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Original Article

Fishing for euros: how mapping applications can assist in maintaining revenues under the Landing Obligation

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With the introduction of the Landing Obligation (LO) in EU fisheries, there is an increasing need for fishers to avoid unwanted catches while maximizing revenues. Improving understanding of the spatio-temporal dynamics of unwanted catches could assist the fishing industry optimize catches by altering where they fish. How following such advice relates to revenues and fishery dynamics requires more consideration. We take an existing hotspot mapping methodology and examine how it could be used to identify fishing opportunities under the LO in Irish (Celtic Sea) and Danish (North Sea and Skagerrak) demersal fisheries. We consider if fishing effort can be relocated to avoid unwanted catches while maintaining revenues. The value per unit effort of fishing activity in both areas was often linked to high catch rates of key demersal species (cod, haddock, hake, and whiting). Our analyses indicated, however, that there are options to fish in areas that could provide higher revenues while avoiding below minimum conservation reference size catches and choke species. This was evident across both case study areas demonstrating that hotspot mapping tools could have wide applicability. There does, however, remain a need to explore how the displacement of vessels may further alter species distributions and fleet economics.

Keywords: discards, economics, fishing tactics, hotspot maps, Landing Obligation, spatial avoidance

Introduction

Discards refer to catches that are returned to the sea during fishing operations. They have long been acknowledged as a widespread part of global fishing operations (Alverson *et al.*, 1994; Jennings *et al.*, 2001; Borges *et al.*, 2005; Catchpole *et al.*, 2014) with 9.1 million tonnes of discards being reported from marine capture fisheries between 2010 and 2014 (Pérez-Roda *et al.*, 2019). The issue of discarding has become a global concern in recent years with the incidental removal of resources threatening the sustainability of many species in addition to representing a waste of a rich source of dietary protein (Kelleher, 2005; Catchpole and Gray, 2010; Bellido *et al.*, 2011; Little *et al.*, 2015; Catchpole *et al.*, 2017). The gradual elimination of discards and unwanted catch in European fisheries was, therefore, identified as one of the main objectives of the EU Common Fisheries Policy reforms in 2013. This resulted in the gradual introduction of the Landing Obligation (LO) from 2015, with this legislation being fully implemented since the start of 2019. The LO prohibits the discarding of species subject to total allowable catches (TACs) and size limits, with some exemptions for species that have high survivability in addition to *de minimis* allowances, which allow for a discard fraction of up to 5% in fisheries when increased selectivity is difficult to achieve (European Commission, 2013; Catchpole *et al.*, 2014).

There are numerous reasons why fishers discard catches, from management constraints to environmental, economic, and social drivers (Alverson *et al.*, 1994; Hatcher, 2014; Rochet *et al.*, 2014; Milisenda *et al.*, 2017). From an economic perspective, it is often suggested that fishers are profit maximizers and will discard any element of their catch that is not profitable to land (Van Putten *et al.*, 2012; Batsleer *et al.*, 2015; Hatcher and Drakeford, 2015). It is also assumed that fishers will target areas of best catch, in terms of greatest catch rate and profitability (e.g. Holland and Sutinen, 1999; Wilen *et al.*, 2002; Tsitsika and Maravelias, 2008). With the introduction of the LO there is an increased incentive to avoid species that could 'choke' a fishery (Schorpe, 2010). The expectation is that fishers operating in mixed fisheries, in particular, where vessels operating a variety of gears target several different species, will modify their fishing behaviour (through technical and/or spatio-temporal changes) to avoid unwanted catches and comply with the prohibition. While advances in gear technology provide methods to increase selectivity, it is almost impossible to fully eliminate all unwanted catches from commercial gears in mixed fisheries while maintaining profitable fishing activity (Guillen *et al.*, 2018; Pointin *et al.*, 2019; Reid *et al.*, 2019; Rodríguez-Rodríguez *et al.*, 2019; Suuronen and Gilman, 2020). In addition to technological developments, therefore, it is assumed that the LO, and the need to avoid unwanted catches, may alter the spatio-temporal patterns of commercial fishing operations.

The importance of better understanding the spatio-temporal distribution of bycatch and adopting spatial avoidance techniques have been recognized by industry and scientists alike (Dunn *et al.*, 2011; Paradinas *et al.*, 2016). In recent years, numerous methods have utilized fisheries and vessel location data to identify and predict how catch compositions are likely to vary over space and time and how this relates to vessel dynamics (Fraser *et al.*, 2008; Lewison *et al.*, 2009; Lee *et al.*, 2010; Paradinas *et al.*, 2016; Bellido *et al.*, 2019; Reid *et al.*, 2019; Calderwood *et al.*, 2020). Scientists are now developing web-based applications to display the data produced by such methods in a digestible format, making the data more accessible to industry stakeholders (Reid *et al.*, 2019; Calderwood *et al.*, 2020). As these tools are developed, it is important to understand how the information within them relates to the many economic drivers of fishing behaviour. Certainly with the introduction of the LO there is a need to determine how any relocation of fishing effort to avoid unwanted catches may impact upon the profitability of fisheries, with regard to both fisheries that relocate activity and those that occur in areas that experience an influx of new fishing activity (Pointin *et al.*, 2019). In addition, a number of these tools have been developed on a case-by-case basis, concentrating on specific gear types or fisheries in specific geographic areas, using different methodologies for the spatial analyses. Furthermore, our understanding of how these methodologies and tools are applicable across multiple fisheries is also important as such work develops in the future (Paradinas *et al.*, 2016; Pennino *et al.*, 2017).

In this article, we aim to determine if it may be possible to relocate fishing effort to avoid unwanted catches while maintaining revenues within a fishery. This was achieved by first determining whether a link existed between the economics of fishing and discarding behaviour prior to the introduction of the LO. We then examine how the mapping of potential discard hotspots, designed to assist fishers in avoiding unwanted catches, also relate to vessel and fleet economics. The potential economic losses or gains associated with avoidance behaviours are examined. The potential displacement of fishing effort, if information in these maps was to be adhered to, is also considered. This work focuses on two case study fisheries: Irish demersal trawlers operating in the Celtic Sea and Danish demersal trawlers operating in the North Sea and Skagerrak.

Methods

Case study fisheries

Data collected from Irish and Danish demersal trawlers operating in the Celtic Sea and the North Sea and Skagerrak were compared (Figure 1). In both cases, only data from vessels operating TR1 gears, which are defined as bottom trawls, Danish seines and similar towed gears (excluding beam trawls) with cod end mesh sizes above 100 mm (European Commission, 2008; Davie and Lordan, 2011), were used. In the Irish fleet, the majority of TR1 vessels operates otter trawls and targets a mixed demersal whitefish fishery. The Irish fleet is subject to individual monthly quotas with no opportunities for quota swapping or sharing (DAFM, 2016a; Calderwood and Reid, 2019). The Danish TR1 vessels mainly operate otter trawls like the Irish, but in addition to whitefish, species like European plaice, anglerfish and *Nephrops* are also valued and targeted catches (Mortensen *et al.*, 2017, 2018; Plet-Hansen *et al.*, 2018). The Danish fleet is governed by an Individual Transferable Quota (ITQ) system, in which some fishers have subsequently formed quota pools to lease quota from other vessels or from a common quota pool (Andersen *et al.*, 2010; Mortensen *et al.*, 2018). Due to the low coverage of observer data, which feeds into the mapping methodology used, selecting data based on the TR1 definition provides sufficient data to formulate species hotspots and allow for the comparison of vessels targeting similar demersal fisheries in the Celtic Sea and North Sea and Skagerrak.

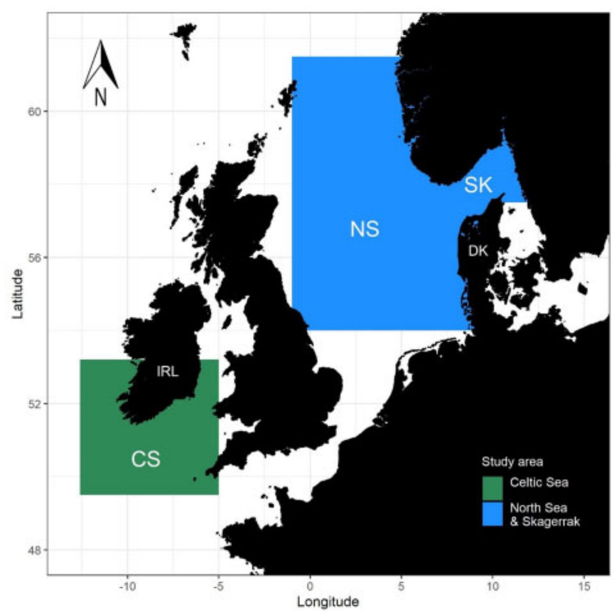

Figure 1. Map of Northwestern Europe with the study areas. Green colour indicates the CS, and blue colour indicates the NS and SK. CS, Celtic Sea; DK, Denmark; IRL, Ireland; NS, North Sea; SK, Skagerrak.

