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-km^2 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 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 (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 km^2 of seabed to depths of 1,000 m. Regions were excluded from the analyses where trawling activity data provided <70% coverage of

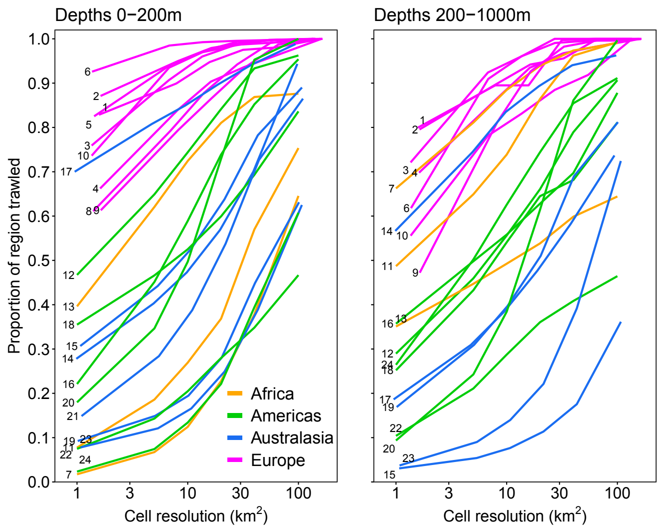

Fig. 1. Relationships between the spatial resolution of effort data and the trawling footprint (approach A, grid cell based; in the text) for depth ranges of 0–200 and >200–1,000 m. Region codes follow Fig. 3 and Table 1. Three regions are not represented in *Right* (depths of 200–1,000 m), because these regions are predominantly <200-m deep.

total trawling activity (*SI Appendix*; excluded regions are listed in *SI Appendix*, Figs. S27–S34, Table S2, and *Text S3*).

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 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 1 y), although 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 that 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 that 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 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, the Americas, and Australasia, respectively, at depths of 0–200 m and 41, 33, 56, and 55%, respectively, at depths of 200–1,000 m. Thus, at coarse resolutions of analysis, such as the 0.5° grid cells (area approximately 3,100 km^2 at the equator) that have sometimes been used to show trawling distributions, trawling footprints will be markedly overestimated, and the extent of untrawled areas will be underestimated.

Although reductions in the scale of grid cell-based analyses to around 1 km^2 will characterize 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 timescales (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 approach C, while the multiyear footprint is better approximated by approach C than by approach 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 1 y) 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 of 0–1,000 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 and *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 1,000 m, based on the assumption of uniform spread within grid cells (approach C), was ≤10% of seabed area in 11 of 24 regions (Fig. 2 and Table 1). A larger fraction, from 10 to 30% of the shelf and upper slope area to 1,000-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 >30–81% of the shelf area trawled. The untrawled area was >50% in 20 of 24 regions. Some of the largest regions that 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 two to four by area) were 17.6, 2.2, and 1.6, respectively (Table 1 and *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 60% of the area of the regions and comprised 52–100% of the total trawling footprint area within regions (mean 78%) (Table 1 and *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 multiyear timescales, which are relevant when considering impact and recovery dynamics of most seabed biota (50).

The frequency of trawling is another relevant metric when assessing trawling impacts on the status of seabed biota (50). We expressed the frequency of trawling disturbance as the average interval between trawling events for each of the trawled grid

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 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 characteristics, 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 = SAR/(b + 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 SAR $\leq$ 0.1 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

