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Defining fishing grounds with vessel monitoring system data

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Methods for defining fishing grounds to support marine spatial planning and management are developed, applied, and compared. The methods are broadly applicable and repeatable because they use vessel monitoring system (VMS) data that are archived and increasingly accessible. For several fleets at regional and national scales, an attempt is made to assess how the choice of criteria for defining grounds influences (i) size, shape, and location, (ii) overlap among grounds, and (iii) the extent to which annual and multi-annual patterns of fishing activity describe grounds used seasonally or by individual vessels. The results show that grounds defined by excluding infrequently fished margins (areas with <10% of total fishing activity) are typically 50% smaller than total fished area. However, landings weight or value (LWV) per unit activity can be higher at the margins, with 10% of activity usually accounting for 10–20% of LWV. The removal of fishing activity in the margins, as a consequence of regulation or fleet behaviour, would lead to disproportionately greater reductions in interactions with other fisheries, sectors, and the environment. Accessible high-resolution information on the "anatomy" of all fishing grounds would better inform debates on the allocation and the use of marine space and the integration of fisheries and environmental management.

Keywords: ecosystem approach, fishing effects, management, marine protected areas, marine spatial planning.

Introduction

Burgeoning coastal populations, demands on marine resources, and technological development are leading to more use of the sea, so managers are seeking to ensure ecological, environmental, and social sustainability and to minimize conflicts for space and resources within and among sectors. In conjunction with sectoral assessment and management, marine spatial planning is increasingly used to support sustainable use (e.g. Douvere, 2008; Ehler and Douvere, 2009; European Commission, 2010). Taking account of the role of fisheries is often central in planning because fishing is widespread on continental shelves, typically impacting an area that exceeds that used by other sectors (Eastwood *et al.*, 2007; Halpern *et al.*, 2008), and because management objectives for fisheries may not be consistent with those for conservation and other uses of the sea (Worm *et al.*, 2009).

Historically, the extent of fishing grounds was mapped at the coarse resolutions for which data were available (typically >100 km^2) or was based on reports from individual vessels or fleet sectors (e.g. Edser, 1925; Graham, 1933; Engelhard, 2005). Latterly, some local and regional studies provided a more detailed picture of activity, based on positions in logbooks, analysis of plotter data, analysis of overflight enforcement data, or direct tracking of subsets of vessels (e.g. Rijnsdorp *et al.*, 1998), but not for the range of fleets or on the spatial scales that would be needed to support most spatial planning. Further, because analyses were usually intended for fisheries-centric uses, they provided no guidance on the trade-offs involved in defining fishing grounds of lesser extent than the total fished area.

The introduction of vessel monitoring systems (VMS) greatly increased the availability of data on the distribution of fishing activity, providing vessel-specific high-resolution data from all fishing grounds used by larger vessels. Although VMS were introduced to support enforcement, processed VMS data are increasingly used to show the locations and dynamics of fishing activity, usually based on density distributions of position records or reconstructed tracks (Dinmore *et al.*, 2003; Murawski *et al.*, 2005; Eastwood *et al.*, 2007; Harrington *et al.*, 2007; Mills *et al.*, 2007; Stelzenmüller *et al.*, 2008; Hintzen *et al.*, 2010; Lee *et al.*, 2010, and references therein). Observed fishing locations reflect choices by fishers, based on factors that include past catch rates, steaming costs, agreements among fishers, avoidance of hazards, and the constraints imposed by costs and regulations (Gillis *et al.*, 1993; Babcock and Pikitch, 2000; Holland and Sutinen, 2000; Rijnsdorp *et al.*, 2000; Chakravorty and Nemato, 2001; Blythe *et al.*, 2002, 2004; Poos and Rijnsdorp, 2007; Branch and Hilborn, 2008).

Although the high-resolution, comprehensive coverage and vessel specificity provided by VMS will potentially support accurate and repeatable assessment of the location of fishing grounds, VMS data are currently reported in many ways. Aside from issues introduced by the choice of analytical scale, where the apparent area of fishing grounds will increase with selected cell size (because any given cell with a record of fishing will qualify as "fished"; Mills *et al.*, 2007; Piet and Quirijns, 2009), measures of the total extent of fishing activity depend on the period when extent is measured, changes in vessels or skippers, variability in fish distributions, and variability in other factors that influence location choice.

The inclusion of infrequently fished areas in fishing grounds may well be contested by other sectors that seek access to marine space, and alternate definitions of fishing grounds might focus on core areas fished more frequently, or yielding most catch or greatest value. Definitions that focus on core areas may result in fishing grounds that would be unacceptable to the fishing industry but acceptable to non-fishing sectors. For fishing grounds that are defined using criteria that reduce spatial extent below the total extent, debate on an acceptable definition would be informed by a systematic analysis of the consequences of adopting different criteria. For instance, the ratio between the boundary length and area of the ground (with consequences for interactions, monitoring, or enforcement), the extent to which grounds for different fleets overlap, and the extent to which activities of individual vessels or changes in the seasonal distribution of vessels are still supported.

Area closures have long been used as a tool to support fishery management objectives but, within the constraints they impose on fishing distributions, there usually remain options for vessels to select fishing grounds. These options are increasingly being reduced, though, as the development of networks of marine protected areas (MPAs) and sites for renewable energy generation compete with fishing for marine space. To support the debate on the use of marine space, it is necessary to develop systematic and widely applicable methods for defining fishing grounds. The need for these is pressing, given the increasing engagement of the fishing industry in spatial planning (Degnbol and Wilson, 2008; Fock, 2008; Pedersen *et al.*, 2009). Scientists alone cannot determine the right definition of a fishing ground, but they can develop alternate methods for defining grounds and assess the implications of using these methods. Such analyses will inform the debate with fishers, other sectors, and planners, contributing to the definition of fishing grounds in marine spatial plans and the treatment of fisheries in impact assessments for MPAs. Further, they will inform the development of methods for defining the track record of the fishing industry during a period of growing competition for space. Formalized definition and reporting of fishing grounds may also be desirable to ensure equitable treatment of different fleets and different management regions.

Here, we develop and compare methods for defining fishing grounds. The methods are needed to inform spatial planning and to document track records for different fisheries. An attempt is made to assess how the choice of criteria for defining grounds can influence their size, shape, and location, and the grounds used by individual vessels are compared with those used regionally and nationally by fleets to assess whether there are common characteristics of fishing grounds that apply at multiple scales. We expect the approaches will have broad application for describing fishing grounds, because they are based on the analysis of VMS data that are increasingly available for larger vessels. In the European Union, for example, all registered fishing vessels 15 m or more long have been monitored with VMS since 2005 (European Commission, 2003, 2009).

Methods

Information on the distribution and intensity of fishing activity was based on the analysis of VMS vessel identity, position, and speed data obtained from the Marine and Fisheries Agency (MFA, now the Marine Management Organization, MMO) of the UK Department of Environment, Food and Rural Affairs (Defra). All available VMS records for the period 2006–2009 were included. Unprocessed VMS data do not indicate whether vessels are in port, fishing, steaming, or at sea but not making way. Therefore, we differentiated records that were linked to fishing activity following the approach of Lee *et al.* (2010). In brief, duplicate VMS records and records close to ports were removed, the interval between remaining records was calculated, and a speed-based rule was applied to identify periods of fishing activity. Each period of fishing activity was assigned to a vessel and gear type by linking the VMS data to national logbook data using the vessel identifier and time.

Fleets were defined broadly as any group of vessels that shared defined characteristics and were selected to achieve a balance between the inclusion of a large proportion of UK fishing effort in the analysis and the need to define groups of vessels that could be treated as operational units and presented in one paper. Clearly, fleets can be defined at many other resolutions (European Commission, 2008a, b), and different resolutions will be appropriate for different forms of analysis, depending on the scientific or management questions posed. Our approach, where VMS data for individual vessels are linked to logbook data and logbook data are used to assign vessels to fleets, is flexible when analyses at different fleet resolution are required. In this analysis, we included beam trawlers, otter trawlers towing demersal otter trawls only, dredgers towing shellfish dredges, netters fishing fixed gillnets, trammelnets or tanglenets, potters fishing traps and pots, and seiners fishing Scottish seines, which together account for most of the bottom fishing activity of UK registered vessels. To contain the scope of the analysis, we studied the activities of individual vessels in a beam trawl fishery, but the approach can be extended easily to other vessels or smaller subsets of our fleets, as required.

