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Original Article

Highly mixed fisheries: fine-scale spatial patterns in retained catches of French fisheries in the Celtic Sea

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Efficiency of mixed-fisheries management and operational implementation of the ecosystem approach to fisheries management rely on the ability to understand and describe the technical and biological interactions between fleets, gears and species. The present study aims to describe fine-scale spatial patterns of the French demersal mixed fisheries in the Celtic Sea and discusses their implications in terms of management. Analysis was made by integrating vessel monitoring systems and logbook data collected between 2010 and 2012 at a 3′*3′ spatial scale through the use of principal component analysis followed by hierarchical clustering. It revealed spatial regions defined by a distinct homogeneous composition of retained catches. Each cluster was also described in terms of the fishing activity: vessel length, effort, power and gear used. The analysis revealed a complex spatial structure in the species assemblage caught and suggests that a single situation cannot describe the mixed fisheries of the Celtic Sea, but rather that there are several distinct cases of mixed fisheries. Our results also highlight the limitations of using the current level of data aggregation commonly requested in international data calls to model these fisheries and suggest that improvements should be made to ensure efficient evaluation of management options. Analyses of spatially resolved fisheries data such as the one presented here open a range of potential applications. In the context of the Common Fisheries Policy reform and the landing obligation, comparison of our results with applications of the same methodology to a subset of vulnerable species or to catches of fish below the minimum conservation reference size would help to identify the geographical areas to avoid and assess potential effort reallocation strategies based on groups of target species.

Keywords: Celtic Sea, integrated VMS and logbook data, mixed fisheries management, retained catches, spatial pattern.

Introduction

European fisheries are highly diverse in exploited species assemblages, which are targeted by a wide variety of fishing gears. Nevertheless, most of the species are managed through Total Available Catch (TAC) based on scientific advice about single species independently, regardless of the status of the other species, even if they are caught simultaneously during the same fishing operation. In response to the request formulated in the *Strategy for Mixed Fisheries and Multi-species* advice, published by the International Council for the Exploration of the Sea (ICES, 2013), and the needs of the new Common Fisheries Policy (CFP), scientific advice is shifting from "self-contained" single species advice to ecoregional mixed-fishery and multi-species advice where management measures for one stock should ultimately integrate the impact on other stocks (EC, 2014).

Pioneering work on mixed-fisheries advice for the North Sea and Baltic was made with the Fish and Fisheries Forecast model (Fcube) (Ulrich *et al.*, 2007, 2011; Hoff *et al.*, 2010), which now routinely provides advice for these areas and has started to be implemented for other ICES ecoregions, such as the Celtic Sea (ICES, 2015a). The overall objective is to understand and model the strength of technical interactions between different gears used in the fishery (ICES, 2015b) by taking into account the competition among fleets for the same species and the catch of several species by a single fleet. This approach also makes it possible to identify "choke" species, i.e. the most constraining stocks, with the final aim of designing management measures with improved consistency of quotas between the different stocks harvested within a mixed fishery. With this new modelling framework, progress has been made in integrating mixed fisheries forecasts into stock advice (short-term mixed fisheries advice; Ulrich et al., 2012) and multi-annual management plans for mixed fisheries [long-term management strategy evaluation (FLBEIA); Garcia et al., 2013; STECF, 2015b]. The new CFP reform and its associated landing obligation regulation will emphasize such mixed-fisheries issues, especially the problems of choke species that would force fisheries to close once the most restrictive quota was reached.

In mixed-fisheries models, the choice of relevant fisheries units is a sensible process to ensure efficient evaluation of management options. A large number of papers have been dedicated to fleet[1] and métier[2] definition (Marchal, 2008; Katsanevakis *et al.*, 2010; Davie and Lordan, 2011; Castro *et al.*, 2012; Deporte *et al.*, 2012; Ulrich *et al.*, 2012) with the key objective of finding the right level of contrast to capture the major differences between fleets. A traditional approach to defining fleet segments and/or métiers is to use social entities rather than natural entities such as catch assemblages (Cardoso *et al.*, 2015). Social entities are related to the fishing operation and characteristics of the vessels. While métiers should reflect the species targeted, the fleet definition typically encompasses several parameters (Marchal, 2008): (i) the physical characteristics of the vessels (length, horsepower and tonnage); (ii) the variables characterizing the fishing activity, such as fishing effort by gear, area or target species; and (iii) a threshold above which a given vessel is considered to belong to a fleet category. Therefore, an optimal level of aggregation would pool vessels or fishing operations into homogeneous groups that have similar fishing patterns, including species assemblages, species sizes, vessels and gear characteristics and spatial coverage. In practice, however, the fleet and métier splits widely used for modelling purposes are based on country, gear type and vessel length for the fleet; and gear, mesh size and (in Europe) ICES area for the métier. These fleet and métier specifications were historically driven by the definition of the EU cod recovery plan in the North Sea (Ulrich *et al.*, 2012) and associated with effort regulation measures; they are now the standards of STECF data calls for all European ecoregions.

In this article, we focus on an important case study for this type of multi-gear, multi-species fishery: the mixed demersal fisheries in the Celtic Sea (ICES area VII, except VIId). The mixed demersal fisheries in the Celtic Sea mainly target cod, haddock, whiting, hake, anglerfish, megrim, plaice, sole, cuttlefish and nephrops using otter and pair trawls, beam trawls, longlines and gillnets (EC, 2014) . This area is an economically important fishing ground for French, Irish, English, Belgian and Spanish vessels. Discarding practices of target and non-target species in relation to small sizes, quota exhaustion and low market value are known to occur to various extents depending on several drivers such as area, period, gears, environment, population dynamics and management measures. A number of technical measures and spatio-temporal closures have been introduced over the years to reduce fishing effort and the discarding of undersize fish, such as Trevose box closure (EC, 2005) in the first quarter or the use of squared mesh panels (EC, 2012). With the new CFP reform, especially article 15, which obliges vessels to land all the catches for species under TAC, including fish that were previously thrown back at sea (discards), these highly mixed fisheries with substantial discard rates will face additional management issues.

