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

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Abstract :

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~~introduction~~ of the Landing Obligation (LO) from 2015, with this legislation being fully implemented since the start of 2019. The LO ~~which has prohibited the~~prohibits the discarding of species subject to TACs (total allowable catches) and size limits, with some exemptions for species which have high survivability in addition to *de minim~~u~~is* allowances, which allow for a discard fraction of up to 5% in fisheries when increased selectivity is difficult to achieve ~~since the beginning of 2019~~ (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 (Schrope, 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) in order to avoid unwanted catches and comply with the prohibition. Whilst advances in gear technology provide methods to increase selectivity it is almost impossible to fully eliminate all unwanted catch 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, 2019). 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 recognised by industry and scientists alike (Dunn *et al.*, 2011; Paradinas *et al.*, 2016). In recent years numerous methods have utilised 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; Calderwood *et al.*, 2019; Reid *et al.*, 2019). 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 (Calderwood *et al.*, 2019; Reid *et al.*, 2019). 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). Additionally, 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. Furthering 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 paper 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 were 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 beanm trawls, with cod end mesh sizes above 100mm (European Commission, 2008; Davie and Lordan, 2011)) ,were used. In the Irish fleet the majority of TR1 vessels operate otter trawls and target 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 comparison of vessels ~~targetting~~targeting similar demersal fisheries in the Celtic Sea and North Sea and Skagerrak.

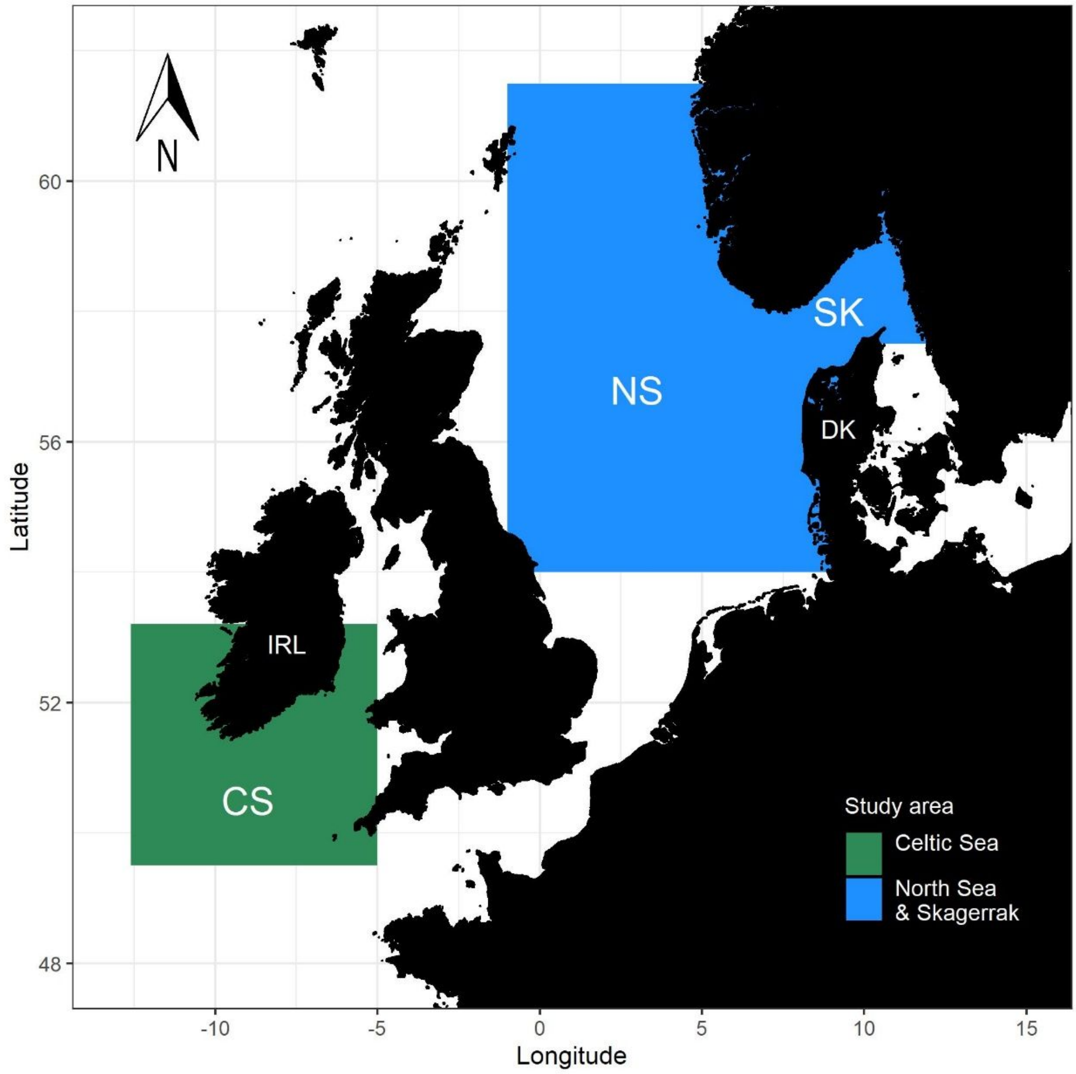

Figure 1: Map of Northwestern Europe with the study areas. Green colour indicates the Celtic Sea (CS), blue colour indicates the North Sea (NS) and Skagerrak (SK). IRL = Ireland, DK = Denmark.

Irish and Danish data

Discard hotspots and VPUE data

Mean value per unit effort data (VPUE ~~–~~– value of landed catch (€)~~euros earned~~ per hour of fishing activity for total landed catch of all species caught) were calculated using VMS (vessel monitoring system) 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. ~~and~~ ~~t~~The~~he~~ monetary value of these catches were provided by the SFPA (Sea Fisheries Protection Agency) alongside logbook data for the Irish fisheries. In the Danish fishery the Danish Fisheries Agency provide 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 ~~D~~daily catch weight and sales value data equally ~~were equally allocated~~ to each location along a vessel's recorded path where the associated vessel was recognised 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 activity per trip. The resultant data were then allocated to 0.2° x 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 onboard 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 market value and abundance. Please see Supplementary Material 1 ~~,~~ for more detail. On-board sampling protocols followed those described by Håkansson (2019) and Borges *et al.* (2005a), 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 ~~D~~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. ~~the Celtic Sea~~In the North Sea and Skagerrak data were collected from and 352 hauls from 250 trips, with an average trip length of 5.1 days, from 127 unique vessels ~~the North Sea and Skagerrak~~ between 2010 and 2015. Danish fisheries observer data were supplemented by Electronic Monitoring (EM) data for 4 vessels, providing information from a total of 8 individual hauls from 8 trips, with an average trip length 7.6 days. Although this is a low number, these 4 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.,* (2019) 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 x 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*., 2019). 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 chi-squared 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 (<) MCRS (minimum conservation reference size) 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 optimise 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.*, (2019). 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 2010-2015 for each species and size class of interest (< and >MCRS cod, haddock, hake and whiting). Data from 2010-2015 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 of saithe during 2012-2014 would be categorised as a saithe 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 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 2010-2015, with fishing data from the following year, however, still proves a valuable insight into how hotspot maps relate to the spatial variation in subsequent catch values and how this information could potentially be utilised following the full implementation of the LO. To achieve this ~~M~~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 maximise 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 CPUE hotspot maps (top 40% of catches by weight) for <MCRS and >MCRS catches respectively 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 (ANOVA) 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 (Schrope, 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 ~~both~~ because of the time lag in stock assessments, the relatively fast northward shift of the distribution in hake in this areas (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). Additionally, the price per kg of hake is generally lower, in the Danish markets, than for cod ~~and haddock for instance~~, 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.