Fishing and non-fishing records during the period of activity were differentiated based on reported vessel speed, and fishing records were assigned to a 3-min grid (cell area $\sim$21 km^2 at 47°N to 14 km^2 at 64°N) covering the areas fished. One advantage of a grid based on units of latitude and longitude as opposed to an equal area grid is that the grid cells map directly into the ICES rectangles used for the logbook-based reporting of effort and landings data. A preliminary analysis was conducted to evaluate how grids based on fixed intervals of latitude and longitude and on equal area would affect the delineated area of fishing grounds and the conclusions of the analyses. The results suggested a maximum difference in fishing ground area of $\pm$3%, with no effect on the conclusions herein. In practice, grid configurations can easily be modified if equivalence of area with latitude were deemed desirable (Lee *et al.*, 2010). For each grid cell, the time associated with the VMS fishing records was summed by vessel, fleet, or area to estimate fishing activity.

When describing patterns of fishing activity, we refer to all areas where VMS fishing positions were recorded, for any defined set of criteria (e.g. time, fleet, area), as fishing grounds. We refer to geographically isolated areas of fishing activity that contribute to the fishing ground as patches. The term fishing activity is used in preference to fishing effort because the methods used for processing VMS data describe the activities of vessels and not the characteristics and fishing performance of the gears deployed. The distinction between activity and effort is particularly important for vessels using static gears such as fixed nets and pots, because the VMS only tracks vessels, whereas the gear may be left unattended to fish for hours or days.

The analyses were conducted in three stages. First, the consequences of using different methods to define fishing grounds for individual vessels in one fishery (southwest UK beam trawl fishery) were assessed. Second, the analysis was repeated for the main fleets operating at a regional scale (southwest UK). Third, the analysis was repeated again for the main UK fleets in Northeast Atlantic continental shelf waters. The nested approach was used to assess the extent to which patterns prevalent at one scale applied to others.

The beam trawl fleet that fishes off the southwest coast of England is well defined by vessel type, gear, and target species. For that fleet, the spatial extent of fishing grounds used by individual vessels and the contribution made by these grounds to annual fishing effort and landings of the vessels was evaluated. Boundaries were defined encompassing given proportions (70, 80, 90, and 100%) of the total activity of each vessel, having ranked grid cells from high to low activity. Cumulative activity was calculated by summing activity by individual grid cell in rank order. The cumulative area was calculated by summing individual grid cell areas. Relationships between cumulative activity and cumulative area were also expressed as proportions, by dividing cumulative activity by total activity, and cumulative area by total area, respectively.

For fleets fishing off the southwest coast of England and Wales (defined as ICES Areas VIIe, f, g, and h), fishing grounds that encompassed 70, 80, 90, and 100% of total recorded beam trawl, dredge, net, otter trawl, and pot activity are described. To define boundaries for the areas encompassing 90, 80, and 70% of recorded activity, grid cells were ranked from high to low activity for any given combination of fishing year and gear. Cumulative activity and cumulative area were then calculated as above.

For beam trawlers, we assessed the extent to which fishing grounds defined with annual activity data for the entire fleet were consistent with the fishing grounds used by the fleet on a seasonal basis (monthly) and by individual vessels of the fleet. The extent to which a defined fishing ground encompassed the activities of the fleet on a month-by-month basis was evaluated by comparing fishing grounds used by the fleet in each month with those used from 2006 to 2009. The extent to which a defined fishing ground included the activities of individual vessels was assessed by comparing fishing grounds of individual vessels in 2009 with the fishing grounds defined for the fleet using VMS data for 2006–2009.

To quantify differences between the spatial patterns of fishing activity associated with different fleets (or for the same fleets in different periods), spatial overlap was calculated based on a modification of the approach of Lee *et al.* (2010). The activity for each fleet in each grid cell was rescaled to sum to 0.5. For any two fleets or periods to be compared, absolute differences in rescaled activity were calculated for every cell in the study area, summed, and subtracted from 1 to provide an index of spatial overlap that could vary from 1 (spatial distribution of activity for the two gears or years was identical for a given cell-size resolution) to 0 (spatial distribution of activity for the two gears or years was entirely different). We also assessed proportional overlap between fishing grounds when grounds were defined as encompassing 100, 90, 80, and 70% of recorded activity. For any pair of fleets, denoted a and b, respectively, proportional overlap of each was expressed as (i) the area of overlap between a and b divided by area a, or (ii) the area of overlap between a and b divided by area b.

For all UK vessels, fishing grounds were described that encompassed 70, 80, 90, and 100% of total recorded beam trawl, dredge, net, otter trawl, pot, and seine activity. Seine activity was included in the UK analysis but not in the regional analysis, because the gear is not used off the southwest coast of England and Wales but is used frequently elsewhere. To define boundaries for the areas encompassing 90, 80, and 70% of recorded activity, grid cells were ranked from high to low activity for any given combination of fishing year and fleet.

When required, the weight and value of landings from each grid cell were estimated by re-allocating landings weight and landings value data from the scale of collection and reporting (ICES rectangles) to the scale of the grid cell, in direct proportion to estimated fishing activity. Landings weight and landings value data were obtained from the UK MFA. This approach for allocating landings assumes that activity and landings are directly related at the scale of subrectangle. This assumption of constant catch per unit effort or value per unit effort (vpue) is an approximation, but deviations from the approximation cannot be assessed because landings and value data are not available at finer scales for the range of fleets and areas we considered.

To place the activity of the bottom-fishing fleets considered in a wider context, landings weight and value for these fleets were compared with landings weight and value for all UK vessels and for all UK vessels >15 m monitored with VMS.

Results

From 2006 to 2009, most fishing activity by individual beam trawlers fishing off the southwest coast of England and Wales was confined to a relatively small proportion of the total area fished by that vessel (Figure 1, top panels). For all vessels, 70% of fishing activity took place in <45% of the area fished, and for all but two vessels, 90% of fishing activity took place in <75% of the area fished. Hence, the grounds fished by individual vessels had extensive but infrequently fished margins.

Relationships between the cumulative area fished by fleets off southwest England and Wales and the cumulative activity in those areas revealed that most of the fishing activity recorded by VMS took place in a relatively small proportion of the total fished area in the period 2006–2009 (Figure 1, centre panels). For all gears, 70% of fishing activity took place in <25% of the area fished and 90% of fishing activity took place in <50% of the area fished. Hence, fishing grounds that encompass all areas where fishing activity of the fleets was recorded had extensive margins where activity was low. This is reflected in the marked decrease in the area of fishing grounds when 10, 20, or 30% of activity in the most lightly fished areas is excluded (Figure 2). If defined fishing grounds were limited to areas encompassing 90% of fleet activity, i.e. by excluding the most lightly fished areas that account for 10% of total activity, this reduced the spatial extent of the fishing grounds by 61% for beam trawlers (to 29 085 km^2), 67% for dredgers (to 11 928 km^2), 53% for netters (to 32 549 km^2), 63% for otter trawlers (to 13 392 km^2), and