Irish and Danish data

Discard hotspots and value per unit effort data

Mean value per unit effort [VPUE—value of landed catch (€) per hour of fishing activity for total landed catch of all species caught] data were calculated using vessel monitoring system (VMS) and logbook data for all TR1 vessels operating in the two case study areas. Logbook data provided for both fisheries contained information on total weight of catches for TAC species. The monetary value of these catches was provided by the Sea Fisheries Protection Agency alongside logbook data for the Irish fisheries. In the Danish fishery, the Danish Fisheries Agency provides the same economic data from sales slips alongside logbook records. The VMStools package in R (Hintzen *et al.*, 2016) was used to remove erroneous data from the VMS dataset and to merge VMS and logbook data (Hintzen *et al.*, 2012; R Development Core Team, 2012). VMStools was then used to allocate daily catch weight and sales value data equally to each location along a vessel's recorded path where the associated vessel was recognized as being engaged in fishing operations, based on vessel's speed (Gerritsen and Lordan, 2011; Hintzen *et al.*, 2012). Value data were standardized to the value of catches per hour of fishing activity, with both catch volume and value being equally allocated across all fishing activities per trip. The resultant data were then allocated to 0.2° × 0.2° rectangles and mean values calculated for each cell. Mean values were first calculated using data collected between 2010 and 2015 to allow for comparison with discarding hotspots prior to the introduction of the LO. This process was repeated to produce mean values for data collected from 2016 to be used when assessing the usefulness of hotspot maps as a discard avoidance tool.

Data collected by on-board observers as part of the EU data collection framework (Council regulation (EC) No 199/2008) were used to determine discarding hotspots within both the Irish and Danish demersal fisheries for four key TAC species: cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), hake (*Merluccius merluccius*), and whiting (*Merlangius merlangus*). These four species were chosen based on their importance in both case study areas in terms of a combination of market value and abundance (see Supplementary Material 1 for more detail) in addition to potentially being key choke species, or species with high discard rates (such as cod in Ireland and whiting in Denmark). On-board sampling protocols followed those described by Håkansson (2019) and Borges *et al.* (2005), thus allowing for data on the weight of TAC species discarded to be raised to haul level using length weight keys for each species sampled. In the Celtic Sea, data were collected from a total of 2674 individual hauls from 226 trips, with an average trip length of 6.1 days, which took place on 50 different vessels between 2010 and 2015. In the North Sea and Skagerrak data were collected from 352 hauls from 250 trips, with an average trip length of 5.1 days, from 127 unique vessels between 2010 and 2015. Danish fisheries observer data were supplemented by Electronic Monitoring (EM) data for four vessels, providing information from a total of eight individual hauls from eight trips, with an average trip length of 7.6 days. Although this is a low number, these four vessels would otherwise not have any records as they had not conducted trips with an observer in the study period. EM sampling followed the descriptions by Bergsson *et al.* (2017) and Plet-Hansen *et al.* (2019), collecting length and weight estimates at the haul level.

Using the hotspot mapping methodology described by Calderwood *et al.* (2020), the 2010–2015 observer data were used to highlight discarding patterns prior to the introduction of the LO for any demersal species. First, the discarding rate (kg hr^{-1} of discards) was calculated per haul for each of the four TAC species selected. All data were then assigned to 0.2° × 0.2° grid cells, based on the geographical midpoint of each haul. Mean annual discard rates were calculated per grid cell and subsequently binned into five equal quantiles, following the removal of zero discard values, for which a separate category was assigned. Finally, an amalgamated map for 2010–2015 was created for each species by identifying grid cells that were consistently within the same binned category over multiple years. Thus, areas that displayed variability over multiple years were removed, leaving just those areas that showed consistent discarding rates over time (Calderwood *et al.*, 2020). Grid cells consistently containing the highest category of discard rates (top 40% of values) were selected and overlaid onto the gridded VPUE data for the period 2010–2015. To determine whether there was a relationship between the occurrence of high discarding hotspots and the value of total catches, the mean VPUE data were also binned into five equal quantiles. A χ^2 test was performed to compare the number of occurrences of discarding hotspots within each of these five VPUE categories for each species individually, and also for all four species together.

Total catch hotspots and VPUE data

Gridded hotspot maps were also created for the total catch rate (kg hr^{-1} caught) for both the above (>) and below (<) minimum conservation reference size (MCRS) components for the four key TAC species. The purpose of these maps is to use observer data to identify consistencies in catch patterns over multiple years, providing a tool to fishers to better inform decision-making on where to fish to optimize opportunities under the LO. In the Celtic Sea, a tri-national observer data set (French, British, and Irish data) was used to create these maps as described in Calderwood *et al.* (2020). The same approach was repeated for the North Sea and Skagerrak using EM data (Plet-Hansen *et al.*, 2019) and observer data from Danish vessels only.

To test how information contained within these maps might relate to future fleet economics, if such maps are to be used as a predictive tool to determine optimum fishing locations under the LO, we compared the two metrics. The mean VPUE of all species landed per 0.2° by 0.2° grid cell for 2016 was compared with the binned hotspot mapping category of the same grid cell calculated using data from 2010 to 2015 for each species and size class of interest (< and >MCRS cod, haddock, hake, and whiting). Data from 2010 to 2015 were used to create the hotspot maps to take account of all catches prior to the introduction of any LO legislation with regard to demersal fisheries to build up a picture of consistent catch patterns prior to the introduction of this legislation. In 2016, some LO restrictions were applicable to TR1 vessels operating in both case study areas. In the Celtic Sea, in 2016 vessels were required to land all whiting if in 2013/2014 >25% of their landed catch had consisted of cod, haddock, whiting, and saithe combined, or land all hake if >30% of their landed catch in 2013/2014 had consisted of this species (DAFM, 2016a). In the North Sea and Skagerrak, TR1 vessels were required to land all haddock and plaice. TR1 vessels with >50% of all landings comprised saithe during 2012–2014 would be categorized as a saithe

Table 1. The MCRS in centimetres for the key TAC species considered in this article.

Species	Minimum conservation reference size (cm), Celtic Sea and North Sea	Minimum conservation reference size (cm), Skagerrak
Cod	35	30
Haddock	30	27
Hake	27	30
Whiting	27	23

targeting vessel and would also be required to land all catches of saithe as well (European Commission, 2015a). In the Danish EM trial in the North Sea and Skagerrak, no significant change in discards of haddock was registered in 2016 compared to 2015 (Plet-Hansen *et al.*, 2019). These introductions may, however, have had some impact on fishing behaviour, as recorded by VMS and logbook data in 2016. A comparison of the hotspot maps, created with observer data from 2010 to 2015, with fishing data from the following year does still prove a valuable insight into how hotspot maps relate to the spatial variation in subsequent catch values and how this information could potentially be utilized following the full implementation of the LO. To achieve this mean VPUE data were tested for normality and homogeneity of variance prior to analysis using a number of tests as well as through the visual inspection of residuals. Normality was tested using Shapiro–Wilk's test with the homogeneity of variance then being tested using either a Bartlett or Levene's test depending on whether the data were deemed to be normal or not (Underwood, 1997). In all cases, data did not conform to the assumptions required for linear regression analysis, so general linear modelling (GLM) was run, fitted with a gamma distribution and a log link function to account for the positive skew of the data (Zuur *et al.*, 2009). Hotspot mapping categories were defined as ordered factors with the species and size category of the corresponding map fitted as additional fixed factors in the GLM. *Post hoc* Tukey tests were used to make comparisons among levels of significant terms.

