Avoiding tradeoffs between global seafood production and seafloor impacts through fisheries innovation

T. Scott Smeltz[1,2], Christopher M. Free[3], Bradley P. Harris[2], Olaf P. Jensen[4], Jonathan H. Grabowski[5], Suresh A. Sethi[2,6]

[1]New York Cooperative Fish and Wildlife Research Unit, Department of Natural Resources, Cornell University, Ithaca, NY 14853, USA

[2]Alaska Pacific University, Fisheries, Aquatic Science and Technology (FAST) Laboratory, Anchorage, AK 99508, USA

[3]Bren School of Environmental Science and Management, University of California, Santa Barbara, Santa Barbara, CA, 93106, USA.

[4]Department of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ, 08901, USA

[5]Department of Marine and Environmental Sciences, Marine Science Center, Northeastern University, Nahant, MA 01907, USA.

[6]U.S. Geological Survey, New York Cooperative Fish and Wildlife Unit, Cornell University, Ithaca, NY 14853, USA.

Keywords: benthic ecosystems; commercial fisheries; gear modifications; maximum sustainable yield; land sparing; animal sourced protein

Abstract

Wild seafood is an important component of the global food supply, satisfying 8% of animal-based protein demands[1]. Trawls account for ~40% of global marine fish catch and can impact benthic habitats, thereby degrading marine ecosystems. Consequently, mitigating seafloor impacts is a key ecosystem consideration for sustainable fisheries. Here, we estimate global seafloor disturbance from fishing and quantify habitat impacts associated with maximizing seafood production to meet growing global food demands. Currently, 8% (3.4 million km^2) of the continental shelf is impacted by fishing gear, a seafloor area comparable to the land area used in terrestrial protein production. If fisheries were managed to achieve maximum sustainable yields, global harvests could increase by 22% (9.1 million mt/year), but with a 10% increase in the seafloor area impacted (290,000 km^2). However, modifications to fishing gears that reduce gear-seafloor interactions may provide a means to overcome this tradeoff. A global

reduction in gear-seafloor interactions of 30%—an amount within the range of existing gear modifications—could mitigate the increase in habitat impacts associated with maximum sustainable harvests from bottom fisheries. Current progress in implementing gear modifications remains slow, emphasizing opportunities to advance technical innovations to balance food production and habitat impacts in the world's fisheries.

Introduction

Wild harvested seafood is a key component of diets throughout the world, accounting for 8% of animal-based protein consumed globally[1]. Human population growth coupled with increasing per capita protein consumption is projected to increase global demand for protein by as much as 50% by 2050[2]. Meeting this demand will require increasing production across multiple food sectors including wild capture seafood. Although commercial fisheries catches have remained relatively stable over the last several decades, recent analyses indicate that increasing global harvest may be achieved not only by improved management of overexploited stocks, but also by increasing fishing pressure on underexploited stocks[3]. Additional harvest opportunities, however, present a challenge in managing and minimizing increased environmental impacts associated with greater seafood production.

All food sectors contend with environmental tradeoffs[4]. Habitat conversion associated with food production systems represents a primary amplifier of climate-driven ecosystem changes and a threat to biological diversity globally[5]. One of the most controversial environmental costs associated with wild capture fishing is disturbance to the seafloor from trawl gears which account for ~40% of all wild harvested seafood[6]. Seafloor impacts from fishing gear include the degradation and removal of epibenthic organisms as well as the scattering of geological structural formations such as cobble piles, which provide critical refuge, spawning, and foraging grounds for marine organisms. Moreover, degradation of these habitats, commonly referred to as ecosystem impacts of fishing, may threaten the sustainability of the harvested fish species that depend on them[7,8].

Recent compilations of global fishing effort derived from the satellite monitored Automatic Identification System (AIS)[9] have provided a view of the global extent of fishing pressure on the seafloor. These data have been used to estimate that the total footprint of all fishing activity from 2012 - 2016 covered up to 55% of the world's oceans[9]. However, there are limitations when estimating the scale of seafloor impacts from the global fishing effort footprint. First, the potential for seafloor impacts is dominated by trawls, whereas pelagic fishing activity, which is also recorded by AIS, results in little or no contact with the ocean bottom and thus negligible seafloor impacts. Second, typically only specific components of fishing gear used on or near the seafloor actually touch it such that the seafloor area potentially impacted during a fishing event is less than its total swept area path[10]. Third, the organisms and geological features that create habitat structure on the seafloor demonstrate varying degrees of susceptibility to contact and capacity to recover from damage or removal[11]. Thus, estimating seafloor disturbance – defined here as the areal extent in which benthic features have been damaged or removed by trawling and have not yet recovered to pre-trawling levels – requires a dynamic impact and recovery model that incorporates habitat specific vulnerabilities, gear characteristics, and an understanding of how gear contacts the seafloor[12].

Minimizing seafloor disturbance is a high priority for many of the world's fishery management bodies (e.g. [13,14]) and a prerequisite for maintaining ocean ecosystem integrity[7]. To date, marine reserves have been the primary tool to meet this objective. While marine reserves have demonstrated successes[15,16], especially when protecting highly vulnerable seafloor habitats, they can have limitations as a commercial fisheries management measure. In many cases, fishing effort is displaced elsewhere, such that spatial closures may not achieve success without other corresponding policies to reduce effort or total allowable catches[17]. But as global demand for protein mounts with increasing human population, reducing fishery harvests as a means to control seafloor impacts may lead to a difficult tradeoff. Aside from the socioeconomic consequences of reduced harvest, there may be concomitant environmental impacts associated with producing substitute protein from other food systems, such as terrestrial crops or livestock. One means to avoid the tradeoff between benthic habitat impacts and foregone fishery harvest is to minimize seafloor disturbance by reducing gear-seafloor interactions – a direct solution that may be met through gear modifications to reduce seafloor contact from fishing, or increases in catch efficiency that maintain harvest rates but with less expended effort.

