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Bottom trawl-fishing footprints on the world's continental shelves

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Bottom trawlers land around 19 million tonnes of fish and invertebrates annually, almost one quarter of wild marine landings. The extent of bottom trawling footprint (seabed area trawled at least once in a specified region and time period) is often contested but poorly described. We quantify footprints using high resolution satellite Vessel Monitoring System (VMS) and logbook data on 24 continental shelves and slopes to 1000m depth, over at least two years. Trawling footprint varied markedly among regions, from <10% of seabed area in Australian and New Zealand waters, the Aleutian Islands, East Bering Sea, South Chile and Gulf of Alaska to >50% in some European seas. Overall, 14% of the 7.8 million km^2 study area was trawled and 86% not trawled. Trawling activity was aggregated; the most intensively trawled areas accounting for 90% of activity comprised 77% of footprint on average. Regional swept-area ratio (SAR) (ratio of total swept-area trawled annually to total area of region, a metric of trawling intensity) and footprint area were related, providing a new approach to estimate regional trawling footprints when high resolution spatial data are unavailable. If SAR was ≤0.1, as in 8 of 24 regions, there was >95% probability that >90% of seabed was not trawled. If SAR was 7.9, equal to the highest SAR recorded, there was >95% probability that >70% of seabed was trawled. Footprints were smaller, and SAR ≤0.25, in regions where fishing rates consistently met international sustainability benchmarks for fish stocks, implying collateral environmental benefits from sustainable fishing.

fisheries | effort | footprint | habitat | seabed

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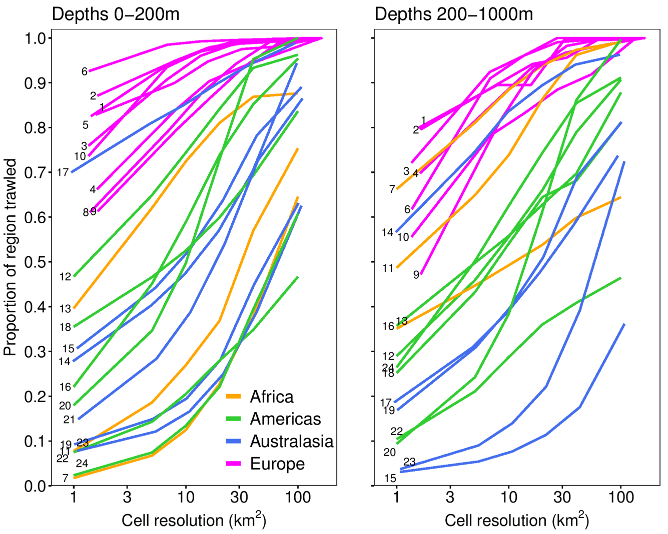

Fig. 1. Relationships between the spatial resolution of effort data and the trawling footprint (Approach A, grid cell-based, see main text), for depth ranges of 0-200m and >200-1000m. Region codes follow Table 1 and Fig. 3. Three regions are not represented on the >200-1000m panel because these regions are predominantly <200m deep.

There has been sustained debate about the extent of bottom trawling impacts on marine environments (1, 2). Both the scale and ecological consequences of trawl impacts have been highlighted, with suggestions that bottom trawls are "annually covering an area equivalent to perhaps half of the world's continental shelf" (1). In contrast, fishing industry representatives often claim the scale of their impact is more limited, highlighting their targeted use of well-defined fishing grounds rather than widespread "ploughing" of the seabed (3). Robust quantification of the distribution and intensity of bottom trawling would provide an evidence base to assess pressures on seabed habitats, to compare the impacts of different fisheries, to characterise fisheries and to estimate the extent of untrawled areas outside Marine Protected Areas (MPA), and fisheries closures (4-9).

Distributions of trawling activity were traditionally reported at a spatial scale of several hundred km^2 and larger; because these coarse scales were used for data collection and recording (10). Activity mapped at coarse scales inevitably provides a misleading picture of the spatial distribution of trawling, since trawled areas combine with untrawled areas (11). Local and regional studies have provided a higher-resolution view of activity from positions in vessel logbooks, analyses of plotter data, analyses of overflight data or direct tracking of subsets of vessels. These show that trawling distributions are often highly aggregated, but coverage of vessels and areas was usually insufficient to map total trawling distributions at the shelf-sea scale (12).

The introduction of Vessel Monitoring Systems (VMS) as a surveillance and enforcement tool revolutionised the study of fishing activity and footprints, providing high-resolution information on locations of individual fishing vessels and complete or almost complete coverage of many fleets (13-15). VMS data enable management authorities to monitor whether a vessel is in an area where it is permitted to fish. VMS data are also used by scientists to show the locations and dynamics of fishing activity, usually based on density distributions of position records or reconstructed tracks (16-18). High-resolution descriptions of trawling activity from VMS have already underpinned studies of fishing behaviour and dynamics (19-20), trawling impacts on species, habitats and ecosystem processes at regional scales (21-28) and provided indicators of fishing pressure (4, 29). They have also supported marine spatial planning (7, 9, 30, 31), including mapping fishing grounds (32-35), and providing advice on siting MPA (7, 33) and assessment of MPA effects (13, 14). VMS data are often linked, vessel by vessel, to the fishing gears that are deployed and catches recorded (17).

