

Bottom trawl fishing footprints on the world's continental shelves

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Bottom trawlers land around 19 million tons 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 1,000-m depth over at least 2 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-km² study area was trawled, and 86% was 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 an 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 was ≤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

There has been sustained debate about the extent of bottom trawling impacts on marine environments (1, 2). Both the scale

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Data deposition: The data reported in this paper have been deposited in a database at the University of Washington (<https://trawlingpractices.wordpress.com/datasets/>). All data are available as an S4 R object to allow interrogation of data and replication of analysis.

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Significance

We conducted a systematic, high-resolution analysis of bottom trawl fishing footprints for 24 regions on continental shelves and slopes of five continents and New Zealand. The proportion of seabed trawled varied >200-fold among regions (from 0.4 to 80.7% of area to a depth of 1,000 m). Within 18 regions, more than two-thirds of seabed area remained untrawled during study periods of 2–6 years. Relationships between metrics of total trawling activity and footprint were strong and positive, providing a method to estimate trawling footprints for regions where high-resolution data are not available. Trawling footprints were generally smaller in regions where fisheries met targets for exploitation rates, implying collateral environmental benefits of effective fisheries management.

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 that 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 characterize fisheries, and to estimate the extent of untrawled areas outside marine protected areas (MPAs) and fisheries closures (4–9).

Distributions of trawling activity were traditionally reported at a spatial scale of several hundred square kilometers 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 (VMSs) as a surveillance and enforcement tool revolutionized 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 behavior and dynamics (19, 20) and trawling impacts on species, habitats, and ecosystem processes at regional scales (21–28), and they have 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 MPAs (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 that are 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 aggrega-

tion 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 km² (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). Furthermore, 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 1 or 2 h), 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 tradeoffs given that bottom trawl fishing makes a substantial contribution to human food supply. Data from the Food and Agriculture Organization of the United Nations (FAO) (47–49) suggest that landings of fish, crustaceans, and mollusks from towed bottom gears from 2011 to 2013 were 18.9–19.8 million t y⁻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 analyze VMS and logbook data to provide standardized high-resolution estimates of bottom trawling footprints on continental shelves and slopes to a depth of 1,000 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 (50). 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 known trawling activity over 2–6 y (usually 3 y, 2008–2010) in each of 24 regions (Fig. 1, Table 1, and *SI Appendix, Figs. S3–S26 and Text S2*). 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 and Text S2*). Trawling activity data were collated and processed for regions spanning 7.8 million km² of seabed to depths of 1,000 m. Regions were excluded from the analyses where trawling activity data provided <70% coverage of

Table 1. Summaries of trawling footprint and fisheries data by region for depths of 0–1,000 m

Region	Region code	Coverage of total bottom trawling effort (%)	Method to assess coverage	Years included	Area 0–1,000 m (10 ³ km ²)	Area 0–200 m (10 ³ km ²)	Regional SAR (km ² y ^{−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 y ^{−1})	Landings per unit area of footprint (t km ^{−2} y ^{−1})
Adriatic Sea (GFCM 2.1)	1	72	Landings	2010–2012	39	37	7.926	82.7	79.1	80.7	59.3	28	0.89
West of Iberia (ICES 9a)	2	81	Effort	2010–2012	40	23	4.321	83.9	58.7	64.3	37.2	14	0.54
Skagerrak and Kattegat (ICES 3a)	3	100	Effort	2010–2012	55	41	3.328	75.0	50.0	54.4	33.0	31	1.04
Tyrrhenian Sea (GFCM 1.3)	4	82	Landings	2010–2012	138	53	2.286	68.4	43.8	49.9	30.2	10	0.15
Irish Sea (ICES 7a)	5	83	Effort	2010–2012	48	48	1.459	82.5	25.4	28.5	14.8	71	5.17
North Sea (ICES 4a–4c)	6	86	Effort	2010–2012	586	523	1.191	89.3	42.2	51.7	39.8	745	2.46
North Benguela Current	7	95	Effort	2008–2010	203	92	0.967	37.0	24.6	27.8	19.4	150	2.66
Western Baltic Sea (ICES 23–25)	8	72	Effort	2010–2012	87	87	0.960	61.1	30.8	36.1	26.5	26	0.83
Aegean Sea (GFCM 3.1)	9	75	Landings	2010–2012	175	64	0.798	52.4	26.7	31.9	23.9	5	0.09
West of Scotland (ICES 6a)	10	81	Effort	2010–2012	161	114	0.453	68.4	19.1	23.0	18.5	75	2.03
South Benguela Current	11	97	Effort	2008–2013	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	2008–2013	140	96	0.247	38.2	9.4	11.1	8.6	8	0.52
Southeast Australian Shelf	14	100	Effort	2009–2012	268	230	0.134	31.9	7.0	8.6	7.3	12	0.53
Northeast Australian Shelf	15	100	Effort	2009–2012	557	337	0.112	19.8	4.7	5.7	4.6	10	0.31
New Zealand	16	90	Effort	2008–2012	1,053	260	0.106	31.3	6.9	8.6	7.5	10	0.11
East Bering Sea	17	97	Effort	2008–2010	634	575	0.089	34.5	6.5	7.9	7.0	1,146	22.88
North California Current	18	100	Landings	2010–2012	119	55	0.077	29.5	5.5	6.9	6.1	305	37.28
Southwest Australian Shelf	19	100	Effort	2009–2012	338	283	0.034	10.5	2.1	2.7	2.3	5	0.57
Aleutian Islands	20	97	Effort	2008–2010	84	35	0.033	12.9	1.8	2.1	1.8	123	70.09
North Australian Shelf	21	100	Effort	2009–2012	794	792	0.026	14.8	1.9	2.2	2.0	150	8.48
Gulf of Alaska	22	85	Effort	2008–2010	398	294	0.024	8.2	1.4	1.7	1.4	138	20.85
Northwest Australian Shelf	23	100	Effort	2009–2012	686	474	0.023	6.5	1.3	1.6	1.4	5	0.47
South Chile	24	85	Effort	2009–2013	189	149	0.004	7.4	0.4	0.4	0.4	5	5.90