Here, we quantify seafloor impacts from fishing and explore options for navigating seafood production and environmental impact tradeoffs. We first assess the areal extent of global seafloor disturbance by trawling activities using a dynamic impact and recovery model[12] and compare area-based production estimates from the ocean with habitat impacts on land from equivalent terrestrial protein production. We then use catch-based stock assessment models to evaluate the potential for sustainable harvest increases from trawl fisheries globally and within large marine ecosystems (LME) to meet growing protein demands, and estimate the increase in seafloor disturbance associated with increasing fishing pressure to achieve maximum sustainable yield (MSY) under conventional gear configurations and fishing practices. Finally, we demonstrate how innovations in fishing gear technology and/or improvements in capture efficiency could reduce the effects of trawling on the seafloor and help mitigate the impacts of fishing on seafloor habitats globally.

Results/Discussion

We used a dynamic benthic habitat impact and recovery model[12] and time series of AIS-derived fishing effort data from 2013 - 2018 to estimate the current scale of global seafloor disturbance, finding that total global seafloor disturbance from trawling was 3.4 million km^2 (8% of the world's continental shelves). This estimate includes upward adjustments for ten LMEs identified as having low AIS coverage of their fleet as indicated by an anomalously low ratio between harvest and AIS-derived fishing effort as compared to well-covered LMEs (Extended Fig. 1). The distribution of seafloor disturbance from fishing varied widely among LMEs (Fig. 1, Extended Table 1). Eight LMEs contributed to over half of the world's total seafloor disturbance, three of which were estimated to have >40% disturbance (Yellow Sea, Iberian Coastal, and Celtic-Biscay Shelf) within the shelf area of their LME. Ten of the world's 66 LMEs were estimated to have <1% of their shelf area disturbed by fishing. Mid- and high-latitude LMEs in the Northern hemisphere, excluding those in the Arctic, generally had higher levels of seafloor disturbance than low-latitude and Southern hemisphere LMEs. The highest concentrations of LMEs with high disturbance (>25% of shelf area) were in European waters and eastern Asia waters. Arctic and Antarctic LMEs had relatively low levels of disturbance (<5%) with the exception of the Barents and Norwegian Seas (Arctic LMEs), which were estimated to have approximately 14% of their shelf area disturbed by fishing.

This disturbance to the seafloor associated with fishing is an environmental cost of harvesting over 40 million mt of seafood (including both reported and reconstructed catches)[6] from the world's oceans each year by trawls. Globally, this amounts to 11.9 mt of seafood harvested per km^2 of seafloor disturbed, though the efficiency of this tradeoff is highly variable among LMEs (Fig. 1 inset). Recognizing that terrestrial land use for food production poses ecological consequences that differ substantially from those incurred from seafloor disturbance, comparisons of habitat impact vs. protein production tradeoffs among key animal production systems provides insight into the opportunity cost of foregone wild capture fisheries production. The edible protein yield of seafood (conventionally measured in megagrams, Mg, equivalent to 1 metric ton) averages about 11% of the live weight of fish caught[18] resulting in an average of 1.3 Mg edible protein harvested per km^2 of seafloor disturbed for bottom trawl fisheries annually. When comparing the amount of habitat impacted from these protein sources, we estimate that protein harvested from the seafloor to be about three times more efficient than beef sourced protein (0.41 Mg edible protein per km^2, including land used for pasturing and feed crops), but about one-tenth the efficiency of pork or poultry (each yield 11 Mg edible protein per km^2, including land used for feed crops)[19].

As the human population grows to a projected 10 billion people over the coming three decades[20], pressure will mount to increase production across food sectors to meet protein demands[21,22]. Using a catch-based stock assessment model to evaluate current exploitation rates of fishing on the seafloor[23], we found that over 83% of the trawl-caught stocks included in the analysis (1,716 of 2,070 stocks) are currently harvested at rates below that associated with MSY (Extended Fig. 2). We estimate that maximum utilization of these stocks, along with rebuilding the 20% of overfished stocks, has the potential to sustainably increase trawl harvest by 22% over current levels, an approximately 9.1 million mt per year harvest increase (1.0 million Mg of additional protein per year). In four LMEs, trawl fisheries as a group are currently overfishing and would require reductions in effort to achieve MSY, presenting opportunities to simultaneously increase harvest in some regions while also reducing seafloor disturbance. However, increasing catches in most LMEs would require additional fishing effort (Fig. 2). Aggregating across all assessed stocks, net global trawl fishing effort would need to increase by 45%, adding over 8 million additional hours of fishing to the world's oceans each year. Under an assumption that this increase in fishing effort would be distributed in proportion to past fishing effort, the cumulative additional impacts on the seafloor would be correspondingly less, increasing total seafloor disturbance by 10% (>290,000 km^2, equivalent to an area the size of Italy) as fishing impacts often overlap in space with already disturbed habitat[12].

While global trawl fisheries have potential for higher harvests, under current fishing practices, increases in seafood from these resources will present a tradeoff between accepting additional seafloor impacts across most LMEs, or alternatively, shifting this foregone harvest to land-based food systems to meet future protein demands. For example, to supply the 1 million Mg of additional protein harvested if MSY were achieved with beef-sourced protein would require an additional 2.4 million km^2 of land devoted to pasture and agricultural land for feed; pork and poultry would require 90,000 km^2 of additional agricultural land for feed. However, it may be possible to avoid this impasse through innovations that allow trawl harvest to increase without incurring additional impacts to the seafloor. Two approaches show promise in this regard.

First, opportunities exist to modify fishing gears to reduce seafloor contact, while still maintaining catch performance. For example, a simple gear modification of attaching small spherical lifting ‘bobbins’ to the sweeps of a bottom trawl has been demonstrated to reduce seafloor contact by up to 95% without significant effect on the catch efficiency of targeted groundfish in large North Pacific fisheries[10] (Fig. 3, A). In other examples, novel trawl door designs have been used to dramatically reduce bottom contact of trawl gear components[24,25] (Fig. 3, B), and newly developed pulse trawls utilize electrical pulses to stimulate groundfish or shrimp upwards for capture above the seafloor[26] (Fig. 3, C). Second, policies or technologies that increase catch efficiency such that less effort is expended per unit harvest can reduce seafloor impact in attaining prescribed catches. By aligning economic incentives with long term sustainable fishing practices, dedicated access privileges based fisheries management helps avoid wasteful fishing practices and reduce the fishing effort needed to achieve a given catch[27]. For instance, upon transitioning to individual harvest quota-based management, total days at sea for Nova Scotia offshore scallop decreased by 15 – 20%[28]. On the other hand, management approaches that reduce the efficiency of fishing - such as marine protected areas located in productive fishing grounds[29]- have the potential to inadvertently increase effort to achieve target catches, resulting in an increase in the area of seafloor impacted per unit of fish harvested.

