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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 guarter 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 km² 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 \leq 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

Reserved for Publication Footnotes

137 There has been sustained debate about the extent of bot-138 tom trawling impacts on marine environments (1, 2). Both the 139 scale and ecological consequences of trawl impacts have been 140 highlighted, with suggestions that bottom trawls are "annually covering an area equivalent to perhaps half of the world's con-142 tinental shelf" (1). In contrast, fishing industry representatives 143 often claim the scale of their impact is more limited, highlighting 144 their targeted use of well-defined fishing grounds rather than 145 widespread "ploughing" of the seabed (3). Robust quantification 146 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 149 and to estimate the extent of untrawled areas outside Marine 150 Protected Areas (MPA), and fisheries closures (4-9). 151

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Distributions of trawling activity were traditionally reported at a spatial scale of several hundred km² 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-(4, 29) 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 km² (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



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.

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 tradeoffs 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 highresolution 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	Cover- age of total bottom trawling effort (%)	Method to assess cover- age	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 as- sumption)	% area of region trawled (approach B, random assump- tion)	% area of region trawled (approach C, uniform assump- tion)	% area of region ac- counting for 90% of trawling activity	Land- ings (10 ³ t yr ⁻¹)	Land- ings per unit are of foot- print (t km ⁻² yr ⁻¹)
Adriatic Sea (GFCM	1	⁷²	Landings	2010-12	39	37	7.926	82.7	^{79.1}	80.7	59.3	28	0.89
2.1) West of Iberia	2	81	Effort	2010-12	40	23	4.321	83.9	58.7	64.3	37.2	14	0.54
Skagerrak and Kattegat	3	100	Effort	2010-12	55	41	3.328	75.0	50.0	54.4	33.0	31	1.04
(ICES 3a) Tyrrhenian Sea (GFCM	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	6	86	Effort	2010-12	586	523	1.191	89.3	42.2	51.7	39.8	745	2.46
North Benguela	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 Zeoptline A	16 uthor	90	Effort	2008-12	1053	260	0.106	31.3	6.9 PNAS	8.6 Issue Date	7.5 9 Volume	10 Issue Nu	0.11 umber
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

Continued from previous page													
Region	Region code	Cover- age of total bottom trawling effort (%)	Method to assess cover- age	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 as- sumption)	% area of region trawled (approach B, random assump- tion)	% area of region trawled (approach C, uniform assump- tion)	% area of region ac- counting for 90% of trawling activity	Land- ings (10 ³ t yr ⁻¹)	Land- ings pe unit ar of foot print (1 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.

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

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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.

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.

With approach A, footprint estimates depend very strongly on grid resolution. As grid-cell area is increased from to 1-3 km² (the scale at which trawling is usually distributed randomly within cells (12)) to $\geq 10^4$ km², 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 km² 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.

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Even though reductions in the scale of grid cell-based analyses to around 1 km² 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 km² 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.

trawled. 677 When using the 1 km² cell-based approach (approach A) to 678 estimate the trawling footprints in the study period, 33.6% of the 679 total area for which we collated \geq 70% of bottom trawling activity 680

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(7.8 million km² 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 km²) 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.

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The overall footprint of trawling to a depth of 1000 m, based on the assumption of uniform spread within grid cells (approach C), was $\leq 10\%$ 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 $= 1 \text{ yr}^{-1}$, 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 749 750 54% is trawled (Fig. 4). For SAR $\leq 0.1 \text{ yr}^{-1}$, as in eight of our 23 751 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. 755

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 km², or 0.9% of the 7.8 million km² 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 $\times 10^5$ km² and the swept-area in the years 2007-2009 was 2.8×10^5 km² 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).

