the bottom, such as longlines, gillnets, and pots, and when fishing grounds overlap, interference may result in fixed gear losses and hazards for the trawls. This has led, in some circumstances, to formal or informal zoning or rotational arrangements. In many cases, inter-gear conflicts reflect competition for the same target resources between small and large-scale fleets, which has led to the establishment of exclusive coastal zones for artisanal or small-scale fisheries where trawling is banned (McConnaughey *et al.*, 2020). An example of this is the Inshore Potting Agreement (IPA), a voluntary fishery management system designed and operated by fishers of south Devon, England to reduce conflict between static-gear (pot and net) and towed-gear (trawl and dredge) fishers. The IPA is regarded as a successful fisheries management regime by fishers and managers because it has effectively allowed fishers from both sectors to operate profitably on traditional fishing grounds (Hart *et al.*, 2002). Oil and gas pipelines and communication cables laid on the seafloor are also typically in conflict with fisheries, and new demands on the seafloor, such as wind farms (Rodmell and Johnson, 2002; Stokesbury *et al.*, 2022), tidal power, and seabed mining, have added to the competition for space. On the West Coast of the United States, communication companies negotiated financial arrangements with trawl fleets, providing research funds administered by the trawl-fishing organizations (https://bandoncable.org/history.asp).

Management actions to reduce impacts

A variety of management measures reduce the impacts of bottom trawling on benthic biota and habitats, minimize bycatch, and reduce fuel usage to address sustainability goals. These measures, voluntary industry actions, and their interactions with existing management systems address conflicting societal, environmental, and economic objectives, often requiring trade-offs. They broadly consist of technical measures related to gear and operations, spatial controls, impact quotas, and fishing-effort controls. Their efficacy and practicality, alone or in combination, depend on the characteristics of the fishery, the management capacity, and the local tradeoffs between environmental effects, food security, income, and employment. Guidance has been proposed to evaluate potential best practises for a region (McConnaughey *et al.*, 2020). In most cases, compliance and performance are predicated on stakeholder engagement (Suuronen *et al.*, 2020; Suuronen, 2022).

Direct impacts on the benthos can be significantly reduced by gear modifications that reduce contact with the seafloor and/or penetration depth while maintaining or increasing the catchability of the target species. Impacts have been reduced with otter trawl doors that do not touch the bottom, elevated footropes, and the use of electricity to cause the fish to swim into a net that is not making bottom contact (Delaney *et al.*, 2022). An absolute prohibition of bottom trawling is the most comprehensive measure of protection and typically provides additional fishing opportunity to alternative gears and thus has been advocated for reasons other than conservation (Blyth-Skyrme *et al.*, 2006). At the same time, absolute prohibition directly affects those employed in the trawl industry and may cause redistribution of effort if the prohibition is localized. Alternative trawl restrictions include freezing the trawling footprint to prevent expansion into previously untrawled areas, but this limits a fleet's adaptability to changing fish distributions.

Particularly sensitive habitats, such as coral, sponge, and nearshore nurseries, can be effectively protected when their locations are known and closures are implemented prior to significant disturbance. Substantial invertebrate bycatch can be mitigated by voluntary or regulated movement to other areas with real-time reporting and closures; however, such "move-on" rules displace effort to similar areas, thereby expanding the overall footprint and its effects. When move-on rules were combined with tradable quotas, detailed maps of sensitive areas, and onboard observers, a substantial reduction in invertebrate bycatch was achieved in British Columbia, Canada without affecting overall fleet performance (Groenbaek *et al.*, 2023). Perhaps the simplest change is to reduce fishing effort when overfishing occurs. This reduces impacts on benthic biota and increases fishery yield (Amoroso *et al.*, 2018; McConnaughey *et al.*, 2020), which may confer economic benefits due to trip reductions and lower fuel usage but would normally have short-term negative economic impacts.