High resolution position data allow the aggregation of trawling to be assessed at multiple scales. Aggregation needs to be accounted for when estimating trawling impacts because repeated passes on a previously trawled seabed each have a smaller impact than the first pass of a trawl on a previously untrawled seabed (36). Analyses at finer scales will better identify aggregation and the presence of untrawled areas (2), which have important implications for impact and recovery dynamics, and reveal smaller trawled areas and lower trawling pressure than analyses at coarser-scales (37-38). The scale at which the spatial distribution of trawling activity can be shown to be random in a given year is typically less than 5 km^2 (e.g. 12), but random trawling activity tends to be uniformly spread at the same scale when data are accumulated over multiple years (39).

An increasing number of regional analyses describe trawling footprints based on VMS or high resolution tow-by-tow observer and logbook data (5, 9, 23, 40). VMS data provide advantages over Automatic Identification System (AIS) data for measuring the totality of these footprints because VMS is usually required for whole fleets and the use of VMS as a formal enforcement tool means that attempts to stop transmissions are usually spotted and rectified (41). Further, vessel identification codes recorded with VMS position data can be linked directly to vessel identification codes used for recording information on gear types and dimensions as well as catch or landings data (17, 42, 43). The main limitation of VMS data in relation to AIS is the relatively low transmission rate, typically one position record every one or two hours, thus requiring the development of methods to identify fishing activity and to interpolate tracks (44-46).

Systematic comparisons of the footprints of bottom trawl fisheries in those regions where the majority of all fishing vessels are monitored using VMS or reporting tow-by-tow observer data would provide an evidence base to resolve uncertainties about the scale and intensity of bottom trawling and to underpin assessments of the impacts of trawling on seabed habitats. Such evidence is also necessary to effectively assess and manage the environmental impacts of fishing methods and to address trade-offs given that bottom trawl fishing makes a substantial contribution to human food supply. Data from the Food and Agriculture Organisation of the United Nations (FAO; 48-50) suggest that landings of fish, crustaceans and molluscs from towed bottom gears from 2011-2013 were 18.9 – 19.8 million t yr^{-1}, equating to 23.3 - 24.4% of mean annual marine wild-capture landings in the same years (*SI Appendix*, Text S1).

Here, we collate and analyse VMS and logbook data to provide standardised high resolution estimates of bottom trawling footprints on continental shelves and slopes to a depth of 1000 m in selected regions of Africa, the Americas, Australasia and Europe. In these analyses, bottom trawling refers to all towed gears making sustained contact with the seabed including beam and otter trawls, and dredges (47). We assess whether the aggregation of bottom trawling activity is a consistent feature of trawl fisheries in different regions, and describe how footprints are related to fisheries landings, effort and the status of fish stocks. We quantify a relationship between trawling footprints and less complex measures of total trawling activity. This relationship can be used to estimate footprints for those areas of the world where high-resolution data are not available, and to predict how fishing footprints may evolve in newly exploited areas given any proposed or projected level of trawling effort (e.g. the Arctic).

Trawling footprints

To estimate bottom-trawling footprints we obtained high-resolution vessel position data accounting for 70%–100% of all

Table 1. Summaries of trawling footprint and fisheries data, by region, for depths of 0-1000 m. Information in brackets following region names indicates when regions largely follow existing fishery management areas (excluding areas deeper than 1000 m). Region codes are used to identify regions in the figures. Regional swept area ratio (SAR) is the mean annual total area swept by trawls divided by the area of the region to 1000 m depth. Trawling footprints are expressed using the three approaches as described in the text: approach A, cell assumption: summing the area of any grid cells in which any trawling activity is recorded; approach B, random assumption: assuming Poisson distribution of effort within cells and approach C, uniform assumption: that trawling is uniformly spread within cells. The percentage of the region accounting for 90% of activity is the sum of the area of the most intensively trawled areas accounting for 90% of total activity divided by the sum of the area accounting for all activity, based, in this calculation, on approach C. Coverage of trawling activity in each region is estimated from the proportion of total landings or effort attributed to vessels providing VMS or logbook data. Landings per unit area of footprint are the mean annual landings of the monitored fleets divided by the footprint area (based on approach C, uniform assumption). Differences in regional swept area ratio and footprint in this table and in a previous analysis for the Adriatic Sea and West of Iberia (23) result from differences in the choice of boundary.