In this study, rather than the common approach of using gear and target species (defined by using the observed catch composition of a fishing operation) as the basis for the analysis of fleet and métier definition, we attempted to identify some spatially homogeneous species assemblages from the raw data (species caught and retained on board) (Shephard et al., 2011)**.** These areas were then characterized in terms of fishing activity (effort, gear and mesh size). This study was based on highly resolved data from integrated logbooks and vessel monitoring systems (VMS) from French demersal fisheries in the Celtic Sea, for which data are available at a square resolution of $3'*3'$. This analysis therefore emphasizes fine-scale spatial structures and multi-species aspects that were often absent from previous approaches, mainly because most data were historically only available at a broader spatial scale (e.g. statistical rectangles).

This analysis will first provide a detailed description of spatial patterns of French landings in the Celtic Sea in a mixed-fisheries context. Results will then be discussed in terms of implications for management, including any gain in knowledge that could improve current international data calls on which most of the modelling work for management purposes is based. Potential applications of the current studies and related ones will be discussed in the context of the new CFP reform.

Material and methods

Data sources

The SACROIS algorithm, developed by IFREMER, is a cross validation tool for fisheries statistics (http://sih.ifremer.fr/Description-des-donnees/Les-donnees-estimees/SACROIS; (Demanèche et al., 2013), in response to article 145 of the EU implementing regulation (EC Reg. 404/2011). This tool cross-checks information from the fishing fleet register, logbooks, fishing forms, sales notes, VMS data and the scientific census of fishing activity calendars, at the most disaggregated levels available. The resulting product is a data set offering the most accurate and exhaustive information for each individual fishing trip. The application checks the different sources of data, with the aim of validating and qualifying landings per species and effort data series. This algorithm relies on two main assumptions: (i) VMS data are filtered for vessel speeds to select records assumed to correspond to events of fishing operations and (ii) the daily retained portion of the catch is allocated between geographic cells according to the daily fishing time spent in each cell as estimated by the previously filtered VMS records. The resulting data (effort and retained catches) are aggregated to a grid of 0.05° longitude×0.05° latitude (which corresponds to $3'*3'$).

[1]The most recent definition of fleet segment and métier are given by the CEC's Data Collection Framework [DCF, Reg. (EC) No 949/2008]. A fleet segment is a group of vessels with the same length class and predominant fishing gear over the year. Vessels may have different fishing activities during the reference period, but might be classified in only one fleet segment.

[2]A métier is a group of fishing operations characterized by a similar exploitation pattern, targeting a similar (assemblage of) species and using similar gear during the same period of the year and/or within the same area.

The data used for this study were extracted from SACROIS for French vessels operating in the Celtic Sea (ICES division VIIe, VIIf, VIIg and VIIh) in the 2010–2012 period. For the purposes of analysis, a filter was applied so that only grid cells containing all the necessary information (species, fishing gears and effort) simultaneously for the 3 years were selected. Missing data, accounting for 2% of the data set, was omitted from the analysis.

Method

The objective of the analysis was to identify and describe areas with similar landings profiles, using a combined set of multivariate methods [principal component analysis (PCA), hierarchical classification and characterization of species-specific composition in clusters].

This analysis was carried out on the main species accounting for 90% of the total landings in terms of landed weight and market value, resulting in a mixture of species with relatively low market price but landed in high quantities (e.g. mackerel) and species caught in small quantities but with high market value (e.g. sole). The remaining species were grouped in the category "others".

The mean retained catch weights per species in each grid cell (over the period 2010–2012) were converted into proportions. A centred and normed PCA was applied to this matrix. The statistical individuals (in rows) were the grid cells ($3'*3'$ squares) and the variables (in columns) were the species. PCA reduces the dimensionality of data and identifies the main recurring species combinations that explain the greatest variation (Legendre and Legendre, 2012). Subsequent application of hierarchical cluster analysis (HCA) identifies groups of cells with similar species composition, using all components accumulating 70% of the explained inertia in the PCA (Deporte *et al.*, 2012). The last components of the PCA were removed to keep down random fluctuations, thus improving the partitioning and homogeneity between and among classes (Legendre and Legendre, 2012).

A distance matrix was constructed by calculating the Euclidean distance between the cells in the selected components space. HCA was applied to this matrix, using Ward's minimum variance method, which consists in minimizing the total within-cluster variance. The most appropriate number of clusters (k) was chosen using the "elbow criterion", which looks at the percentage of variance explained as a function of the number of clusters.

The spatial clusters were described according to several indicators. Specific species composition was evaluated using the following: (i) the proportions of landings for each species in each cluster and (ii) Indicator Value (IndVal) index, which measures the association between a species and a cluster (Legendre and legendre 2012). This index is defined by the product of *specificity*, i.e. the proportion of a species in a cluster and *fidelity*, i.e. proportion of clusters where a species is present. Clusters were then described in terms of fishing activity, including the proportion of the different gears, vessel sizes, power and mesh sizes used.

The mean effort (in hours), number of boats, landings (in tons) per métier and the total surface of the cluster (sum of the $3'*3'$ squares included in the cluster, with a mean cell size of 30.9 km^2) were given for a posteriori lpue calculation. Fishing effort was calculated as the time (in hours) spent fishing by gear in each $3'*3'$ spatial square on a monthly basis and then the annual sum. For the analyses, the average fishing effort over the 3 years was used.

Analyses were performed using the ade4, labdv and mapplots packages available for R.2.15.0 (http://www.R-project.org/).

Results

In the Celtic Sea, French landings ranged between 81 949 and 64 817 tons between 2010 and 2012, which correspond to 164–149 million euros at first sale, respectively. This fishery involved 258–289 vessels, performing an average of 10 120 fishing operations a year. The French landings were composed of 148 species. However, the following analysis was run on the species that accounted for the top 90% of the landings in terms of weight and value, resulting in a shortlist of 28 species.