Below MCRS avoidance scenarios

Under the LO, all catches of TAC species will have to be landed regardless of size, but only those catches >MCRS can be sold for human consumption (European Commission, 2015b). To maximize revenue, it would be important to target >MCRS catches while avoiding <MCRS fish (Table 1). We therefore assessed how the hotspot maps could be used to avoid <MCRS catches of the four key TAC species while targeting >MCRS catches of the same species. We then determined how this spatial avoidance could impact VPUE. The areas identified as consistently being in the top two categories in catch per unit effort (CPUE) hotspot maps (top 40% of catches by weight) for <MCRS and >MCRS catches were overlaid for each species. Grid cells were then identified either as being in the <MCRS or >MCRS category or as an area where high catch rates of these two size classes overlapped. Total vessel activity and associated VPUE were extracted from each relevant grid cell using 2016 logbook and VMS data. The mean 2016 VPUE data associated with each cell were again tested for normality and homogeneity of variance as previously described, but they did not meet the assumptions of analysis of variance even following data transformation. Due to the positive skew of the data, they were again analysed with a GLM fitted with a gamma distribution and log link function (Zuur *et al.*, 2009). The size category (three levels: <MCRS, >MCRS, overlap) was fitted as a fixed factor in the GLM. To account for the small and uneven sample sizes associated with each category, the analysis was run using Type III sum of squares (Quinn and Keough, 2002).

Species avoidance scenarios

The above procedure was applied to different cases illustrating one common choke species in the Irish fishery and one common choke in the Danish fishery (Schorpe, 2010). For the Irish fishery, the analysis focused on the overlap of the top two CPUE categories for the >MCRS components of whiting, which currently has reasonably large quota available, and haddock, which often has limited quotas available (Calderwood *et al.*, 2016). For the Danish fishery, we focused on the optimization of >MCRS cod catches (an important target species for Danish TR1 vessels in the North Sea) and the avoidance of hake, which is currently increasing in the North Sea. This has resulted in the TAC being relatively low compared to the spawning stock biomass because of the time lag in stock assessments and the relatively fast northward shift of the distribution in hake in this area (Kraak *et al.*, 2013; Baudron and Fernandes, 2015) and because historical catches of hake were low in the North Sea when catch shares were allocated within EU member states (Baudron and Fernandes, 2015). In addition, the price per kilogram of hake is generally lower, in the Danish markets, than that of cod, and the fish also has a tendency to be damaged during the haul, due to abrasion and pressure from the surrounding catch, which further reduces its sale value (Catchpole *et al.*, 2018; Plet-Hansen *et al.*, 2019). Thus, the top two CPUE categories for the >MCRS components of cod and hake were plotted and analysed. All analyses were undertaken in R 3.2.5 (R Core Team, 2017), and an overview of the data used in each section of the analyses is presented in Figure 2.

Results

Discarding hotspots and VPUE

There are spatial differences in where peak quantities of discards occur, for the four key commercial species highlighted, for both Irish and Danish fisheries. There are also differences in the relationship between discarding hotspots and landing values. In the Celtic Sea, discarding hotspots for both haddock and whiting are numerous and spread across the area. The majority of hotspots for both species has been identified between 5°W and 11°W and 50.5°N and 52.5°N, although hotspots for whiting are concentrated to the east of 9°W (Figure 3b and d). The majority of cod in the Irish fishery is consistently discarded in the southeast region of the study area with most discarding hotspots being below 51.5°N and/or east of 10°W (Figure 3a). Hake discards were also more concentrated south of 51°N (Figure 3c). There was a significant relationship between the occurrence of discarding hotspots and the mean catch value for all species in the Irish fishery (Supplementary Material 2A; Table 2). In the case of whiting, the greatest number of discarding hotspots was associated with the highest value fishing areas. Yet only 13 discarding hotpots were associated with these high value areas, representing 11.4% of such areas. The occurrence of discarding hotspots for cod, haddock, hake ,and the four species combined was mainly associated with the second highest value category, representing 8.8, 11.4, 9.6, and 26.3% of the total area associated with that value category, respectively.

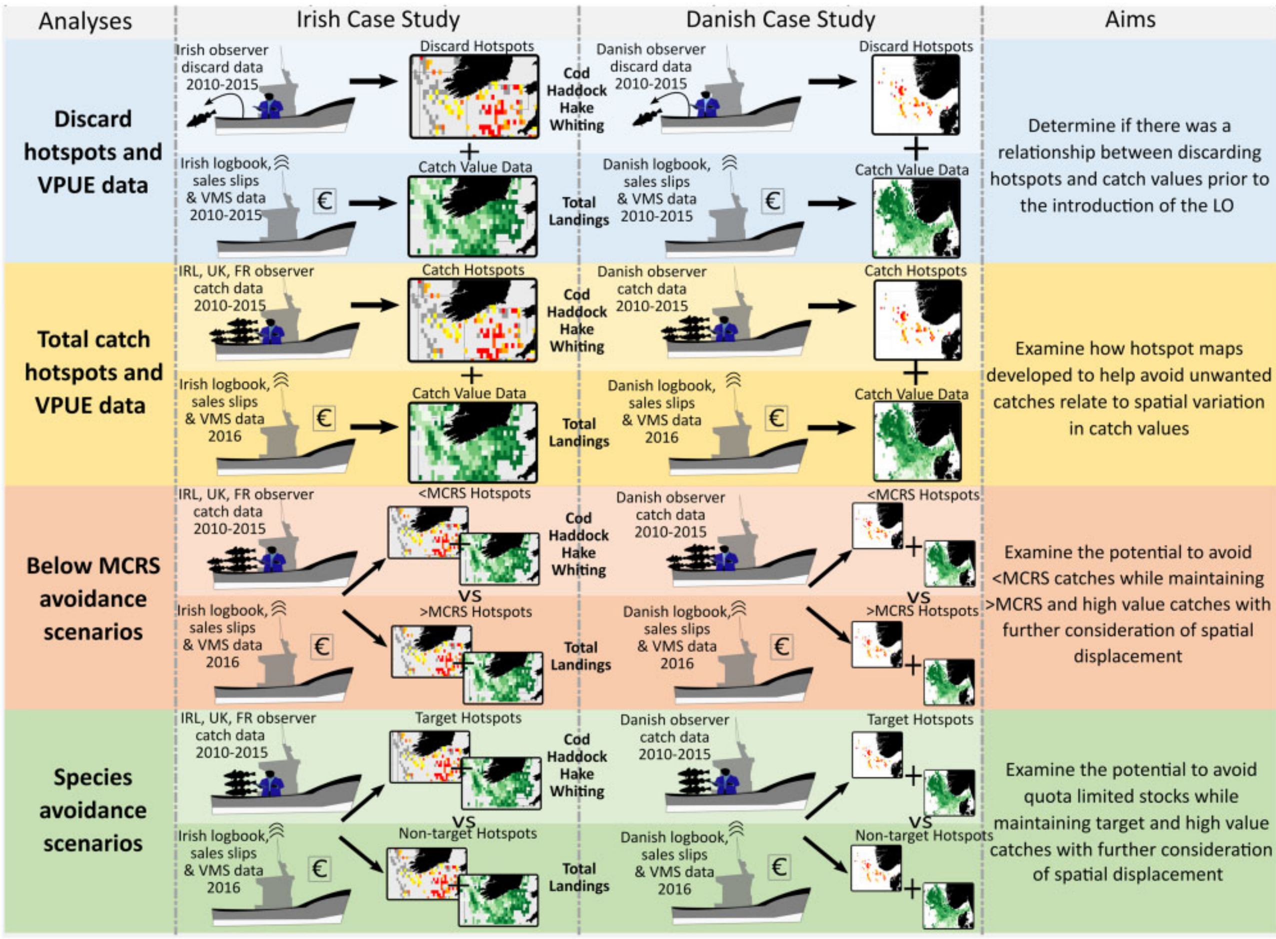

Figure 2. A schematic diagram to show the data inputs for each of the four sections of the analysis.

For the Danish fishery, cod discarding hotspots tend to be closer to the south and southwest coast of Norway as well as in the central North Sea. Haddock discarding hotspots overlap with several cod discarding hotspots in the northern North Sea but also occur along the 58° parallel north (Figure 4a and b). Except for one discarding hotspot, all hake hotspots occur in Skagerrak (Figure 4c). Whiting discarding hotspots are either at the boundary between Skagerrak and Kattegat or overlapping with haddock discarding hotspots, mainly in the northern North Sea (Figure 4d). An area between the Shetland Islands and Norway is low in discard hotspots for the Danish case, even when plotting discard hotspots for all four study species in one map (Figure 4e). In the Danish case, a significant relationship was found between VPUE and discarding hotspots for cod, haddock, and the combined species map only (Supplementary Material 2B; Table 2). Both cod and haddock had the highest number of discarding hotspots associated with grid cells in the second highest value category, the hotspots only overlapped with areas identified with the highest VPUE in 1.4, 1.4, and 3.3% of cases. It can be seen on the maps that this is mainly because of a large area in the northern North Sea with high value cells and no discarding hotspots identified (Figure 4).