Through innovative approaches to modify fishing gear or increase catch efficiency, it may be possible to significantly reduce the seafloor impact of trawl fisheries at seascape scales. Using the global dynamic impact and recovery model and aggregating across LMEs, we find that MSY harvest levels from trawls could be achieved with no net increase in aggregate seafloor impact if fleets were to employ gears with 30% less contact, increase CPUE by 33%, or combine both efforts in lesser extents (Fig. 3, D). Regardless of future catch targets, innovations to reduce seafloor contact would be beneficial for reducing ocean ecosystem impacts from fishing under current harvest levels. For example, we estimate that fishing gear modifications that lead to a relatively small 10% reduction in bottom contact would lead to a global reduction of 136,000 km^2 of seafloor disturbance, whereas a 50% reduction in contact—within the limits of existing successful gear modification experiments—would spare 782,000 km^2 of seafloor disturbance across the world’s continental shelves.

While the rising cost of land has driven dramatic land use efficiency improvements in terrestrial-based animal protein systems over the last half century[30], fisheries innovations have progressed at a slower pace. Impediments to fisheries innovations are both economic and regulatory; however, solutions to catalyze progress in many fisheries are already available. The costs to research and implement new fishing technologies can be high, especially for undercapitalized fisheries, but growing activity in conservation finance[31] may provide capital to accelerate technological advances. Similarly, fisheries governance reforms that align economic incentives with reductions in seafloor impacts through individual habitat quotas may spur gear and fishing practice innovations among fishers[32].

Acknowledgements

This work was funded by the Atkinson Center Academic Venture Fund, and the Alaska Education Tax Credit funds through the Groundfish Forum and the Pollock Conservation Cooperative. We thank D. Kroodmsa and T. Clavelle of Global Fishing Watch for supplying AIS fishing data. We are grateful to R. Murphy, D. Verna, and A. Kroska for comments that improved this piece.

Author contributions

T. S. S., S. S., B. H., and O.J. conceived of the project. T.S.S. conducted the seafloor disturbance analyses. C.F. conducted the catch-only stock assessment analyses. All authors contributed to the writing.

Methods

Seafloor disturbance model

Seafloor disturbance was estimated using a spatiotemporal model that incorporates impact and recovery dynamics to track the proportion of disturbed and undisturbed areas within grid cells over discrete time steps. The full model is detailed in [12]. We used a 2 km x 2 km grid over monthly time steps for these analyses, limiting the domain to the world's continental shelves, defined here as depths from 0 m - 1,000 m. Impacts are defined as the proportional amount of undisturbed seafloor within a grid cell that transitions to a disturbed state over a time step. Disturbances are calculated for each grid cell and time step as the product of the total swept area ratio (SAR), gear contact adjustment, and habitat susceptibility, which is then adjusted to account for overlapping effort on the assumption that fishing effort is randomly distributed within a grid cell and time step. The SAR is the summed footprint of all trawl activity within the grid cell and time step; contact adjustment is the proportion of the footprint that contacts the seafloor; susceptibility is the proportion of habitat features that would be disturbed by contact. In the main text, contact adjustment is referred to in terms of contact reduction for ease of interpretation, where contact reduction is the complement of contact adjustment ($contact\ reduction = 1 - contact\ adjustment$). Recovery is the proportional amount of disturbed seafloor that transitions back to an undisturbed state and is parametrized in this analysis by the mean time required for seafloor habitats to recover from to 5% to 95% of their pre-disturbance levels. The susceptibility and recovery parameters are based on the seafloor habitat types within a grid cell from a global benthic habitat database described below.

Fishing effort and gear parameters

Fishing effort data was provided by Global Fishing Watch (https://globalfishingwatch.org/) which they compiled from AIS data using a neural network to identify vessel type and behavior (e.g. fishing or transiting)[9]. We acquired the data as daily hours fished by gear type on a 0.01-degree grid for 2013 – 2018. Our seafloor impact analyses included only effort designated as trawlers. The effort data was aggregated to an equidistant 2 km x 2 km raster grid on monthly time steps. Fishing hours in each grid cell and time step were converted to SAR as: $SAR = (fishing\ hours)x(speed)x(gear\ width)/(grid\ area)$. Gear towing speeds were set at 7.408 km hr^{-1} (4 knots), following the average speed used to detect trawler fishing activity in the AIS data[9]. Gear width was set to 200 m for all effort, a conservative impact estimate at the global scale, corresponding to the upper range of trawl widths [33].

Susceptibility and recovery of seafloor habitats

The recovery rate and susceptibility of seafloor habitats was based on the habitat type of each grid cell. Global maps of seafloor habitats[34] were acquired from the National Center for Ecological Analysis and Synthesis. The downloaded maps were resampled to the 2 km x 2 km grid and aggregated into three broad habitat categories (soft substrate, hard substrate, and rocky reef) to align with habitat categories employed by the habitat vulnerability meta-analysis used to parameterize recovery [11,35,36]. We generally employed conservative estimates of susceptibility and recovery parameters, using the slowest recovery rates reported by these meta-analyses: 9.6 years for soft substrates, 9.1 years for hard substrates, and 25.3 years for rocky reefs. Susceptibility was set to 0.3 for all habitat types following the findings of [11]. Additional detail on benthic recovery rate sources and standardization efforts is provided in the Supplementary Methods.