Region	Region code	Coverage of total bottom trawling effort (%)	Method to assess coverage	Years included	Area 0-1000m (10^3 km^2)	Area 0-200m (10^3 km^2)	Regional swept area ratio (km^2 km^{-2} yr^{-1})	% area of region trawled (approach A, cell assumption)	% area of region trawled (approach B, random assumption)	% area of region trawled (approach C, uniform assumption)	% area of region accounting for 90% of trawling activity	Landings (10^3 t yr^{-1})	Landings per unit area of footprint (t km^{-2} yr^{-1})
Adriatic Sea (GFCM 2.1)	1	72	Landings	2010-12	39	37	7.926	82.7	79.1	80.7	59.3	28	0.89
West of Iberia (ICES 9a)	2	81	Effort	2010-12	40	23	4.321	83.9	58.7	64.3	37.2	14	0.54
Skagerrak and Kattegat (ICES 3a)	3	100	Effort	2010-12	55	41	3.328	75.0	50.0	54.4	33.0	31	1.04
Tyrrhenian Sea (GFCM 1.3)	4	82	Landings	2010-12	138	53	2.286	68.4	43.8	49.9	30.2	10	0.15
Irish Sea (ICES 7a)	5	83	Effort	2010-12	48	48	1.459	82.5	25.4	28.5	14.8	71	5.17
North Sea (ICES 4a,b,c)	6	86	Effort	2010-12	586	523	1.191	89.3	42.2	51.7	39.8	745	2.46
North Benguela Current	7	95	Effort	2008-10	203	92	0.967	37.0	24.6	27.8	19.4	150	2.66
Western Baltic Sea (ICES 23-25)	8	72	Effort	2010-12	87	87	0.960	61.1	30.8	36.1	26.5	26	0.83
Aegean Sea (GFCM 3.1)	9	75	Landings	2010-12	175	64	0.798	52.4	26.7	31.9	23.9	5	0.09
West of Scotland (ICES 6a)	10	81	Effort	2010-12	161	114	0.453	68.4	19.1	23.0	18.5	75	2.03
South Benguela Current	11	97	Effort	2008-13	122	56	0.440	29.9	12.2	13.8	9.5	114	6.73
Argentina	12	96	Effort	2010 and 2013	910	837	0.276	45.3	14.2	17.6	14.8	590	3.68
East Agulhas Current	13	93	Effort	2008-13	140	96	0.247	38.2	9.4	11.1	8.6	8	0.52
Southeast Australian Shelf	14	100	Effort	2009-12	268	230	0.134	31.9	7.0	8.6	7.3	12	0.53
Northeast Australian Shelf	15	100	Effort	2009-12	557	337	0.112	19.8	4.7	5.7	4.6	10	0.31
New Zealand	16	90	Effort	2008-12	1053	260	0.106	31.3	6.9	8.6	7.5	10	0.11
East Bering Sea	17	97	Effort	2008-10	634	575	0.089	34.5	6.5	7.9	7.0	1146	22.88
North California Current	18	100	Landings	2010-12	119	55	0.077	29.5	5.5	6.9	6.1	305	37.28

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Region	Region code	Coverage of total bottom trawling effort (%)	Method to assess coverage	Years included	Area 0-1000m (10^3 km^2)	Area 0-200m (10^3 km^2)	Regional swept area ratio (km^2 km^{-2} yr^{-1})	% area of region trawled (approach A, cell assumption)	% area of region trawled (approach B, random assumption)	% area of region trawled (approach C, uniform assumption)	% area of region accounting for 90% of trawling activity	Landings (10^3 t yr^{-1})	Landings per unit area of footprint (t km^{-2} yr^{-1})
Southwest Australian Shelf	19	100	Effort	2009-12	338	283	0.034	10.5	2.1	2.7	2.3	5	0.57
Aleutian Islands	20	97	Effort	2008-10	84	35	0.033	12.9	1.8	2.1	1.8	123	70.09
North Australian Shelf	21	100	Effort	2009-12	794	792	0.026	14.8	1.9	2.2	2.0	150	8.48
Gulf of Alaska	22	85	Effort	2008-10	398	294	0.024	8.2	1.4	1.7	1.4	138	20.85
Northwest Australian Shelf	23	100	Effort	2009-12	686	474	0.023	6.5	1.3	1.6	1.4	5	0.47
South Chile	24	85	Effort	2009-13	189	149	0.004	7.4	0.4	0.4	0.4	5	5.90

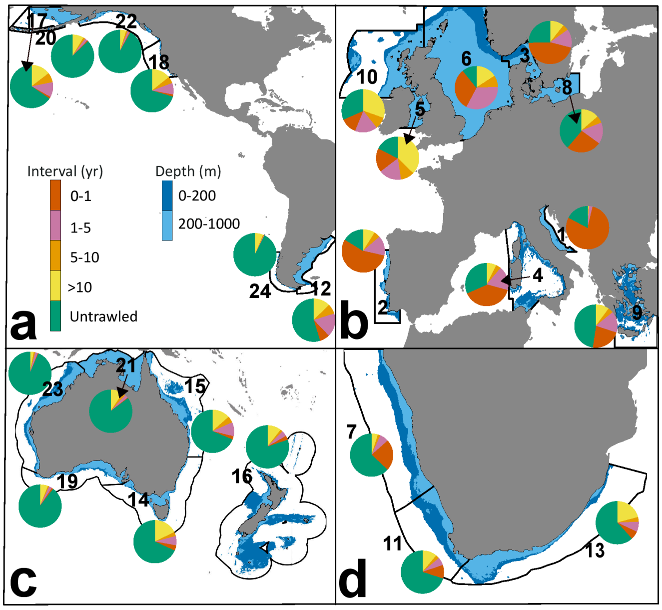

Fig. 2. Mean interval between trawling events and the proportion of unfished area at depths 0-1000m for regions in (a) Americas, (b) Europe, (c) Australasia and (d) Africa. Black lines indicate boundaries of study regions, pale blue tones depths 0-200m in the study regions, darker blue tones depths 0-1000m in the study regions, and all deeper areas and areas outside study regions are shown in white. In all numbered regions, the proportion of bottom trawling included in this analysis exceeds 70% of total activity (Table 1). Region codes follow Table 1 and Fig. 3.