Fuel consumption is the primary source of the carbon footprint for all fishing vessels. Gear modifications that reduce contact with the seafloor reduce fuel consumption and extend gear life, which improves overall profitability if target-species catchability is maintained or nearly so. However, in some fisheries, there is a trade-off between the catchability of the target species and bycatch reduction. Gear that reduces bycatch may require more effort (and fuel) to achieve the same landings. Management measures that increase target-species abundance will normally be expected to increase catch rates and thus lower fuel use per tonne captured. Newly constructed vessels tend to have reduced fuel use as a major design criterion.

Many of the same measures that reduce benthic impacts and reduce fuel use are also used to manage bycatch and reduce discards. Technical, administrative, and economic measures include modifications to fishing gear or fishing practises, time and area restrictions, bycatch limits, effort restrictions, and discard bans (i.e. landing obligations), and may also lead to active avoidance of high bycatch areas and involve cooperative fleet communications, awareness raising, and training (Pascoe, 1997; Suuronen and Gilman, 2020; Suuronen *et al.*, 2020). Technical measures to manage trawling bycatch are based on a large body of empirical experiments intended to improve species- and size-selectivity by modifying gear and operations (Kennelly and Broadhurst, 2021), with attention paid to unobserved mortality rates (Rose *et al.*, 2013). Real-time closures involving move-on protocols may be effective in dynamic situations where the bycatch level is unpredictable. Bycatch quotas or limits on "choke species" are incentives to avoid premature closures of target fisheries before quota uptake is achieved. Measures to limit effort are based on the simple rationale that less effort equates to less bycatch (Alverson *et al.*, 1994). An outright discard ban, where all catches of species or stocks with an established TAC or covered by minimum landing size regulations must be kept on board, landed, and deducted from established quotas, was implemented by the EU Common Fisheries Policy and represents a fundamental regulatory shift from landings to catches (Karp *et al.*, 2019), but has proven ineffective because of numerous exceptions and the difficulty in implementation and enforcement (Uhlmann *et al.*, 2019; Borges, 2021).

Management measures that minimize the footprint of fishing have been shown in one study to lead to higher yields than measures that spread fishing activity more widely and evenly across the seabed (Bloor *et al.*, 2021). This was demonstrated in a case study in the Isle of Man, where a territorial use rights-based fishery ring-fenced vulnerable habitat from fishing while demarcating a fishing zone within the management system. Pre-open season fishery surveys directed fishing activity specifically to high-density aggregations of target species (scallops), thereby increasing the efficiency with which the total allowable catch was taken and reduced the amount of seabed impacted to a negligible level (3% of the available area for fishing; Bloor *et al.*, 2021). Using such approaches or regulating the overall fishing mortality rate proportionally mitigates the indirect effects of bottom trawling.

Bottom trawling, like other forms of fishing, may cause bycatch of species of conservation concern; the best known is the bycatch of turtles. Technical solutions, in the form of turtle excluder devices, have been shown to be very effective at reducing turtle bycatch (Magnuson *et al.*, 1990) (Jenkins, 2012). Similarly, excluder devices for marine mammal bycatch have been implemented and shown to be effective (Hamilton and Baker, 2015).

A significant obstacle in bycatch reduction has been the limited uptake by fishers of remedial changes proposed that they consider inconvenient and costly (Suuronen, 2022). Some demersal trawl fleets have made great strides in reducing bycatch, and the bottom-trawl fishery for flatfish in the Bering Sea now has only 6–8% bycatch of all species (personal communication Phil Ganz, NMFS). This reduction has been achieved primarily by bycatch limits and fleet coordination providing strong incentives for vessels to avoid areas with high bycatch. This example serves as an aspirational target for other trawl fisheries.

Can other fishing methods replace bottom trawling?

It is possible to capture some of the same species caught with bottom trawls with other gears. However, transitioning from one gear type to another is seldom easy or practical and has many uncertainties and economic risks (Suuronen *et al.*, 2012). The size and design of existing fishing vessels and their machinery often limit the possibilities of changing the fishing method. Furthermore, fishing practises have evolved over time and are often “tailor-made” to particular species and conditions.