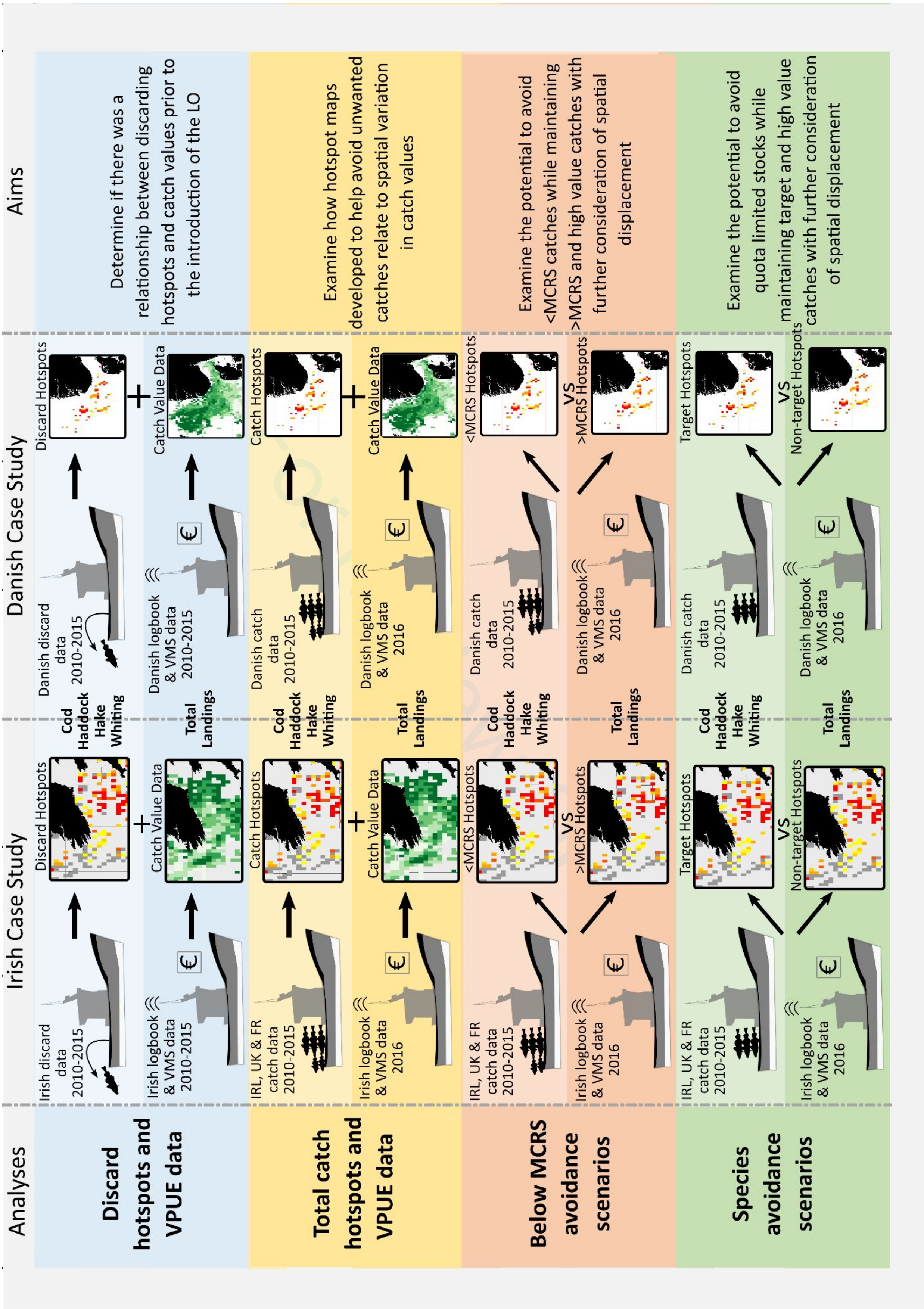

Figure 2: A schematic diagram to show the data inputs for each of the four sections of the analysis.

Table 1: The Minimum Conservation Reference Size (MCRS) in cm for the key TAC species considered in this paper.

Species	Minimum Conservation Reference Size (cm), Celtic and North Sea	Minimum Conservation Reference Size (cm), Skagerrak
Cod	35	30
Haddock	30	27
Hake	27	30
Whiting	27	23

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 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 have been identified between 5° and 11°W and 50.5° and 52.5°N although hotspots for whiting are concentrated to the east of 9°W (Figure ~~2B~~ 3B and ~~2D~~3D). 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 ~~2A~~3A). Hake discards were also more concentrated south of 51°N (Figure 3~~2~~C). There was a significant relationship between the occurrence of discarding hotspots and the mean catch value for all species in the Irish fishery (Supplementary ~~1A~~2A; Table 2). In the case of whiting the greatest number of discarding hotspots were 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 were 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.