The distribution of eigenvalues resulting from the PCA applied to the proportion of the average retained catches of each species in each $3'*3'$ square indicates that the first two axes explain 35% of the total variance and that this percentage reaches 60% if we include the six first axes (Figure 1a). A HCA was then performed on the output coordinates from the PCA. The analysis grouped into clusters all $3'*3'$ squares that showed similar patterns in the species assemblage caught. The number of clusters was set to 9, which corresponds to the first relevant plateau in Figure 1b [see Supplementary Data for the map built with 12 clusters (second plateau), and the related paragraph of the discussion]. The same colour code was assigned to each $3'*3'$ square belonging to the same cluster. Then these colours were applied to all the squares on a map of the Celtic Sea (Figure 2).

The map shows how the retained catches are highly structured in space, describing patches with fractal boundaries. Clusters were described in terms of species assemblage (Table 1, characterizing the percentage of species caught and Indval index in each cluster) and exploitation pattern (Table 2, characterizing the percentage of landings by gear, vessel length and mesh size in each cluster). Then, a simultaneous analysis of the cluster map (Figure 2), effort maps by fishing gear (Figure 3) and tables enable to highlight important similarities or differences between clusters.

Cluster 1, shown in red on Figure 2 and Tables 1 and 2, is essentially located in the central part of the western English Channel (ICES division VIIe). Profiles of landings there are dominated by shellfish and the "other group" (Table 1). This area is exploited using a variety of fishing gears including, by order of importance: otter trawl with small mesh sizes (70–99 and 32–69 mm mesh sizes), coastal dredge (70–99 and 16–31 mm mesh sizes) and gillnets ($\geq$120 mm mesh size). One can note that the majority of vessels operating in the area are small boats (under 24 m long, apart from the large pelagic trawlers) and that the spatial partitioning of effort indicates that the different fishing gears do not operate in the same areas (Table 2 and Figure 3).

Cluster 2, in violet, is also specific to area VIIe but is located much closer to the boundary with the eastern Channel (Figure 2). As for Cluster 1, retained catches are also dominated by the "other" group and account for large landings of cephalopods. However, the remaining important species are not shellfish but less important commercial fish species such as gurnard, bib and small-spotted catshark (Table 1). Differences in fishing activity are also quite clear, with a strong dominance of OTB that accounts for 90% of the landings, and almost no contribution (<1%) from dredges and gillnets (Table 2). Remarkably, the effort maps show that twin trawls do not visit area VIIe, where

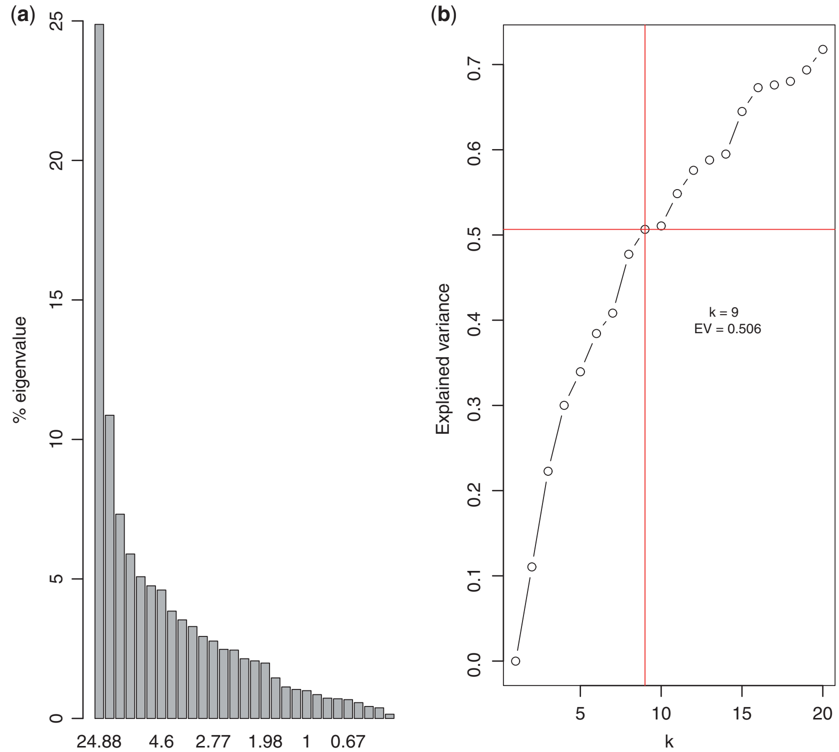

Figure 1. (a) Distribution of eigenvalues of the principal component analysis. (b) Percentage of explained variance as a function of the number of clusters.

only otter trawls can operate because of hard-bottom substrate (Figure 3).

Cluster 3, in green, has a specific "zebra" shape in the south of the Celtic Sea (VIIh, Figure 2). The species assemblage is dominated by monkfish, haddock, rays and megrim. This fishing ground is known as "Hauteur" by the French fishers that target monkfish, rays and haddock on the top of underwater sedimentary ridges. This area is only visited by trawlers, with a clear dominance of twin trawls with 100–119 mm mesh size that are responsible for 87% of the catches (Table 2).

Cluster 4, in yellow, corresponds to the continental slope where landings are clearly dominated by pelagic species (jack, horse and Atlantic mackerels and hake) targeted by large pelagic trawls (vessels superior to 40 m long using mesh sizes between 32 and 69 mm are responsible for 74% of the catches in this cluster) and gillnetters with mesh sizes ≥100 mm (which contribute to 18% of the catches, Table 1). Their activity in this area is well identified on the effort maps (Figure 3).

Cluster 5, in orange, has several non-continuous patches along the English coast (Figure 2). The typical profile of landings consists of a strong gadoid assemblage (including, by order of importance, haddock, whiting and cod) with a substantial amount of monkfishes. The other species include cephalopods, spotted ray, red gurnard and pouting. These gadoid patches are mainly targeted by otter trawls and otter twin trawls using mesh size ranges of 100–119 mm (85% and 7% of the landings, respectively).