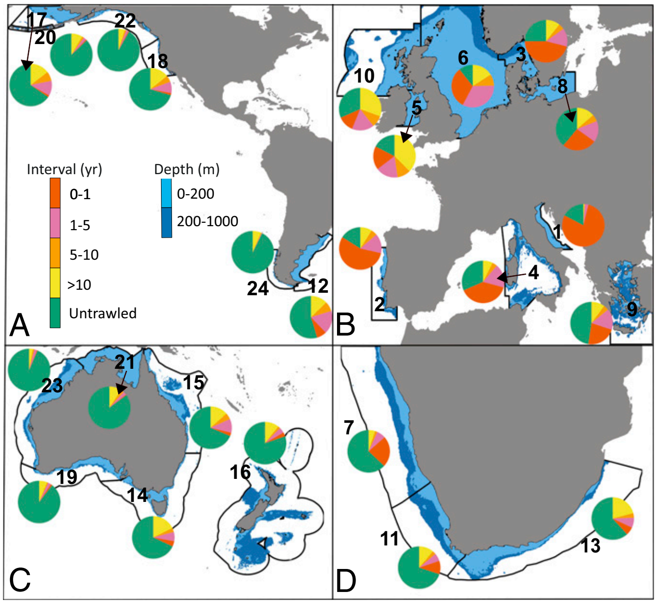

Fig. 2. Mean interval between trawling events and the proportion of unfished area at depths 0–1,000 m for regions in (*A*) the Americas, (*B*) Europe, (*C*) Australasia, and (*D*) Africa. Black lines indicate boundaries of study regions, pale blue tones indicate depths of 0–200 m in the study regions, darker blue tones indicate depths of 200–1,000 m 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 Fig. 3 and Table 1.

been able to include 100% of known trawling activity in our analyses. If we assume that the relationship between SAR and trawling footprint applies in all of the cases where coverage is <100%, then the combined trawling footprint across all regions would increase by 71,000 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 subregional 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 US 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 1,000 m is ∼4.6×10^5 km^2, and the swept area in the years 2007–2009 was 2.8×10^5 km^2 y^{-1}. This leads to a mean SAR of 0.64 y^{-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%, and else "muddySand" (53). Sediment data could be obtained for 90% of cells in all regions, except for New Zealand (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 toward 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 (42). While this result may be more nuanced with a more highly resolved classification of habitat types (23), a consistent and highly resolved ecologically based habitat classification is not available for all regions.

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 ≥30% of the seabed was not trawled during the study period in all regions except the Adriatic Sea. In 20 of 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 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

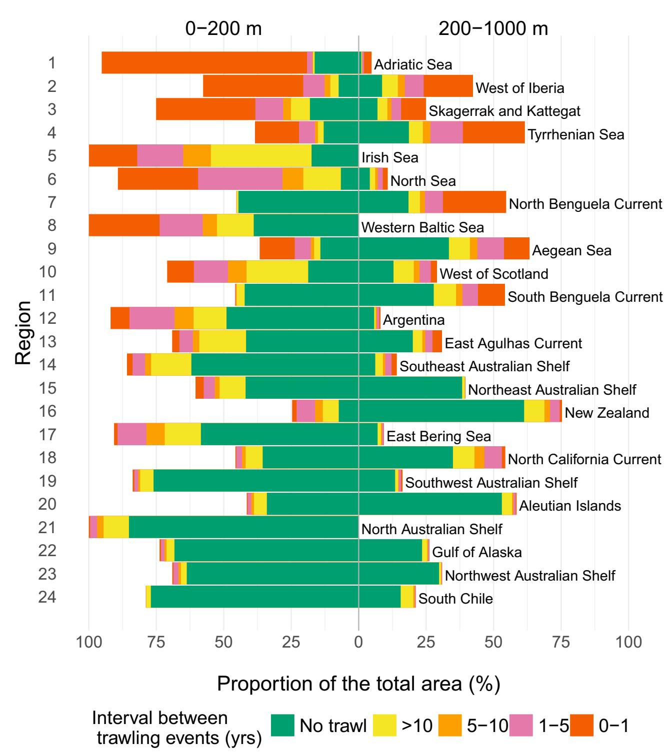

Fig. 3. Proportions of the total area of each region, at depths of 0–200 and >200–1,000 m, trawled at different frequencies. Region code numbers increase as regional SAR decreases.