Model runs

Three types of model runs were used in these analyses: 1) initial condition burn-in, 2) baseline model runs, and 3) forward projection scenarios. To create reasonable initial conditions of seafloor disturbance for the start of the baseline model, we first conducted a "burn-in" model run. This entailed setting seafloor disturbance to 0% for all grid cells domain-wide for the initial conditions of the burn-in and randomly selecting and applying effort levels from all available years of fishing effort data for each respective month (e.g., for each January in the burn-in, a random January realization of effort was selected from 2013-2018). This burn-in was run for 30 years to allow ample time for seafloor disturbance to equilibrate under effort levels representative of current fishing levels.

Next, the baseline model was run using the final month results of the burn-in as its initial conditions. The baseline model was run using monthly fishing effort data in consecutive order from 2013 - 2018. Results presented in the main text reflect the estimates for December 2018, the terminal month of the fishing effort data. Based on discussions with the data providers, some LMEs, particularly at lower latitudes, were known to have low AIS coverage of their trawl fisheries. We identified ten LMEs as likely to have low AIS coverage of their bottom-tendered gear fleets by identifying LMEs that were univariate outliers in their ratio of 2014 total harvest to fishing effort (Extended Fig. 1). We upward adjusted estimated seafloor disturbance for these LMEs using k-means clustering to group all LMEs into ten catch groups based on their harvest profiles (proportional harvest of functional groups). For each catch group, we used a linear model relating logit-transformed seafloor disturbance (%) to logged total harvest (mt year^{-1}) using the remaining LMEs with high AIS coverage. Adjusted estimates for the low coverage LMEs were then estimated from these models. At the global scale, this increased estimated seafloor disturbance from 2.9 million km^2 (unadjusted estimated) to 3.4 million km^2 (adjusted estimate, reported in main text), a 13% increase (see Extended Table 1 for LME-specific adjusted values). These effort-adjusted LMEs were excluded from subsequent harvest and contact adjustment scenario analyses.

Four forward projection scenarios were conducted: 1) current fishing effort, 2) MSY fishing effort, 3) current fishing effort with contact reduction, and 4) MSY fishing effort with contact reduction. The terminal month of the baseline model was used as initial conditions for all forward projection model runs. For each run of the forward projection scenarios, fishing effort for each month was randomly selected from all available years (same process as the random selection for the initial condition burn-in). In the current fishing effort scenario, we drew directly from the realized fishing data. The MSY scenario adjusted the realized fishing data with an LME-specific parameter representing the ratio of estimated fishing effort at MSY to baseline fishing effort (E_{msy}/E_{base}). The contact adjustment scenarios used realized fishing effort, but adjusted impacts over a range of contact reductions (0%, 10%, 20%, 30%, 40%, and 50%). The MSY fishing with contact reduction was a combination of the two scenarios. These forward projections were each run for 30 years, using the mean of the last 15 years as reported values. Uncertainty in these estimates was calculated from the standard error of these means, and reflect the variability in year-to-year fishing effort intensity and spatial distribution of fishing effort. All reported estimates of relative change in seafloor disturbance for the MSY, contact reduction, and MSY/contact reduction scenarios are relative to the current fishing effort scenario.

MSY forward projection scenarios

Running the MSY scenarios required estimation of the E_{msy}/E_{base} ratio for each LME as well as estimating fishery yield at MSY. This required first estimating the exploitation rate, U, and standing biomass, B, for trawl caught stocks both at MSY (U_{msy}, B_{msy}) and baseline levels (U_{base}, B_{base}). We estimated these parameters using Robin-Hood cMSY (RH-cMSY) [23], an adaptation of the catch-MSY catch-only stock assessment method[37,38], to assess marine fish and invertebrate stocks in the Sea Around Us Database[6]. We defined stocks as LME and species combinations and evaluated the 2,070 stocks with at least 20 years of reported catch data and more than 1,000 mt of maximum reported catch, which captured 54.6% of global reconstructed trawl catch.

RH-cMSY is based on the cMSY[38] stock reduction analysis but uses information from data-rich stocks to set priors for data-poor stock parameters. In general, both methods reconstruct historical abundance and exploitation rates by simulating biomass trajectories that could feasibly produce the observed catch time series given assumptions about initial and final year depletion and population parameters such as carrying capacity, *K* and intrinsic growth rate, *r*. RH-cMSY primarily differs from cMSY in that it uses meta-analyses of data-rich stocks in the RAM Legacy Stock Assessment Database[39] to set priors for all four values. Furthermore, it uses a Pella-Tomlinson rather than a Schaefer surplus production model to account for asymmetry in production[40] and does not use the “tip of the triangle” assumption employed in cMSY.

Yield for each stock in the MSY scenarios was calculated from the U_{msy} and B_{msy} parameters estimated in the RH-cMSY analysis as: $Y_{msy} = U_{msy}B_{msy}$. Yield for the LME was the sum of the yield from all stocks within the LME. However, this only reflects the data- rich stocks included in the RH-cMSY analysis, thus the percent change in yield at MSY over baseline conditions presented in the main text reflects only these stocks. Estimations of total yield at MSY (mt year $^{-1}$) presented in the main text apply this percent change to the total LME-wide baseline yield.

Estimating E_{msy}/E_{base} began from the basic fishery equation relating yield, effort, stock biomass, and catchability, q: $Y = qEB$. Solving for E then gives the ratio as follows:

$$\frac{E_{msy}}{E_{base}} = \left(\frac{Y_{msy}}{q_{msy}B_{msy}}\right)\left(\frac{q_{base}B_{base}}{Y_{base}}\right) \tag{1}$$

To estimate this ratio, a relationship between catchability at MSY and baseline conditions is needed. As a simplifying assumption we assumed that catchability at MSY is equal to that at baseline conditions ($q_{msy} = q_{base}$), reducing eq. (1) to:

$$\frac{E_{msy}}{E_{base}} = \left(\frac{Y_{msy}}{B_{msy}}\right)\left(\frac{B_{base}}{Y_{base}}\right) \tag{2}$$

Additionally, because E_{msy}/E_{base} is used at the level of the LME, the yields and stock biomasses in eq. (2) reflect the sum of these values across an LME for stocks included in the RH-cMSY analysis.