Total catch hotspots and VPUE

There was no significant difference between the different species and size classes of each when examining the relationship between the mean value of catches in each grid cell and the associated level of consistent catches (based on CPUE) for Irish and Danish fisheries ($\chi^2 = 4.855$, $df = 7$, $p = 0.678$ and $\chi^2 = 5.840$, $df = 7$, $p = 0.559$). There was, however, a significant overall relationship between the mean value of catches in each grid cell of the hotspot maps examined and the associated level of consistent catches identified for both Irish and Danish fisheries ($\chi^2 = 42.395$, $df = 5$, $p < 0.001$ and $\chi^2 = 31.273$, $df = 4$, $p < 0.001$; Figure 5). *Post hoc* tests revealed that the value of total catches associated with the highest two CPUE categories in the hotspot maps was greater than the value of catches associated with all other hotspot mapping CPUE categories for Irish fisheries. For the Danish fisheries, it was only the highest CPUE category where the value of total catches was greater than the value of catches associated with all other hotspot mapping CPUE categories.

Below MCRS avoidance scenarios

For all four species in the Celtic Sea (Figure 6), the majority of the grid cells where there are consistently high catch rates for both the < and >MCRS fish are concentrated between 5–9°W and 50–53°N. Apart from haddock, the consistent >MCRS category occupies the most cells for each species for Celtic Sea fisheries. Haddock had an equal number of grid cells assigned to the >MCRS category and to the overlap of the < and >MCRS category. For all species, the percentage of vessel activity in each of

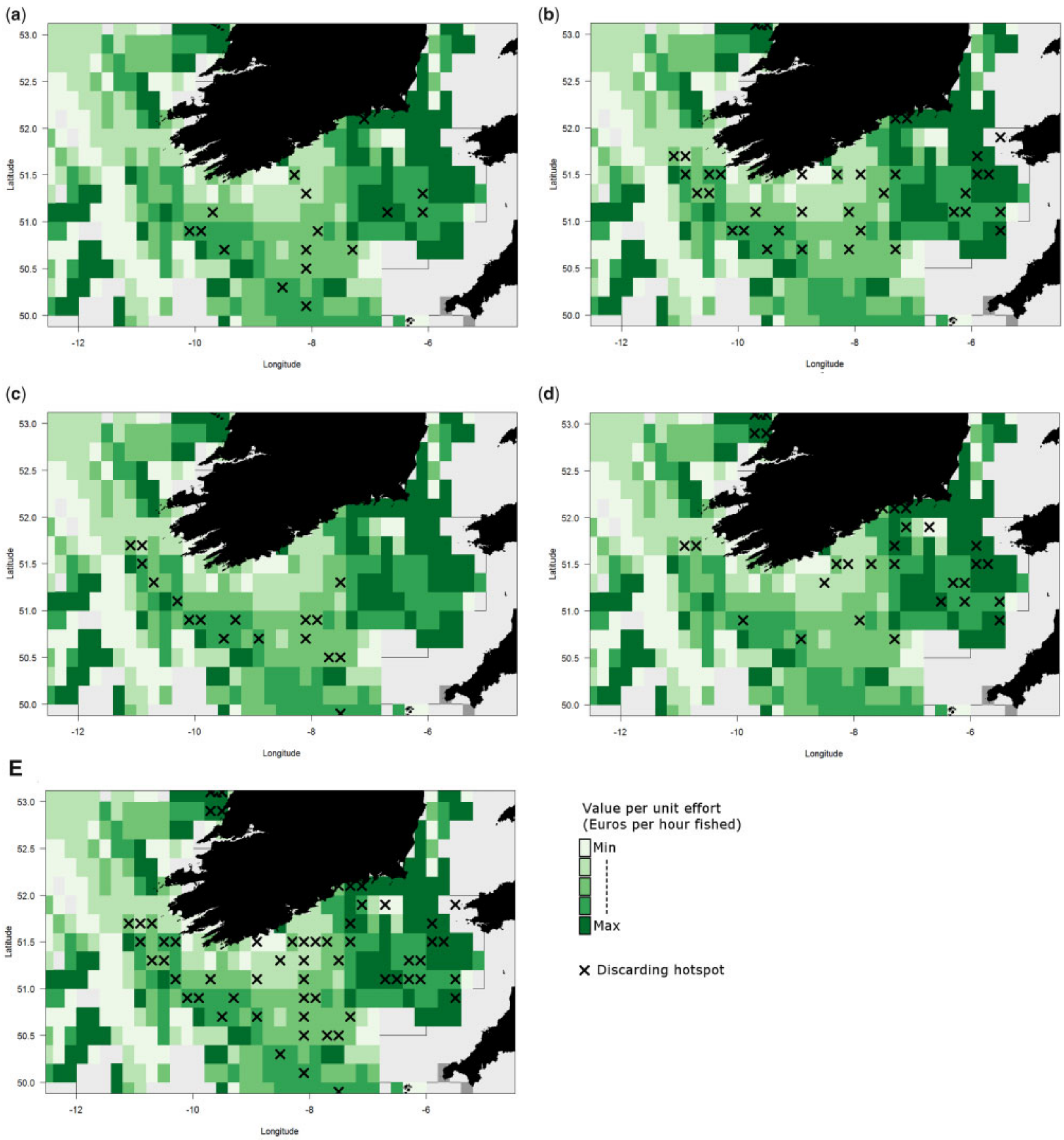

Figure 3. Maps showing the mean value of total catches (euro per hour) for the Irish fleet in the period 2010–2015 related to discarding hotspots identified during the same period for (a) cod, (b) haddock, (c) hake, (d) whiting, and (e) cod, haddock, hake, and whiting combined.

these areas in relation to activity in the Celtic Sea study area is greater for areas with consistently high catch rates of >MCRS species compared to where high >MCRS catch rates overlap with <MCRS catch rates (Supplementary Material 3). The highest percentage of vessel activity was recorded in areas with just >MCRS cod, with 10.8% of all fishing activity in the Celtic Sea area in 2016 occurring in this area. For each species, there was no statistically significant difference between the mean value of catches attributed to each of the cell categorization classes (Table 3), although there was a visible trend for lower values being associated with areas of high <MCRS catches for whiting and to a lesser extent cod (Supplementary Material 3).

For North Sea Danish fisheries, an area between 58–60°N and 2–4°E is associated with high >MCRS catch rates of cod. There is also a cluster of high >MCRS grid cells in the Skagerrak, but it should be noted that the MCRS is 5 cm lower for cod in Skagerrak than in the North Sea (Figure 7). Above MCRS catch rates of cod are associated with the highest number of grid cells

Table 2. χ^2 results testing the relationship between the value of catches for the Irish fleet operating in the Celtic Sea and the Danish fleet operating in the North Sea and Skagerrak in 2010 and 2015 and the association of discarding hotspots for cod, haddock, hake, whiting, and a combination of these species.

Area	Species	χ^2	df	p
Celtic Sea	Cod	18.12	4	**0.001**
	Haddock	14	4	**0.007**
	Hake	26.5	4	**<0.001**
	Whiting	14.25	4	**0.006**
	All	33.63	4	**<0.001**
North Sea and Skagerrak	Cod	19.769	4	**<0.001**
	Haddock	12.667	4	**0.013**
	Hake	3.500	4	0.478
	Whiting	8.000	4	0.092
	All	22.154	4	**<0.001**

Significant values ($p < 0.05$) are indicated in bold.

and associated vessel activity, but there was no significant difference in value fished between the three categories. Areas identified as having high catch rates of <MCRS cod are spread across the central North Sea and Skagerrak, while the overlap of the two size classes is identified throughout the North Sea. For haddock, 12 cells were assigned to both >MCRS catch rates and the overlap of > and <MCRS catch rates. A greater proportion of vessel activity was associated with the overlapped areas, although there was no significant difference in the mean value of catches across all three categories (Supplementary Material 3, Table 3). For hake, 26 out of 32 cells were categorized as having high >MCRS catch rates and only 2 cells were identified as having overlapping high < and >MCRS catch rates. In terms of vessel activity, the majority of overall vessel activity also occurred in the >MCRS catch rate areas, although areas associated with high <MCRS catch rates of hake also have a large share of activity while representing a much smaller area. Only a minute part of the vessel activity is associated with the two cells identified as overlapping areas, but these two cells have the highest mean VPUE (Supplementary Material 3). Whiting and hake show the highest hotspot cell counts and vessel activity associated with high >MCRS catch rate areas. However, where overlapping areas were few for hake, the smallest cell count and vessel activity occur for <MCRS associated areas for whiting. Just like for hake, the mean VPUE of cells is highest for overlapping areas for whiting (Supplementary Material 3; Table 3).