Pots and longlines have been demonstrated to be an economically viable fishing method for Pacific cod and sablefish in the Gulf of Alaska and the Bering Sea (Thomsen *et al.*, 2010), and such gears can be more species- and size-selective in addition to having a lower benthic impact. In some circumstances, bottom seining can be used. The seine net is lighter in construction, but the area swept can be 1.25–10 times larger than other bottom trawling. Because there are no trawl doors or warps, there is less pressure on the seabed. Nonetheless, there are several operational limitations in bottom seine fisheries, and it can be an alternative for bottom trawling only in specific cases (Suuronen *et al.*, 2012). As with all fishing methods, increasing the use of pots and longlines will increase the risk of entanglement and bycatch of species of concern, for example, right whales in the Gulf of St. Lawrence, which interact with lobster fisheries.

There does not appear to be an economically viable alternative to bottom trawling to catch high volumes of flatfish, and bottom trawling or dredges appear to be the only effective method for capturing offshore scallops, clams, and certain species of shrimp.

The use of electric stimulation (e.g. in pulse trawling) (Soetaert *et al.*, 2015) and lights (Lomeli *et al.*, 2021) to lift fish off the bottom and reduce the need for bottom contact has been highly developed. Scientific trials have shown that pulse trawls reduce the mortality of non-target invertebrate benthic megafauna, discards, and fuel emissions compared to the conventional tickler chain beam trawl (ICES, 2018; Bergman and Meesters, 2020). Nevertheless, in early 2019, the European Union parliament decided to forbid any pulse trawling after July 2021 due to concerns over possible damage to fauna from electrical stimulation.

Environmental impacts compared to alternative foods

All food production has multidimensional environmental impacts, including fuel use, carbon footprint, water use, nutrient release into water, soil, and atmosphere, acidifying compound release, antibiotics use, toxic chemical use, including pesticides and herbicides, soil erosion, and introduction of exotic species and diseases in aquaculture, livestock, and for pest control. There is an extensive literature of some of these impacts using life cycle assessment (LCA) that covers some of these metrics (for instance, see the meta-analysis in Hilborn *et al.*, 2018; Tlusty *et al.*, 2019).

In the following sections, we present data comparing the environmental impacts of different forms of food production. But in comparing bottom trawling to other food production systems, two issues arise. There are relatively few LCAs of trawling, but more of capture fisheries and individual LCAs differ in whether the impacts are limited to harvesting, or also include consideration of processing, transport, and retail. As a generalization, all capture fisheries use no antibiotics, no fertilizer or pesticides, do not introduce exotic species, do not cause soil erosion, and use very little freshwater. The use of fuel in capture fisheries releases some acidifying compounds, and toxic antifouling paint is used. However, processing and packaging require considerable amounts of water, and a range of toxic substances may be used in the manufacture of the packaging. The environmental impacts may be dramatically different depending on the product form. For instance, Vázquez-Rowe *et al.* (2014) found 50-fold differences in water demand between canned and fresh sardines. The sample size of bottom trawl LCAs is too small to do a realistic comparison to livestock or crops for anything except energy use and carbon footprint.

Carbon footprint

Table 3 compares the carbon footprint of processed products from LCA of crops, livestock, and capture fisheries. The average carbon footprint for bottom-trawl fisheries from published LCAs is higher than all other foods listed except beef and much higher than plant-based foods. But we include the three bottom-trawl fisheries that represent the most well-managed in terms of stock condition and capacity management, and these show carbon footprints below chicken and pork but above crops. The Alaska pollock fishery uses mid-water gear but is estimated to be in bottom contact roughly half the time, so it is included here. These cases illustrate that bottom trawling does not necessarily have a high carbon footprint, and the high carbon footprint of bottom-trawl fisheries on average reflects the fact that most of the LCA studies of trawl fisheries have a competitive race-to-fish feature and stock abundance is relatively poor.