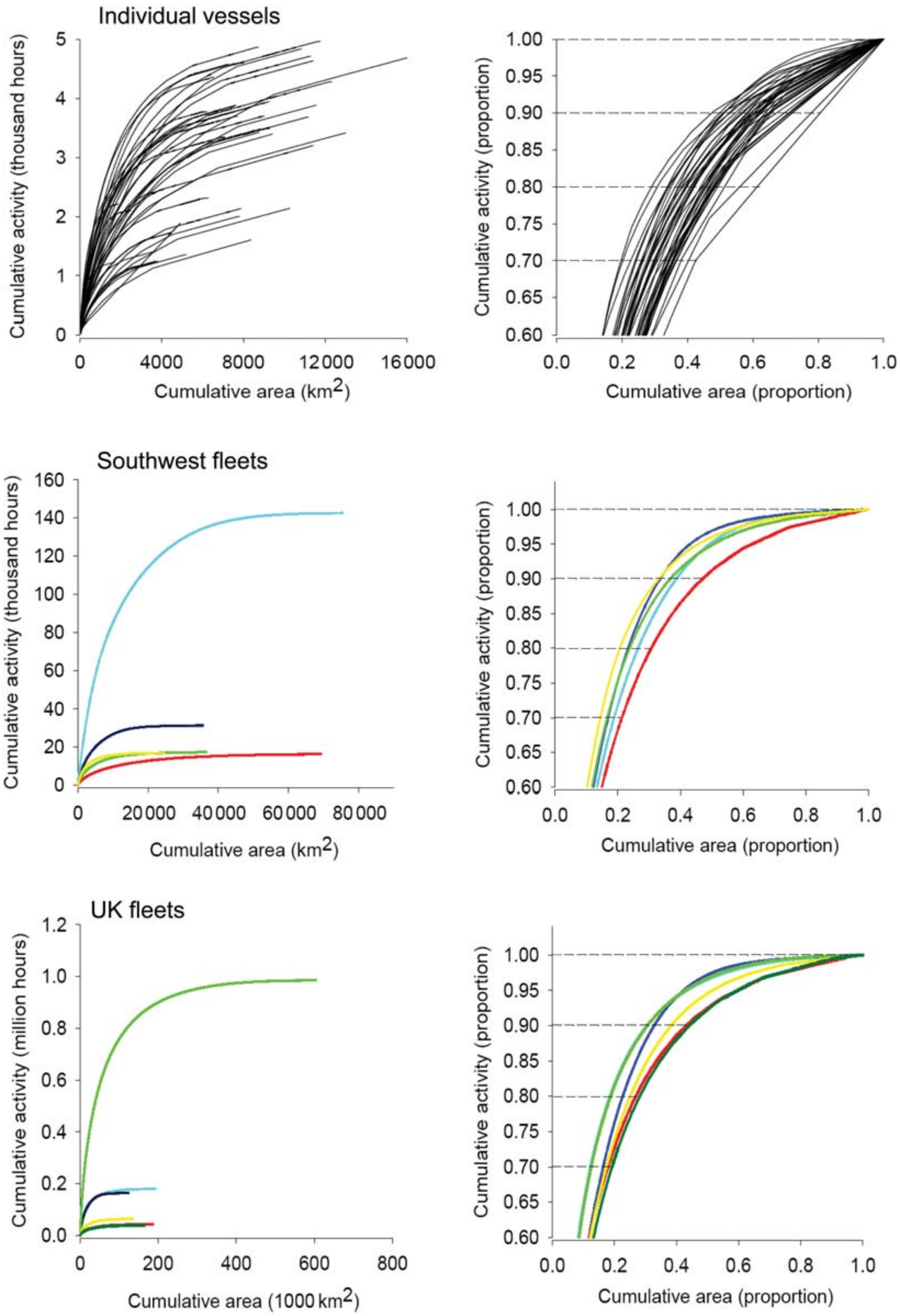

Figure 1. The relationship between the cumulative area fished and cumulative fishing activity for individual beam trawlers fishing off the southwest coast of England and Wales (top left panel), for fleets fishing off the southwest coast of England and Wales (centre left panel), and for fleets fishing around the UK (bottom left panel). Corresponding panels to the right show the relationships between the cumulative area fished as a proportion of the total area and the cumulative activity as a proportion of the total. Data for the years 2006 – 2009 combined. Black, individual beam trawlers; cyan, beam trawlers; blue, dredgers; red, netters; green, otter trawlers; yellow, potters; grey, seiners.

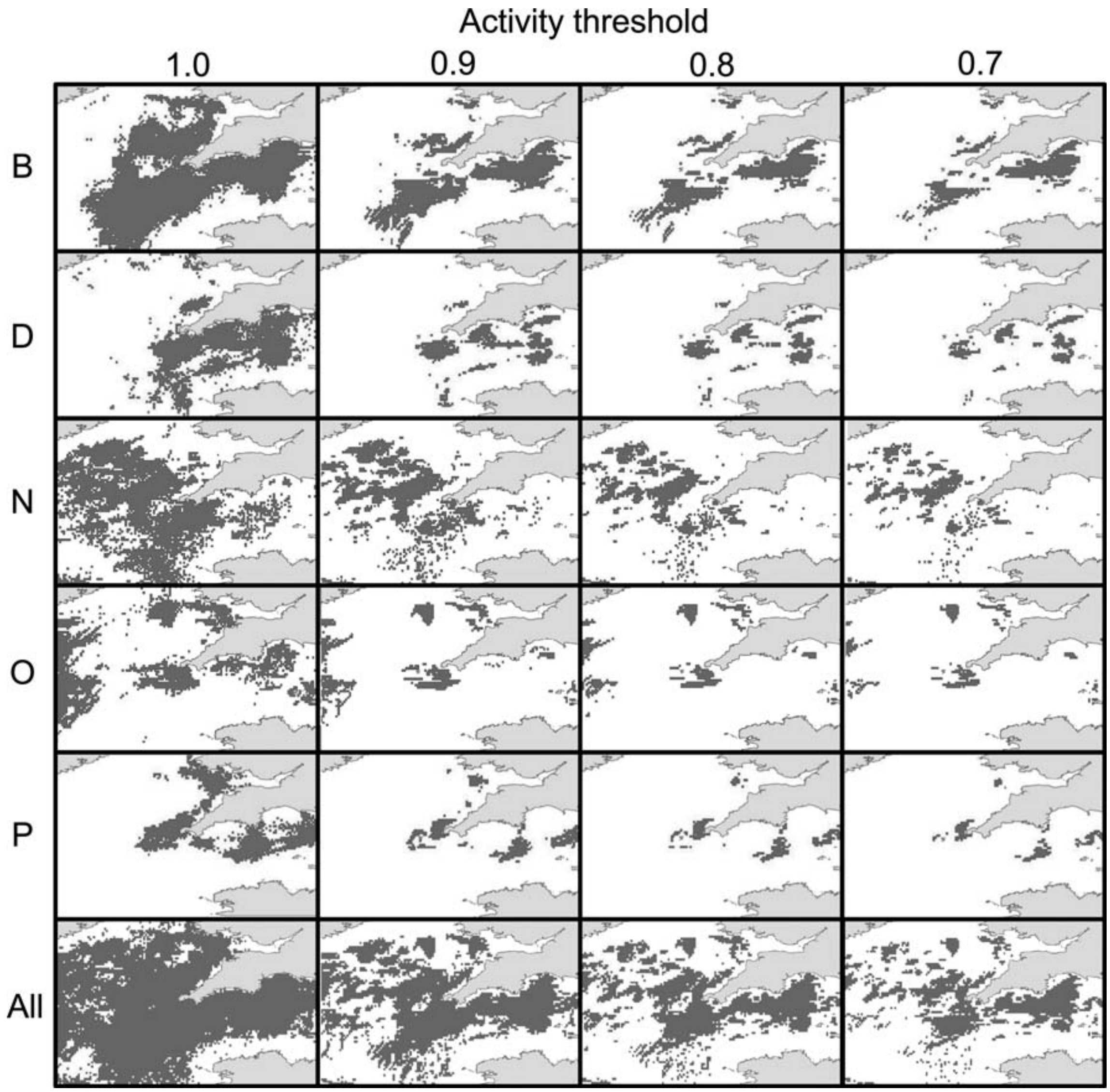

Figure 2. Spatial distribution of fishing grounds off the southwest coast of England and Wales when grounds are defined as areas that include 100, 90, 80, and 70% of fishing activity (activity threshold, shown as proportions). Data for the years 2006–2009 combined. Fleet codes: B, beam trawlers; D, dredgers; N, netters; O, otter trawlers; P, potters; All, all fleets combined.

67% for potters (to 8037 km^2). For lower activity thresholds of 80 and 70% of total activity, the relative reduction in spatial extent is progressively less.