Species avoidance scenarios

The majority of grid cells in Figure 8a represents areas identified as having consistently high catch rates of both >MCRS haddock and whiting, with this overlap being identified in 26 grid cells and by 3.6% of all fishing activity in the region (Supplementary Material 4). Only two grid cells and 0.6% of the area's fishing activity are represented by areas with high whiting catches that are not overlapped by those areas with high haddock catches. There is no statistically significant difference between the mean value of catches associated with each of the areas identified on the map ($\chi^2 = 0.198$, df $= 2$, $p = 0.906$).

In the Danish example, cod has the highest number of grid cells assigned as having high catch rates while cells identified as having high catch rates of hake but no cod amount to 15 cells (Figure 8b). A total of 13 cells are identified as having overlap between cod and hake, of which 9 occur in the northern North Sea at around 58–60.5°N and 0.5–3.5°E. The vessel activity is much more associated with cod-related grid cells, while the vessel activity in grid cells with overlap between cod and hake and purely hake is roughly the same at 1.8–2.6% compared to 7.9% for areas with cod only (Supplementary Material 4). However, while the 13 cells with high catch shares of both cod and hake have a low share of the total vessel activity, the mean value per unit of effort is significantly different ($\chi^2 = 10.345$, df $= 2$, $p = 0.006$) between groups and is highest in the 13 cells with overlap between hake and cod.

Discussion

This study sought to determine if the extracted value of fisheries could be maintained following the relocation of fishing effort to avoid unwanted catches. First, a link between discarding hotspots and the VPUE of catches was established across two case studies from Irish and Danish fisheries for four key demersal species. In the context of the introduction of the LO, we considered how hotspot mapping tools may influence fishing behaviour, again finding a link between areas with predicted high catch rates and subsequent high VPUE of fishing activities. Further exploration of <MCRS fish and choke species avoidance scenarios using hotspot maps did demonstrate in some cases the options to avoid <MCRS fish or choke species remain limited. Although options did exist to avoid unwanted catches while still fishing in areas of high VPUE for all examples considered (Figure 9). Spatio-temporal measures, potentially coupled with advanced mapping technology, may prove useful to optimize the use of available quotas. This work did further provide an opportunity to examine how a tool developed for assisting in avoiding unwanted catches in the Celtic Sea can be applied elsewhere, demonstrating the wider applicability of this methodology.

When developing tools to aid in the spatio-temporal avoidance of unwanted catches, it is important to first consider how discarding practices relate to the wider fishery and overall VPUE of fishing activities. Our results show that discarding hotspots are widespread across each study region for all four species considered, but there is clear spatial variation in discarding between each of the species. We have considered these spatial distribution patterns broadly on a multi-annual basis, and more nuanced patterns may be evident if data were explored on a more seasonal basis. Due to the limited nature of observer data used in the construction of the hotspot maps, however, we were only able to construct an annual overview of fishing patterns in relation to discard and catch hotspots. There is also the potential that discarding trends may vary on shorter time scales and be influenced by the time left before a boat returns to port or by quota availability at the end of a season, although contradictory evidence exists as to whether remaining quota allocation influences discarding behaviour (Poos *et al.*, 2010; Calderwood and Reid, 2019). Again the resolution of the data available did not allow further consideration of these factors at this time.

Still, as may be expected in most instances, the discarding hotspots are found in areas where there are frequent occurrences of each species (Gerritsen *et al.*, 2012; Marine Institute, 2018). Where discarding hotspots occur in areas not associated with high catch rates of the same species, they are often associated with areas of high catches of other commercial species. For example, discarding hotspots are associated with ICES functional unit

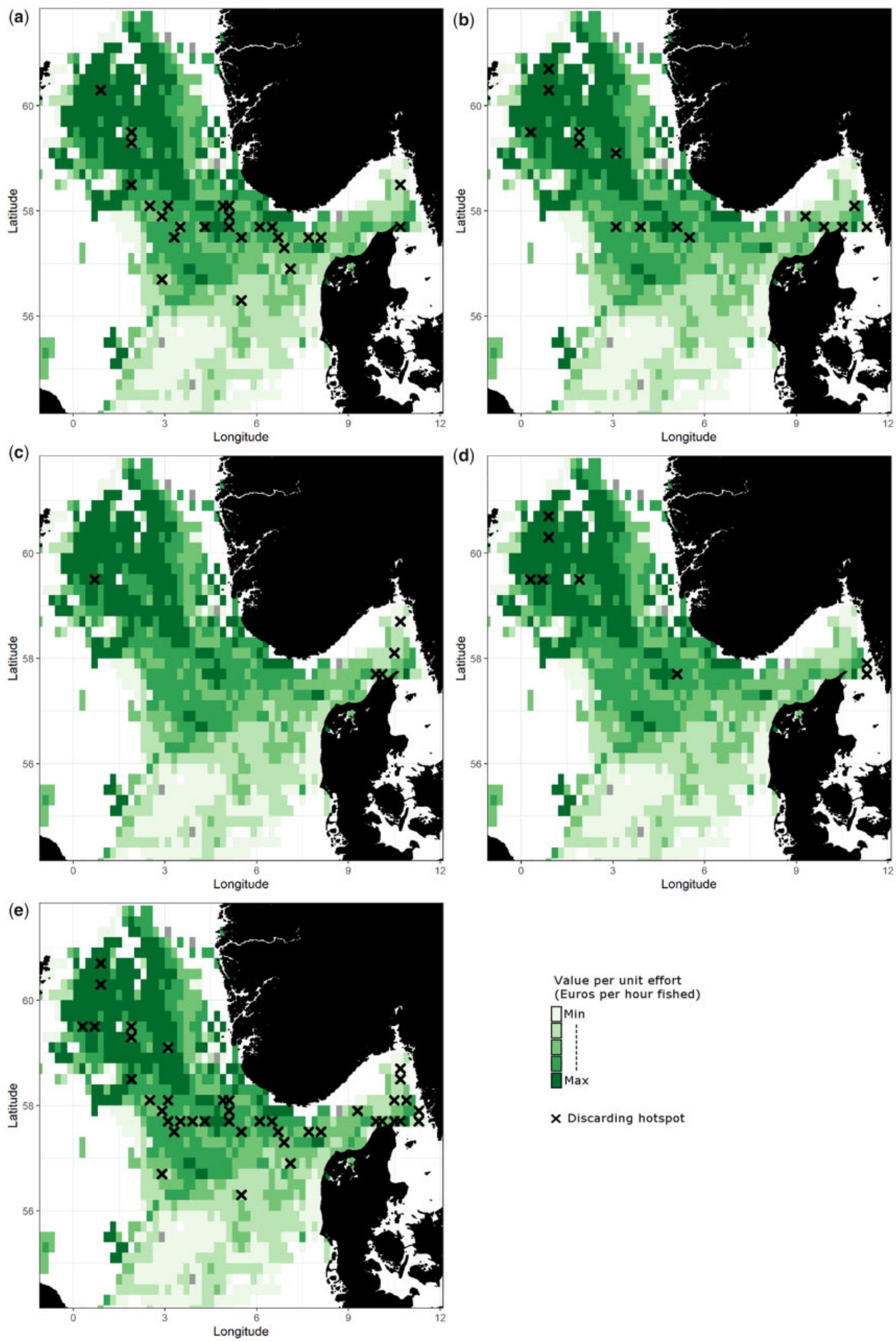

Figure 4. Maps showing the mean value of total catches (euro per hour) for the Danish fleet in the period 2010–2015 related to discarding hotspots identified during the same period for (a) cod, (b) haddock, (c) hake, (d) whiting, and (e) cod, haddock, hake, and whiting combined.