789 Bottom trawling may impact a range of seabed types within 790 a given footprint. For regions where $\geq 70\%$ of trawling activity 791 was recorded we quantified the intersection of trawling with 792 four broad seabed types. We defined seabed types based on 793 sediment composition obtained from the dbSEABED database 794 of marine substrates (51). A simple sediment classification rather 795 than a more highly resolved habitat classification was adopted to 796 enable equitable treatment of habitat across all regions and for 797 consistency with habitat types reported in most trawling impact 798 studies (36,52-55). Grid cells were classified to sediment types by 799 denoting: "gravel" if gravel>30%, else "sand" if mud<20%, else 800 "mud" if sand < 20%, else "muddySand" (53). Sediment data could 801 be obtained for 90% of cells in all regions, except for New Zealand 802 EEZ (86%), Aleutian Islands (72%), Gulf of Alaska (68%) and 803 Argentina (52%). 804

Within all regions, the bottom trawling footprint on each 805 sediment type was correlated with total area by sediment type (SI 806 Appendix, Fig. S38). This result implies that bottom trawling ac-807 tivity is not consistently directed towards certain sediment types. 808 This is expected since we compiled activity by multiple fleets 809 rather than individual types of bottom trawl fishery (e.g. stratified 810 by gears, fleets) and because fishers are targeting different fish 811 species with different trawl gears on many types of seabed (e.g. 812 42). While this result may be more nuanced with a more highly 813 resolved classification of habitat types (e.g. 23), a consistent and 814 highly resolved ecologically-based habitat classification is not 815 available for all regions. 816

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817 International calls for MPA coverage of 10% of ocean area 818 (56) to 30% or more (57), often focus on the protection of seabed 819 from bottom trawling. Our results demonstrate that \geq 30% of the 820 seabed was not trawled during the study period in all regions 821 except the Adriatic Sea. In 20 of the 24 regions ≥50% of the seabed was not trawled during the study period. This proportion 822 823 of untrawled seabed is already much greater than the proportion 824 proposed for protection within MPA (56, 57), demonstrating 825 opportunities in many regions to site MPAs in areas that have 826 not been affected by, and would not displace, trawling activity. 827 Further, since trawling footprints were distributed more or less 828 evenly in relation to broad sediment types, the large proportions 829 of untrawled area in a region may imply a relatively representa-830 tive range of seabed types currently remain untrawled. But, as described in relation to the habitat analysis, this conclusion may 831 832 not hold when habitat types are more highly resolved or when active management intervention affects the distribution of fishing 833 834 activity.

835 Finally, we assessed relationships between regional SAR and 836 metrics of the intensity of fisheries exploitation. There was a 837 significant, but noisy, positive relationship between regional SAR 838 and relative rates of fishing mortality F (expressed as the ratio 839 between recorded F and the reference point F_{MSY} , Fig. 5, SI 840 Appendix Text S5, Table S3). Broadly, when regional SAR was 841 ≤0.25, as in 12 of our 24 study regions, fishing rates on all stocks 842 for which we had data were close to or below F_{MSY} . Conversely, 843 when regional SAR was >0.25, F was greater than F_{MSY} for 85% 844 of the stocks. A regional SAR of 0.25 corresponds to a trawling 845 footprint spanning of around 10% of the area of a region, based 846 on the uniform assumption and the relationship between SAR 847 and footprint (approach C, Fig. 4 and see SI Appendix, Fig. S39 for 848 the direct relationship trawling footprint and relative F). When 849 regional SAR exceeded three, as recorded in two Mediterranean 850 regions and one Baltic region, all stocks for which we had data 851 were fished at or above F_{MSY} (Fig. 5). When we conducted a 852 more constrained analysis, which only included those stocks with 853 distributions spanning at least 50% or 70% of the region to which 854 they were assigned, the breakpoint remained close to SAR=0.25 855 in both cases (SI Appendix, Fig. S40, S41). The relationships 856 between trawling footprints (approach C) and relative F (SI 857 Appendix, Fig. S39) also held when we only included those stocks 858 with distributions spanning at least 50% or 70% of the region to 859 which they were assigned (SI Appendix, Fig. S42, S43). Thus, in 860 regions where fishing rates consistently met international sustain-861 ability benchmarks for fish stocks, trawling footprints based on 862 approach C were typically ≤11% of region area. These patterns 863 imply that fisheries management systems that effectively meet 864 reference points for exploitation rates on bottom dwelling stocks 865 will achieve collateral environmental benefits because SAR and 866 thus trawling footprint will be lower. 867

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 km², 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 885 SAR and footprint, providing a new method to estimate trawling 886 footprints for regions where high-resolution data from logbooks, 887 automatic identification systems and satellite vessel monitoring 888 systems are not available. Regional SAR and trawling footprints 889 were generally smaller in regions when fisheries were meeting 890 reference points for sustainable exploitation rates on bottom 891 892 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 km²) or 1×1 minute of longitude and latitude (1.9km² 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 sweptarea (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.