Data availability

The fishing effort data that support the findings of this study are available Global Fishing Watch [https://globalfishingwatch.org/] and the fishery catch data are available from Sea Around US [http://www.seaaroundus.org/].

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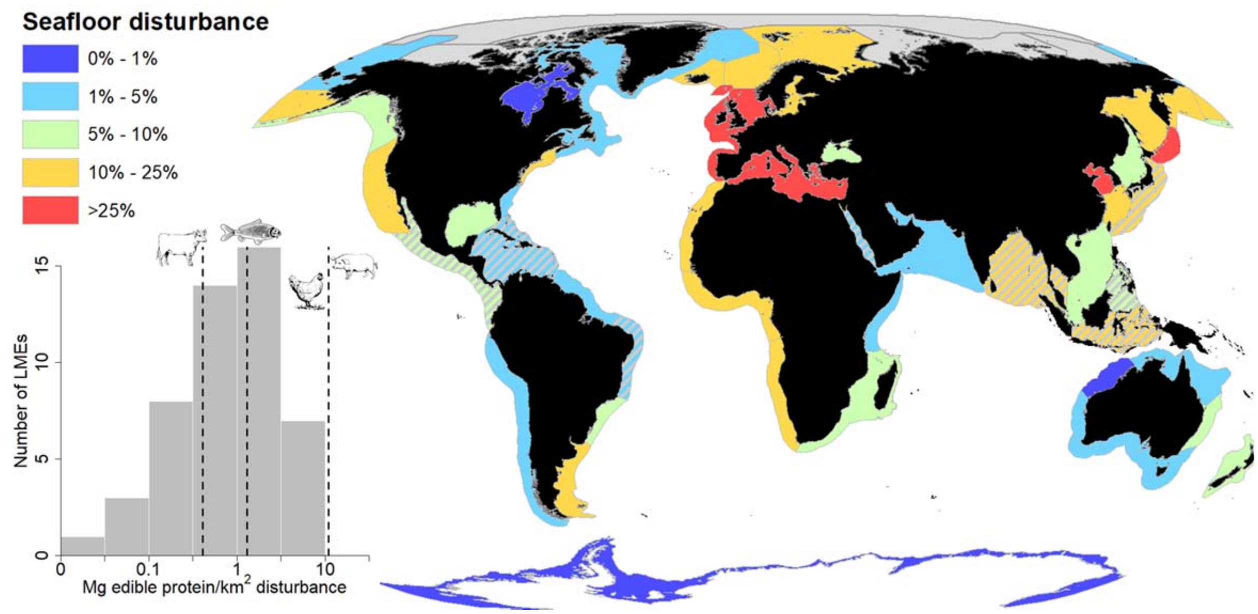


Figure 1. Seafloor disturbance (% of continental shelf area) throughout the world's Large Marine Ecosystems (LMEs). Hashed areas show LMEs with low AIS coverage for which fishing effort was estimated using an upward adjustment procedure. The inset figure shows habitat-use efficiency (Mg edible protein produced per km^2 of disturbed habitat) on log_{10} scale associated with bottom-tendered fisheries for the world's LMEs. Dashed vertical lines show the global habitat use efficiency for fishing across LMEs, as well as reported values for worldwide beef production (generally less efficient) and pork and poultry production (more efficient)[19].