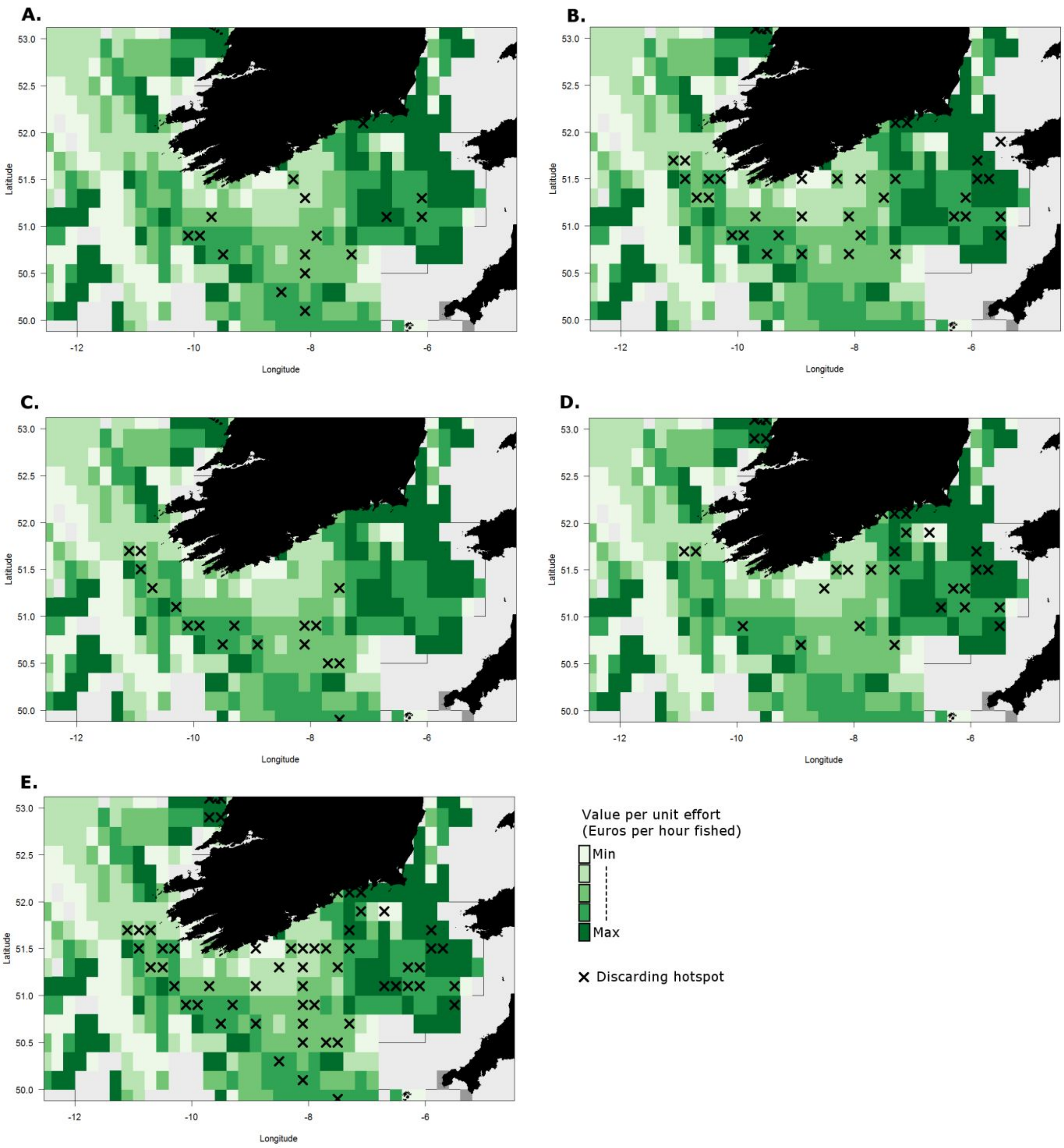

Figure 32: Maps showing the mean value of total catches (euro per hour) for the Irish fleet in the period 2010 - 2015 related to discarding hotspots identified during the same period for A. cod, B. haddock, C. hake, D. whiting and E. cod, haddock, hake and whiting combined.

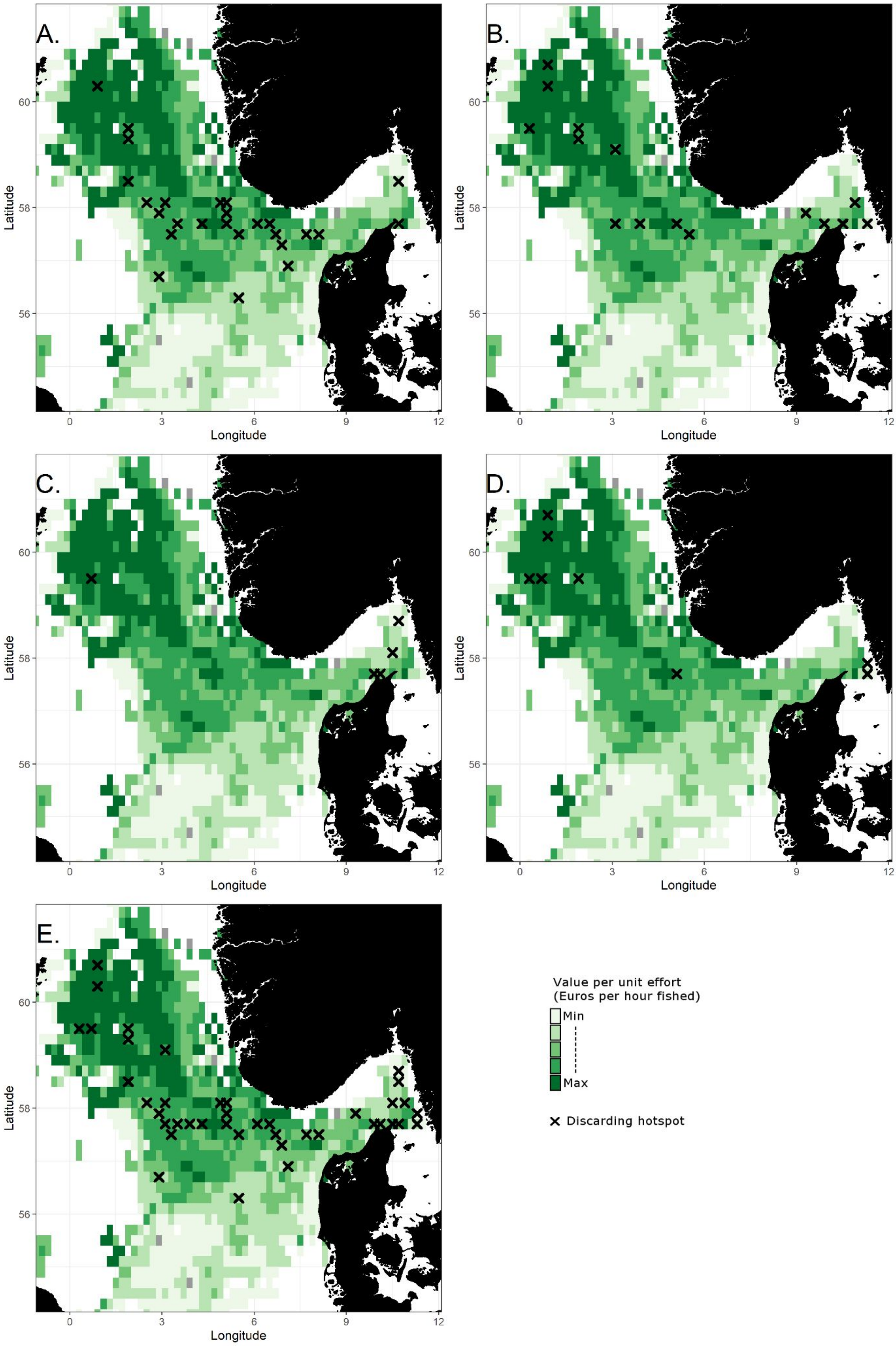
A.
B.
C.
D.
E.
Latitude
Longitude
60
58
56
0
3
6
9
12
Value per unit effort
(Euros per hour fished)
Min
Max
Discarding hotspot

Figure 4~~3~~: 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, E. cod, haddock, hake, and whiting combined.

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°~~th~~ parallel north (Figure 4~~3~~A and 3B). Except for one discarding hotspot, all hake hotspots occur in Skagerrak (Figure 4~~3~~C). 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 4~~3~~D). 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 4~~3~~E). In the Danish case a significant relationship was found between VPUE and discarding hotspots for cod, haddock and the combined species map only (Supplementary ~~1B~~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 respectively. 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~~3~~).

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

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 & 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**

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 (χ^2=4.855, df=7, p=0.678 and χ^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 (χ^2=42.395, df=5, p<0.001 and χ^2=31.273, df=4, p<0.001; Figure 54). Post-hoc tests revealed that the value of total catches associated with the highest two CPUE categories in the hotspot maps were 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 were greater than the value of catches associated with all other hotspot mapping CPUE categories.