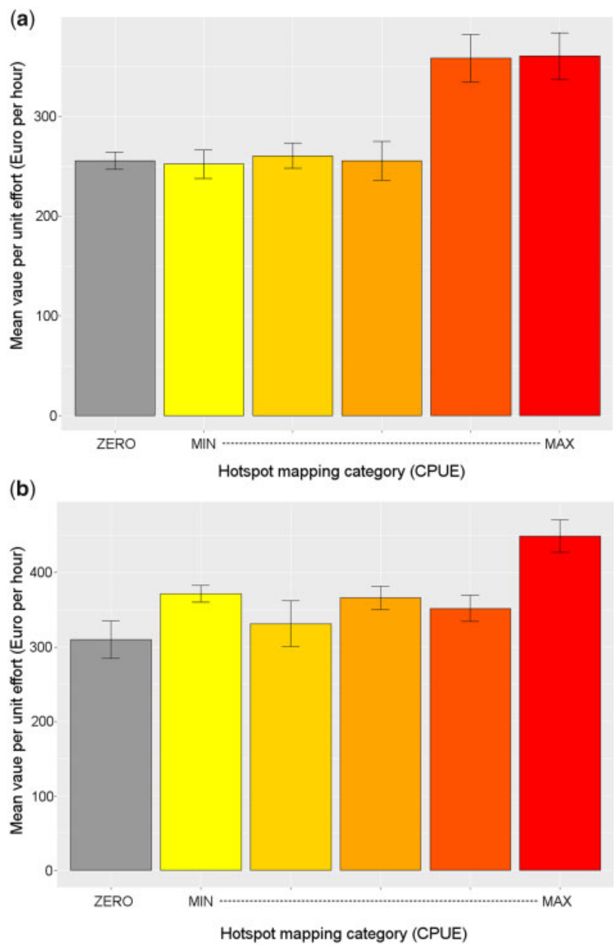

Figure 5. Bar charts showing the relationship between the mean VPUE of fishing effort in each 0.2° × 0.2° rectangle and the associated levels of catches (CPUE) consistently identified in these areas by hotspot maps amalgamated for all species and size classes for (a) the Irish fishery in the Celtic Sea and (b) the Danish fishery in the North Sea and Skagerrak.

22, also known as 'The Smalls', a prawn ground where landings are dominated by *Nephrops norvegicus* in the Celtic Sea (ICES, 2018a), and hotspots in the Skagerrak bordering the Kattegat management area, which are also important fishing grounds for *Nephrops* (Ravensbeck *et al.*, 2015; ICES, 2018b). There are also a few discarding hotspots for cod and haddock occurring in the Central North Sea, likely associated with plaice catches in these shallower areas (Mortensen *et al.*, 2015; ICES, 2018c). For discarding hotspots that occur in areas where there are high catches of other commercially important species, such as *Nephrops*, spatial avoidance may not be possible as a tactic to reduce discards. In such areas, increased uptake of more selective gears, which may allow for the escape of gadoid species while retaining flatfish and crustaceans, could be beneficial instead (O'Neill *et al.*, 2019). Identifying these discarding hotspots that are primarily the result of bycatch in other species fisheries is of critical importance, and this could be achieved by focusing similar analyses on more fleet segments and metiers, but this again requires a greater provision of fisheries data from the fleet.

If a fisher is a profit maximizer, and economic drivers influence the spatial nature of fisheries, the results from this study indicate that there are options to fish in areas associated with higher-value catches while potentially avoiding catches that would otherwise be discarded. There is greater value associated with cells that have consistently high catches of all species studied. Certainly larger volumes of landings are often associated with higher earnings in mixed fisheries, as long as there is a good mix of marketable species within the catch. We do, however, only consider the value of landed catches and not the total profits made by a vessel after accounting for running and staff costs during this study. Travelling further to areas where there is the potential to catch more valuable species or larger volumes of fish may be counteracted by increased fuel costs associated with steaming to these locations. Yet the majority of discarding hotspots is not associated with areas with the highest value catches suggesting that fishers have many potential options to make money across both case study areas while avoiding unwanted catches.

Fine-scale spatial knowledge of fisheries and the economic value associated with them may be important in helping to provide the knowledge to reduce unwanted catches while maintaining income (Mateo *et al.*, 2017; Calderwood *et al.*, 2020). Developing tools and resources to effectively communicate such information to the fishing community could therefore be essential in both of the case study areas to ensure that fishers are enabled to make optimum decisions with regard to where to fish to optimize catches while maintaining profitability. This could take the form of fleet communication programmes, for which numerous examples have been highlighted from fisheries throughout the world (Gilman *et al.*, 2006; Little *et al.*, 2015; Eliasen and Bichel, 2016), or decision support tools provided by the scientific community, as are increasingly being developed (Reid *et al.*, 2019).

Despite general similarities in the relationship observed between the discarding patterns and overall VPUE in the two case studies in 2010–2015, the strategies adopted to avoid unwanted catches may be quite different between Danish and Irish fishers. This is mainly due to the difference in the quota allocation and management system in these two countries. Danish fishers may better be able to mitigate quota restriction by acquiring additional quota for the specific species since Denmark manages its quota allocations with an ITQ system (Andersen *et al.*, 2010; Mortensen *et al.*, 2018), while Ireland has fixed monthly quotas (DAFM, 2016b; Calderwood and Reid, 2019).

Unlike Irish fishers, Danish fishers can therefore avoid Category 1 choke situations, as defined by the North Sea Advisory Council, whereby there is sufficient quota at a member state level but a choke is caused by the way in which quota is distributed within a region or fleet segment (North Sea Advisory Council, 2017). However, depending on the price of acquiring additional quota, this may induce a loss, as quota prices change according to supply and demand (Mortensen *et al.*, 2018). While the ITQ system allows more flexibility for Danish fishers, this does not mean that Danish fishers may simply trade their way out of quota restrictions and consideration of such costs in relation to the value of landed catches is important. In addition, there may be insufficient quota at member state or EU levels (choke categories 2 & 3; North Sea Advisory Council, 2017).

Regardless of the flexibilities available within different quota management systems around the EU, the introduction of the LO will require fishers to increase efforts to avoid unwanted species and subsequent choke situations (Borges and Penas Lado, 2019). This legislation presents a pressing need for fishers to avoid