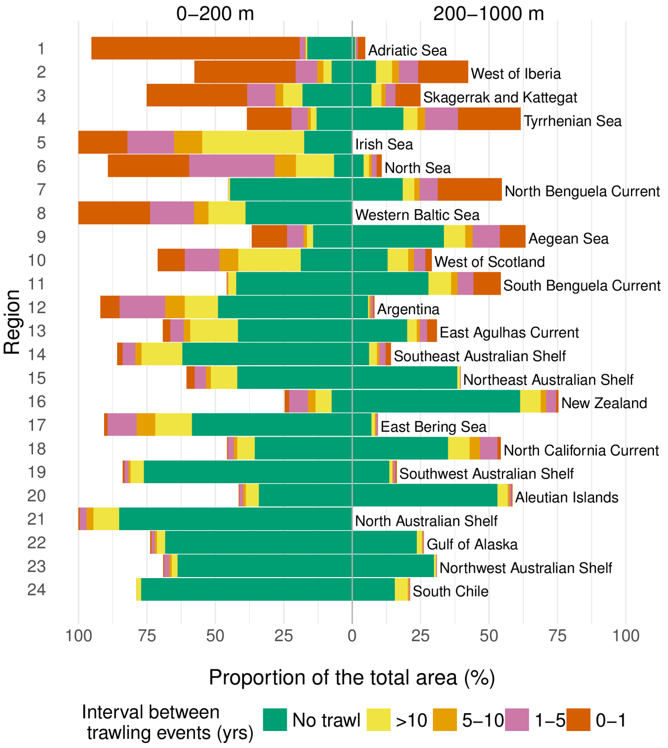

Fig. 3. Proportions of the total area of each region, at depths of 0-200m and >200-1000m, trawled at different frequencies. Region code numbers increase as regional Swept Area Ratio (SAR) decreases.

known trawling activity over two to six years (usually the three years, 2008-2010) in each of 24 regions (Fig. 1, Table 1, *SI Appendix*, Text S2, Figures S3-S26). Footprints were defined as the area of seabed trawled at least once in a specified region and time period, with area trawled determined from gear dimensions and tow locations (*SI Appendix*, Table S1, Text S2). Trawling activity data were collated and processed for regions spanning 7.8 million km^2 of seabed to depths of 1000 m. Regions were excluded from the analyses where trawling activity data provided <70% coverage of total trawling activity (*SI Appendix*, excluded regions listed in Table S2, Text S3, Figures S27-S34).

Trawling footprints may be estimated in at least three ways. All of these rely on gridding the region used by fisheries at a defined scale, and then generating measures of the area trawled within every grid cell by overlaying information on the positions of fishing tows. Areas trawled in every grid cell are then summed

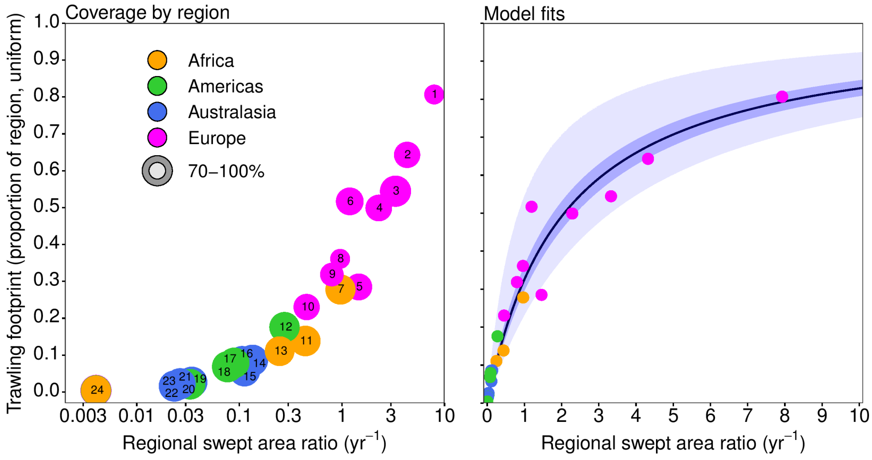

Fig. 4. Relationship between the regional swept area ratio (SAR) and the trawling footprint (Approach C, assumes uniform spread in grid cells, see main text). Left panel: symbol sizes indicate the proportion of total fishing activity recorded in each region (all > 70%), numbers in symbols identify regions listed in Table 1 and Fig. 3. Right panel: black line is the fitted relationship footprint = SAR/ (b+SAR); dark blue shading indicates 95% confidence intervals for model fit and light blue shading indicates 90% prediction intervals for footprint.