When 10, 20, or 30% of total activity was excluded, changes in the predicted weight and value of landings from the fishing grounds off southwest England and Wales fell disproportionately fast for otter trawlers and gillnetters (Table 1; percentage reduction in weight or value exceeds the percentage reduction in area). For other fleets, the reductions in activity and reductions in estimated landings weight and value were broadly consistent.

As areas that made the least contribution to total activity were excluded, the fishing grounds so defined were increasingly contiguous and characterized by fewer but smaller patches (Figures 2 and 3). When 10% of activity was excluded, more small patches than larger ones were defined as fishing grounds, but the larger patches of >50 grid cells accounted for most of the area of the fishing ground. For all fleets except netters (in relation to the number of patches), and otter trawlers and dredgers (in relation to the mean size of patches when 10% of activity was excluded), there were disproportionate reductions in the ratio patch boundary length:patch area, and in patch numbers as activity was excluded (Figure 3).

Overlaps between fishing grounds off the southwest UK decreased with the exclusion of low-activity areas. The greatest relative decreases were always when the first 10% of total activity was excluded (Figure 4; Supplementary Figure S1). The small levels of overlap between fleets based on data for the period 2006–2009 were consistent with little overlap between fleets in individual years (Supplementary Table S1), although the locations of fishing grounds changed to some extent from year to year (Supplementary Table S2).

After accounting for overlaps, the total area of fishing grounds off southwest UK was 130 669 km^2, or 73.6% of ICES Areas VIIe–h. If fishing grounds were treated as areas that only included 90% of the recorded activity for each fleet (Figure 2), then the total area designated as fishing grounds in areas VIIe–h fell to

Table 1. Changes in the predicted weight and the value of landings from fishing grounds in waters southwest of England and Wales when grounds are defined by including 90, 80, and 70% of total fishing activity (expressed as proportions).

		Percentage of landings weight by activity threshold			Percentage of landings value by activity threshold		
Year	Gear	0.9	0.8	0.7	0.9	0.8	0.7
2006	Beam trawl	0.890	0.788	0.687	0.879	0.773	0.667
2007		0.908	0.810	0.721	0.900	0.796	0.700
2008		0.915	0.820	0.725	0.907	0.804	0.702
2009		0.921	0.829	0.732	0.918	0.822	0.719
2006–2009		0.907	0.810	0.715	0.899	0.797	0.696
2006	Otter trawl	0.715	0.590	0.468	0.814	0.679	0.548
2007		0.886	0.777	0.669	0.889	0.784	0.678
2008		0.935	0.842	0.728	0.932	0.833	0.716
2009		0.851	0.791	0.694	0.884	0.755	0.649
2006–2009		0.859	0.741	0.630	0.880	0.763	0.648
2006	Dredge	0.841	0.688	0.545	0.837	0.685	0.544
2007		0.886	0.808	0.734	0.890	0.818	0.746
2008		0.945	0.875	0.813	0.946	0.879	0.821
2009		0.940	0.863	0.755	0.938	0.863	0.753
2006–2009		0.896	0.796	0.696	0.897	0.800	0.701
2006	Net	0.868	0.765	0.670	0.894	0.800	0.708
2007		0.854	0.746	0.650	0.857	0.754	0.661
2008		0.888	0.784	0.686	0.885	0.786	0.686
2009		0.868	0.733	0.592	0.866	0.733	0.593
2006–2009		0.868	0.757	0.651	0.876	0.768	0.663
2006	Pot	0.907	0.815	0.709	0.912	0.823	0.723
2007		0.937	0.847	0.743	0.938	0.851	0.748
2008		0.944	0.878	0.801	0.944	0.874	0.794
2009		0.932	0.870	0.787	0.926	0.860	0.771
2006–2009		0.925	0.845	0.751	0.927	0.845	0.752

73 098 km^2 or 41.3% of the total. This consisted of 131 non-contiguous patches with a mean size of 558 km^2 and a total boundary length of 12 104 km^2. Of these, 70 are single-cell patches, and if these patches are excluded, the average size of patches rises to 1176 km^2 and the total boundary length falls to 10 818 km.

The extent to which the defined beam trawl fishing grounds off southwest England and Wales encompassed the activities of individual vessels was assessed by comparing fishing grounds of individual vessels in 2009 with the fishing grounds defined for the fleet from 2006 to 2009. Any grid cell that was fished for >10 h per year was assumed to contribute to the fishing ground of an individual vessel in that year. For 44 of the 47 vessels classified as beam trawlers and fishing in the ICES Areas VIIe, f, g, or h in 2009, the defined fishing ground for the fleet included 67–100% of the individual activity of each vessel (mean among vessels 95%, median 97%). The other three vessels did not meet the criteria for inclusion in the analysis.

The extent to which defined fishing grounds encompassed monthly variation in fleet activity was assessed by comparing fishing grounds of the beam trawl fleet in 2009 with the fishing grounds defined for the fleet for 2006–2009. Any grid cell fished for >10 h per month was assumed to contribute to the fishing ground of the fleet in that month. Beam trawl grounds that included 90% of total fishing activity for the period 2006–2009 encompassed 90–99% of the activity of the fleet in every month of the year (mean 95%).

Relationships between the cumulative area fished and the cumulative activity in those areas also demonstrated that most fishing activity took place in a relatively small proportion of the total area fished from 2006 to 2009 (Figure 1, lower panels). For all gears, 70% of fishing activity took place in <25% of the area fished and 90% of fishing activity in <50% of the area fished. Therefore, as in the southwest, fishing grounds had extensive margins where activity is low, reflected in the marked decrease in the area of fishing grounds when 10, 20, or 30% of activity was excluded (Figure 5). If defined fishing grounds were limited to an area including 90% of activity, this reduced the spatial extent of the defined fishing ground by 70% for beam trawlers (to 58 562 km^2), 67% for dredgers (to 40 386 km^2), 57% for netters (to 80 908 km^2), 69% for otter trawlers (to 184 783 km^2), 62% for potters (to 51 622 km^2), and 56% for seiners (to 72 624 km^2) relative to the total area fished. The fishing grounds for individual fleets, based on 90% of total activity, each accounted for 4.5–18.4% of UK waters (Table 2, Supplementary Figure S2). For all fleets combined, the equivalent area was 401 310 km^2 or 37.4% of UK waters (Supplementary Figure S3). This compared with 895 968 km^2, or 68.7% of UK waters, when 10% of activity in the least frequently fished areas was not excluded.

As in southwest waters, the exclusion of areas that made the least contribution to total activity led to grounds that were increasingly contiguous and characterized by fewer but smaller patches (Figure 3). For all UK fleets, there were disproportionate reductions in the number of patches, but only small declines in the ratio of the total patch boundary length:total patch area, because increasing amounts of activity were excluded (Figure 3).

Overlaps between fishing grounds used by UK vessels fell rapidly as the activity threshold for defining fishing grounds was reduced from 100 to 70%, with the fastest relative decrease in overlap almost always between 100 and 90% (Figures 5 and 6). With a 90% activity threshold, there were low levels of overlap between grounds used by different fleets in the period 2006–2009 (Table 3), consistent with little overlap between gears in individual years (Supplementary Table S3).

Landings weight and value by UK fleets fell disproportionately fast with the exclusion of activity from defined grounds for most gears and years considered (Table 4). For combined activity for 2006–2009, the decrease in landed weight with the exclusion of 10% of activity was greatest for otter trawls (22%), with decreases of 10–20% for other gears (Table 4). For pots, the proportional exclusion of activity was most closely linked to the proportional decrease in landings weight or value (LWV).