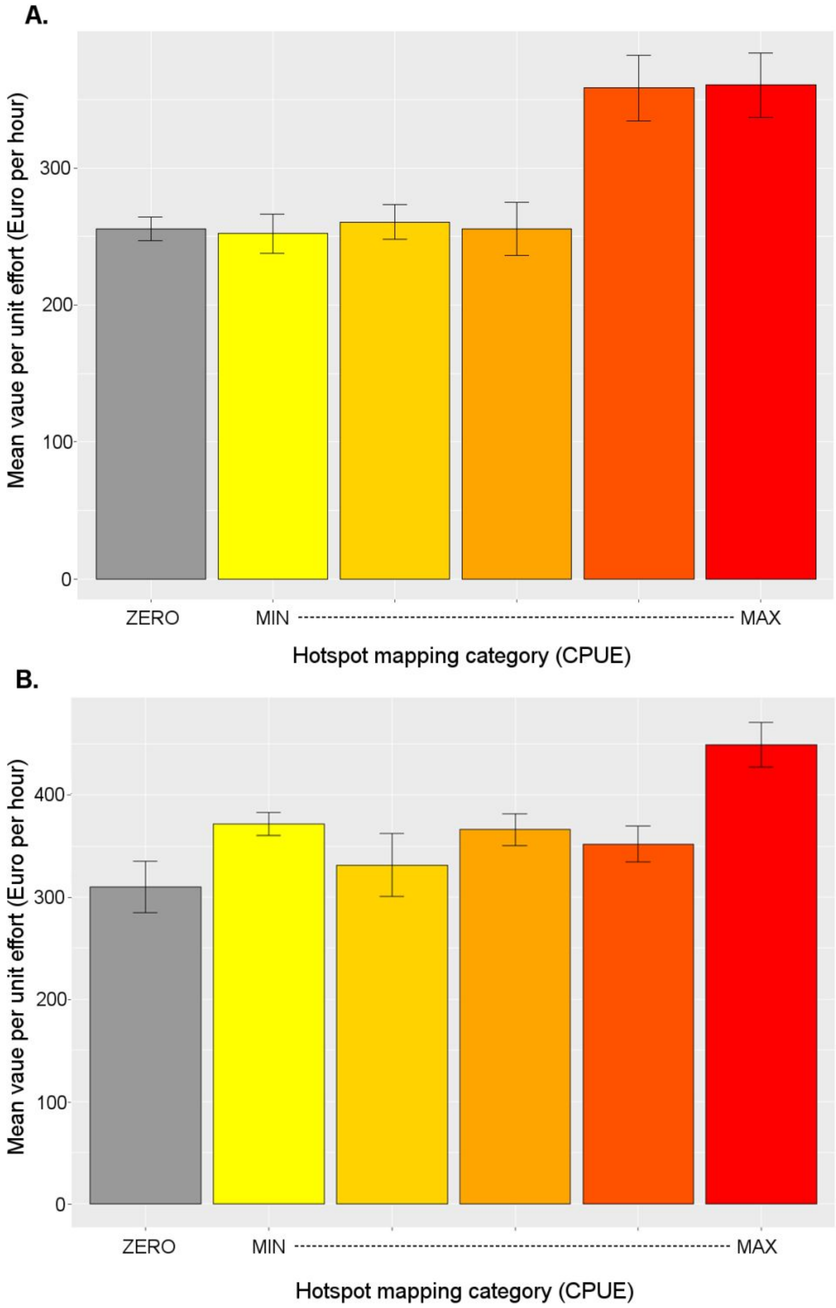

Figure 54: Bar charts showing the relationship between the mean VPUE of fishing effort in each 0.2 x 0.2 degree rectangle and the associated levels of catches (CPUE) consistently identified in these areas by hotspot maps amalgamated for all species and size classes for A. the Irish fishery in the Celtic Sea and B. the Danish fishery in the North Sea and Skagerrak

Below MCRS Avoidance Scenarios

For all four species in the Celtic Sea (Figure 65) the majority of the grid cells where there are consistently high catch rates for both the < and > MCRS fish are concentrated between 5°W-9°W and 50°N-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 <&>MCRS category. For all species the percentage of vessel activity in each of 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 23). 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 categorisation 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 23).

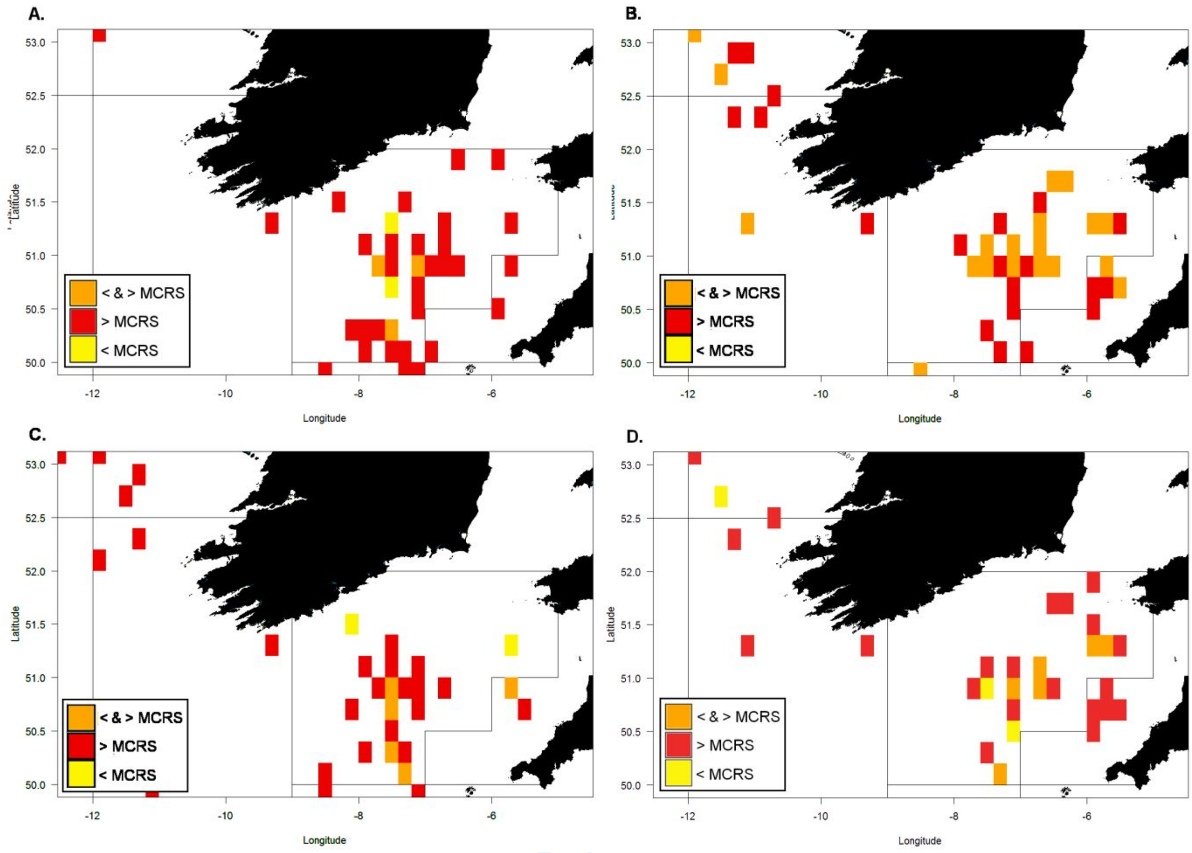

Figure 6~~5~~: Maps showing where areas identified as consistently having high catch rates, as identified by hotspot maps constructed with observer data from 2010-2015 (top 40% of catches based on kg caught per hour of fishing activity) for >MCRS and <MCRS catches overlap and where they are spatially 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 (< & > 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. Significant value ($p < 0.05$) are indicated in bold.

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**

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~~6~~). Above MCRS catch rates of cod are associated with the highest number of grid cells 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 are 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 ~~2~~3, Table 3). For hake, 26 out of 32 cells were categorised 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 3~~2~~). Whiting and hake show the highest ~~discarding~~ 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 too (Supplementary 3~~2~~; Table 3).