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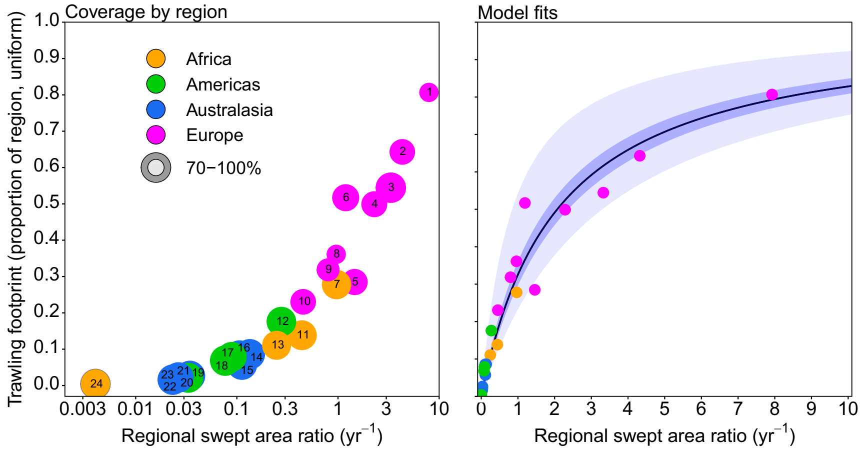

Fig. 4. Relationship between the regional SAR and the trawling footprint (approach C, assumes uniform spread in grid cells; in the text). (*Left*) Symbol sizes indicate the proportion of total fishing activity recorded in each region (all >70%), and numbers in symbols identify the regions listed in Fig. 3 and Table 1. (*Right*) The 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.

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 and *SI Appendix*, Table S3 and *Text S5*). 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; *SI Appendix*, Fig. S39 has 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*, Figs. S40 and 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*, Figs. S42 and 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 1,000 m, globally approximates 42.5 million km^2; thus, the data that 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 tons y^{-1}; assuming mean global landings of 19.35 million tons y^{-1}) (Table 1 and *SI Appendix*, *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, the east coast of the United States and Canada, Brazil shelf, and Southeast Asia).

To conclude, there are large differences in trawling footprints among study regions. However, for almost all of the shelves and slopes that we studied, total footprints to depths of 200 and 1,000 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 one-half of the regions. There were strong positive relationships

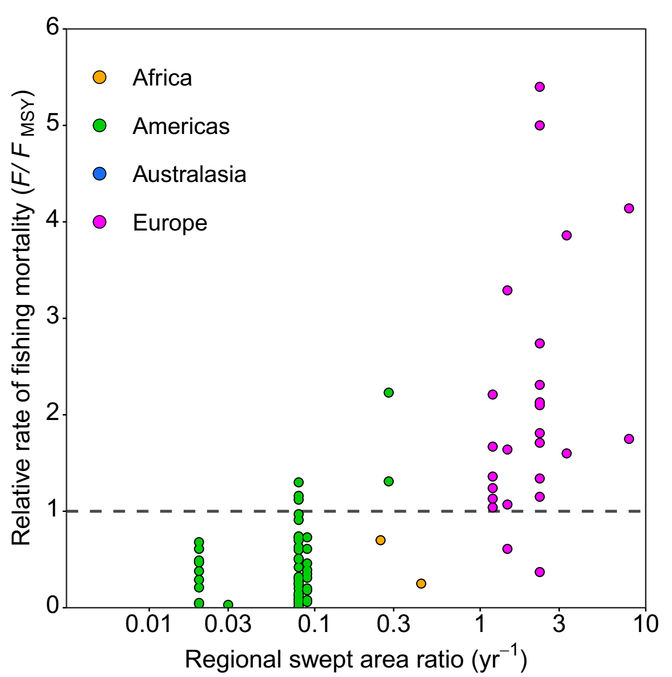

Fig. 5. Relationships between the relative rate of fishing mortality and the regional SAR by region. Circles denote the ratio of fishing mortality (F; mean 2010–2012) to the F_{MSY} reference point for individual bottom dwelling stocks. The black horizontal dashed line indicates F/F_{MSY} = 1, usually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