934 The selection of regional boundaries will influence the results of the footprint analysis. Thus boundaries were selected and fixed before we 935 started the analyses, primarily based on the shelf and slope area to 1000 936 m and adjacent to nations for which we expected data to be available, but 937 also guided by biogeographic and oceanographic features, and in some cases 938 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 939 not use existing classifications like Large Marine Ecosystems (LME) because, 940 in many cases, use of LMEs would lead to mixed jurisdictions and fisheries 941 from multiple countries in one region, and would have reduced the overall 942 coverage of trawling activity. The proportional coverage of trawling activity by region was estimated from the proportion of catch or fishing effort 943 recorded by the trawlers for which we obtained data as a proportion of total 944 catch or effort by all trawlers in the region (Table 1).

945 In some regions, such as Europe, small inshore vessels may use towed 946 bottom gears but may not be subject to the same monitoring or reporting 947 requirements as larger vessels. Even in regions where we have high coverage of reported catch or effort, some inshore bottom trawling activity may not 948 be included. We therefore caution that the results for these regions may not 949 be informative for the immediate inshore zone (typically to 3 miles offshore) 950 and further data collection and analyses would be needed to address this 951 data gap 952

Fishing mortality

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953 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 954 used to describe the sustainability of fishing rates in each region. For each 955 one of the 23 areas with high coverage of trawling activity (>70%), data on 956 the intensity of the fishing pressure for stocks targeted by bottom contact fishing gears were obtained from the RAM Legacy database (60, Version 957 4.30; http://ramlegacy.org). RAM Legacy is currently the most comprehen-958 sive repository of stock assessment data containing time series of biomass, 959 catches, fishing mortality, recruitment and management reference points 960 for more than 1000 stocks of marine and anadromous fishes. Stocks were 961 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 962 spatial distribution of the stock matched at least one of the regions with high 963 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 966 (Text S5, Table S3). 967

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- 1. Watling W, Norse EA (1998) Disturbance of the seabed by mobile fishing gear: a comparison to forest clear cutting. Cons Biol 12: 1180-1197.
- 2. NRC (2002) Effects of trawling and dredging on seafloor habitat. National Academy Press, Washington DC.
- Kaiser MJ et al. (2016) Prioritization of knowledge-needs to achieve best practices for bottom 3. 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.
- Gerritsen HD, Minto C, Lordan C (2013) How much of the seabed is impacted by mobile 5. fishing gear? absolute estimates from Vessel Monitoring System (VMS) point data. ICES J Mar Sci 70: 523-531.
- Kaiser MJ, Collie JS, Hall SJ, Jennings S, Poiner IR (2002) Modification of marine habitats 6. by trawling activities: prognosis and solutions. Fish Fisheries 3: 114-136
- 7. Fock H (2008) Fisheries in the context of marine spatial planning: defining principal areas for fisheries in the German EEZ. Marine 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(2):e01696
- Edser T (1925) A short account of the statistics of the sea fisheries of England and Wales 10. Rapp P-v Réun 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, Dichmont C, Milton D, Haywood M, Vance D, Hall N, Die D (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.
- Russo T, D'Andrea L, Parisi A, Cataudella S (2014) VMSbase: An R-package for VMS and 16. logbook data management and analysis in fisheries ecology. PLoS ONE 9(6): 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.
- Watson JT, Havnie AC (2016) Using Vessel Monitoring System data to identify and character-19. ize trips made by fishing vessels in the United States North Pacific. PLoS ONE 11: e0165173.
- 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 Model 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. New Zealand Aquatic Environment and Biodiversity Report 144, 184 pp.
- 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. New Zealand Aquatic Environment and Biodiversity Report 73: 144 pp.
- Eigaard OR et al. (2016) The footprint of bottom trawling in European waters: distribution, 23. 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: 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. JAppl 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
 - 8 | www.pnas.org --- ---