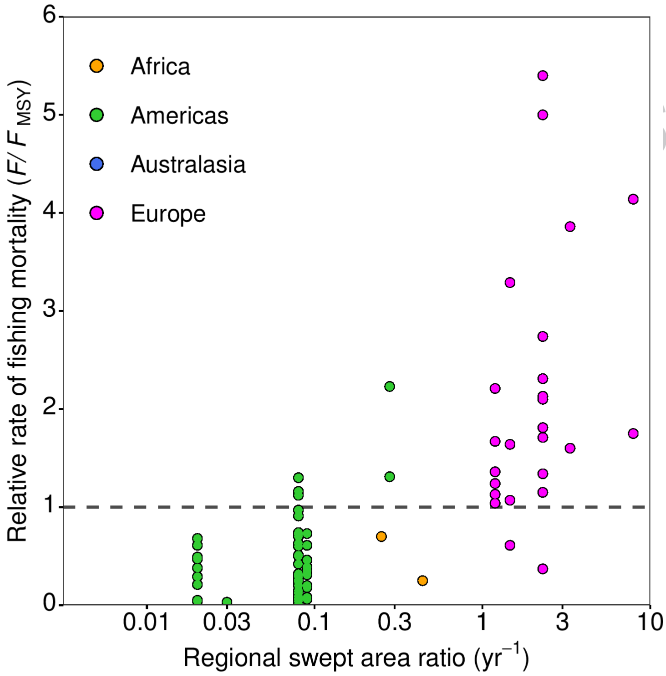

Fig. 5. Relationships between the relative rate of fishing mortality and the regional swept area ratio (SAR) by region. Circles denote the ratio of fishing mortality (F, mean 2010-2012) to the F_{MSY} reference point for individual bottom dwelling stocks. The black horizontal dashed line indicates F/ F_{MSY}= 1, usually treated as a desirable upper limit on fishing rates by managers. One value of F/ F_{MSY} >8, for a Mediterranean stock, and in a region where the regional swept area ratio is 7.93, is excluded from the figure for clarity.

across the region. The approaches differ in how they estimate the area trawled within each grid cell. Approach A involves summing the area of any grid cells in which any trawling activity is recorded in a defined time period (usually one year), even though some of the area within a grid cell may not have been trawled in that time period. Approach B involves summing the area trawled within each grid cell in a defined time period, where the area trawled is estimated based on the assumption that the number of times any point within the cell is trawled is randomly (Poisson) distributed (5). Approach C involves summing the area trawled within each grid cell in a defined time period, where the area trawled is estimated based on the assumption trawling is uniformly spread within the cell.

With approach A, footprint estimates depend very strongly on grid resolution. As grid-cell area is increased from to 1-3 km^2 (the scale at which trawling is usually distributed randomly within cells (12)) to ≥10^4 km^2, the estimated area of trawling footprints increased substantially (Fig. 1). Median increases in footprints were 34%, 63%, 48% and 57% in Europe, Africa, Americas and Australasia respectively at depths 0-200 m, and 41%, 33%, 56% and 55% at depths 200-1000 m. Thus, at coarse resolutions of analysis, such as the 0.5° grid cells (area approximately 2185 km^2 at 45° N or S) that have sometimes been used to show trawling distributions (11), trawling footprints will be markedly overestimated and the extent of untrawled areas underestimated.

Even though reductions in the scale of grid cell-based analyses to around 1 km^2 will characterise trawling footprints more accurately, these footprint estimates will still be larger than those resulting from more detailed analysis of the distribution of individual trawling tracks within cells. This is because it is impossible, or statistically unlikely, that a grid cell is trawled in its entirety when trawling intensity is low. Approaches B and C directly address this issue. Approach B provides a more accurate estimate of annual trawling footprint because the distribution of trawling at any point within cells of close to 1 km^2 area has been shown to be random on annual time-scales (39). Approach C is more appropriate to estimate aggregate footprint over many years because trawling within cells tends to spread more uniformly as many years of trawl location data are aggregated. Thus annual mean footprint is better approximated by approach B than by C while the multi-year footprint is better approximated by approach C than by B.

To estimate the trawled area within grid cells, we first calculated the annual swept area ratio (SAR) for each grid cell. In general, SAR is defined as the total area swept by trawl gear over a defined time-period (usually one year) divided by the total seabed area at a defined spatial scale (usually from grid cell to region). The total area swept within a defined area (e.g. a grid cell) is calculated as the product of trawling time, towing speed and dimensions of gear components contacting the seabed (42), summed over the different types of trawl gear operating in the area. The estimated mean annual SAR in each grid cell is then used as the mean of an assumed random distribution (Poisson, approach B), or uniform spread (approach C), of trawling within each cell to determine the proportion of grid cell area that was trawled at least once (i.e. contributes to footprint area) or not trawled.

When using the 1 km^2 cell-based approach (approach A) to estimate the trawling footprints in the study period, 33.6% of the total area for which we collated ≥70% of bottom trawling activity

(7.8 million km^2 of seabed at depths 0-1000 m) was trawled and 66.4% was untrawled. When we accounted for untrawled areas inside trawled grid cells assuming random trawling distributions (approach B), trawled area fell to just 11.7% and untrawled area was 6.9 million km^2 or 88.3% of total area. When we assumed uniform trawling distributions within trawled cells (approach C), trawled area was 14.0% and untrawled area was 86.0% (6.7 million km^2) of total area. The overall pattern was consistent with regional patterns, with approach A yielding higher estimates of footprint than approaches B and C (Table 1, *SI Appendix* Fig. S35). We primarily report footprints based on the uniform approach C, as these best approximate the aggregate footprint of trawling over many years.