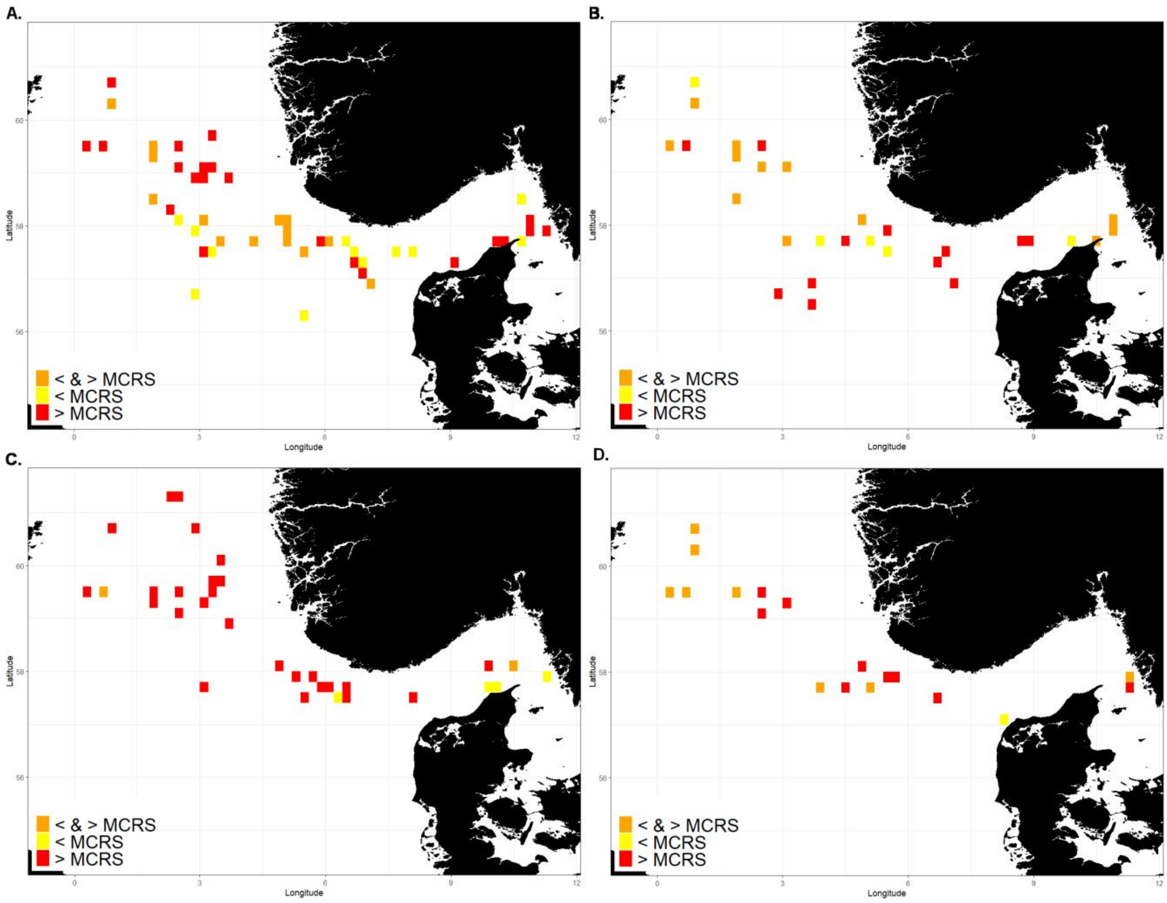

Figure 7~~6~~: Maps showing where cells identified as consistently having high catch rates, as identified by hotspot maps constructed with observer data from 2010-2015 (top 40% of catches based on kg caught per hour of fishing activity) for >MCRS and <MCRS catches overlap and where they are spatially separate for A. Cod B. Haddock, C. Hake and D. Whiting using VMS data from 2016.

Species avoidance scenarios

The majority of grid cells in ~~f~~Figure 8~~7~~A represent 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 4). Only 2 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 (χ^2=0.198, df=2, p=0.906).

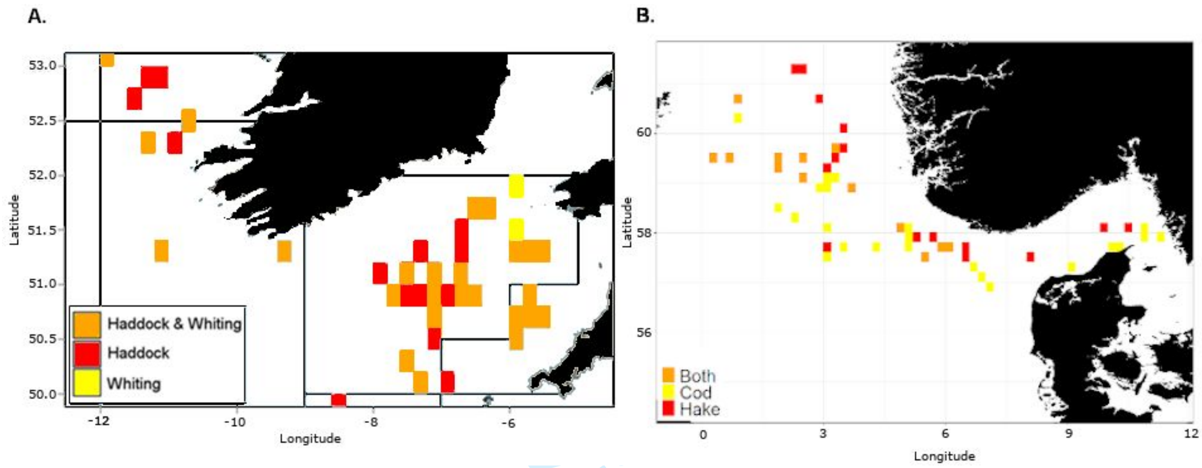

Figure 8~~7~~: Map showing where areas identified as consistently having high catch rates, as identified by hotspot maps constructed with observer data from 2010-2015 (top 40% of catches based on kg caught per hour of fishing activity) for a. haddock and whiting catches overlap and where they are spatially separate in the Celtic Sea and B. cod and hake and where they overlap in the North Sea and Skagerrak.

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 8~~7~~B). 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^o-60.5^o N and 0.5-3.5^o 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 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 significant different

(χ^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 and 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 optimise the use of available quotas. This work did further provide an opportunity to examine how a tool developed for assisting in avoiding unwanted catches the Celtic Sea can be applied elsewhere, demonstrating the wider applicability of this methodology.

	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 hale 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.

When developing tools to aid in the spatio-temporal avoidance of unwanted catches it is important to firstly 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, ~~A~~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 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, that 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 focussing similar analyses on more fleet segments and metiers, but this again requires a greater provision of fisheries data from the fleet. ~~. It is particularly obvious in the *Nephrops* cases we identified. These fisheries have been the subject of considerable selectivity research (e.g. Cosgrove *et al.*, 2018), and are the most promising for a gear-based discard reduction. Gear based selectivity measures may be less promising in the case of mixed demersal gadoid fisheries, unless combined with other measures (Sigurrdottir *et al.*, 2015), and this should include behavioural and tactical measures (Pointin *et al.*, 2019).~~

If a fisher is a profit maximiser, 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. ~~T~~There is ~~understandably~~ greater value associated with cells that have consistently high catches of all species studied. ~~This is not unexpected, with~~Certainly larger volumes of landings are often ~~being~~ associated with higher earnings in mixed fisheries, ~~regardless of species caught~~as long as there are 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 are not associated with areas with the highest value catches suggesting fishers ~~can~~ 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.*, 2019). 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 fishers are enabled to make optimum decisions with regard to where to fish to optimise catches while maintaining profitability. This could take the form of fleet communication programs, for which numerous examples ~~are increasingly being~~have been highlighted from fisheries throughout the world (Gilman *et al.*, 2006; Eliasen and Bichel, 2015; Little *et al.*, 2015), or decision support tools provided by the scientific community as are increasingly being developed ~~.~~ ~~Decision support tools provided by the scientific community, either using survey or commercial data, could also be beneficial. Again such tools are increasingly being developed but our results indicate the real potential of such applications in information decision making in Irish and Danish fisheries~~ (Reid *et al.*, 2019).