Annual total landings by UK vessels in the years 2006–2009 ranged from 581 000 to 620 000 t, with an annual first sale value of £615–675 million. Of these landings, 84–86% by weight and 74–76% by value were taken by vessels >15 m that are tracked with VMS. The UK bottom fishing fleets considered accounted for 37–42% (191 000–216 000 t year^{-1}) of landed weight and 57–66% (£296–315 million annually) of landed value by >15 m vessels; the other landings were principally mackerel and herring taken by pelagic fleets (MMO, 2010). The contributions of individual UK fleets to total landings weight by all UK fleets were beam trawlers 8–12%, dredgers 11–13%, netters 2%, otter trawlers 64–68%, potters 5–6%, and seiners 5–6%. The equivalent contributions to total values were beam trawlers 12–15%, dredgers 9–12%, netters 3–4%, otter trawlers 63–66%, potters 4–5%, and seiners 4–5%. The southwest fleets accounted for 8–9% (16 000–18 000 t annually) of landed weight and 11–12%

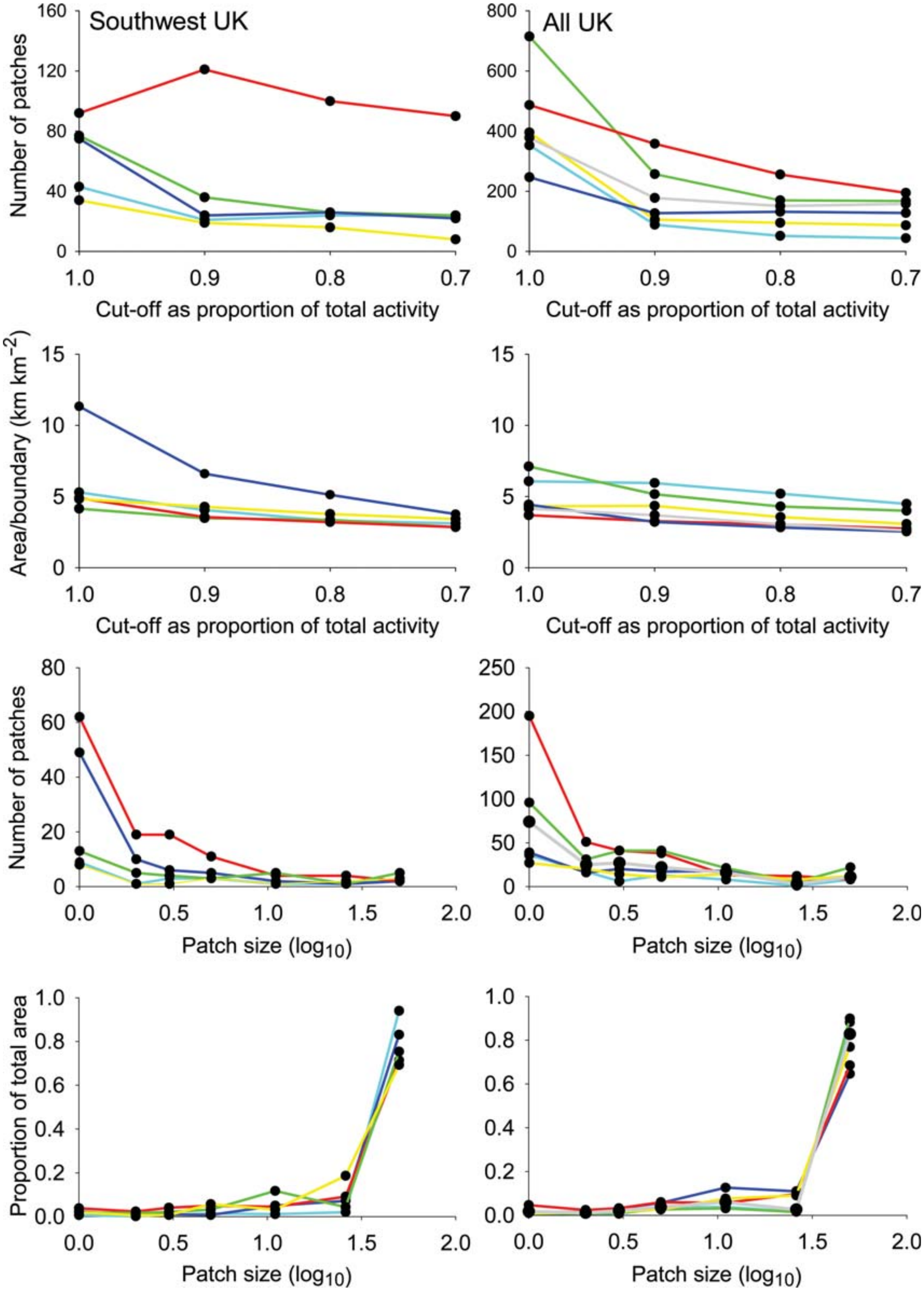

Figure 3. Relationships between the proportion of total activity used to define fishing grounds and the number of patches that comprise a fishing ground (left panels, upper two rows) or the ratio of boundary length:area for these patches (right panels, upper two rows), and between patch size and the number of patches (left panels, lower two rows) or the total area of patches (right panels, lower two rows) that comprise a fishing ground. Data for the years 2006 – 2009 are combined for southwest and UK fleets. Fleet codes: cyan, beam trawlers; blue, dredgers; red, netters; green, otter trawlers; yellow, potters; grey, seiners.

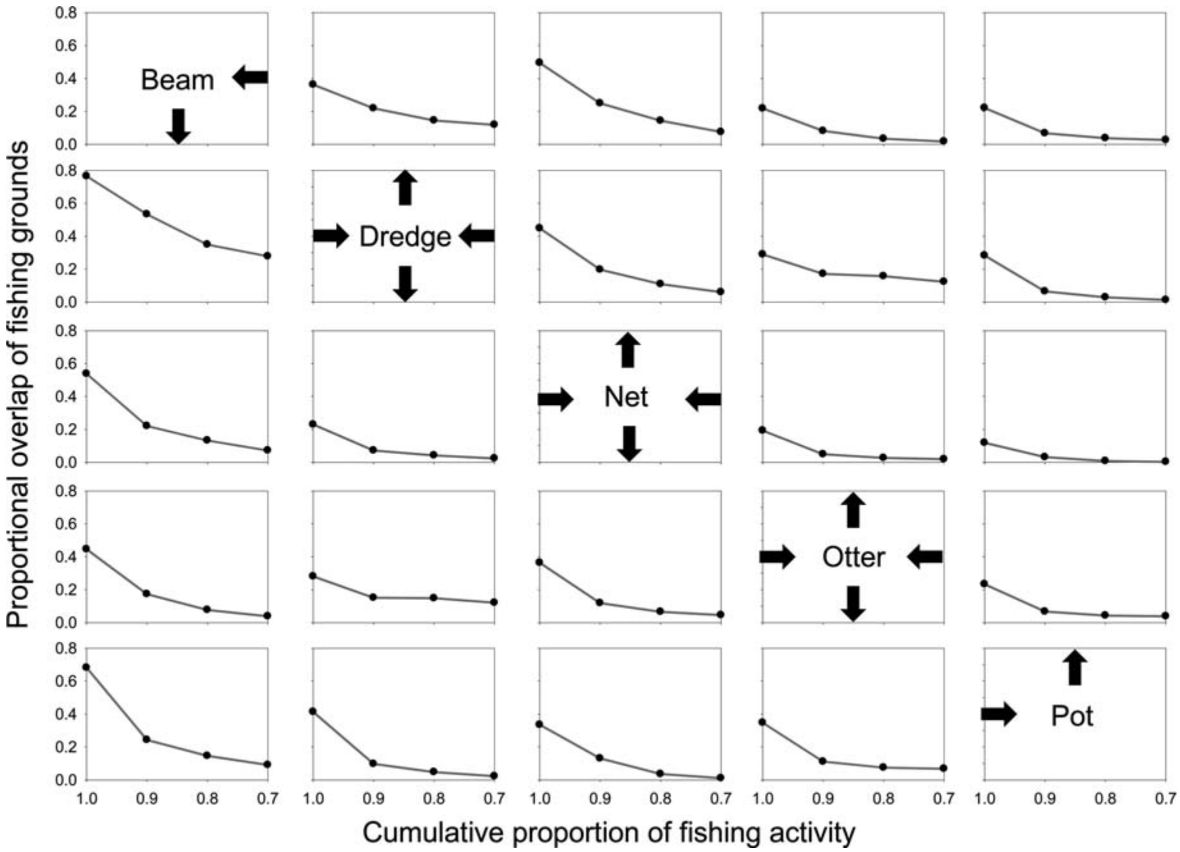

Figure 4. Relationship between the proportional overlap of fishing grounds in southwest UK waters and the cumulative proportion of total fishing activity that is used to define those fishing grounds (activity thresholds). Arrows denote the sequence of overlap. For example, a down arrow from beam leading to a right-pointing arrow for dredge indicates that beam fishing grounds overlap dredge fishing grounds by the proportions shown.