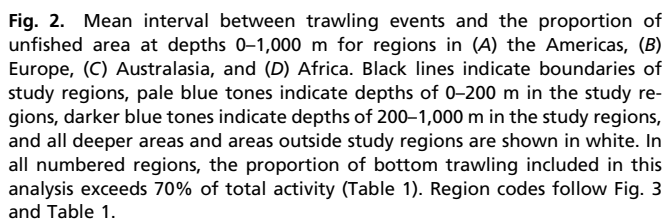
Information in parentheses after region names indicates when regions largely follow existing fishery management areas (excluding areas deeper than 1,000 m). Region codes are used to identify regions in the figures. Regional SAR is the mean annual total area swept by trawls divided by the area of the region to 1,000-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 area of the region 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 SAR 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. GFCM, General Fisheries Commission for the Mediterranean; ICES, International Council for the Exploration of the Sea.

cells. This metric is the inverse of the cell-specific SAR. More than one-half of 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 y, such 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- to 200- and 200- to 1,000-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 charac-

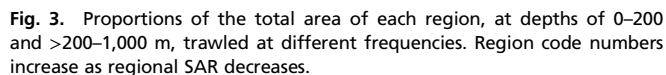
teristics, may be used to predict trawled and untrawled areas of seabed at regional scales. For example, for mean regional SAR = 1 y^{-1} , the prediction probability intervals for footprint [where the mean estimate of footprint by region = $\text{SAR}/(b + \text{SAR})$, with $b = 2.072$; SE = 0.154] indicate >0.95 probability that at least 23% of the region remains untrawled and 0.90 probability that 33–54% is trawled (Fig. 4). For $\text{SAR} \leq 0.1 \text{ y}^{-1}$, as in 8 of our 23 regions, there was a >0.95 probability that at least 90% of the seabed was untrawled. For SAR of 7.93 y^{-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 cutoffs 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 allows us to approximate the increase in trawling footprint that would result if we had



Bottom trawling may impact a range of seabed types within a given footprint. For regions where $\geq 70\%$ 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

International calls for MPAs coverage of 10% of ocean area (56) to 30% or more (57) often focus on the protection of seabed from bottom trawling. Our results show that $\geq 30\%$ of the seabed was not trawled during the study period in all regions except the Adriatic Sea. In 20 of 24 regions, $\geq 50\%$ 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 MPAs (56, 57), showing opportunities in many regions to site MPAs in areas that have not been affected by and would not displace trawling activity. Furthermore, 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. However, as described in relation to the habitat analysis, this conclusion may not hold when



between regional SAR and footprint, providing a method to estimate trawling footprints for regions where high-resolution data from logbooks, AISs, and satellite VMSs 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 (47) (*SI Appendix, Text S1*). Species or species groups not caught with mobile bottom gears were excluded as were species with mean landings of $<1,000 \text{ t yr}^{-1}$, which account for a negligible proportion of the total ($<1\%$ but cannot be quantified precisely due to nonrecording). 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 the FAO (48, 49, 58). The calculation excludes fish that 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 $1 \times 1 \text{ km}$ (1 km^2) or $1 \times 1 \text{ min}$ of longitude and latitude (1.9 km^2 at 56° north or 56° south) 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 that 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 and Text S2*). The methods were adopted by regional specialists to provide their most reliable estimates of grid cell SAR and thus, footprint within the region. Details of analytical approaches for each region are described in *SI Appendix, Figs. S3–S34, Table S1, and Text S2*. 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, Figs. 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 timescales. 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 1,000 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. After these boundaries were defined, we split the designated area based on 0- to 200-m and 200- to 1,000-m depths. We could not use existing classifications, like large marine ecosystems (LMEs), 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 additional 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 1 of 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; 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 1,000 stocks of marine and anadromous fishes. Stocks were included in the analyses when (i) both trawl footprint data and a fishing mortality reference point were available for the years 2008–2010; (ii) the spatial distribution of the stock matched at least one of the regions with high coverage ($>70\%$) of trawling activity; and (iii) 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 *SI Appendix, Table S3 and Text S5*.

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