Cluster 6, in dark purple, represents areas often spatially close to Cluster 5, but is also characterized by a gadoid assemblage. The species composition is different, however, with more cod caught and less whiting on an average. The remaining catches are also quite distinct from Cluster 5 (john dory, mackerel and pollack, but no rays) despite the fact that the exploitation pattern in terms of gear and mesh sizes is consistent [77% of the landings coming from OTB (Bottom otter trawls bottom, implicitly single trawl) and 8% from OTT (Otter twin trawl)]. Nevertheless, gillnetters are more active in this area than in Cluster 5 (Table 2).

It is worth noting that Cluster 7, in pink, delineates the nephrops fishing units in the Celtic Sea (Figure 2). Analysis of retained catch profile indicates that this species is closely related to the catches of the gadoid species, especially cod and haddock. The area is mostly exploited by otter twin trawlers (83% of the landings, Table 2). Interestingly, the shape of this cluster is well described in the effort map for this fishing gear (Figure 3).

Cluster 8, in brown, is mostly distributed in ICES division VIIh, like Cluster 3, with a few patches close to Cluster 4 along the continental slope (Figure 2). This cluster has a similar species assemblage to Cluster 3 but with different relative species contributions (monkfishes, haddock, ray and megrim) and a non-negligible pelagic component (especially hake and mackerel). The fishing activity is quite diverse in this cluster, with four dominant gears (OTT, OTB, OTM and gillnet) responsible for 55%, 25%, 11% and 8% of the landings, respectively (Table 2).

Cluster 9, in blue, is widely distributed and defined by important landings of mackerel, haddock and monkfishes. Monkfishes are found in almost all clusters and are known to inhabit areas both inside and outside the Celtic Sea, including the Bay of Biscay and West of Scotland. The second most caught species, haddock, is also caught across the entire Celtic Sea. In line with

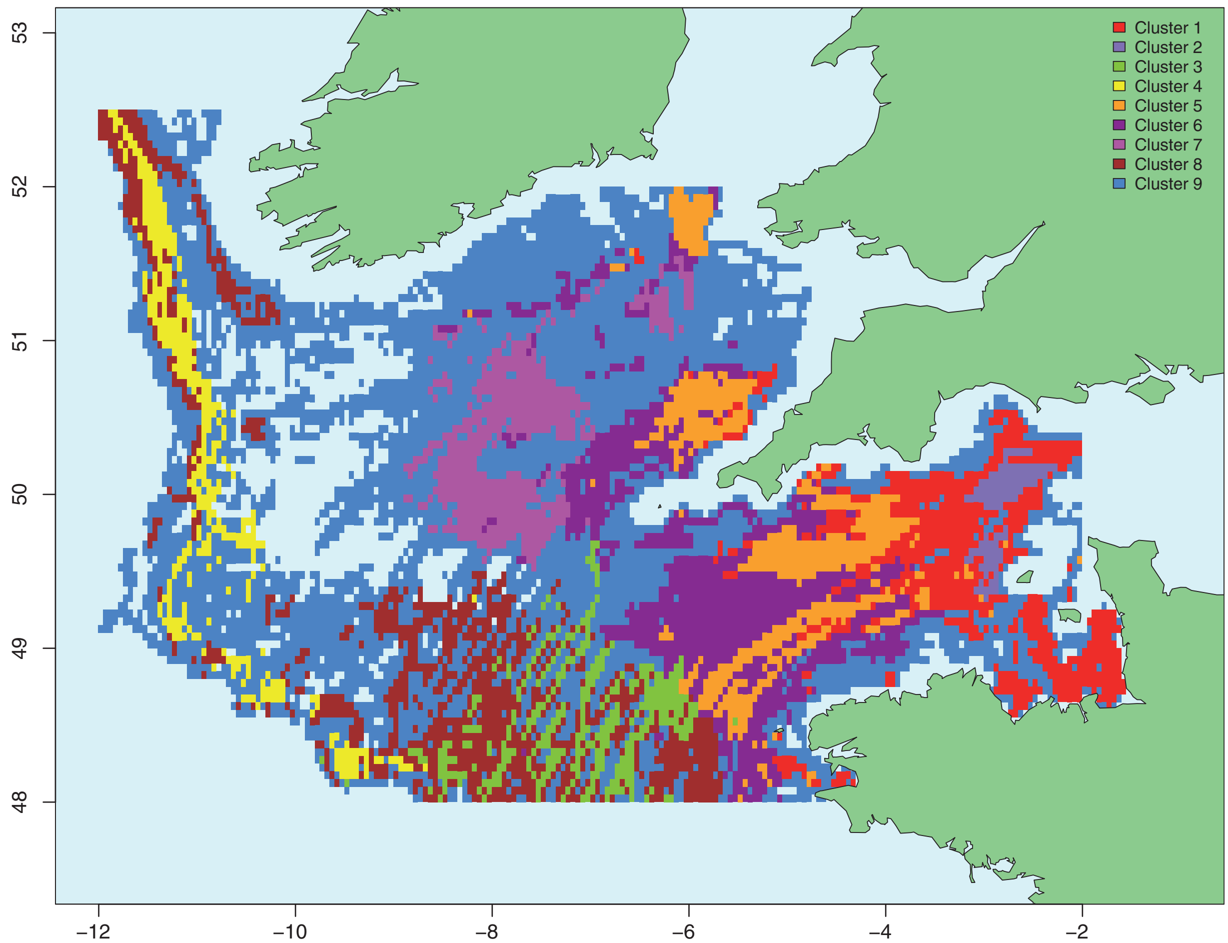

Figure 2. Cluster map. The same colour code was assigned to each 3′*3′ square belonging to the same cluster (nine clusters).

Cluster 8 and because of its broad spatial coverage, this cluster is characterized by a high diversity of fishing activity (gear, vessel size and mesh size) with no clear dominance.

Interestingly, the cluster analysis and the effort maps leave an entire area which appears to be "empty" because the French fleet made no catches there.