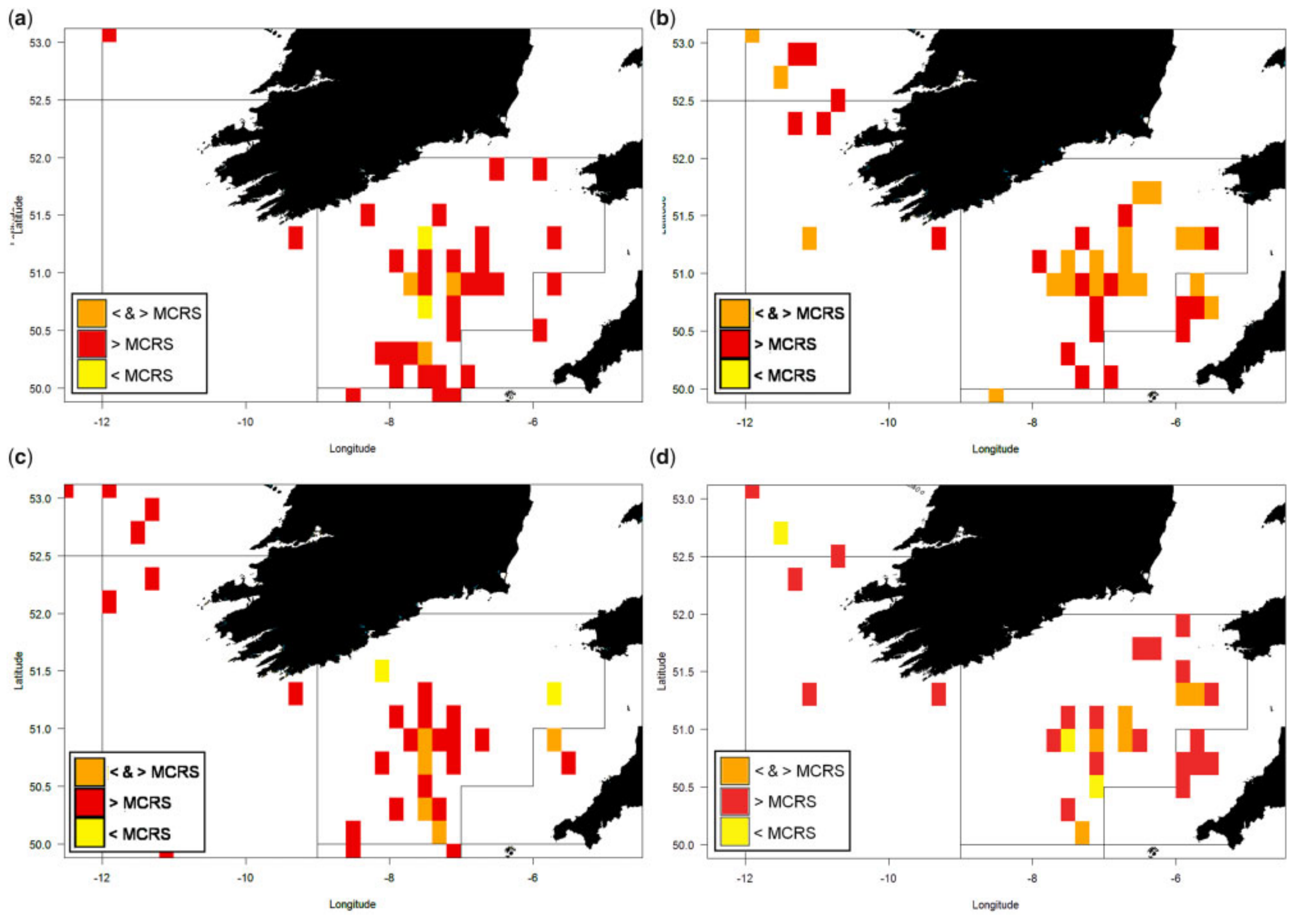

Figure 6. Maps showing where areas identified as consistently having high catch rates, as identified by hotspot maps constructed with observer data from 2010 to 2015 (top 40% of catches based on kilogram of caught per hour of fishing activity) for >MCRS and <MCRS catches overlap, and where they are spatially separate for (a) cod, (b) haddock, (c) hake, and (d) whiting using VMS data from 2016.

Table 3. Model results testing the relationship between the category of grid cells (< and >MCRS catches, >MCRS catches, and <MCRS catches) with the mean value of total catches associated with these gird cells for the Irish fleet operating in the Celtic Sea and the Danish fleet operating in the North Sea and Skagerrak.

Area	Species	χ^2	Df	*p*
Celtic Sea	Cod	2.341	2	0.310
	Haddock	1.749	2	0.417
	Hake	0.207	2	0.901
	Whiting	5.355	2	0.069
North Sea & Skagerrak	Cod	4.405	2	0.111
	Haddock	2.596	2	0.2731
	Hake	15.020	2	**<0.001**
	Whiting	8.090	2	**0.018**

Significant values ($p < 0.05$) are indicated in bold.

catches <MCRS, despite some limited *de minimis* exemptions, as these now count against quotas without providing the revenue associated with >MCRS landings (European Commission, 2013). The mapping methodology presented here can highlight areas with consistently high catches of both the < and >MCRS components of catches, indicating where there is a higher chance of catching larger individuals while avoiding juveniles, and hence maximizing revenue, but options to avoid certain components of the catch are difficult for some species. In the Celtic Sea, for example there are no areas where cells representing <MCRS haddock hotspots are not overlapped by >MCRS hotspots. Cells associated solely with >MCRS hotspots have, however, been identified with close proximity to all of the haddock hotspots and with similar VPUE values. There is, therefore, no economic reason to not avoid the overlap areas, but if all vessels chose to adopt this behaviour the displacement of fishing activity could alter the associated fleet economics in the future. This is also true of the Danish fishery, where, although the value from fishing in all of the haddock hotspots is fairly consistent, a larger proportion of fishing activity is currently associated with the overlap hotspot areas. Such overlap, as seen in both case studies, is likely due to the frequent co-occurrence of adult and juvenile fish with the whole catch composition having an influence on fishing behaviour. This could again lead to the displacement of fishing activities and increased pressure on the >MCRS hotspots if vessels were to use the hotspot maps in an effort to avoid juvenile haddock catches.

These examples highlight how the provision of such mapping tools to the fishing industry could be useful in reducing <MCRS catches. More modelling work, potentially utilizing random utility models, could be of use for both the Irish and Danish case

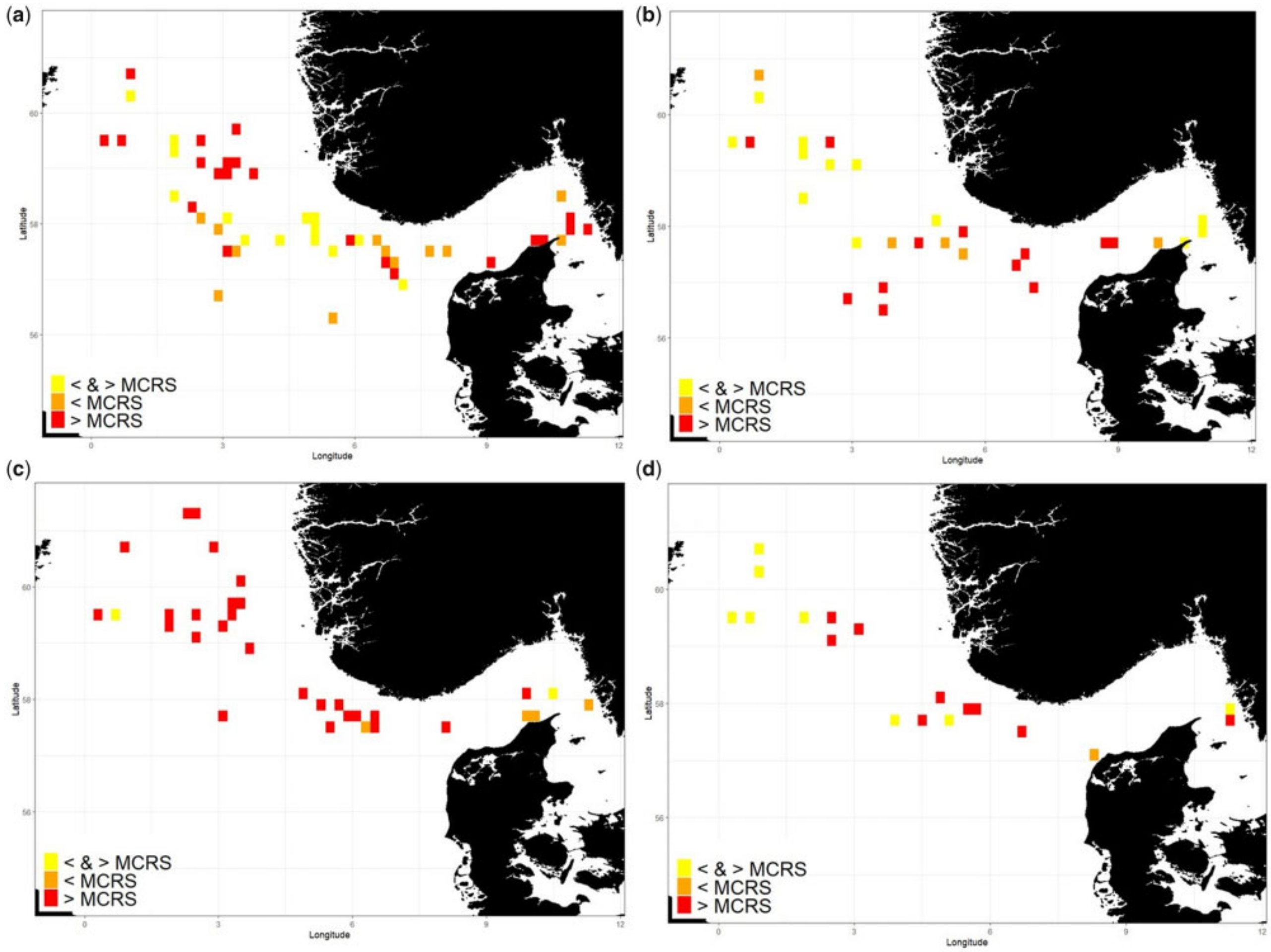

Figure 7. Maps showing where cells identified as consistently having high catch rates, as identified by hotspot maps constructed with observer data from 2010 to 2015 (top 40% of catches based on kilogram of caught per hour of fishing activity) for >MCRS and <MCRS catches overlap, and where they are spatially separate for (a) cod, (b) haddock, (c) hake, and (d) whiting using VMS data from 2016.