~~It is worth noting however, that in the Irish case study many of the high VPUE areas coincide with high value catches of anglerfish and megrim along the 12°W line to the south west of the Celtic Sea in addition to the *Nephrops* fishing grounds (Marine Institute, 2018). Thus although it is possible to fish in areas where high revenues can be made while avoiding discarding hotspots, these high revenue areas may not correspond to areas of high catches of all species. Certainly if quota for these other high value species were exhausted Irish fishers may not have the same opportunities to target areas with known high value catches while reducing unwanted catches. For this case study area there are certainly trade-offs that would have to be made with regard to maximising revenues while avoiding low quota or quota restricted species.~~

Despite general similarities in the relationship observed between the discarding patterns and overall VPUE in the two case studies in 2010-2015, ~~and without considering how VPUE values may be driven by different species in each area,~~ 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, 2016; Calderwood and Reid, 2019). ~~With the LO in place, fisheries may face four categories of choke situations, which can close the fishery. These are categorised by the North Sea Advisory Council NSAC as (North Sea Advisory Council, 2017):~~

~~Category 1: Sufficient quota at Member State level—choke is due to distribution within the Member State such that a region or fleet segment does not have enough and this can be resolved by the Member State itself.~~

~~Category 2: Sufficient quota at EU level, but insufficient quota at MS level—choke is due to a mismatch of catches and the distribution of quotas between Member States and can theoretically be resolved between themselves in a regional context.~~

~~Category 3: Insufficient quota at EU level—choke is due to insufficient quota within the relevant sea basin to cover present catches or catch levels that can be realistically reduced, resulting in a total stop of fishing for a Member State or Member States.~~

~~Category 4: Economic choking may occur at the vessel level when there is a considerable bycatch of a low value species and the boat is filled with fish that will not deliver a profit~~

Unlike Irish fishers, Danish fishers can therefore avoid ~~the~~ 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 ~~doesn't~~ 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.~~,~~ ~~both because of profitability of the fishery and because of the remaining choke categories.~~ Additionally 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 catches <MCRS~~, as prior to the introduction of the LO these had to be discarded but now they have to be landed and count against available quota~~, 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 maximising 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 ~~associated with all of these cells.~~values. There is, therefore, no economic reason to not avoid the overlap areas. But ~~I~~if all vessels chose to adopt this behaviour~~, however,~~ 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 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.

~~Again t~~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 utilising Random Utility Models, could be of use for both the Irish and Danish case 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 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,~~-~~. ~~with l~~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.

~~Like the avoidance of <MCRS fish, choke situations are a key concern for fishers operating under the LO, especially for mixed fisheries where one species can be more quota restricted than another co-occurring species (Schrope, 2010).~~ 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 incentivise fishing in areas where hake catches can be minimised. 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. Further, 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 emphasises 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 is 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 gives 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. ~~And w~~When it comes to avoiding <MCRS fish in particular there are numerous options across both our

case study examples to do so ~~through the use of spatial avoidance,~~ 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 less than 1% of fishing operations, and the risk of an observer effect influencing this data (Schaeffer and Hoffman, 2004; 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. ~~Because of this relative paucity of data, the hotspot analyses had to be done using data pooled over a number of years.~~ Yet ~~I~~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 ~~the information presented in such maps~~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 optimise catches while remaining profitable. ~~relate to fleet economics and other drivers of fishing behaviour, and how such economic data could be provided and presented to determine if the advice presented is likely to be followed.~~ Additionally ~~F~~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 utilise more selective gears or avoid areas with high bycatch risk. The ability to identify where these measures may be required~~, however,~~ is a useful tool in the management of fisheries.

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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 GDPR legislation. It may be possible to share amalgamated data on reasonable request to the corresponding author.

Author Contributions

J.C. and K.P-H. contributed equally to the development of the work presented, the analysis conducted and the writing of the manuscript. C.U. and D.R. guided the development of this work and contributed to the writing of the manuscript.

References

Alverson, D. L., Freeberg, M. H., Murawski, S. A., and Pope, J. G. 1994. A global assessment of fisheries bycatch and discards. Rome. 233 pp.

Andersen, P., Andersen, J. L., and Frost, H. 2010. ITQs in Denmark and Resource Rent Gains. Marine Resource Economics, 25: 11–22.

Bastardie, F., Nielsen, J. R., and Miethe, T. 2014. DISPLACE: A dynamic, individual-based model for spatial fishing planning and effort displacement - integrating underlying fish population models. Canadian Journal of Fisheries and Aquatic Sciences, 71: 366–386.

Batsleer, J., Hamon, K. G., van Overzee, H. M. J., Rijnsdorp, A. D., and Poos, J. J. 2015. High-grading and over-quota discarding in mixed fisheries. Reviews in Fish Biology and Fisheries, 25: 715–736.

Baudron, A. R., and Fernandes, P. G. 2015. Adverse consequences of stock recovery: European hake, a new ‘choke’ species under a discard ban? Fish and Fisheries, 16: 563–575.

Bellido, J. M., Santos, M. B., Pennino, M. G., Valeiras, X., and Pierce, G. J. 2011. Fishery discards and bycatch: Solutions for an ecosystem approach to fisheries management? Hydrobiologia, 670: 317–333.

Bellido, J. M., Paradinas, I., Vilela, R., Bas, G., and Pennino, M. G. 2019. A Marine Spatial Planning Approach to Minimze Discards: Challenges and Opportunities of the Landing Obligation in European Waters. *In* The European Landing Obligation: Reducing Discards in Complex, Multi-Species and Multi-Jurisdictional Fisheries, pp. 239–256. Ed. by S. S. Uhlmann, C. Ulrich, and S. J. Kennelly. Springer, Cham.

Bergsson, H., Plet-Hansen, K. S., Jessen, L. N., Jensen, P., and Bahlke, S. Ø. 2017. Final Report on Development and usage of REM systems along with electronic data transfer as a measure to monitor compliance with the Landing Obligation – 2016. 61 pp.

Borges, L., Rogan, E., and Officer, R. 2005. Discarding by the demersal fishery in the waters around Ireland. Fisheries Research, 76: 1–13.

Borges, L., and Penas Lado, E. 2019. Discards in the Common Fisheries Policy: The Evolution of the Policy. *In* The European Landing Obligation: Reducing Discards in Complex Multi-Species and Multi-Jurisdictional Fisheries, pp. 27–47. Ed. by S. S. Uhlmann, C. Ulrich, and S. J. Kennelly. Springer, Cham.

Calderwood, J., Cosgrove, R., Moore, S.-J., Hehir, I., Curtin, R., Reid, D., and Graham, N. 2016. Assessment of the impacts of the Landing Obligation on Irish Vessels. http://www.bim.ie/media/bim/content/publications/Lo,report,2016_final.pdf.