Discussion

Fine-scale spatial knowledge of fisheries is now recognized as an essential tool for effective fisheries management, avoiding failures caused by inappropriately defined boundaries, disregard for spatial dynamics in assessments, and incompatible ocean uses (Lorenzen *et al.*, 2010). The present study provides the first fine-scale spatial analysis of French landings and fishing time in the Celtic Sea. The results show that retained catches are highly structured in space, forming distinct homogeneous patches of species assemblages. The spatial distance between grid cells was not taken into account in the cluster analysis, so the emerging spatial pattern only results from similarities between the composition of retained catches in neighbouring cells (as in Gerritsen *et al.*, 2012). Additionally, Figure 3 illustrates the considerable spatial structure in effort (fishing time) by gear. When jointly analyzing the two maps, one can see the lack of similarity between the cluster map of retained catches and the one showing effort by fishing gear. Several clusters are associated with a high diversity of gears, landing a homogeneous species assemblage. As a result, there is no clear link between retained catch assemblages and fishing gears used. These two observations support our approach that focuses on spatially homogeneous species assemblages from catch instead of gear and metier based on broad target species (CRU for crustaceans, DEF for demersal fish, DWS deep water species). Detailed seabed habitat maps are not available for the entire area, preventing us from investigating in detail the relationship between species assemblages and benthic characteristics in the Celtic sea.

The cluster analysis highlights key issues for the management of mixed fisheries. This study suggests that no single situation describes the mixed fisheries in the Celtic Sea, but rather that there are several distinct cases of mixed fisheries: e.g. (i) a single species can be caught in different areas and targeted by a diversity of métiers (e.g. Monkfish), (ii) a single species can be targeted in a specific area but with large retained catches of other important commercial species (e.g. Cluster 7, where the target species is nephrops but where valuable gadoid species are also caught), and (iii) the local topography and nature of the fishing ground can result in some assemblages of species changing over a very short spatial distance (Clusters 8, 9 and 3 in the "Hauteur" area, ICES division VIIh).

Working at a fine spatial scale reveals that management areas such as ICES divisions and statistical rectangles cannot take into account the spatial heterogeneity of fishing grounds. It also offers

Table 1. Characterization of clusters in terms of species assemblage.

Cluster	FAO	Species	Landings %
1	**QSC**	**Queen scallop**	17.3
	OTH	Others	13.6
	SCE	**Great atlantic scallop**	10.1
	GKL	**Common european bittersweet**	8.0
	CTC	Common cuttlefish	7.8
	SCR	**Spinous spider crab**	5.8
	BIB	Pouting (Bib)	5.0
	GUR	Red gurnard	4.6
	WHG	Whiting	3.6
	HAD	Haddock	3.5
2	**OTH**	**Others**	14.1
	GUR	**Red gurnard**	12.0
	BIB	**Pouting (Bib)**	11.8
	CTC	**Common cuttlefish**	10.6
	WHG	**Whiting**	8.7
	SYC	**Small-spotted catshark**	7.4
	QSC	Queen scallop	5.9
	MNZ	Monkfishes	4.6
	HAD	Haddock	4.4
3	**MNZ**	**Monkfishes**	33.5
	HAD	Haddock	13.5
	RJN	**Cuckoo ray**	12.3
	LEZ	**Megrims**	8.7
	CTC	Common cuttlefish	7.8
	OTH	Others	6.9
4	**JAX**	**Jack and horse mackerel**	59.8
	HKE	**European hake**	18.7
	MAC	**Atlantic mackerel**	14.1
5	**HAD**	**Haddock**	19.4
	WHG	Whiting	12.8
	MNZ	Monkfishes	12.1
	OTH	Others	7.6
	COD	Atlantic cod	6.0
	CTC	Common cuttlefish	5.6
	GUR	Red gurnard	4.7
	BIB	Pouting (Bib)	4.2
	RJM	**Spoteed ray**	4.0
	SQZ	Inshore squids	4.0
6	HAD	Haddock	24.8
	MNZ	Monkfishes	15.4
	COD	Atlantic cod	8.6
	OTH	Others	8.5
	WHG	Whiting	7.2
	CTC	Common cuttlefish	3.6
	JOD	John dory	3.6
	JAX	Jack and horse mackerel	3.2
	GUR	Red gurnard	3.1
	POL	Pollack	2.8
7	MNZ	Monkfishes	17.2
	COD	**Atlantic cod**	15.3
	HAD	Haddock	15.2
	NEP	**Norway lobster**	14.0
	OTH	Others	8.9
	LEZ	Megrims	8.8
8	MNZ	Monkfishes	32.2
	LEZ	Megrims	11.5
	RJN	Cuckoo ray	9.2
	HKE	European hake	8.5
	HAD	Haddock	8.0
	JAX	Jack and horse mackerel	7.5
	OTH	Others	6.3
9	JAX	Jack and horse mackerel	17.9
	HAD	Haddock	16.1
	MNZ	Monkfishes	12.7
	OTH	Others	9.4
	HKE	European hake	9.1
	COD	Atlantic cod	7.0
	LEZ	Megrims	4.9
	WHG	Whiting	4.2

Continued

Table 1. continued

Species names in bold correspond to Indval species. Only 80% of the landed species are presented.

very useful complimentary information for spatial management purposes. This study shows that ICES area VIIe is different from the central Celtic Sea in terms of species assemblage caught (more bivalves, crustaceans and cephalopods) and fishing activity (dredge areas, trawls using smaller mesh sizes, smaller boats or no twin trawls). For species harvested in the entire study zone, use of smaller mesh sizes in a specific area could influence the length distribution of landings and amount of discarded fish. This emphasizes the need to process the data at least at the ICES-area level or to account for mesh sizes in the definition of métiers. This is often specified in the data call, but not always possible, especially for discard estimates, because of sampling size.