(£34–37 million annually) of landed value by the UK fleets considered. The contributions of individual fleets in the southwest to total landings weight from the southwest fleets considered (in ICES Areas VIIe–h) were beam trawlers 45–53%, dredgers 18–26%, netters 7–9%, otter trawlers 5–10%, and potters 9–15%. The equivalent contributions to total values were beam trawlers 55–62%, dredgers 13–18%, netters 8%, otter trawlers 5–10%, and potters 8–11%.

Discussion

We hope that this exploration of methods and criteria for defining fishing grounds can catalyse both debate and further analyses that will lead to widely accepted definitions of fishing grounds in marine spatial plans, provide track records for the fishing industry, and inform debate on space allocation between fishers, other users of the marine environment, managers, and planners. For all gear and scales of time and space considered, the full extent of areas fished consisted of relatively small, intensively fished core areas, and relatively large, infrequently fished margins. Consequently, excluding areas of little activity when defining fishing grounds leads to disproportionately large reductions in area and in potential interactions with other fisheries and sectors. For the fleets considered, a 90–50 rule applies broadly, i.e. 90% of the activity in <50% of the total area fished, although for individual vessels, activity may be more homogenous. The analyses of landings weight and value did show that weight and value per unit fishing activity can be higher in low-activity areas but, for most grounds based on a 90% threshold, the weight or value of landings from low-activity areas did not exceed 20% of the total. Landings value, however, is not a measure of profit from the fishery because it does not account for fishing costs, so it may provide a misleading assessment of the economic benefits of fishing the margins. The results do not show that there is a correct way to define a fishing ground, because this is a matter for society, informed by science, but definitions based on areas smaller than the total extent would result in relatively small impacts on one sector in relation to the benefits that may accrue to others.

The analyses are based on VMS records that are transmitted mainly at 2-h intervals. Working with data of this type introduces biases and errors that need to be considered when interpreting the analyses. First, there is the risk that records classified as fishing are incorrectly classified. Misclassification is believed to be <5% for towed gears (Lee *et al.*, 2010), but is not well quantified for static gears. Second, the use of point data in lieu of information on the fishing tracks of vessels means that estimates of the total area fished (sum of the areas of all grid cells where fishing is recorded) will decrease with decreasing activity. The value of the threshold beyond which this decrease begins will depend on grid-cell resolution and the density of VMS records considered. It is possible to interpolate between successive VMS records to reconstruct fishing tracks and to predict other cells fished. Although track reconstruction for beam trawlers has been attempted (Mills

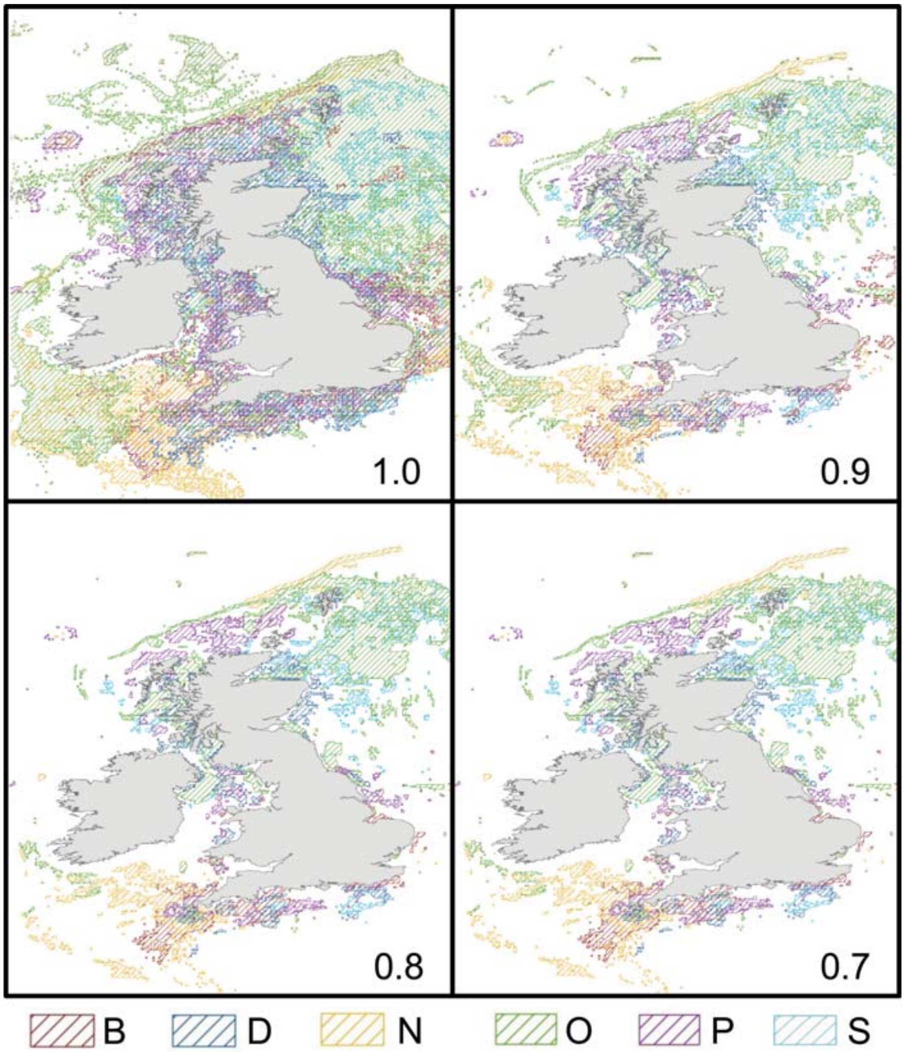

Figure 5. Spatial distribution of fishing grounds used by UK fishing vessels when the grounds are defined as areas that include 100, 90, 80, and 70% of fishing activity (activity threshold shown as proportion), with data for the years 2006–2009 combined. Fleet codes: B, beam trawlers; D, dredgers; N, netters; O, otter trawlers; P, potters; S, seiners).

et al., 2007) and there is ongoing work to improve methods (Hintzen *et al*., 2010), we did not use track reconstruction because a point summation method, as adopted here, remains more transparent to many users than generating tracks which, when based on 2-h polling and applied to vessels that can be towing gears at a mean speed of 3–4 knots (Lee *et al*., 2010), can imply a level of precision not appropriate for the data and can still lead to significant underestimates of area fished (South *et al*., 2009). Further, even if it performed well, track reconstruction could not be applied ubiquitously because it was not applicable for vessels fishing unattended and/or static gear. If and when methods of track reconstruction are improved, the frequency of VMS polling increases, and fishing grounds have to be defined for very small numbers of vessels over relatively short periods (when the total number of records would necessarily be low), then it would be appropriate to revisit track-based methods for defining the fishing grounds used by vessels fishing towed gear.

The scale of the analysis will influence the boundaries and areas of the grounds defined. We worked with gridded data at a resolution of 0.05° because this is the approach used to provide the fishing activity data used to inform marine planning in the UK. Many other approaches, from working directly with the raw position data to defining conditions that limit the complexity of boundaries, would be feasible. Pragmatism would likely favour reducing the complexity of boundaries to provide clarity in mapping and written regulations. However, as the number of inflection points is decreased, other areas with more or less activity than those defined for any given activity threshold will be included or excluded. It would be of value to explore the consequences of using alternate methods to define boundaries, to inform debate, and to determine if there are acceptable solutions in the UK and more widely. This exploration should also consider the existing capacity and future potential of monitoring, management, and compliance agencies to work with boundaries of different levels of complexity.