Calderwood, J., Robert, M., Pawlowski, L., Vermard, Y., Radford, Z., Catchpole, T. L., and Reid, D. G. 2020. Hotspot mapping in the Celtic Sea: An interactive tool using multinational data to optimise fishing practices. Marine Policy, 116: 103511.

Calderwood, J., and Reid, D. G. 2019. Quota exhaustion and discarding: how Ireland's monthly quota system has a limited relationship with discarding patterns in the commercial fishing fleet. ICES Journal of Marine Science, 76: 244–254.

Catchpole, T., Ribeiro-Santos, A., Mangi, S. C., Hedley, C., and Gray, T. S. 2017. The challenges of the landing obligation in EU fisheries. Marine Policy, 82: 76–86.

Catchpole, T. L., and Gray, T. S. 2010. Reducing discards of fish at sea: a review of European pilot projects. Journal of Environmental Management, 91: 717–723.

Catchpole, T. L., Feekings, J. P., Madsen, N., Palialexis, A., Vassilopoulou, V., Valeiras, J., Garcia, T., *et al.* 2014. Using inferred drivers of discarding behaviour to evaluate discard mitigation measures. ICES Journal of Marine Science, 71: 1277–1285.

Catchpole, T. L., Elliott, S., Peach, D., Mangi, S. C., and Gray, T. S. 2018. How to deal with the EU landing obligation: Lessons from an English discard ban sea trial. ICES Journal of Marine Science, 75: 270–278.

DAFM. 2016a. Demersal Landing Obligation 2016: Information Booklet. 11 pp. https://www.agriculture.gov.ie/media/migration/seafood/sea-fisheriespolicymanagementdivision/landingobligationsdiscardsban/LandObligInfoBooklet2016150216.docx.

DAFM. 2016b. Fisheries Quota Management in Ireland. https://www.agriculture.gov.ie/media/migration/seafood/sea-fisheriespolicymanagementdividion/QuotaMgmtPolicyApril16250416.doc.

Davie, S., and Lordan, C. 2011. Examining changes in Irish fishing practices in response to the cod long-term plan. ICES Journal of Marine Science, 68: 1638–1646.

Dunn, D. C., Boustany, A. M., and Halpin, P. N. 2011. Spatio-temporal management of fisheries to reduce by-catch and increase fishing selectivity. Fish and Fisheries, 12: 110–119.

Eliasen, S. Q., and Bichel, N. 2015. Fishers sharing real-time information about 'bad' fishing locations. A tool for quota optimisation under a regime of landing obligations. Marine Policy, 64: 16–23.

European Commission. 2008. European Commission Council Regulation (EC) No 199/2008 of 25 February 2008 concerning the establishment of a Community framework for the collection, management and use of data in the fisheries sector and support for scientific advice regarding the Common Fisheries Policy.

European Commission. 2013. Proposal for a Regulation of the European Parliament and of the Council amending Council Regulations (EC) No 850/98, (EC) No 2187/2005 (EC) No 1967/2006, (EC) No 1098/2007, No 254/2002, (EC) No 2347/2002 and Landing, (EC) No 1224/2009 and repealing (EC) No 1434/98 as regards the landing obligation.

European Commission. 2015a. Commission Delegated Regulation (EU) 2015/2440 of 22 October 2015 establishing a discard plan for certain demersal fisheries in the North Sea and in Union waters of ICES Division IIa.

European Commission. 2015b. Regulation (EU) 2015/812 of the European Parliament and of the Council of 20 May 2015 amending Council Regulations (EC) No 850/98, (EC) No 2187/2005, (EC) No 1967/2006, (EC) No 1098/2007, (EC) No 254/2002, (EC) No 23347/2002 and (EC) No 1224/2009, and Reg. Official Jounral of the European Union, 133: 1–20.

Fraser, H. M., Greenstreet, S. P. R., Fryer, R. J., and Piet, G. J. 2008. Mapping spatial variation in demersal fish species diversity and composition in the North Sea: Accounting for species- and size-related catchability in survey trawls. ICES Journal of Marine Science, 65: 531–538.

Gerritsen, H., and Lordan, C. 2011. Integrating vessel monitoring systems (VMS) data with daily catch data from logbooks to explore the spatial distribution of catch and effort at high resolution. ICES Journal of Marine Science, 68: 245–252.

Gerritsen, H. D., Lordan, C., Minto, C., and Kraak, S. B. M. 2012. Spatial patterns in the retained catch composition of Irish demersal otter trawlers: High-resolution fisheries data as a management tool. Fisheries Research, 129–130: 127–136.

Gilman, E. L., Dalzell, P., and Martin, S. 2006. Fleet communication to abate fisheries bycatch. Marine Policy. 30: 360-366.

Guillen, J., Holmes, S. J., Carvalho, N., Casey, J., Dörner, H., Gibin, M., Mannini, A., *et al.* 2018. A review of the European union landing obligation focusing on its implications for fisheries and the environment. Sustainability 2018. 10, 900.

Håkansson, K. B. 2019. Observer at-sea, sampling frame, 2019. 1–9 pp.

Hatcher, A. 2014. Implications of a Discard Ban in Multispecies Quota Fisheries. Environmental Resource Economics, 58: 463–472.

Hatcher, A., and Drakeford, B. 2015. Mapping and modelling the incentives for a landing obligation in demersal fisheries A study commissioned by Fisheries Innovation Scotland (FIS). http://www.fiscot.org/.

Hintzen, N. T., Bastardie, F., Beare, D., Piet, G. J., Ulrich, C., Deporte, N., Egekvist, J., *et al.* 2012. VMStools: Open-source software for the processing, analysis and visualisation of fisheries logbook and VMS data. Fisheries Research, 115–116: 31–43.

Hintzen, N. T., Bastardie, F., and Beare, D. 2016. vmstools: For analysing fisheries VMS (Vessel Monitoring System) data. https://cran.r-project.org/package=vmstools.

Holland, D. S., and Sutinen, J. G. 1999. An empirical model of fleet dynamics in New England trawl fisheries. Canadian Journal of Fisheries and Aquatic Sciences, 56: 253–264.

ICES. 2018a. Norway lobster (*Nephrops norvegicus*) in divisions 7.g and 7.f, Functional Unit 22 (Celtic Sea, Bristol Channel). 7 pp. http://www.ices.dk/sites/pub/Publication Reports/Advice/2018/2018/nep.fu.22.pdf.

ICES. 2018b. ICES Advice on fishing opportunities, catch, and effort - Greater North Sea Ecoregion nep.fu.7 Norway lobster (Nephrops norvegicus) in Division IVa , FU 7 (Northern North Sea , Fladen Ground).

ICES. 2018c. Ecosystem Overview - Greater North Sea Ecoregion.

Jennings, S., Kaiser, M., and Reynolds, J, D. 2001. Marine Fisheries Ecology. Wiley-Blackwell, Oxford.

Kelleher, K. 2005. Discards in the world's marine fisheries, An update. FAO Fisheries Technical Paper. No. 470. Rome, FAO, 131p.

Kraak, S. B. M., Bailey, N., Cardinale, M., Darby, C., De Oliveira, J. A. A., Eero, M., Graham, N., *et al.* 2013. Lessons for fisheries management from the EU cod recovery plan. Marine Policy, 37: 200–213.