Many previous papers have focussed on fleet and métier definition, but few studies explicitly account for the spatial dimension. The spatial clusters identified in this study can be used to define relevant fleets/métiers in mixed-fisheries models. These models are often built upon publically available international data sets initially tailored to answer specific data calls. Our results can provide some insights that could improve such data calls with the objective of providing a better description of the Celtic Sea fisheries. STECF data sets use the fleet definition as specified in the 2008 long-term management plan for cod in the North Sea (regulation (EC) 1342/2008). These gear/mesh groupings are now applied to other areas than the North Sea and are widely used in bio-economics modelling, technical regulations and regional discard plans. Our study demonstrates that there are limitations to using these fleet/métier definitions for a region with fisheries distinct from those operating in the North Sea. While TR1 [aggregation level grouping trawlers with large mesh size (over 100 mm)] and TR2 (aggregation level grouping trawlers with smaller mesh size) may adequately segregate demersal gadoid fisheries from nephrops-directed fisheries in the North Sea, this is not the case in the Celtic Sea, as nephrops are mostly caught with large mesh sizes (Cluster 7, Tables 1 and 2), at least by the French fleet. Additionally, "TR" pools together OTT and OTB gears. However, the effort maps and Table 2 indicate small overlapping areas between the two gears/métiers and differences in landed species profiles. It is worth noting, that ICES data call for the Celtic Sea also pools together OTT and OTB fishing gears.

First runs of mixed-fisheries models such as Fcube identified important inconsistencies between TACs of the three main gadoid stocks (cod, haddock and whiting), leading to patterns of high discarding when all TACs are entirely taken (ICES, 2014). The statement is reinforced by our results, showing that these three species are often caught together in similar spatial units that form patches along the English coast (Clusters 5 and 6).

Table 2. Characterization of clusters in terms of fishing activity.

Cluster	Surface (km^2)	Gear code	% Lands	Mean effort (thousand h)	Mean nb of boats	Long.	Mesh size (mm)	Mean power (kW)	% Lands
1	23 268	OTB (+TB)	64.7	82.3	49	10 m<24 m	70–99	413	43.7
						24 m<40 m	32–69	520	11.6
						10 m<24 m	100–119	442	5.6
						24 m<40 m	100–119	560	2.7
		DRB	21.5	19.0	18	10 m<24 m	70–99	250	11.7
							16–31	252	9.0
		GNS+GTR+GTN	6.7	5.9	15	10 m<24 m	>120	290	6.6
		OTM	4.3	0.7	12	>40 m	32–69	2900	4.0
		SDN+SSC	2.2	0.9	3	24 m<40 m	100–119	588	1.2
		Others	<1%	–	–	–	–	–	–
2	3254	OTB	91.0	219.3	27	10 m<24 m	70–99	459	49.1
						24 m<40 m	32–69	526	32.2
						10 m<24 m	100–119	454	6.7
						24 m<40 m	100–119	546	2.6
		OTM	4.6	1.1	5	>40 m	32–69	3107	4.2
		SDN+SSC	3.8	9.1	1	24 m<40 m	100–119	588	1.9
							70–99	588	1.9
		Others	<1%	–	–	–	–	–	–
3	10 352	OTT	87.7	158.9	23	10 m<24 m	100–119	420	72.0
							70–99	413	9.0
						24 m<40 m	100–119	454	6.6
		OTB (+TB)	10.8	16.1	28	10 m<24 m	100–119	430	6.3
						24 m<40 m	100–119	568	3.6
		Others	<1%	–	–	–	–	–	–
4	11 495	OTM	74.2	2.0	1	>40 m	32–69	2673	74.2
		GNS	18.7	32.6	8	24 m<40 m	100–119	548	15.2
						10 m<24 m	100–119	450	2.9
		OTB	3.9	13.2	10	24 m<40 m	32–69	598	2.6
							100–119	660	1.2
		OTT	3.2	12.3	10	24 m<40 m	100–119	685	1.7
						10 m<24 m	100–119	559	1.5
		Others	<1%	–	–	–	–	–	–
5	19 189	OTB (+TB)	85.0	146.0	41	10 m<24 m	100–119	443	34.8
						24 m<40 m	100–119	554	22.8
							32–69	518	14.8
						10 m<24 m	70–99	454	12.3
		OTT	7.3	9.8	21	10 m<24 m	100–119	436	7.0
		GN+GNS+GTR+ GTN	3.5	9.9	11	10 m<24 m	>120	261	3.4
		OTM	3.1	0.4	8	>40 m	32–69	2667	2.9
		Others	<1%	–	–	–	–	–	–
6	35 566	OTB (+TB)	77.6	59.5	39	10 m<24 m	100–119	434	31.6
						24 m<40 m	100–119	558	24.6
							32–69	515	12.5
						10 m<24 m	70–99	434	8.7
		GN+GNS+GTR+GTN	9.1	9.8	11	10 m<24 m	>120	255	9.0
		OTT	8.3	6.9	28	10 m<24 m	100–119	429	7.6
		OTM	3.7	0.2	9	>40 m	32–69	2679	3.5
		SDN+SSC	1.3	0.5	2	24 m<40 m	100–119	588	1.2
		Others	<1%	–	–	–	–	–	–
7	16 964	OTT	82.8	78.9	14	10 m<24 m	100–119	399	82.7
		OTB (+TB)	14.7	15.9	20	10 m<24 m	100–119	374	11.7
						24 m<40 m	100–119	573	2.9
		SDN+SSC	2.5	1.0	1	24 m<40 m	100–119	588	2.5
		Others	<1%	–	–	–	–	–	–
8	32 692	OTT	55.3	39.8	24	10 m<24 m	100–119	430	44.6
						24 m<40 m	100–119	500	6.8
						10 m<24 m	70–99	411	3.6
		OTB (+TB)	25.6	13.6	34	24 m<40 m	32–69	515	15.2
							100–119	638	6.8
						10 m<24 m	100–119	423	3.1
		OTM	11.1	0.1	3	>40 m	32–69	2697	11.1
		GNS+GTR	7.9	2.6	11	24 m<40 m	100–119	544	3.5
							>120	569	2.5
						10 m<24 m	>120	372	1.3
		Others	<1%	–	–	–	–	–	–

Continued

Table 2. continued

Cluster	Surface (km^2)	Gear code	% Lands	Mean effort (thousand h)	Mean nb of boats	Long.	Mesh size (mm)	Mean power (kW)	% Lands
9	153 326	OTB (+TB)	40.4	8.1	68	10 m<24 m	100–119	430	15.5
						24 m<40 m	100–119	575	14.0
							32–69	730	6.4
						10 m<24 m	70–99	411	4.1
		OTT	26.5	6.7	32	10 m<24 m	100–119	423	25.1
						24 m<40 m	100–119	571	1.2
		OTM	21.8	0.1	14	>40 m	32–69	2638	21.4
		GN+GNS+GTR+GTN	9.0	1.4	23	24 m<40 m	>120	436	4.3
						10 m<24 m	>120	299	2.5
						24 m<40 m	100–119	511	1.7
		Others	<1%	–	–	–	–	–	–

Percentage of landings inferior to 1% were grouped.