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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.
- 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. Marine Policy 45: 293-300.
- 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.
- Maina I, Kavadas S, Katsanevakis S, Somarakis S, Tserpes G, Georgakarakos S (2016). A 32. methodological approach to identify fishing grounds: A case study on Greek trawlers. Fish Res 183: 326-339.
- Jennings S, Lee J (2012) Defining fishing grounds with vessel monitoring system data. ICES J Mar Sci 69: 51-63
- 1054 34 Wang Y, Wang Y, Zheng J (2015) Analyses of trawling track and fishing activity based on the 1055 data of Vessel Monitoring System (VMS): a case study of the single otter trawl vessels in the 1056 Zhoushan fishing ground. J Ocean Uni China 14: 89-96.
- Good N, Peel D, Tanimoto M, Officer R, Gribble N (2007) Innovative stock assessment and effort mapping using VMS and electronic logbooks. Final report on FRDC project 2002/056. Brisbane, Australia: Department of Primary Industries and Fisheries. 182 pp.
- Kaiser MJ et al. (2006) Global analysis of response and recovery of benthic biota to fishing. 36. Mar Ecol Prog Ser 311: 1-14.
- Jennings S, Freeman S, Parker R, Duplisea DE, Dinmore TA (2005) Ecosystem consequences 37 of bottom fishing disturbance. Am Fish Soc Symp 41: 73-90.
- Piet GJ, Quirijns FJ (2009) The importance of scale for fishing impact estimations. Can J Fish Aquat Sci 66: 829-835.
- 30 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 1066 Norwegian demersal stern trawlers for estimating trawled areas in the Barents Sea. ICES 1067 J Mar Sci 68: 1615–162.
- Shepperson JL, Hintzen NT, Szostek CL, Bell E, Murray LG, Kaiser MJ (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.
- 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.
- Peel D, Good N (2011) A hidden Markov model approach for determining vessel activity 44 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.
- 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.
- Hiddink JG et al. (2017) Global analysis of depletion and recovery of seabed biota following 47. bottom trawling disturbance. Proc Natl Acad Sci USA 114: 8301-8306
- 48 FAO (2016) Fishery and Aquaculture Statistics (FishStatJ). FAO Fisheries and Aquaculture Department [online or CD-ROM]. Rome.
- FAO (2014) Regional guidelines for the management of tropical trawl fisheries in Asia. APFIC/FAO Regional Expert Workshop on Phuket, Thailand, 30 September-4 October 2013. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand, RAP Publication 2014/01, 91 pp
- FAO (2015) Low value and trash fish in the Asia-Pacific region. Collected papers of the APFIC 50 Regional workshop. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand, 267

Footline Author

- 51. Jenkins CJ (1997) Building Offshore Soils Databases. Sea Technology 38: 25-28.
- protected areas: conservation or geopolitics. Ocean Coastal Mgmt 85: 112-118.
- 57. O'Leary BC, Winther-Janson M, Bainbridge JM, Aitken J, Hawkins JP, Roberts CM (2016) Effective coverage targets for ocean protection. Cons Letters 9: 398-404. 58.
- 52. Pitcher CR et al. (2016) Implications of current spatial management measures for AFMA ERAs for habitats. FRDC Project No 2014/204. CSIRO Oceans & Atmosphere, Brisbane, 50pp 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
- 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, Kelleher K (2005) Discards in the world's marine fisheries: an update. FAO Fish Tech Paper Ricard D et al. (2012) Examining the knowledge base and status of commercially exploited marine species with the RAM Legacy Stock Assessment Database. Fish Fisheries 13: 380-398.

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59.

60.