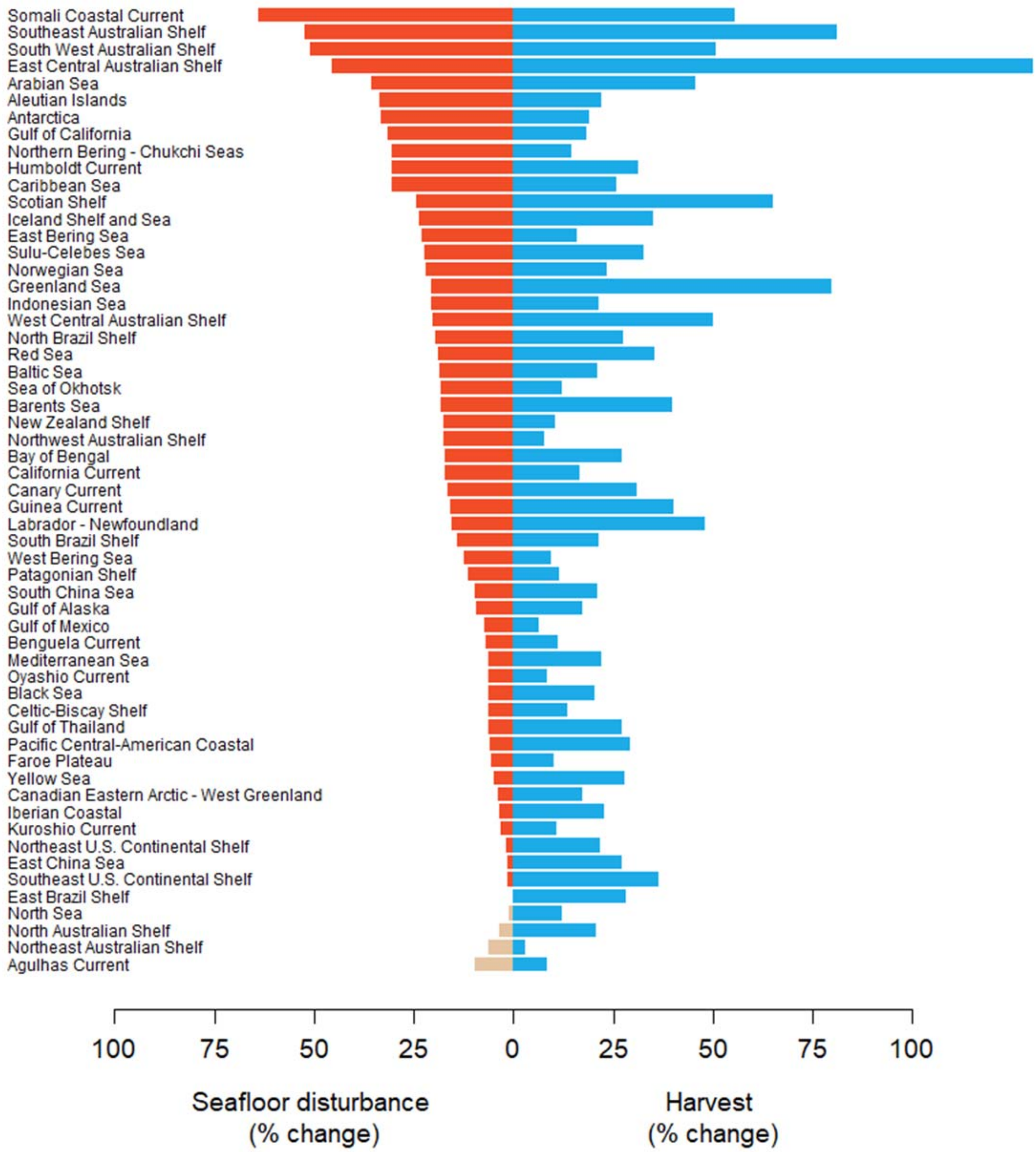


Figure 2. Tradeoffs between increased bottom-tendered fishery harvest and seafloor disturbance among the world's Large Marine Ecosystems (LMEs). Increases in LMEs seafloor disturbance depend on both the amount of effort needed to achieve maximum sustainable yields (MSY) and the spatial distribution of effort, where more concentrated fishing effort can lead to incrementally lower increases in areas impacted relative to regions with more diffusely spread effort. Blue bars show the percent increase in yearly harvest at MSY fishing over current harvest level. Red bars show the estimated percent increase in seafloor disturbance over current levels. Tan bars indicate a percent reduction in seafloor disturbance for four LMEs currently fishing above MSY in which case reducing fishing effort would lead to both increased harvest and reduced habitat impacts.

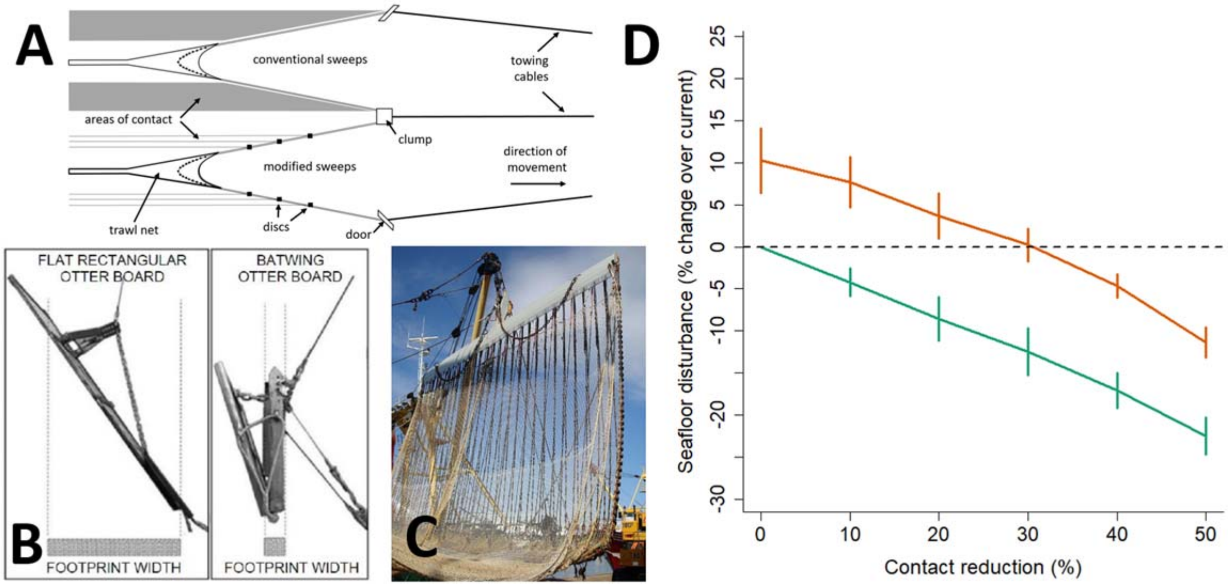
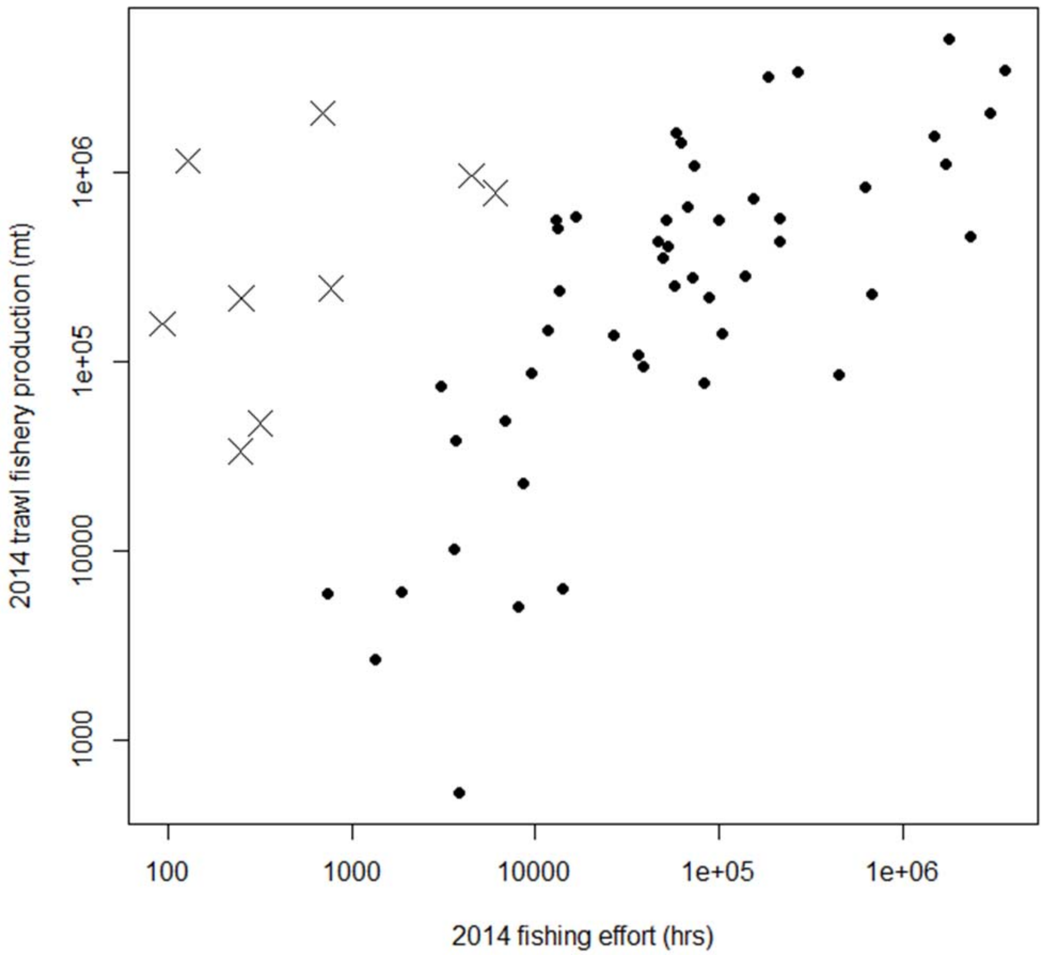
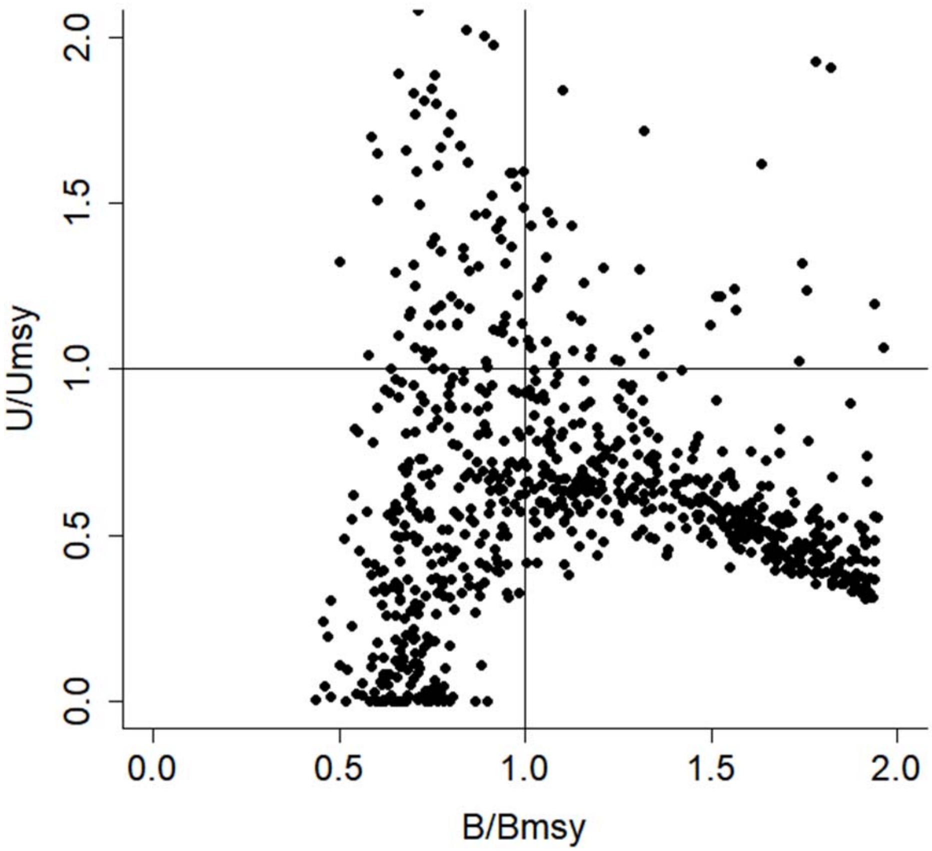