The overall footprint of trawling to a depth of 1000 m, based on the assumption of uniform spread within grid cells (approach C), was ≤10% of seabed area in 11 of the 24 regions (Table 1, Fig. 2). A larger fraction, from 10% to 30% of the shelf and upper slope area to 1000 m depth, was trawled in the Irish Sea, North Benguela Current, South Benguela Current, Argentina, East Agulhas Current and West of Scotland. The remaining seven regions, all in the northeast Atlantic and Mediterranean, had >30% to 81% of the shelf area trawled. The untrawled area was >50% in 20 of the 24 regions. Some of the largest regions we considered were among the least intensively trawled. Thus trawling footprint in the largest region, New Zealand, was 8.6%, while footprints in Argentina, North Australian Shelf and North West Australian Shelf (ranked 2-4 by area) were 17.6%, 2.2% and 1.6% respectively (Table 1, *SI Appendix* Fig. S36). Concentration of trawling activity within footprints varied among regions. The most intensively trawled area accounting for 90% of total trawling activity (calculated with the uniform spread assumption, approach C) ranged from 0.4% to 40% of the area of the regions and comprised 52% to 100% of the total trawling footprint area within regions (mean 78%) (Table 1, *SI Appendix* Fig. S37). We focus on approach C when making these comparisons because this approach provides more reliable estimates of trawling footprints on the multi-year time-scales which are relevant when considering impact and recovery dynamics of most seabed biota (47).

The frequency of trawling is another relevant metric when assessing trawling impacts on the status of seabed biota (47). We expressed the frequency of trawling disturbance as the average interval between trawling events for each of the trawled grid cells. This metric is the inverse of the cell-specific SAR. More than half the seabed area is trawled at an interval of at least once per year, on average, in the region with the highest regional SAR (Adriatic Sea, Fig. 2). Over one quarter of the seabed area is trawled with this frequency in five of the other eight European seas (Fig. 2). In all Australasian regions, three quarters of the seabed is never trawled, or is trawled less than once every 10 years, as is the case in the South Benguela Current, East Agulhas Current, North California Current, East Bering Sea, Aleutian Islands, Gulf of Alaska and South Chile (Fig. 2). Within regions, there tended to be large differences in the proportions of the seabed area untrawled in the 0-200 m and 200-1000 m depth bands (Fig. 3), likely reflecting the different foci and development of bottom trawl fisheries in these regions.

Among regions there was a strong relationship between regional SAR and the total trawling footprint based on the uniform assumption (Fig. 4). This relationship between regional SAR and regional trawling footprint implies that regional SAR estimates, calculated from basic information on fishing effort (measured as time trawling) and some knowledge of gear and vessel characteristics, may be used to predict trawled and untrawled areas of seabed at regional scales. For example, for mean regional SAR = 1 yr^{-1}, the prediction probability intervals for footprint (where the mean estimate of footprint by region = SAR/ (b+SAR), with b = 2.072 s.e. 0.154) indicate >0.95 probability that at least 23% of the region remains untrawled and 0.90 probability that 33 to 54% is trawled (Fig. 4). For SAR ≤0.1 yr^{-1}, as in eight of our 23 regions, there was a >0.95 probability that at least 90% of the seabed was untrawled. For SAR of 7.93 yr^{-1}, equal to the highest SAR recorded (Adriatic Sea), there is a >95% probability that more than 70% of the seabed was trawled.

Regions were included in the main analyses when catch or effort data indicated that the trawling activity recorded with VMS or observer data was at least 70% of total activity. Alternative cut-offs of 80% or 90% did not lead to significant changes in the mean relationships shown in Fig. 4, but confidence and prediction intervals increased substantially if only the few regions with >90% activity were included. This relationship between regional SAR and trawling footprint based allows us to approximate the increase in trawling footprint that would result if we had been able to include 100% of known trawling activity in our analyses. If we assume the relationship between SAR and trawling footprint applies in all the cases where coverage is <100%, then the combined trawling footprint across all regions would increase by 71000 km^2, or 0.9% of the 7.8 million km^2 study area, if we obtained data on all trawling activity. This would represent an increase of 8.2% in the total area trawled across all 24 regions, with higher regional increases in regions where coverage of effort was closer to 70%.

We calculated regional SAR with high resolution data, but it can also be calculated as the product of total annual hours of trawling, mean towing speed and gear width without information on the location of trawlers at sub-regional scales. Regional SAR calculated from this more widely available information might then be used to predict trawling footprint, using the relationship in Fig. 4. We applied this approach to the bottom trawl shrimp fisheries off the U.S. coast of the Gulf of Mexico, a region for which we had no VMS data. The area of the northern Gulf of Mexico shelf and slope to a depth of 1000 m is approximately 4.6 × 10^5 km^2 and the swept-area in the years 2007-2009 was 2.8 × 10^5 km^2 yr^{-1}. This leads to a mean SAR of 0.64 yr^{-1}. If the relationship described in Fig. 4 applies to these bottom trawl fisheries then there is a 0.9 probability that 16-43% of this region of the Gulf of Mexico is trawled, based on the uniform assumption, and a 0.95 probability that more than 56% is untrawled (*SI Appendix*, Text S4).