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 t y^{-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 × 1 km (1 km^2) or 1 × 1 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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1. Watling W, Norse EA (1998) Disturbance of the seabed by mobile fishing gear: A comparison to forest clear cutting. *Conserv Biol* 12:1180–1197.
2. NRC (2002) *Effects of Trawling and Dredging on Seafloor Habitat* (National Academy Press, Washington, DC).
3. Kaiser MJ, et al. (2016) Prioritization of knowledge-needs to achieve best practices for bottom trawling in relation to seabed habitats. *Fish Fish* 17:637–663.
4. Piet GJ, Hintzen NT (2012) Indicators of fishing pressure and seabed integrity. *ICES J Mar Sci* 69:1850–1858.
5. Gerritsen HD, Minto C, Lordan C (2013) How much of the seabed is impacted by mobile fishing gear? Absolute estimates from Vessel Monitoring System (VMS) point data. *ICES J Mar Sci* 70:523–531.
6. Kaiser MJ, Collie JS, Hall SJ, Jennings S, Poiner IR (2002) Modification of marine habitats by trawling activities: Prognosis and solutions. *Fish Fish* 3:114–136.
7. Fock H (2008) Fisheries in the context of marine spatial planning: Defining principal areas for fisheries in the German EEZ. *Mar Policy* 32:728–739.
8. Churchill JH (1989) The effect of commercial trawling on sediment resuspension and transport over the Middle Atlantic Bight continental shelf. *Cont Shelf Res* 9:841–864.
9. Bastardie F, et al. (2017) Spatial planning for fisheries in the Northern Adriatic: Working toward viable and sustainable fishing. *Ecosphere* 8:e01696.
10. Edser T (1925) A short account of the statistics of the sea fisheries of England and Wales. *Rapp P-V Reun Cons Int Explor Mer* 36:2–25.
11. Jennings S, et al. (1999) Fishing effects in northeast Atlantic shelf seas: Patterns in fishing effort, diversity and community structure. III. International trawling effort in the North Sea: An analysis of spatial and temporal trends. *Fish Res* 40:125–134.
12. Rijnsdorp AD, Buys AM, Storbeck F, Visser EG (1998) Micro-scale distribution of beam trawl effort in the southern North Sea between 1993 and 1996 in relation to the trawling frequency of the sea bed and the impact on benthic organisms. *ICES J Mar Sci* 55:403–419.
13. Dinmore TA, et al. (2003) Impact of a large-scale area closure on patterns of fishing disturbance and the consequences for benthic communities. *ICES J Mar Sci* 60:371–380.
14. Murawski SA, Wigley SE, Fogarty MJ, Rago PJ, Mountain DG (2005) Effort distribution and catch patterns adjacent to temperate MPAs. *ICES J Mar Sci* 62:1150–1167.
15. Deng R, et al. (2005) Can vessel monitoring system data also be used to study trawling intensity and population depletion? The example of Australia's northern prawn fishery. *Can J Fish Aquat Sci* 62:611–622.