Figure 3. Gear modifications and their effect on global seafloor disturbance. Panels A, B, and C show examples of recently developed gear modifications that reduce seafloor contact. Panel A is a drawing of a groundfish trawl equipped with conventional sweeps compared to one outfitted with bobbins (reproduced with permission from [10]). Panel B shows a conventional trawl door compared to a modified ("batwing") trawl door (reproduced with permission from [25]). Panel C shows a pulse trawl which uses electrical pulses instead of direct contact with the seafloor to stimulate fish (photo by I. Wilms). Panel D shows estimated change in global seafloor disturbance (% change over current) under a range of contact reduction scenarios; zero contact reduction indicates seafloor disturbance under current fishing practices. The green line shows the seafloor disturbance scenarios under current fishing levels in which global trawl harvest remains stable relative to 2013-2018 harvest rates, whereas the orange line indicates disturbance scenarios under global bottom-tendered fishing associated with maximum sustainable yields. Vertical bars give two standard errors reflecting year-to-year variability in simulated fishing effort.



Extended Figure 1. Relationship between 2014 bottom-tendered fishery production (mt) and fishing effort (hrs) for large marine ecosystems (LMEs). The X's signify LMEs that were identified as outliers in their ratio of production: effort (suggesting missing fishing effort) and consequently had adjustments made to their estimates of seafloor disturbance.



Extended Figure 2. Status of global bottom-tendered gear fisheries showing exploitation rate and stock biomass relative to MSY of stocks estimated using the RH-cMSY catch-only assessment model. The vertical axis is the ratio of current exploitation rate to that at MSY (U/U_{MSY}). The horizontal axis is the ratio of current stock biomass to that at MSY (B/B_{MSY}). Fisheries in the upper left quadrant are currently overexploited and have stock biomasses below those associated with MSY, indicating opportunities for which reductions in fishing effort could both increase harvests and stock sizes, as well as reduce seafloor impacts. In contrast, underexploited fisheries below the horizontal U/U_{MSY} = 1.0 line would require increases in fishing effort to achieve MSY and thus may increase seafloor disturbances under conventional fishing practices.