The aforementioned limitations of VMS data mean that changes in the boundaries and patchiness of fishing grounds are driven by real changes in activity distributions and by absolute levels of activity. Overestimation of the dispersion of fishing activity, and hence overestimation of the patchiness, is necessarily

Table 2. Characteristics of fishing grounds used by UK vessels, based on excluding the most lightly fished areas that contribute to <10% of total activity in the period 2006–2009.

Parameter	Beam trawl	Otter trawl	Dredge	Net	Pot	Seine
Total area of fishing ground (km^2)	58 562	184 909	40 386	80 844	51 622	72 547
Area:boundary (km^2 km^{-1})	5.95	5.17	3.22	3.28	4.35	3.69
Number of patches	89	257	127	358	106	178
Mean size of patches (km^2)	658	719	318	226	487	408
Number of single cell patches	36	96	39	195	27	74
Proportion of area of UK waters	0.052 (0.147)	0.184 (0.493)	0.045 (0.127)	0.048 (0.094)	0.062 (0.146)	0.077 (0.167)

Values in parenthesis are the corresponding values if no activity were excluded. For calculating the proportion of UK waters, only those fishing grounds within the UK median line were considered.

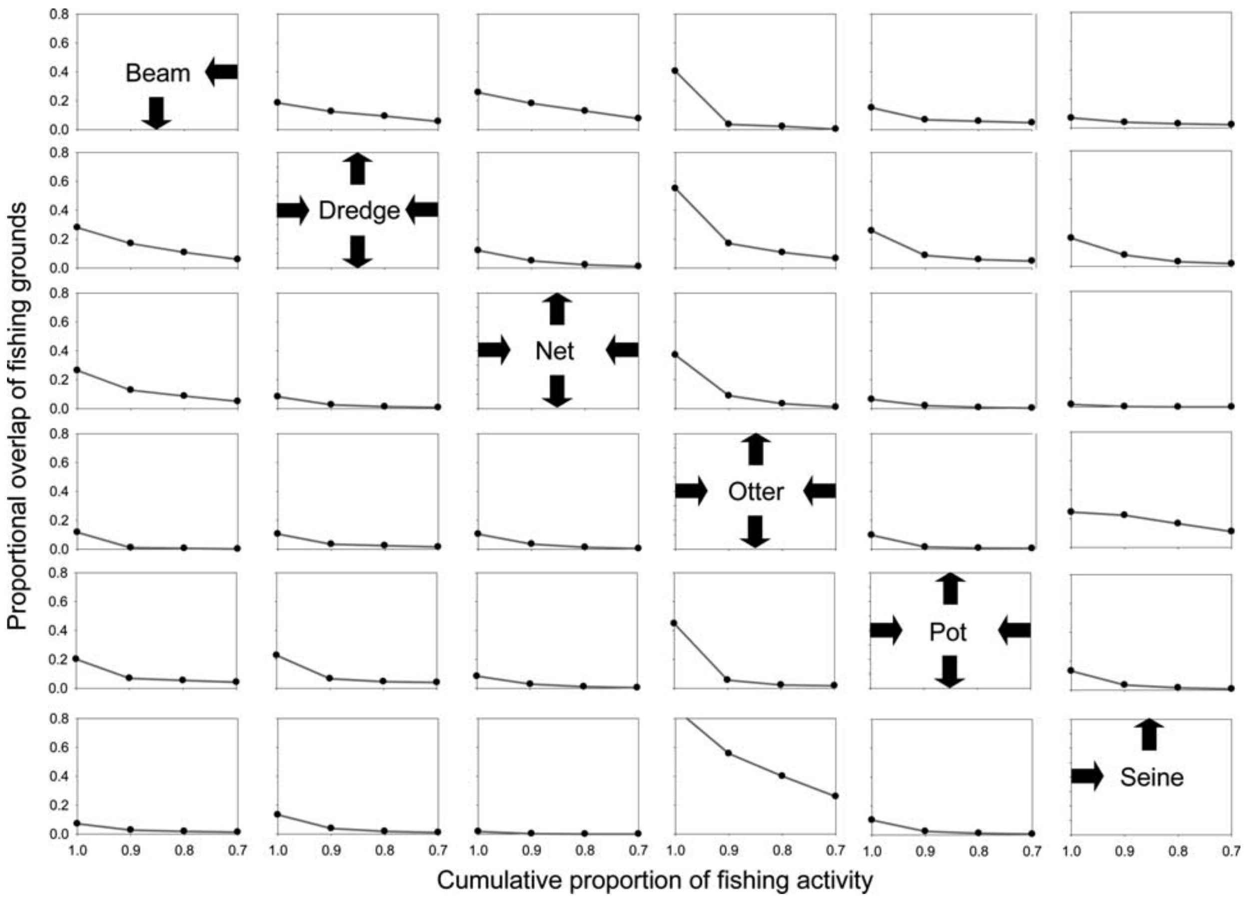

Figure 6. Relationship between the proportional overlap of fishing grounds in UK waters and the cumulative proportion of total fishing activity that is used to define those fishing grounds (activity thresholds). Arrows denote the sequence of overlap (see explanation in legend to Figure 4).

greater in less-actively fished areas because there is less probability that a fishing position will be recorded in any given grid cell, even if a fishing track crosses it. However, in the context of this analysis, this is not a significant concern, because the reductions in area fished, overlap of grounds, and fishing impacts will be underestimated rather than overestimated when low activity levels are excluded and hence the definitions of footprint, overlap, and impact are conservative.

Vessels were classified here into a tractable number of fleets that covered a large proportion of UK fishing activity. The classification is unbalanced to the extent that the activities of vessels are not homogenous within and among fleets. For example, beam trawlers are mainly similar vessels targeting similar species with similar gear, whereas otter trawlers include many types of vessel fishing in different areas for a broad range of demersal species. The extent of variation in the activities of vessels in any defined fleet will determine the extent to which the cumulative relationships between area fished and activity, value, or landings are driven by common patterns of activity among vessels or by differing patterns of activity. If they are driven by different patterns of activity, for example, the shape of the cumulative relationships may be driven by the activities of different fleet segments with (i) low overall activity but high landings or value of landings per unit activity, and (ii) high overall activity but low landings or value of landings per unit activity. This may lead to an apparent discrepancy between the cumulative relationship for LWV as a function of

Table 3. Proportional overlap between fishing grounds used by different groups of UK vessels, where fishing grounds are defined by excluding the most lightly fished areas that contribute to <10% of total activity in the period 2006–2009.

	Beam trawl	Otter trawl	Dredge	Net	Pot	Seine
Beam trawl		0.02	0.13	0.18	0.07	0.04
Otter trawl	0.01		0.03	0.04	0.02	0.22
Dredge	0.17	0.17		0.05	0.09	0.08
Gillnet	0.13	0.09	0.03		0.02	0.00
Pot	0.07	0.06	0.07	0.03		0.04
Seine	0.03	0.56	0.04	0.00	0.02	

Table 4. Annual changes in the predicted weight and the value of landings from fishing grounds used by UK vessels, when grounds are defined as areas that include 90, 80, and 70% of total activity (expressed as proportions).