The Impossible Burger is included because it is the only example we know of for which a plant-based meat or fish imitation has had an LCA performed, and this product is frequently billed as more environmentally friendly because it is plant-based.

Biodiversity

Under an ecosystem-based approach to fisheries management, the sustainability of fisheries is assessed considering both the impact on the target species and on the marine ecosystem. Both the MSC standard and the Seafood Watch scoring criteria consider bycatch of species of concern and impacts on habitat. But when we consider calls to greatly reduce or ban trawling, we must consider the consequences not only to the marine ecosystem, but the ecosystem consequences in both the ocean and on land if that food production is replaced by other fisheries, aquaculture, agriculture, and livestock. The most likely aquaculture replacement for trawl-caught fish is through fed aquaculture, which largely relies on crops as feed, as does almost all livestock production. Crop production, whether directly for human consumption or feed for livestock and aquaculture, replaces the natural, although potentially degraded, ecosystem with a totally artificial monoculture, intentionally removing the native vegetation and any biota dependent upon that. The most prominent cause of extinction risk is agriculture (IUCN, 2020), and the impact of agriculture on biodiversity has been shown to be the most significant form of land use after urbanization (Newbold *et al*., 2015). LCAs have not provided useful data on the biodiversity impacts of food production systems.

One of the few studies to directly compare a wide range of biodiversity between farming and undisturbed habitat was done in Tanzania. The study compared small-scale farmland to the adjacent Serengeti National Park and to biodiversity in a nearby national park. Hilborn and Sinclair (2021) found that the primary producers, grasses, shrubs, and trees on farmland had been reduced by 80–90%, and the ungulates, birds, and predators that depend on the primary producers were all reduced by over 80%. Only rodents were more abundant in the farmland. In contrast, even the places most heavily impacted by trawling are transformed less than by agriculture. As we saw earlier, well-managed trawl fisheries uniformly reduce benthic ecosystem biota in sand, mud, and gravel systems by <10% (Mazor *et al*., 2021). Hilborn and Sinclair (2021) also summarize data from 26 marine ecosystem models used to compare current fished conditions to unfished conditions. They found no significant change in trophic levels 1, 2, and 3 due to fishing, and only a 10% reduction in the abundance of trophic level 4 and a 30% reduction of trophic level 5. While the total abundance of a trophic level may not be the most relevant measure of fishing impact, it does illustrate the fact that lower trophic levels in marine ecosystems are largely unaffected by fishing—although individual species may be. In contrast, agriculture intentionally removes the lowest trophic levels.

Perhaps the clearest difference between the ecosystem impacts of marine capture fisheries and agriculture's impact on terrestrial systems is encapsulated in the MSC's Principle 2, which states, "Fishing operations should allow for the maintenance of the structure, productivity, function, and diversity of the ecosystem on which the fishery depends. The ecosystem includes habitat and associated dependent and ecologically related species." Many trawl fisheries have met this standard, yet no form of large-scale crop production could do so, whether for direct human consumption or as feed for livestock or aquaculture.

Other impacts

Catching fish in the ocean uses no pesticides or fertilizer, almost no freshwater, and no antibiotics (Sharpless and Evans, 2013). The global impacts from these would be increased if bottom trawling was banned and/or agriculture or aquaculture increased to compensate, although there are significant differences in these impacts among cropping systems. Crops grown on unirrigated land do not require water other than rainfall to grow, and organic agriculture does not use antibiotics, synthetic fertilizers, or pesticides, although organic fertilizer contributes to significant nutrient release and hypoxia. Livestock raised in natural habitats has far less impact on native flora and fauna than the land transformation required for crop production.

A major issue for many forms of agriculture is exotic pests, and one method used to control these has been the introduction of exotic predators. This has often had a serious impact on native species (Hoddle, 2004), with the cane toad introduction in Australia perhaps the best known.