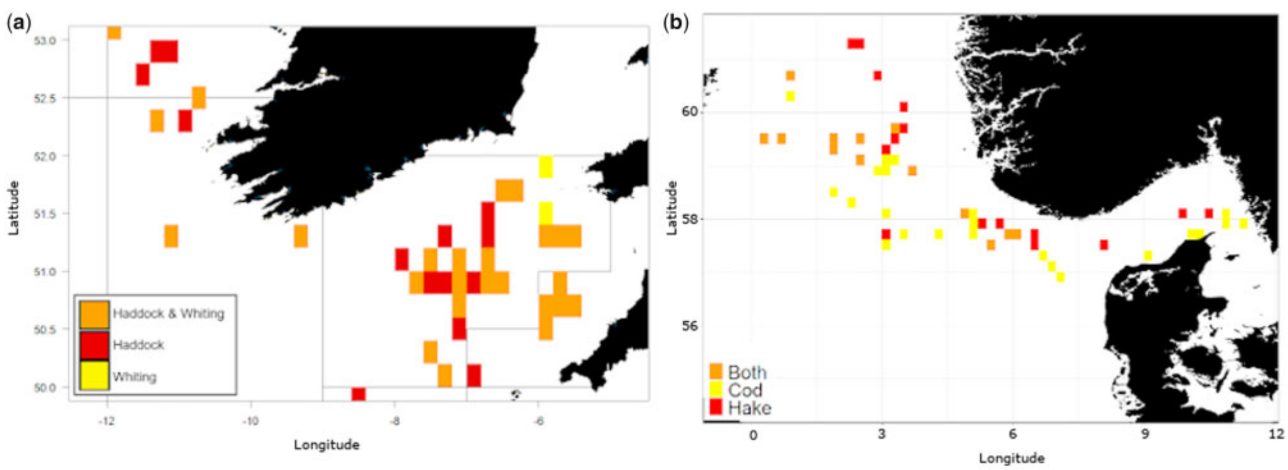

Figure 8. Map showing where areas identified as consistently having high catch rates, as identified by hotspot maps constructed with observer data from 2010 to 2015 (top 40% of catches based on kilogram of caught per hour of fishing activity) for (a) haddock and whiting catches overlap, where they are spatially separate in the Celtic Sea and for (b) cod and hake catches overlap, and where they are spatially separate in the North Sea and Skagerrak.

	Irish Case Study	Danish Case Study
Discard hotspots and VPUE data	Significant positive relationship between occurences of discarding hotspots and total VPUE for **cod, haddock, hake, whiting** & **all species combined.**	Significant positive relationship between occurences of discarding hotspots and total VPUE for **cod, haddock** & **all species combined.**
	For both there remain areas with high VPUE not assocaited with discarding hotspots.	
Total catch hotspots and VPUE data	Significant positive relationship between species hotspots and VPUE from total landings in the subsequent year.	
Below MCRS avoidance scenarios	More vessel activity associated with areas where >MCRS catches don't overlap with <MCRS catches for all **4 species.** No difference in VPUE assocaited with each catch hotspot category.	More vessel activity associated with areas where >MCRS catches don't overlap with <MCRS catches for **cod**, **hake** & **whiting**. Higher VPUE values associated with <&>MCRS hotspot overlap areas for **hake & whiting**
Species avoidance scenarios	Less fishing activity recorded in areas where haddock and whiting hotspots overlap compared to where they don't. Although no differences in VPUE of total catches assocaited with each area whether hotspots overlap or not.	More vessel activity associated with high cod hotspots than high hake hotspots, or the overlap of the two. VPUE of total catches is highest in areas where high hake and cod hotspots overlap.

Figure 9. A summary of the results of each of the four sections of the analysis for the two case study areas.

studies presented here to determine how relocation of fishing effort may further affect fleet economics (Bastardie *et al.*, 2014). To do this, a full understanding of the drivers of fishing behaviour is required, which would again require the provision of more catch and effort data. In the Danish fishery, for example high catches of <MCRS hake occur in areas with low overall associated VPUE. This would provide an incentive to avoid these areas and target the >MCRS only areas where greater revenues can be achieved. However, the main driver for the discarding of hake in the Danish demersal mixed fishery is likely not undersized catches, as by far the majority of observed discards of hake has previously been shown to be >MCRS. Low market value and damaged fish are therefore being pointed to as more important discard drivers (Catchpole *et al.*, 2018; Plet-Hansen *et al.*, 2019). As such it may be more important for Danish fishers to avoid all areas associated with high hake catches and concentrate on catching other species with a higher deemed value. This kind of understanding of the dynamics at play in the decision-making process is important for managers to consider when providing appropriate information to fishers.

Greater differences were apparent between the species and choke avoidance scenarios compared to the <MCRS avoidance scenarios for each case study. There is less overlap of cod and hake in the Danish fishery than for haddock and whiting in the Irish fishery, potentially providing more opportunities for the Danish fishery to avoid a choke. However, there is a higher VPUE associated with overlapping areas for cod and hake in the North Sea and Skagerrak and, because of the potential discard drivers for hake, it may be that the Danish fishery has an economic driver for risking catching hake while targeting cod. Managers should maybe consider how they could further incentivize fishing in areas where hake catches can be minimized. In the Irish example, there is no difference in the value of catches in the three areas highlighted (single species or overlap) so no financial deterrent from avoiding hotspots where both whiting and haddock are commonly caught together. Furthermore, with very few areas where whiting hotspots occur alone, there could potentially be a displacement of vessels into the whiting only areas if vessels were to try and reduce the risk of also catching haddock. Again this might alter whiting catch rates and the overall VPUE associated with these areas in the long run. This emphasizes that, while there are some economically attractive areas to fish to avoid unwanted catches of a given species in the Celtic Sea, the generally homogenous nature of the fishery makes it difficult to do this without unintended impacts elsewhere or on other species.

The overall similarities in findings between the case studies despite the difference in both observer coverage and management framework give us hope that the methods applied do reveal useful and pertinent spatial patterns. Better understanding of the relationship between discarding hotspots and fleet economics can help us to further understand the drivers of fishing behaviour in space and time. When it comes to avoiding <MCRS fish in

particular, there are numerous options across both our case study examples to do so while still fishing in areas associated with high VPUE. The tools highlighted in this study also offer potential in choke situations, but the nature of mixed fisheries mean the options to fish perfectly in line with available quotas are limited. A further barrier to operational use of this type of analysis lies in the very limited amount of observer data collected, at <1% of fishing operations, and the risk of an observer effect influencing this data (Schaeffer and Hoffman, 2002; Plet-Hansen *et al.*, 2018). Certainly the variation in observer coverage on different types of vessels, in different areas, and across different seasons and years may influence the resultant hotspot maps. With the data available to us, however, pooling data annually provided the most useful information with regard to better informing fishing behaviour to avoid unwanted catches. Yet if we were able to access accurate and extensive catch data from the fishing fleets, the analyses could be more up to date, more resolved in time and space, and more useful to the fishers themselves. This view was expressed by a number of fishers who had considered using the hotspot maps themselves and would make the tool much more valuable.

The possibility of adding economic data and information into such tools could also be beneficial in further informing decision-making in fisheries and fisheries management. It is however recognized that this would require a sea change in the way fisheries currently provide data, but the pay-offs could be substantial. Certainly the mapping tool presented, among a suite of those currently being developed, could play an important role in providing the spatial solutions to reduce unwanted catches. This spatial data could also highlight areas in which the use of more selective gears is most needed, but further consideration needs to be given to how such information is related to the potential value of catches, and how this can be effectively communicated so that fishers can make the most informed decision on how to optimize catches while remaining profitable. In addition, fisheries scientists need to avoid giving advice on fishing behaviour for the industry that is economically unviable. Further incentives may be required in some instances to either utilize more selective gears or avoid areas with high bycatch risk. The ability to identify where these measures may be required is a useful tool in the management of fisheries.

Supplementary data

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

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Data availability statement

The data underlying this article cannot be shared publicly due to its' sensitive nature on a commercial and personal level and the requirements of general data protection legislation. It may be possible to share amalgamated data on reasonable request to the corresponding author.

Author contributions

JC and KSP-H contributed equally to the development of the work presented, the analysis conducted, and the writing of the manuscript. CU and DGR guided the development of this work and contributed to the writing of the manuscript.

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