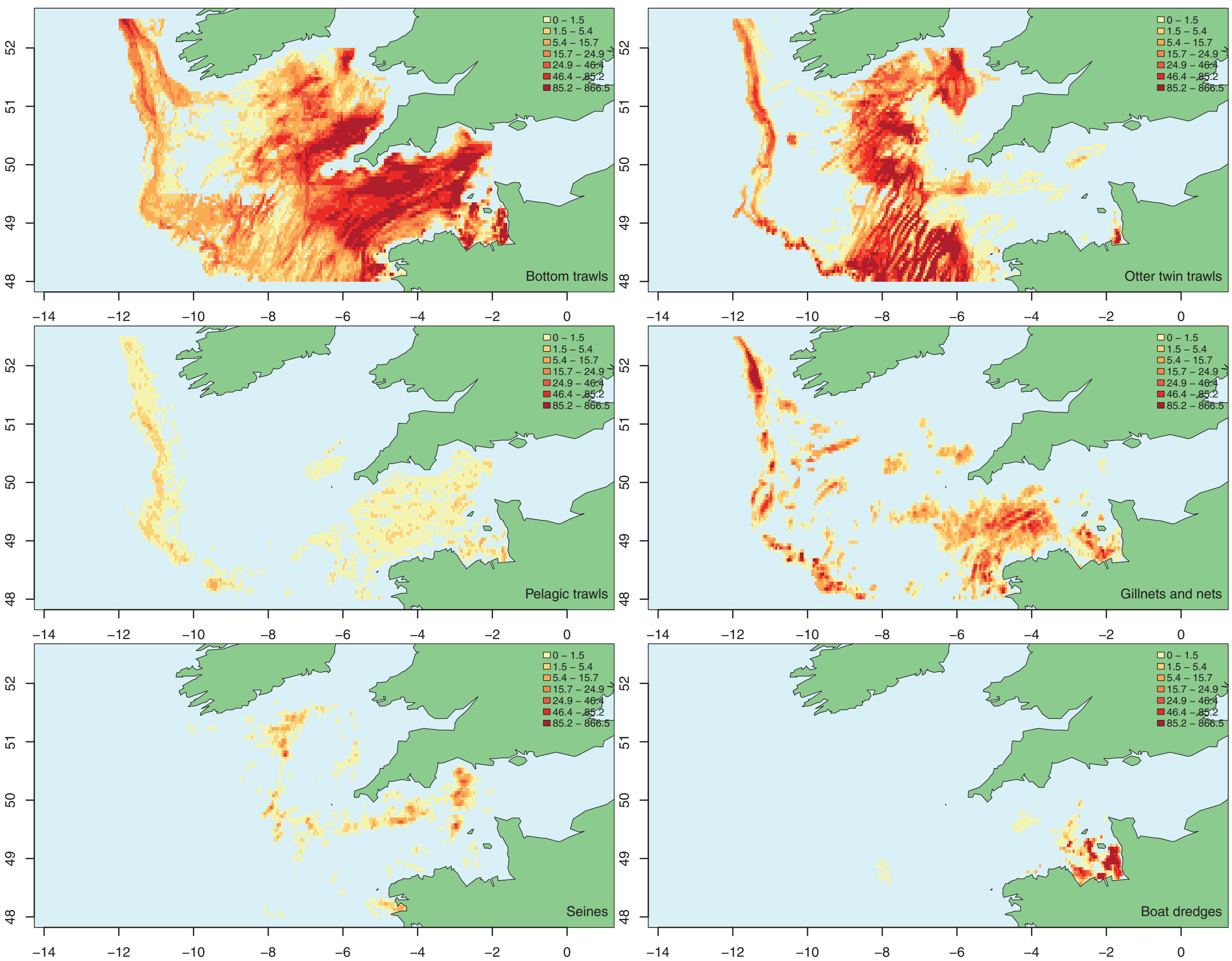

Figure 3. Effort map. Fine-scale (3′*3′) spatial distribution of fishing hours by fishing gears.

The future implementation of the landing obligation will exacerbate problems with choke species in mixed fisheries. Comparison of cluster maps built on retained catches (like the one presented here) and on at-sea observer data (especially on catches of fish below the minimum conservation reference size) or on subsets of vulnerable species would help to identify areas that should be avoided because of high bycatch rate, and potential areas where effort could be reallocated. Looking at our results, one clear example would be the OTT fleet targeting nephrops, which has a high probability of being choked by their simultaneous captures of gadoids in case of restrictive TACs at national or vessel levels. Possibilities of effort reallocation would be difficult as nephrops grow on a well-known and restricted habitat. In contrast, spatiotemporal changes in fishers' strategies would be easier for métiers targeting monkfish and haddock, e.g. as their catches are more widely distributed. More precise scenarios can be investigated by running the same analysis for a specific fleet or métier.