		Percentage of landings weight by activity threshold			Percentage of landings value by activity threshold		
Year	**Gear**	**0.9**	**0.8**	**0.7**	**0.9**	**0.8**	**0.7**
2006	Beam trawl	0.749	0.550	0.428	0.767	0.599	0.487
2007		0.807	0.632	0.508	0.819	0.672	0.558
2008		0.837	0.665	0.531	0.851	0.707	0.586
2009		0.816	0.615	0.486	0.826	0.665	0.551
2006–2009		0.800	0.612	0.486	0.811	0.657	0.542
2006	Otter trawl	0.753	0.619	0.491	0.846	0.716	0.591
2007		0.833	0.701	0.571	0.863	0.744	0.624
2008		0.759	0.627	0.504	0.833	0.708	0.585
2009		0.774	0.625	0.499	0.797	0.651	0.525
2006–2009		0.778	0.641	0.514	0.835	0.705	0.581
2006	Dredge	0.747	0.574	0.489	0.840	0.712	0.600
2007		0.891	0.830	0.719	0.890	0.802	0.714
2008		0.804	0.725	0.637	0.911	0.825	0.727
2009		0.913	0.828	0.734	0.912	0.820	0.730
2006–2009		0.840	0.734	0.646	0.887	0.787	0.690
2006	Net	0.804	0.688	0.590	0.862	0.751	0.652
2007		0.863	0.771	0.684	0.884	0.796	0.707
2008		0.901	0.815	0.725	0.897	0.815	0.728
2009		0.864	0.762	0.651	0.871	0.771	0.661
2006–2009		0.857	0.757	0.661	0.878	0.782	0.685
2006	Pot	0.882	0.778	0.675	0.888	0.789	0.688
2007		0.907	0.798	0.707	0.917	0.806	0.713
2008		0.906	0.821	0.749	0.904	0.827	0.753
2009		0.895	0.796	0.698	0.901	0.807	0.710
2006–2009		0.898	0.798	0.707	0.906	0.808	0.713
2006	Seine	0.894	0.792	0.684	0.892	0.791	0.684
2007		0.904	0.807	0.718	0.901	0.804	0.715
2008		0.888	0.800	0.720	0.885	0.799	0.717
2009		0.874	0.776	0.677	0.848	0.748	0.646
2006–2009		0.889	0.793	0.699	0.881	0.785	0.691

area and the cumulative relationship for activity as a function of area. For otter trawlers, perhaps the most heterogeneous fleet in this analysis, there was a significant disconnect between the value and weight of landings from the areas least intensively fished and the amount of activity recorded there. An additional analysis for otter trawlers, disaggregating them into a series of fleets characterized by gear type and target species, would help to resolve the extent of any bias introduced by aggregating vessels of many types.

There are higher-resolution classifications of fleets that would provide more homogeneity within categories, such as those described in the EC Data Collection Framework. Decisions on fleet categories for defining fishing grounds would have to take account of many issues, including the compatibility of the fishing activity with other fishing activities and sectors, target species, and the management instruments affecting the fishery.

As we have considered the distribution of fishing activity at a number of levels from individual vessel to fleet, from monthly to annual and multi-annual, and from regional to national, we expect our qualitative conclusions to be relatively robust to changes in vessel classification. The analysis is limited to vessels monitored by VMS (>15 m) and ignores the activity of smaller vessels. It also ignores the activities of non-UK vessels for which the vessel-specific information needed to conduct this analysis were not available. For these reasons, the analyses remain illustrative in relation to the swathe of fisheries-related issues that need to be addressed as part of a spatial planning process.

Reported overlaps between fishing grounds used by different fleets depend on the classifications adopted, and the amalgamation of annual or multi-annual activity data means that overlaps do not necessarily indicate direct interactions between vessels. However, the overlaps are of interest in relation to marine spatial planning if fishing grounds for different fleets need to be defined and areas identified where the consequences of interactions might need to be evaluated.

Activity rather than LWV was used for defining thresholds and fishing grounds because the spatial resolution of the underlying landings data is coarse (ICES rectangles). Landings data could only be assigned to the smaller grid cells used for the VMS analysis based on the assumption of constant landings per unit effort or vpue. Deviations from this approximation cannot be assessed because landings and value data were not available at finer scales for the range of fleets and regions considered. This situation is expected to improve if electronic logbooks are adopted widely, and all methods can then be repeated using thresholds based on proportions of LWV rather than proportions of activity.

For the fleets and vessels investigated, year-to-year variation in fishing grounds from 2006 to 2009 was limited. Grounds defined based on the analysis of total activity from 2006 to 2009 usually included most of the activity in any of these years. For the beam trawl fleet fishing off southwest England and Wales, definition of the fishing ground based on collective activity also captured the activity of individual vessels, with none fishing an area markedly different from that of the fleet. Further, fishing grounds defined using annual data encompassed most of the activity of the fleet in every month of the year, so did not exclude significant seasonal fishing opportunity.

If fishing grounds were defined as part of a spatial planning process, then the restriction of fishing activity to areas of <100% of recorded activity will lead to disproportionate reductions in footprint and increased opportunities for other uses. It is likely that there will be growing pressure for the allocation of more marine space to non-fishery use (e.g. marine renewables, nature conservation), because fishing has by far the biggest footprint at present (Eastwood *et al.*, 2007). The results here show the consequences of defining fishing grounds to include specified proportions of total activity, but it would be a societal decision to choose activity cut-offs that best satisfied potential trade-offs between incompatible or competing interests and management objectives. It is to be hoped that the types of analysis presented here will better inform the associated debate and decisions.

When taking account of fisheries in a planning process, a range of approaches might be considered. These include (i) giving fishers access rights to core areas defined based on track record, (ii) not giving fishers total access rights to core areas, but allowing them to be displaced from these areas by other uses of marine space (e.g. conservation, marine renewables), (iii) giving fishers continued access to the full extent of existing fishing grounds, and (iv) giving fishers open access to any areas from which they are not displaced by other uses. If the possibility of limiting the fishing industry to defined grounds based on track record was considered, it would be necessary to assess the potential consequences. First, if accessible grounds were based on the total extent of existing activity, the fishing industry would be largely unaffected in the short term. In the longer term, however, and without a process for revision, the restrictions could prevent adaptation of the industry to changes in fuel prices or fish distribution (Holland and Sutinen, 2000; Abernethy *et al*., 2010). Second, if grounds were limited by excluding those infrequently fished areas that account for a small proportion of total activity, the fishing industry would be affected in the short term. Vessels that lost access to less frequently fished areas would have to operate in the defined fishing ground, where they would face increased crowding and competition. This may limit their capacity to replace income and landings that would otherwise be taken from the less frequently fished areas. However, if management measures simultaneously limited fishing effort or quota, then the required move into the defined ground may be consistent with the choices of fishers who increasingly focus on core areas as competition for space and resources is reduced (Gillis *et al*., 1993). If management and/or a favourable environment lead to more fishing opportunities in the longer term, then fisheries constrained to a small ground may not take advantage of the catching opportunities that arise from the wider distribution associated with greater abundance. Limiting fishing to areas less than the total extent may also limit the capacity of fishing vessels to avoid interaction with other sectors, unless the activities of those sectors are restricted in areas designated as fishing grounds.

Although grounds could be defined and vessels constrained to grounds as part of a spatial planning process, the extent of grounds may also change in response to fishery regulation. If effort or catch controls, for example, led to vessels concentrating in the most intensively fished parts of the existing fishing grounds, then the reduction in large but infrequently fished areas on the margins of the ground would lead to significantly reduced interaction with other fisheries and sectors and, for towed gears, would significantly reduce the direct impacts of gears on a given habitat. If the fishing industry were not provided with assured access to defined grounds based on track record, then it would become necessary to assess the potential consequences. For example, placing restrictions on fisheries within areas that make the greatest contribution to total activity may lead to displacement that extends the total area of the fishing ground and increases interactions with other fisheries and sectors. Further, the analysis here describes the activities of UK vessels, but management of fisheries in Europe is achieved through the Common Fisheries Policy, so the activities of, and interactions with, vessels from other nations have to be considered, as do the effects of restrictions in areas of national authority on the interactions between vessels.

There are many ways to define fishing grounds, and this initial analysis is intended to catalyse a necessary debate involving fishers, non-fishing sectors, planners, and managers. For several gear types, at regional and national scales, the methods used to define grounds will influence their size, shape, and overlap, and the extent to which they encompass individual and seasonal activity. Selecting a method and definition appropriate to any management situation is ultimately a choice for society, but importantly, if fishing grounds are defined by excluding those infrequently fished areas that account for a small proportion of total activity, then there could be disproportionately large reductions in area fished, environmental impacts, and interactions with other fisheries and sectors.

Supplementary material

The supplementary material available at the *ICESJMS* online version of this manuscript includes Figures S1, S2, and S3 showing the relationships between the extent and overlap of fishing grounds and the criteria used to define them, and Tables S1, S2, and S3 quantifying the overlap between the fishing grounds used by different fleets both within and among years.

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