Bottom trawl fishing footprints on the world’s continental shelves

Ricardo O. Amoroso,a,1 C. Roland Pitcher,b,1 Adriaan D. Rijnsoever,c,1 Robert A. McConnaughey,d,1 Ana M. Parma,e,1 Petri Suuronen,f,1 Ole R. Eigaard,f,1 Francois Bastardie,g,1 Niels T. Hintzen,h,1 Franziska Althaus,i,1 Susan Jane Baird,j Jenny Black,k Lene Buhl-Mortensen,l,1 Alexander B. Campbell,m,1 Rui Catarino,o,1 Jeremy Collie,f,1 James H. Cowan Jr.n,1 Deon Durholtz,o,1 Nadia Engstrom,p,1 Tracey P. Fairweather,p,1 Heino O. Fock,p,1 Richard Ford,p,1 Patricio A. Gálvez,p,1 Hans Gerritsen,q,1 Maria Eva Gonzorama,q,1 Jessica A. González-v,1 Steven S. Intelmann,r,1 Jayson M. Semmens,s,1 Cristina Silvann,t,1 Angelo Tsolosoo,t,1 Bart Vanelserlandu,1 Corey B. Wakefield,v,1 Brent A. Woodl,1 Ray Hilborn,w,1 Michel J. Kaisery,x,1 and Simon Jenningsy,z