16. Russo T, D'Andrea L, Parisi A, Cataudella S (2014) VMSbase: An R-package for VMS and logbook data management and analysis in fisheries ecology. *PLoS One* 9: e100195.
17. Hintzen NT, et al. (2012) VMStools: Open-source software for the processing, analysis and visualisation of fisheries logbook and VMS data. *Fish Res* 115–116:31–43.
18. Lee J, South AB, Jennings S (2010) Developing reliable, repeatable, and accessible methods to provide high-resolution estimates of fishing-effort distributions from vessel monitoring system (VMS) data. *ICES J Mar Sci* 67:1260–1271.
19. Watson JT, Haynie AC (2016) Using Vessel Monitoring System data to identify and characterize trips made by fishing vessels in the United States North Pacific. *PLoS One* 11:e0165173.
20. Vermard Y, Rivot E, Mahevas S, Marchal P, Gascuel D (2010) Identifying fishing trip behaviour and estimating fishing effort from VMS data using Bayesian hidden Markov models. *Ecol Modell* 221:1757–1769.
21. Baird SJ, Hewitt J, Wood BA (2015) Benthic habitat classes and trawl fishing disturbance in New Zealand waters shallower than 250 m (Ministry for Primary Industries, Wellington, New Zealand), New Zealand Aquatic Environment and Biodiversity Report 144, p 184.
22. Baird SJ, Wood BA, Bagley NW (2011) Nature and extent of commercial fishing effort on or near the seafloor within the New Zealand 200 n. mile Exclusive Economic Zone, 1989–90 to 2004–05 (Ministry for Primary Industries, Wellington, New Zealand), New Zealand Aquatic Environment and Biodiversity Report 73, p 144.
23. Eigaard OR, et al. (2016) The footprint of bottom trawling in European waters: Distribution, intensity and seabed integrity. *ICES J Mar Sci* 74:847–865.
24. Pitcher CR, et al. (2016) Effects of trawling on sessile megabenthos in the Great Barrier Reef, and evaluation of the efficacy of management strategies. *ICES J Mar Sci* 73(Suppl 1):i115–i126.
25. Lambert GI, Jennings S, Kaiser MJ, Davies TW, Hiddink JG (2014) Quantifying recovery rates and resilience of seabed habitats impacted by bottom fishing. *J Appl Ecol* 51: 1326–1336.
26. Diesing M, Stephens D, Aldridge J (2013) A proposed method for assessing the extent of the seabed significantly affected by demersal fishing in the Greater North Sea. *ICES J Mar Sci* 70:1085–1096.
27. Pitcher CR, Poiner IR, Hill BJ, Burridge CY (2000) Implications of the effects of trawling on sessile megazoobenthos on a tropical shelf in northeastern Australia. *ICES J Mar Sci* 57:1359–1368.
28. Hiddink JG, Jennings S, Kaiser MJ (2007) Assessing and predicting the relative ecological impacts of disturbance onto habitats with different sensitivities. *J Appl Ecol* 44: 405–413.
29. EC (2008) Commission Decision of 6 November 2008 adopting a multiannual Community programme pursuant to Council Regulation (EC) No 199/2008 establishing a Community framework for the collection, management and use of data in the fisheries sector and support for scientific advice regarding the common fisheries policy (2008/949/EC). *Official J European Union* 346:37–88.
30. Campbell MS, Stehfest KM, Votier SC, Hall-Spencer JM (2014) Mapping fisheries for marine spatial planning: Gear-specific vessel monitoring system (VMS), marine conservation and offshore renewable energy. *Mar Policy* 45:293–300.
31. Stelzenmuller V, Rogers SI, Mills CM (2008) Spatio-temporal patterns of fishing pressure on UK marine landscapes, and their implications for spatial planning and management. *ICES J Mar Sci* 65:1081–1091.
32. Maina I, et al. (2016) A methodological approach to identify fishing grounds: A case study on Greek trawlers. *Fish Res* 183:326–339.
33. Jennings S, Lee J (2012) Defining fishing grounds with vessel monitoring system data. *ICES J Mar Sci* 69:51–63.
34. Wang Y, Wang Y, Zheng J (2015) Analyses of trawling track and fishing activity based on the data of Vessel Monitoring System (VMS): A case study of the single otter trawl vessels in the Zhoushan fishing ground. *J Ocean Univ China* 14:89–96.
35. Good N, Peel D, Tanimoto M, Officer R, Gribble N (2007) Innovative stock assessment and effort mapping using VMS and electronic logbooks (Department of Primary Industries and Fisheries, Brisbane, Australia), Final Report on FRDC Project 2002/056, p 182.