Bottom trawling may impact a range of seabed types within a given footprint. For regions where ≥70% of trawling activity was recorded we quantified the intersection of trawling with four broad seabed types. We defined seabed types based on sediment composition obtained from the dbSEABED database of marine substrates (51). A simple sediment classification rather than a more highly resolved habitat classification was adopted to enable equitable treatment of habitat across all regions and for consistency with habitat types reported in most trawling impact studies (36 ,52-55). Grid cells were classified to sediment types by denoting: "gravel" if gravel>30%, else "sand" if mud<20%, else "mud" if sand<20%, else "muddySand" (53). Sediment data could be obtained for 90% of cells in all regions, except for New Zealand EEZ (86%), Aleutian Islands (72%), Gulf of Alaska (68%) and Argentina (52%).

Within all regions, the bottom trawling footprint on each sediment type was correlated with total area by sediment type (*SI Appendix*, Fig. S38). This result implies that bottom trawling activity is not consistently directed towards certain sediment types. This is expected since we compiled activity by multiple fleets rather than individual types of bottom trawl fishery (e.g. stratified by gears, fleets) and because fishers are targeting different fish species with different trawl gears on many types of seabed (e.g. 42). While this result may be more nuanced with a more highly resolved classification of habitat types (e.g. 23), a consistent and highly resolved ecologically-based habitat classification is not available for all regions.

International calls for MPA coverage of 10% of ocean area (56) to 30% or more (57), often focus on the protection of seabed from bottom trawling. Our results demonstrate that ≥30% of the seabed was not trawled during the study period in all regions except the Adriatic Sea. In 20 of the 24 regions ≥50% of the seabed was not trawled during the study period. This proportion of untrawled seabed is already much greater than the proportion proposed for protection within MPA (56, 57), demonstrating opportunities in many regions to site MPAs in areas that have not been affected by, and would not displace, trawling activity. Further, since trawling footprints were distributed more or less evenly in relation to broad sediment types, the large proportions of untrawled area in a region may imply a relatively representative range of seabed types currently remain untrawled. But, as described in relation to the habitat analysis, this conclusion may not hold when habitat types are more highly resolved or when active management intervention affects the distribution of fishing activity.

Finally, we assessed relationships between regional SAR and metrics of the intensity of fisheries exploitation. There was a significant, but noisy, positive relationship between regional SAR and relative rates of fishing mortality F (expressed as the ratio between recorded F and the reference point F_{MSY}, Fig. 5, *SI Appendix* Text S5, Table S3). Broadly, when regional SAR was ≤0.25, as in 12 of our 24 study regions, fishing rates on all stocks for which we had data were close to or below F_{MSY}. Conversely, when regional SAR was >0.25, F was greater than F_{MSY} for 85% of the stocks. A regional SAR of 0.25 corresponds to a trawling footprint spanning of around 10% of the area of a region, based on the uniform assumption and the relationship between SAR and footprint (approach C, Fig. 4 and see *SI Appendix*, Fig. S39 for the direct relationship trawling footprint and relative F). When regional SAR exceeded three, as recorded in two Mediterranean regions and one Baltic region, all stocks for which we had data were fished at or above F_{MSY} (Fig. 5). When we conducted a more constrained analysis, which only included those stocks with distributions spanning at least 50% or 70% of the region to which they were assigned, the breakpoint remained close to SAR=0.25 in both cases (*SI Appendix*, Fig. S40, S41). The relationships between trawling footprints (approach C) and relative F (*SI Appendix*, Fig. S39) also held when we only included those stocks with distributions spanning at least 50% or 70% of the region to which they were assigned (*SI Appendix*, Fig. S42, S43). Thus, in regions where fishing rates consistently met international sustainability benchmarks for fish stocks, trawling footprints based on approach C were typically ≤11% of region area. These patterns imply that fisheries management systems that effectively meet reference points for exploitation rates on bottom dwelling stocks will achieve collateral environmental benefits because SAR and thus trawling footprint will be lower.

Our group made significant efforts internationally to obtain high-resolution trawling activity data for regions where these data are recorded. The seabed area including the continental shelf area to 1000 m globally approximates 42.5 million km^2, thus the data we acquired cover 18.4% of this. Our data accounted for a similar proportion (19.5%) of estimated global landings by bottom trawlers (3.78 million tonnes yr^{-1}, Table 1; assuming mean global landings of 19.35 million tonnes yr^{-1}, Text S1). Regions where data were not available to us included some areas where we expect high levels of bottom fishing activity (e.g. Bay of Biscay, east coast U.S. and Canada, Brazil shelf and southeast Asia).

To conclude, there are large differences in trawling footprints among study regions. But, for almost all the shelves and slopes we studied, total footprints to depths of 200 m and 1000 m, based on the more representative assumption of uniform spread of trawling activity within cells, are well below the 50% previously suggested (1) and are less than 10% overall in almost half the regions. There were strong positive relationships between regional SAR and footprint, providing a new method to estimate trawling footprints for regions where high-resolution data from logbooks, automatic identification systems and satellite vessel monitoring systems are not available. Regional SAR and trawling footprints were generally smaller in regions when fisheries were meeting reference points for sustainable exploitation rates on bottom dwelling stocks, implying collateral environmental benefits from successful fisheries management of these bottom dwelling stocks.