Aquaculture deserves special consideration because it is the most obvious immediate substitute for food produced by trawling. There are two basic types of aquaculture: those species cultured with feed supplied by the grower and those that feed themselves. Unfed production systems typically have a very low impact (Hilborn, 2018), with farmed seaweed, and mollusks having a particularly low impact. But the species of fish grown in aquaculture most similar, or identical to those from bottom-trawl fisheries are almost all fed, primarily from crops as well as fish meal from capture fisheries. While aquaculture species often are more efficient converters of feed to flesh than livestock, fed aquaculture has a higher environmental impact relative to capture fisheries across most measures (Hilborn, 2018).

Another concern about aquaculture is how diseases, both endemic and exotic, which have been a recurring problem in aquaculture (Diana, 2009), negatively impact native species.

Summary of the comparison of environmental impacts of bottom trawling to alternative foods

Bottom trawling appears to have a lower impact on most environmental indicators than most other food production systems and, on average, has a higher carbon footprint. There are efforts to reduce the impact of every food production system by technical innovation and changing practise among producers. In bottom-trawl fisheries, fuel consumption and carbon footprint can be reduced by new designs of doors and nets, more efficient vessel engines, better management of fish stocks, and restructuring access to fishing quotas to eliminate competitive fishing. We saw three examples in Table 3 of how successful these efforts can be. Similar efforts are underway to reduce the amount of water needed to grow crops and to lower pesticide, fertilizer, and antibiotic use. Thus, the comparisons made here are not static, and we would expect the various impacts to decline over time in all the food production systems.

Our synthesis of information on the relative sustainability of food production systems has brought to attention improvements needed to better assess fishing with bottom trawls and guide management measures or industry actions for meeting sustainability goals. In particular, a global assessment requires studies of the unknown carbon footprint of fuel consumption by the Asian and African fleets, as well as new data from Europe to reflect contemporary fishery conditions. Subsequently, comprehensive LCAs of bottom trawling, including loads and impacts for the harvesting, processing, transport, and retail components, are needed for a more informed sustainability evaluation and for comparisons with other food production systems.

Conclusions

Bottom trawling is a food production method that has environmental impacts. However, trawling impacts are well below most animal-source foods from livestock or fed aquaculture for many categories of impacts such as water use, antibiotic use, and nutrient release. We suggest that while banning bottom trawling would decrease marine impacts, it would actually increase negative global environmental impacts as trawl caught foods would be replaced with those of terrestrial origin or aquaculture species fed largely with higher-impact crops. The negative environmental impacts of bottom trawling have been reduced by maintaining stocks at high abundance with low fishing mortality rates, eliminating the race to fish through cooperative fisheries, bycatch limits that incentivize bycatch avoidance (Calderwood *et al.*, 2023), technical modification of fishing gear to reduce or eliminate bottom contact and bycatch (Bloor *et al.*, 2021), fuller utilization of lower-value species that would otherwise be discarded, and reduction of subsidies—especially fuel subsidies that encourage inefficient fisheries and increase CO_2 emissions. These proven management measures and voluntary actions are adaptable to a range of local conditions (McConnaughey *et al.*, 2020) and, if applied on a global basis, would dramatically reduce the negative environmental impacts of bottom trawling.

The overall sustainability of bottom-trawl fisheries is perhaps best demonstrated by the 83 bottom-trawl fisheries that are currently certified by the MSC, which represent 252 individual fishery species units of certification. Collectively, MSC-certified fisheries constitute 50% of the global harvest of groundfish stocks summarized in Hilborn *et al.*, (2021). Taking this as a measure of progress, it is largely confined to large industrial fisheries in temperate latitudes. However, MSC certification of bottom trawls is not totally confined to groundfish; 48 of the bottom trawl units of certification are for shrimp, prawns, nephrops, or scallops. The evidence is that bottom-trawl fisheries can be well managed and be considered sustainable, but many fisheries using bottom trawl gear need to improve their performance to meet current standards.

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Data availability

No new data were assembled for this project.

Author contributions

All authors contributed to the writing and editing of the paper.

Conflict of interest

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