Extended Table 1. Seafloor disturbance, harvests, and estimated maximum sustainable yields for trawl fisheries by large marine ecosystem (LME).

LME	**Seafloor disturbance (%)**	**Shelf area (sq. km)**	**2014 trawl harvest (1,000 mt)**	E_{msy}/E_{last}*	Y_{msy}/Y_{last}†
Agulhas Current	7.2	470,184	108.9	0.87	1.25
Aleutian Islands	6.8	83,264	508.1	1.85	1.13
Antarctic	0.2	2,721,116	146.7	1.85	1.08
Arabian Sea	1.9	861,776	584.5	2.28	1.42
Baltic Sea	20.2	377,548	436.4	1.77	1.42
Barents Sea	14.3	1,793,564	229.3	1.55	1.67
Bay of Bengal	0.5 (15.5)‡	897,204	2,072.5	1.89	1.27
Beaufort Sea	0.1	620,780	0	-§	-
Benguela Current	17.1	400,664	1,095.2	1.25	1.27
Black Sea	5.8	190,820	355.9	1.3	1.46
California Current	10.9	206,296	407.3	1.55	1.21
Canadian Eastern Arctic -West Greenland	3.6	1,004,632	141.8	1.1	1.25
Canadian High Arctic - North Greenland	0	372,060	0	-	-
Canary Current	22.9	269,340	3,229.3	1.71	1.24
Caribbean Sea	0 (2.5) ‡	850,176	33.8	1.41	1.55
Celtic-Biscay Shelf	45.9	591,924	1,109.8	1.41	1.25
East-Central Australian Shelf	5.7	87,520	5.1	3.46	4.47
East Bering Sea	14.3	633,352	735.9	1.59	1.12
East Brazil Shelf	0.2 (4.2) ‡	200,136	38.7	1.59	1.27
East China Sea	20.2	682,420	3,489.5	1.43	1.29
East Siberian Sea	0	612,960	0	-	-
Faroe Plateau	34.1	87,984	287.3	1.24	0.92
Greenland Sea	3.1	561,164	77.1	1.74	1.92
Guinea Current	17.8	377,376	1,624.7	1.95	1.44
Gulf of Alaska	8.9	441,872	565.0	1.29	1.19
Gulf of California	0.3 (7.1) ‡	125,020	160.5	1.74	1.16
Gulf of Mexico	5.5	726,084	566.3	1.18	1.08
Gulf of Thailand	0.8 (14) ‡	381,072	1,163.6	1.4	1.31
Hudson Bay Complex	0.2	1,234,880	0.5	-	-
Humboldt Current	2.8	403,220	139.0	1.73	1.83
Iberian Coastal	44.5	88,436	86.3	1.3	1.51
Iceland Shelf and Sea	24.9	286,752	575.6	1.95	1.9
Indonesian Sea	0.1 (13.2) ‡	1,136,496	968.5	1.69	1.18
Insular Pacific-Hawaiian	0.1	52,192	0	-	-

LME	Seafloor disturbance (%)	Shelf area (sq. km)	2014 trawl harvest (1,000 mt)	E_{msy}/E_{last}*	Y_{msy}/Y_{last}[†]
Kara Sea	0.4	923,308	0	-	-
Kuroshio Current	6.9 (12.3) [‡]	227,912	782.3	1.08	1.33
Laptev Sea	0.1	818,764	0	-	-
Mediterranean Sea	25.7	1,035,708	461.9	1.46	1.3
New Zealand Shelf	7.5	546,724	278.4	1.43	1.15
Newfoundland-Labrador Shelf	4.4	868,248	253.2	1.29	1.86
North Australian Shelf	1.5	771,604	22.9	1.13	1.26
North Brazil Shelf	1.4	519,492	94.0	1.69	1.43
North Sea	37.8	667,836	1,572.5	0.94	1.1
Northeast Australian Shelf-Great Barrier Reef	1.6	496,736	6.3	0.98	1.23
Northeast U.S. Continental Shelf	11.8	307,664	561.9	1.23	1.38
Northern Bering - Chukchi Seas	2.2	1,159,852	240.3	1.68	1.16
Northwest Australian Shelf	0.9	508,748	10.3	1.31	1.3
Norwegian Sea	14.4	217,312	218.8	1.68	1.45
Oyashio Current	25.9	101,540	663.9	1.1	1.12
Pacific Central-American Coastal	0 (8.2) [‡]	298,504	246.2	0.96	1.14
Patagonian Shelf	14.6	1,137,476	848.9	1.35	1.17
Red Sea	0 (4.5) [‡]	387,040	47.5	1.85	1.61
Scotian Shelf	2.1	277,256	49.0	1.51	2.05
Sea of Japan / East Sea	9.3	369,320	1,454.1	NA	NA
Sea of Okhotsk	14.5	1,063,660	3,418.0	1.49	1.35
Somali Coastal Current	1.4	136,572	87.4	2.59	1.48
South Brazil Shelf	8.2	347,128	74.8	1.38	1.23
South China Sea	6.6	1,727,392	5,149.6	1.52	1.18
Southeast Australian Shelf	1.3	239,984	6.1	2.48	3.64
Southeast U.S. Continental Shelf	1.9	297,204	38.8	1.21	1.48
Southwest Australian Shelf	1.3	347,704	6.0	1.81	2.28
Sulu-Celebes Sea	0 (7.9) [‡]	346,416	217.9	2.02	1.34
West-Central Australian Shelf	2.1	167,408	2.7	1.63	2.06
West Bering Sea	24	154,720	438.9	1.22	1.04
Yellow Sea	41.1	430,080	2,055.6	1.74	1.22
Central Arctic	0	22,772	0	-	-

*Ratio of effort needed to achieve MSY relative to the last year of catch data (2014), estimated by the RH-cMSY catch-only model.

†Ratio of yield needed at MSY relative to the last year of catch data (2014), estimated by the RH-cMSY catch-only model.

[‡]Numbers given in parentheses indicate adjusted estimates of seafloor disturbance due to low AIS coverage.

[§]Dashes (-) indicate insufficient data to calculate.