36. Kaiser MJ, et al. (2006) Global analysis of response and recovery of benthic biota to fishing. *Mar Ecol Prog Ser* 311:1–14.
37. Jennings S, Freeman S, Parker R, Duplisea DE, Dinmore TA (2005) Ecosystem consequences of bottom fishing disturbance. *Am Fish Soc Symp* 41:73–90.
38. Piet GJ, Quirijns FJ (2009) The importance of scale for fishing impact estimations. *Can J Fish Aquat Sci* 66:829–835.
39. Ellis N, Pantus F, Pitcher R (2014) Scaling up experimental trawl impact results to fishery management scales - a modelling approach for a "hot time." *Can J Fish Aquat Sci* 71:733–746.
40. Skaar KL, Jørgensen T, Ulvestad BKH, Engås A (2011) Accuracy of VMS data from Norwegian demersal stern trawlers for estimating trawled areas in the Barents Sea. *ICES J Mar Sci* 68:1615–1620.
41. Shepperson JL, et al. (2018) A comparison of VMS and AIS data: The effect of data coverage and vessel position recording frequency on estimates of fishing footprints. *ICES J Mar Sci* 75:988–998.
42. Eigaard OR, et al. (2016) Estimating seabed pressure from demersal trawls, seines, and dredges based on gear design and dimensions. *ICES J Mar Sci* 73:i27–i43.
43. Gerritsen H, Lordan C (2011) Integrating vessel monitoring systems (VMS) data with daily catch data from logbooks to explore the spatial distribution of catch and effort at high resolution. *ICES J Mar Sci* 68:245–252.
44. Peel D, Good N (2011) A hidden Markov model approach for determining vessel activity from vessel monitoring system data. *Can J Fish Aquat Sci* 68:1252–1264.
45. Hintzen NT, Piet GJ, Thomas B (2010) Improved estimation of trawling tracks using cubic Hermite spline interpolation of position registration data. *Fish Res* 101:108–115.
46. Lambert GI, et al. (2012) Implications of using alternative methods of vessel monitoring system (VMS) data analysis to describe fishing activities and impacts. *ICES J Mar Sci* 69:682–693.
47. FAO (2016) *Fishery and Aquaculture Statistics (FishStatJ)* (FAO Fisheries and Aquaculture Department, Rome).
48. FAO (2014) Regional guidelines for the management of tropical trawl fisheries in Asia. *Proceedings of the APFIC/FAO Regional Expert Workshop on Phuket, Thailand* (FAO Regional Office for Asia and the Pacific, Bangkok, Thailand), RAP Publication 2014/01, p 91.
49. FAO (2015) *Low Value and Trash Fish in the Asia-Pacific Region. Collected Papers of the APFIC Regional Workshop* (FAO Regional Office for Asia and the Pacific, Bangkok, Thailand), p 267.
50. Hiddink JG, et al. (2017) Global analysis of depletion and recovery of seabed biota after bottom trawling disturbance. *Proc Natl Acad Sci USA* 114:8301–8306.
51. Jenkins CJ (1997) Building offshore soils databases. *Sea Technol* 38:25–28.
52. Pitcher CR, et al. (2016) Implications of current spatial management measures for AFMA ERAs for habitats (CSIRO Oceans & Atmosphere, Brisbane, Australia), FRDC Project No. 2014/204 Report, p 50.
53. Pitcher CR, et al. (2017) Estimating the sustainability of towed fishing-gear impacts on seabed habitats: A simple quantitative risk assessment method applicable to data-limited fisheries. *Methods Ecol Evol* 8:472–480.
54. Collie JS, Hall SJ, Kaiser MJ, Poiner IR (2000) A quantitative analysis of fishing impacts on shelf-sea benthos. *J Anim Ecol* 69:785–798.
55. Rijnsdorp AD, et al. (2016) Towards a framework for the quantitative assessment of trawling impact on the seabed and benthic ecosystem. *ICES J Mar Sci* 73:i127–i138.
56. Leenhardt P, Cazalet B, Salvat B, Claudet J, Feral F (2013) The rise of large-scale marine protected areas: Conservation or geopolitics. *Ocean Coast Manage* 85: 112–118.
57. O'Leary BC, et al. (2016) Effective coverage targets for ocean protection. *Conserv Lett* 9:398–404.
58. Morgan GR, Staples DJ (2006) *The History of Industrial Marine Fisheries in Southeast Asia* (FAO Regional Office for Asia and the Pacific, Bangkok, Thailand), RAP Publication 2006/12, p 28.
59. Kelleher K (2005) Discards in the world's marine fisheries: An update. *FAO Fish Tech Pap* 470:1–131.
60. Ricard D, et al. (2012) Examining the knowledge base and status of commercially exploited marine species with the RAM Legacy Stock Assessment Database. *Fish Fish* 13:380–398.