aSchool of Aquatic and Fishery Sciences, University of Washington, Seattle, WA 98195; bCommonwealth, Scientific and Industrial Research Organisation (CSIRO) Oceans and Atmosphere, Brisbane, QLD 4001, Australia; cWageningen Marine Research, Wageningen UR, 1970 AB Uimuiden, The Netherlands; dAlaska Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Seattle, WA 98115; eCentro Nacional Patagónico, Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Puerto Madryn, 9120 Argentina; fFood and Agriculture Organization of the United Nations, 00153 Rome, Italy; gLuonnonvarakeskus/Natural Resources Institute Finland, 00790 Helsinki, Finland; hNational Institute of Aquatic Resources, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark; iCSIRO Oceans and Atmosphere, Hobart, TAS 7001, Australia; jNational Institute of Water and Atmospheric Research, Wellington, 8011, New Zealand; kGNS Science, 3040 Lower Hutt, New Zealand; lInstitute of Marine Research, 5817 Bergen, Norway; mSchool of Mathematics and Physics, University of Queensland, Brisbane, QLD 4072, Australia; nMarine Laboratory, Marine Scotland Science, Aberdeen, AB11 9DB, Scotland; oInternational Council for the Exploration of the Sea, 1553 Copenhagen V, Denmark; pGraduate School of Oceanography, University of Rhode Island, Narragansett, RI 02882; qCollege of the Coast and Environment, Louisiana State University, Baton Rouge, LA 70803; rFisheries Management, Offshore Resources, Department of Agriculture, Forestry and Fisheries of the Republic of South Africa, 8000 Cape Town, South Africa; sQueensland Department of Agriculture and Fisheries, Brisbane, QLD 4001, Australia; tHünen Institute, 22767 Hamburg-Altona, Germany; uMinistry for Primary Industries, 6140 Wellington, New Zealand; vInstituto de Fomento Pesquero, Blanco 839, Valparaíso, Región de Valparaíso, Chile; wMarine Institute, H91 R673 Oranmore, Ireland; xInstitute of Investigation of Hydrobiology, Universidad Nacional de la Patagonia San Juan Bosco, 9100 Trelew, Chubut, Argentina; ySchool of Ocean Sciences, Bangor University, LL59 SAB Anglesey, United Kingdom; zInstitute of Arctic and Alpine Research, University of Colorado at Boulder, Boulder, CO 80309-0450; AADepartment of Aquatic Resources, Swedish University of Agricultural Sciences, Department of Biology, University of Rome Tor Vergata, 00133 Rome, Italy; BBConsiglio Nazionale delle Ricerche, Istituto di Scienze Marine, 16012 Ancona, Italy; CCDepartment of Marine and Antarctic Studies, University of Tasmania, Hobart, TAS 7001, Australia; DDInstituto Português do Mar e da Atmosfera, Department of Oceanography, University of Lisbon, 1800-037 Lisbon, Portugal; EEInstituto de Investigación de Hidrobiología, Universidad Nacional de la Patagonia San Juan Bosco, 9100 Trelew, Chubut, Argentina; FFCommonwealth, Scientific and Industrial Research Organisation (CSIRO) Marine and Atmospheric Research, 4300-02281; GGMarine Institute, H91 R673 Oranmore, Ireland; HHInstituto de Investigación de Hidrobiología, Universidad Nacional de la Patagonia San Juan Bosco, 9100 Trelew, Chubut, Argentina; IIInstitute for Marine and Antarctic Studies, University of Tasmania, Hobart, TAS 7001, Australia; JJInstituto Português do Mar e da Atmosfera, Departamento de Mar e Recursos Marinhos, 1495-165 Lisboa, Portugal; KKGraduate School of Oceanography, University of Rhode Island, Narragansett, RI 02882; LLInstitute of Marine Biological Resources and Inland Waters, Hellenic Centre for Marine Research, 19013 Anavyssos, Attiki, Greece; MMNational Oceanic and Atmospheric Administration’s National Marine Fisheries Service, Juneau, AK 99802; NNAgri-Food and Biosciences Institute, BT9 5PX Belfast, Northern Ireland, United Kingdom; OOCommercial Fisheries and Aquaculture, New South Wales Department of Primary Industries, Coffs Harbour, NSW 2450, Australia; PPNorthern Territory Department of Primary Industry and Fisheries, Darwin, NT 0801, Northern Territory, Australia; QRInstitute of Marine Biological Resources and Inland Waters, Hellenic Centre for Marine Research, 71003 Heraklion, Crete, Greece; RSCentre for Environment, Fisheries and Aquaculture Science, NR33 0HT Lowestoft, United Kingdom; STLaboratory of Experimental Ecology and Aquaculture, Department of Biology, University of Rome Tor Vergata, 00133 Rome, Italy; UTConsiglio Nazionale delle Ricerche, Istituto di Scienze Marine, 16012 Ancona, Italy; VVInstitute of Marine and Antarctic Studies, University of Tasmania, Hobart, TAS 7001, Australia; WWInstituto Português do Mar e da Atmosfera, Departamento do Mar e Recursos Marinhos, 1495-165 Lisboa, Portugal; XXAnimal Sciences Unit—Fisheries and Aquatic Production, Institute for Agricultural and Fisheries Research, 8400 Oostende, Belgium; YYMarine Stewardship Council, EC1A 2DH London, United Kingdom; and ZZSchool of Environmental Sciences, University of East Anglia, NR4 7TJ Norwich, United Kingdom

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, and slopes to 1,000-m depth over at least 2 years. Trawling footprint was 95% probability that >95% probability that >95% probability that >70% of seabed was not trawled. If SAR was ≤0.1, in as 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 small and SAR was ≤0.25 in regions where fishing maps consistently met international sustainability benchmarks for fish stocks, implying coastal environmental benefits from sustainable fishing.
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 untouched 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 (12), but random trawling activity tends to be uniformly spread at the same scale when data are accumulated over multiple years (39).

An increasing number of regional analyses describe trawling footprints based on VMS or high-resolution tow-by-tow observer and logbook data (5, 9, 23, 40). VMS data provide advantages over automatic identification system (AIS) data for measuring the totality of these footprints, because VMS is usually required for whole fleets and the use of VMS as a formal enforcement tool means that attempts to stop transmissions are usually spotted and rectified (41). Furthermore, vessel identification codes recorded with VMS position data can be linked directly to vessel identification codes used for recording information on gear types and dimensions as well as catch or landings data (17, 42, 43). The main limitation of VMS data in relation to AIS is the relatively low transmission rate (typically one position record every 1 or 2 h), thus requiring the development of methods to identify fishing activity and to interpolate tracks (44–46).