Lee, J., South, A. B., and Jennings, S. 2010. Developing reliable , repeatable , and accessible methods to provide high-resolution estimates of fishing-effort distributions from vessel monitoring system (VMS) data. ICES Journal of Marine Science, 67: 1260–1271.

Lewison, R. L., Soykan, C. U., and Franklin, J. 2009. Mapping the bycatch seascape: multispecies and multi-scale spatial patterns of fisheries bycatch. Ecological Applications, 19: 920–930.

Little, A. S., Needle, C. L., Hilborn, R., Holland, D. S., and Marshall, T. 2015. Real-time spatial management approaches to reduce bycatch and discards: experiences from Europe and the United States. Fish and Fisheries, 16: 576–602.

Marine Institute. 2018. The Stock Book 2018: Annual Review of Fish Stocks in 2018 with Management Advice for 2019. Galway, Ireland.

Mateo, M., Pawlowski, L., and Robert, M. 2017. Highly mixed fisheries: Fine-scale spatial patterns in retained catches of French fisheries in the Celtic Sea. ICES Journal of Marine Science, 74: 91–101.

Milisenda, G., Vitale, S., Massi, D., Enea, M., Gancitano, V., Giusto, G. B., Badalucco, C., *et al.* 2017. Spatio-temporal composition of discard associated with the deep water rose shrimp fisheries (Parapenaeus longirostris, Lucas 1846) in the south-central Mediterranean Sea. Mediterranean Marine Science, 18: 53–63.

Mortensen, L. O., Ulrich, C., Eliasen, S. Q., Lund, H., Krag, L. A., Frandsen, R. P., Karlsen, J. D., *et al.* 2015. MINIDISC - Minimering af discards i danske fiskerier. 89 pp.

Mortensen, L. O., Ulrich, C., Eliasen, S., and Olesen, H. J. 2017. Reducing discards without reducing profit: Free gear choice in a Danish result-based management trial. ICES Journal of Marine Science, 74: 1469–1479.

Mortensen, L. O., Ulrich, C., Hansen, J., and Hald, R. 2018. Identifying choke species challenges for an individual demersal trawler in the North Sea , lessons from conversations and data analysis. Marine Policy, 87: 1–11.

North Sea Adviasory Council. 2017. NSAC Advice Ref.14-1617: Managing Fisheries within the Landing Obligation. 21 pp. http://nsrac.org/wp-content/uploads/2015/12/14-1617-Managing-the-Fisheries-within-the-Landing-Obligation.pdf.

O'Neill, F. G., Feekings, J., Fryer, R. J., Fauconnet, L., and Afonso, P. 2019. Discard Avoidance by Improving Fishing Gear Selectivity: Helping the Fishing Industry Help Itself. *In* The European Landing Obligation: Reducing Discards in Complex, Multi-Species and Multi-Jurisdictional Fisheries, pp. 279–296. Ed. by S. Uhlmann, C. Ulrich, and S. J. Kennelly. Springer.

Paradinas, I., Marin, M., Pennino, M. G., López-Quílez, A., Conesa, D., Barreda, D., Gonzalez, M., *et al.* 2016. Identifying the best fishing-suitable areas under the new European discard ban. ICES Journal of Marine Science, 73: 2479–2487.

Pennino, M. G., Valeiras, J., Vilela, R., and Bellido, J. M. 2017. Discard management: A spatial multicriteria approach. Marine Policy, 77: 144–151.

Pérez-Roda, A., Gilman, E., Huntington, T., Kennelly, S. J., Suuronen, P., Chaloupka, M., and Medley, P. 2019. A third assessment of global marine fisheries discards. FAO Fisheries and Aquaculture Technical Paper no. 633. Rome. FAO. 78 pp.

Plet-Hansen, K. S., Larsen, E., Mortensen, L. O., Nielsen, J. R., and Ulrich, C. 2018. Unravelling the scientific potential of high resolution fishery data. Aquatic Living Resources, 31: 14 pp.

Plet-Hansen, K. S., Bergsson, H., and Ulrich, C. 2019. More data for the money: Improvements in design and cost efficiency of electronic monitoring in the Danish cod catch quota management trial. Fisheries Research, 215: 114–122.

Pointin, F., Daurès, F., and Rochet, M.-J. 2019. Use of avoidance behaviours to reduce the economic impacts of the EU Landing Obligation: the case study of a mixed trawl fishery. ICES Journal of Marine Science, 76: 1554–1566.

Poos, J. J., Bogaards, J. A., Quirijns, F. J., Gillis, D. M., and Rijnsdorp, A. D. 2010. Individual quotas, fishing effort allocation, and over-quota discarding in mixed fisheries. ICES Journal of Marine Science, 67: 323–333.

Quinn, G. P., and Keough, M. . 2002. Experimental Design and Data Analysis forBiologists. Cambridge University Press, Cambridge.

R Core Team. 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org/.

R Development Core Team. 2012. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/. R Foundation for Statistical Computing, Vienna, Austria.

Ravensbeck, L., Ståhl, E. E., Levring, J., and Andersen, P. 2015. Analyse af de erhvervsøkonomiske konsekvenser af discardforbuddet. 37 pp. https://curis.ku.dk/ws/files/143083454/IFRO_Rapport_242.pdf.

Reid, D. G., Calderwood, J., Afonso, P., Bourdaud, P., Fauconnet, L., González-irusta, J. M., Mortensen, L. O., *et al.* 2019. The Best Way to Reduce Discards Is by Not Catching Them! *In* The European Landing Obligation: Reducing Discards in Complex, Multi-Species and Multi-Jurisdictional Fisheries, pp. 257–278. Ed. by S. S. Uhlmann, C. Ulrich, and J. Kennelly, Steven. Springer, Cham.

Rochet, M. J., Catchpole, T., and Cadrin, S. 2014. Bycatch and discards: From improved knowledge to mitigation programmes. ICES Journal of Marine Science, 71: 1216–1218.

Rodríguez-Rodríguez, G., Ballesteros, V. H. M., Valeiras, J., and Bellido, J. M. 2019. Input-output analysis of the economic impacts of the landing obligation: Snap-shot from the trawler fleet in Northern Iberian waters (Spain). Ocean and Coastal Management, 172.

Schaeffer, J. S., and Hoffman, E. M. 2004. Performance of Barbed and Barbless Hooks in a Marine Recreational Fishery. North American Journal of Fisheries Management, 22: 229–235.

Schorpe, M. 2010. Fisheries: What's the catch? Nature, 465: 540–542.

Suuronen, P., and Gilman, E. 2020. Monitoring and managing fisheries discards: New technologies and approaches. Marine Policy. 166: 103554.

Tsitsika, E. V., and Maravelias, C. D. 2008. Fishing strategy choices of purse seines in the Mediterranean: Implications for management. Fisheries Science, 74: 19–27.

Underwood, A. J. 1997. Experiments in Ecology. Cambridge University Press, Cambridge.

Van Putten, I. E., Kulmala, S., Thébaud, O., Dowling, N., Hamon, K. G., Hutton, T., and Pascoe, S. 2012. Theories and behavioural drivers underlying fleet dynamics models. Fish and Fisheries, 13: 216–235.

Wilen, J. E., Smith, M. D., Lockwood, D., and Botsford, L. W. 2002. Avoiding surprises: Incorporating fisherman behavior into management models. Bulletin of Marine Science, 70: 553–575.

Zuur, A. F., Ieno, E. N., Walker, N., Saveliev, A. A., and Smith, G. M. 2009. Mixed effects models and extensions in ecology with R. Statistics for Biology and Health. Springer, New York.