Methods

Bottom trawling contribution to global landings

Marine global landings by mobile bottom fishing gears for the years 2011-2013 were estimated from FAO landings data (48) (*SI Appendix*, Text S1). First, species or species groups not caught with mobile bottom gears were excluded, as were species with mean landings of <1000 t yr^{-1} which account for a negligible proportion of the total (<1% but cannot be quantified precisely due to non-recording). For remaining species or species groups, we estimated the proportion caught by mobile bottom fishing gear (*SI Appendix*, Text S1) and combined this with estimates of mean annual landings of marine fishes that are not identified by FAO (49-50, 58). The calculation excludes fish which are caught but discarded (59).

Estimating trawling footprints

We estimated the area trawled within each grid cell using approach B (assuming random trawling distribution) and approach C (assuming a uniform spread of trawling distribution). Both approaches required estimates of grid cell SAR. Grid cell SAR was estimated for individual cells, typically 1×1 km (1 km^2) or 1×1 minute of longitude and latitude (1.9km^2 at 56°N or S) in grids spanning each region. At these spatial scales trawling tends to be randomly distributed within years, but tends to be uniformly spread on longer timescales (39), consistent with the assumptions we make to estimate footprint. For each grid cell the SAR was calculated as the ratio of the total trawl swept-area (estimated from gear dimensions, towing speed and towing time) divided by grid-cell area. Methods of analysis varied among regions depending on how vessels were tracked (VMS or observers, logbooks), on how fishing tracks were reconstructed from position data and how fishing tracks were linked to vessel, gear dimension and catch information (*SI Appendix* Table S1, Text S2). The methods were adopted by regional specialists to provide their most reliable estimates of grid cell SAR, and thus footprint, within region. Details of analytical approaches for each region are described in the *SI Appendix* (Table S1, Text S2, Fig. S3-S34). Data used in the analyses can be accessed from a database deposited with the University of Washington (https://trawlingpractices.wordpress.com/datasets/).

At broad scales, the distributions of bottom trawling tend to be consistent from year to year as activity is strongly tied to fish distributions, and limited by environmental, technical and economic constraints on areas of gear deployment in the absence of changing management regulations (11). Even so, our analyses of changes in activity distribution from year to year in each region do show that there are often small increases in cumulative footprint area as additional years are included in the computations (*SI Appendix*, Fig. S3-S34). In regions where footprint is small the absolute effects of these increases would be trivial and substantial areas are still expected to remain untrawled on decadal time-scales. In regions where habitat is relatively uniform and footprint is large it is possible that the entire region available to trawlers would be fished on decadal timescales if economically viable to do so, with the exception of any management areas where bottom fishing is banned or where the seabed is unsuitable for use of towed bottom gears.

The selection of regional boundaries will influence the results of the footprint analysis. Thus boundaries were selected and fixed before we started the analyses, primarily based on the shelf and slope area to 1000 m and adjacent to nations for which we expected data to be available, but also guided by biogeographic and oceanographic features, and in some cases existing management regions. Once these boundaries were defined we split the designated area based on 0-200 m and 200-1000 m depths. We could not use existing classifications like Large Marine Ecosystems (LME) because, in many cases, use of LMEs would lead to mixed jurisdictions and fisheries from multiple countries in one region, and would have reduced the overall coverage of trawling activity. The proportional coverage of trawling activity by region was estimated from the proportion of catch or fishing effort recorded by the trawlers for which we obtained data as a proportion of total catch or effort by all trawlers in the region (Table 1).

In some regions, such as Europe, small inshore vessels may use towed bottom gears but may not be subject to the same monitoring or reporting requirements as larger vessels. Even in regions where we have high coverage of reported catch or effort, some inshore bottom trawling activity may not be included. We therefore caution that the results for these regions may not be informative for the immediate inshore zone (typically to 3 miles offshore) and further data collection and analyses would be needed to address this data gap.

Fishing mortality

Estimates of the ratio of fishing mortality rates (F) to fishing mortality reference points (F_{MSY}) for 87 stocks caught with towed bottom gears were used to describe the sustainability of fishing rates in each region. For each one of the 23 areas with high coverage of trawling activity (>70%), data on the intensity of the fishing pressure for stocks targeted by bottom contact fishing gears were obtained from the RAM Legacy database (60, Version 4.30; http://ramlegacy.org). RAM Legacy is currently the most comprehensive repository of stock assessment data containing time series of biomass, catches, fishing mortality, recruitment and management reference points for more than 1000 stocks of marine and anadromous fishes. Stocks were included in the analyses when: (1) both trawl footprint data and a fishing mortality reference point were available for the years 2008-2010; (2) the spatial distribution of the stock matched at least one of the regions with high coverage (>70%) of trawling activity; (3) the largest proportion of landings from the stock, by gear, is taken with bottom trawls. Additional descriptions of the methods, the stocks included, stock distributions in relation to the study regions and resulting status estimates are provided in the *SI Appendix* (Text S5, Table S3).

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