Systematic comparisons of the footprints of bottom trawl fisheries in those regions where the majority of all fishing vessels are monitored using VMS or reporting tow-by-tow observer data would provide an evidence base to resolve uncertainties about the scale and intensity of bottom trawling and to underpin assessments of the impacts of trawling on seabed habitats. Such evidence is also necessary to effectively assess and manage the environmental impacts of fishing methods and to address tradeoffs given that bottom trawl fishing makes a substantial contribution to human food supply. Data from the Food and Agriculture Organization of the United Nations (FAO) (47–49) suggest that landings of fish, crustaceans, and mollusks from towed bottom gears from 2011 to 2013 were 18.9–19.8 million t y⁻¹, equating to 23.3–24.4% of mean annual marine wild-capture landings in the same years (SI Appendix, Text S1).

Here, we collate and analyze VMS and logbook data to provide standardized high-resolution estimates of bottom trawling footprints on continental shelves and slopes to a depth of 1,000 m in selected regions of Africa, the Americas, Australasia, and Europe. In these analyses, bottom trawling refers to all towed gears making sustained contact with the seabed, including beam and otter trawls and dredges (50). We assess whether the aggregation of bottom trawling activity is a consistent feature of trawl fisheries in different regions and describe how footprints are related to fisheries landings, effort, and the status of fish stocks. We quantify a relationship between trawling footprints and less complex measures of total trawling activity. This relationship can be used to estimate footprints for those areas of the world where high-resolution data are not available and to predict how fishing footprints may evolve in newly exploited areas given any proposed or projected level of trawling effort (e.g., the Arctic).

Trawling Footprints

To estimate bottom trawling footprints, we obtained high-resolution vessel position data accounting for 70–100% of all known trawling activity over 2–6 y (usually 3 y, 2008–2010) in each of 24 regions (Fig. 1, Table 1, and SI Appendix, Figs. S3–S26 and Text S2). Footprints were defined as the area of seabed trawled at least once in a specified region and time period, with area trawled determined from gear dimensions and tow locations (SI Appendix, Table S1 and Text S2). Trawling activity data were collated and processed for regions spanning 7.8 million km² of seabed to depths of 1,000 m. Regions were excluded from the analyses where trawling activity data provided <70% coverage of
and 55%, respectively, at depths of 200 m. Medians across the region. The approaches differ in how they estimate the area trawled within each grid cell. Approach A 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 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 km² [the scale at which trawling is usually distributed randomly within cells (12)] to \( \geq 10^2 \) km², the estimated area of trawling footprints increased substantially (Fig. 1). Median increases in footprints within regions (mean 78%) (Table 1 and Fig. S37). 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), ranged from 10% to 30% 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 \( >30\text{–}81\% \) 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
Among regions, there was a strong relationship between regional SAR and trawling footprint that would result if we had included in the main analyses when catch 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 ≤ 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

<table>
<thead>
<tr>
<th>Region</th>
<th>Method to assess coverage</th>
<th>Years included</th>
<th>Area 0–1,000 m² (10⁶ km²)</th>
<th>Area 0–200 m (10⁶ km²)</th>
<th>Regional SAR (km² km⁻² y⁻¹)</th>
<th>% Area of region trawled (approach A, cell assumption)</th>
<th>% Area of region trawled (approach B, uniform assumption)</th>
<th>% Area of region trawled (approach C, uniform assumption)</th>
<th>% Area of region accounting for 90% of fishing activity</th>
<th>Landings per unit area of footprint (10⁴ t km⁻² y⁻¹)</th>
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<tbody>
<tr>
<td>Adriatic Sea (GFCM 2.1)</td>
<td>1 Effort</td>
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<td>39</td>
<td>37</td>
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<td>0.4</td>
<td>5</td>
</tr>
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</table>
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 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 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 x 10⁶ km², and the swept area in the years 2007–2009 was 2.8 x 10⁶ 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).