This study is similar to the one by (Gerritsen et al., 2012), where the data analyzed were of the Irish landings in the Ireland EEZ. In contrast with (Gerritsen et al., 2012) though, a PCA was carried out before the cluster analysis to reduce the multidimensional catch matrix to a smaller number of informative components and to account for interactions among species across grid cells (Deporte *et al.*, 2012). As such, this study is more focused on a multi-species approach than was that of (Gerritsen et al., 2012). On the overlapping area (northern Celtic Sea), fishing grounds identified by (Gerritsen et al., 2012) are also delineated in the present study. Examples include the nephrops fishing ground (Cluster 7), some gadoid patches (Cluster 5) and part of the "empty areas" (50.5°N; 10°W). This is an expected result as the nature of the bottom and environmental conditions are structuring factors for local species composition (Fraser et al., 2008). Both species abundance and bottom grounds have a structuring influence on the type of fishing gears to be used. Therefore, the fact that both studies show similar results validates both methodological approaches. As a consequence, analysis of the French VMS data in the Celtic Sea increases the spatial coverage of the picture drawn by Gerritsen *et al.* in 2012. Interestingly, the spatial clustering is also remarkably well correlated with a fishing ground map drawn based on fishers' knowledge (Pichon, 1992, Supplementary Figure S6).

When carrying out a cluster analysis, it is important to define the most appropriate number of clusters. A restricted number of clusters leads to large and therefore non-informative split, whereas the multiplication of too many clusters complicates the interpretation of the similarities between units. When increasing the number of clusters from 9 to 12 (Supplementary Figure S2), most of the clusters remained unchanged, which demonstrates their robustness. Three clusters were affected in their species composition and spatial coverage. The widely distributed Cluster 9 is split into two: Clusters 9 and 12. These both have the same percentage of mackerel and monkfish in their catch profiles, but Cluster 9 is also characterized by pelagic species, with a high proportion of hake, whereas Cluster 12 shows more catches of haddock, cod and whiting in the central part of the Celtic Sea. Interestingly, Cluster 5 becomes split into two (Clusters 5 and 11) which improves the identification of hot spots of the three main gadoid species (haddock, whiting and cod, Cluster 11) and also distinguishes the Celtic Sea patches from the one in the Channel. Spotted ray are also specific to Cluster 11. Finally, a new specific area appears in the Bay of Mont Saint Michel with a main interest in scallop (Cluster 10).

Because this analysis was derived from commercial landings data, its view does not reflect actual species abundance in the Celtic Sea, but is instead the result of local interactions between environment (depth, bottom type, hydrological conditions, and biological interactions) and fishing activity (catchability, fisher behaviour such as targeting and discarding practices, and management constraints) (Shephard et al., 2011; Engelhard et al., 2015). The maps presented in this study illustrate an average situation over 3 years (2010, 2011 and 2012). Establishing an average picture is an important element in designing multi-annual management measures and scenarios and developing a dedicated modelling framework. In parallel, it is also essential to understand the consequences of year-specific events such as episodes of high and low recruitments for instance, which are known to drive population dynamics in the Celtic Sea (ICES, 2014). It is well known that when the abundance of a species increases steeply, its spatial distribution tends to expand and the opposite is also the case. Analyses were run annually to investigate temporal variability (Supplementary Figures S3–S5). The main spatial patterns appear relatively stable over the years, supporting a strong spatial signal in the retained catches and spatial fishing footprint However, some clusters contracted or expanded according to year, such as Cluster 5 and local inter-annual variability in effort intensity and location can be observed. Gadoid patches were not present in the area to the south of Cornwall (VIIe) in 2010 and expanded in 2012. Indeed, 2012 exhibited high catch consistently, with substantially heightened TACs for the three main gadoid species compared with the other years, as the result of strong 2009 year classes fully entering the fisheries (ICES, 2014). Some areas were more variable than others, which could result from low fishing effort (e.g. low sampling/landings). This may be the case for the area to the south of Ireland, which is visited more by Irish vessels than by French ones (STECF, 2015a).

Analyses of the fine scale spatial patterns of landings and effort, because they describe the systems with increased accuracy and detail, have many applications: from model structure to scenario definition and evaluation of management measures. The cluster maps can be used to parameterize spatially explicit models (such as ISIS-FISH, e.g. Pelletier et al., 2009) or help in defining fishing units that implicitly account for spatial pattern in non-spatial models. The analysis can be performed on a quarterly basis and used to propose temporal closure of some areas to reduce the impact of fishing on certain species and habitat at sensitive periods such as reproduction. Based on additional assumptions, such as effort reallocation pattern, the consequences of spatiotemporal closure for catch reduction (and revenue if sale prices are available) can be calculated in detail (Gerritsen *et al.*, 2012). Indeed, results would be more accurate than performing such analysis at a statistical rectangle level. Spatial coverage of a closed area could be defined more precisely, which could guarantee a more efficient regulation of fishing effort with less detrimental effects for fishers than implementing a measure at a higher scale such as a statistical rectangle. For example, identification of small scale empty patches (as the white cells highlighted in Figure 2) can be used to propose conservation measures as their create *de factor* refugia for vulnerable species (Shephard et al., 2012). Such results could also help to improve sampling stratification or be included in analyses with other economic activities in a context of spatial planning management. Finally, the results of our analysis could also be used to calculate landing per unit effort (lpue) per cluster. Indeed, lpue are often used as tuning time series in stock assessment models and help identify areas with high catch rates. Fine scale spatial analyses of total effort, total catches and lpue could also help in identifying if fishers allocate their maximum effort in areas where targeting retained catches is potentially greatest.

First attempts to develop short and long-term mixed fisheries models in the Celtic Sea revealed that such an exercise requires an accurate description of the national fisheries that play a substantial role in the area. Aggregated data sets and stock assessment outputs from ICES and STECF data calls need to be combined to build the biological components of the models that correctly split the effort between fleets and define the catchability of each métier. These data sets include catch composition, discards, effort and catch-at-age for all species, fleets and métiers, and economic information. One of the major constraints for the implementation of such approaches is the lack of detailed internationally available data. Therefore, the major challenge consists of allocating catch data for each species to fleets, and effort information to each metier, as the level of aggregation is different between data sources and countries, which tends to result in a complex process of aggregation/disaggregation of the available data sets. A key process to improving mixed fisheries models in the Celtic Sea would be to expand this analysis by including high-resolution data sets from all major countries involved in the Celtic Sea fisheries. This type of analysis would also help to identify how "empty" (in terms of catches and effort) some areas really are. Unfortunately, fine-scale logbook and VMS data are still difficult to access and share; preventing the short term development of such global approaches.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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