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 “muddy Sand” (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. S3B). 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...
landings by bottom trawlers (3.78 million tons y\(^{-1}\)) accounted for a similar proportion (19.5\%) of estimated global fisheries activity recorded in each region (all >70\%), and numbers in symbols identify the regions listed in Fig. 3 and Table 1. Our group made significant efforts internationally to obtain high-resolution trawling activity data for regions where these 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 \(F_{\text{MSTY}}\)) (Fig. 5 and SI Appendix, Table S3 and Text S5). Broadly, when regional SAR was \(\leq 0.25\), as in 12 of our 24 study regions, fishing rates on all stocks for which we had data were close to or below \(F_{\text{MSTY}}\). Conversely, when regional SAR was \(>0.25\), \(F\) was greater than \(F_{\text{MSTY}}\) 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 \(F_{\text{MSTY}}\) (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 \(\leq 11\%\) 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 19.55 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. 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.](https://www.pnas.org/cgi/doi/10.1073/pnas.1802379115)
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%) and 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 spreading of 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 min of longitude and latitude (1.9 km² 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 swat sweep 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 fishing 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 general, the 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 existing management boundaries. 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 (Fref) for 87 stocks caught with towed bottom gears were used to describe the sustainability of fishing rates in each region. For each of the 23 areas with high coverage of trawling activity (>70%), data on the intensity of the fishing pressure for stocks targeted by bottom contact fishing gears were obtained from the RAM Legacy database (60) (Version 4.30; 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 marine fish stocks. The F/Fref ratio was calculated for each region and 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.

ACKNOWLEDGMENTS. Funding for meetings of the study group and salary support for R.O.A. were provided by the following: David and Lucille Packard Foundation; the Walton Family Foundation; the Alaska Seafood Cooperative; American Seafoods Group US; Blumar Seafoods Denmark; Clearwater Seafoods Inc.; Esperian Group; Glacier Fish Company LLC US; Gortons Seafood; Independent Fisheries Limited N.Z.; Nippon Suisan (USA), Inc.; Pesca Chile S.A.; Pacific Andes International Holdings, Ltd.; San Arawa, S.A.; Sanford Ltd. N.Z.; Seafarers Group Ltd. N.Z.; Scotiabank Group;温和 Fukuda Suisan (TS), Ltd.; the Australian Government; the Food and Agriculture Organisation of the United Nations. Additional funding to individual authors was provided by European Union Project BENTHIS EU-FFP 312088 (to A.D.R., O.R.E., F.B., N.T.H., L.B.-M., R.C., H.O.F., H.G., J.M.H., P.J., S.K., M.L., E.G., M.A.N., P.E.P., T.R., A.S., B.V., and M.J.K.); the Instituto Português do Mar e da Atmosfera, Portugal (C.S.); the International Council for the Exploration of the Sea Science Fund (R.O.A. and K.M.H.); the Commonwealth Scientific and Industrial Research Organisation (C.R.P. and T.M.); the National Oceanic and Atmospheric Administration (R.A.M.); New Zealand Ministry for Primary Industries Projects BEN2012/01 and DAE2010/04D (to S.J.B. and R.F.); the Institute for Marine and Antarctic Studies, University of Tasmania, Australia (L.M.S.); and UK Department of Environment, Food and Rural Affairs Project MF1225 (to S.J.).

13. Dormer E, 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.


45. FAO (2016) Fishery and Aquaculture Statistics (FishStat) (FAO Fisheries and Aquaculture Department, Rome).


48. FAO (2017) Open access to seafood and fishery data: A global perspective. FAO Fisheries and Aquaculture Statistics (FishStat) (FAO Fisheries and Aquaculture Department, Rome).

49. FAO (2015) Towards a framework for the quantitative assessment of low value and trash fish in the Asia-Pacific region. FAO Fisheries and Aquaculture Statistics (FishStat) (FAO Fisheries and Aquaculture Department, Rome).

50. FAO (2014) Defining and monitoring seafood traceability. FAO Fisheries and Aquaculture Statistics (FishStat) (FAO Fisheries and Aquaculture Department, Rome).


