Hotspot mapping in the Celtic Sea: An interactive tool using multinational data to optimise fishing practices

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Abstract :

As a result of the introduction of the Landing Obligation in European fisheries there is a need to equip industry with the tools and knowledge to avoid unwanted catches. Optimising fishing practices in terms of time and location fished have been acknowledged as being important in modulating catch composition. Mapping techniques used to identify and manage the spatio-temporal nature of bycatch, however, remain underutilized. Data collected on board commercial fishing vessels by observers provides an important source of information on the component of catches discarded. Using a unique dataset, combining observer data for Irish, French and British vessels operating in the Celtic Sea between 2010 and 2015, maps were developed to identify where catches of quota restricted species or under minimum conservation reference size (MCRS) fish were consistent through time. Different catch metrics, based on CPUE and proportion of species in the catch, were compared as a basis for the maps. Our results indicate that it is possible to target above MCRS catches whilst avoiding below MCRS catches of the same species. Quota restricted species such as haddock can also be avoided whilst targeting other commercially exploited species including whiting. To allow all the information produced to be easily interpreted, the maps have been incorporated into a user-friendly app, to better inform decision making and potentially increase fishing opportunities under the Landing Obligation.

Keywords : Landing obligation, Discards, Consistent maps, Fishing tactics, Shiny app, Celtic sea

1. Introduction

The reduction of discards and unwanted catch in European fisheries was identified as one of the main objectives of the EU Common Fisheries Policy reforms in 2013, resulting in the introduction of the Landing Obligation (LO), whereby discarding of quota species in European fisheries will be prohibited by 2019 [1,2]. Implementation of the LO presents major challenges especially for mixed fisheries [3]. Whilst improvements in gear selectivity can help in reducing unwanted catches there remains a need to avoid areas with an abundance of unwanted catch if this legislation is to be adhered to [4-7]. Altering fishing practices in terms of time and location of fishing has, therefore, been acknowledged as being important in optimising catch composition and extending fishing opportunities [4,8-10].

For fishermen to effectively target their fishing practices it is vital that industry stakeholders are provided with as much information about the distribution of fish as possible. Survey data collected from research vessels, observer data collected from commercial fishing vessels and catch information from logbooks or electronic monitoring technology coupled with VMS (vessel monitoring systems) data can be used to produce maps that identify species hotspots [11–14]. The inclusion of discards in such data sources provides more precise estimates of catch than just using landings data alone [15]. Maps produced from observer data could, therefore, provide a real insight into the spatial distribution of all species caught by commercial vessels. Fishing suitability and bycatch hotspot maps have indeed been developed using fisheries data and statistical modelling techniques to assist in forecasting fish distributions and to provide insight into regional discarding issues in locations including; the Canadian Arctic, Danish waters, the Spanish Mediterranean and the northwest Atlantic [4,16–18]. Whilst such advanced spatial analysis techniques and methods used to identify and manage the spatio-temporal nature of bycatch have been developed in a number of global fisheries they generally remain underutilized by industry [16,19]. In addition to developing such maps there is a need to ensure the resultant outputs are presented in an easily digestible and accessible format. Further, it is essential that spatial analysis and mapping are based on as much suitable data as possible. Whilst observer data does provide information on the whole catch and not just the component later landed there are problems associated with discard sampling from observers, including low sampling frequency and irregular sampling design [20].

The Celtic Sea is an area on the western edge of Europe extending from the western Channel, south of England up around the west coast of Ireland, across the continental shelf to the west of Scotland. The Celtic Sea is an extensively fished ecosystem, providing valuable fisheries for several species, which often co-occur within a mixed species assemblage [21]. Due to its geographical location this area supports a number of international fleets including those from Ireland, France, and the UK. Whilst individual EU member states are required to collect fisheries data as part of the EU data collection framework (Council regulation (EC) No 199/2008) there is no obligation to share this data directly with other EU member states. Sharing and compiling data, especially that collected by observers, can increase sampling frequency and coverage and assist in overcoming some of the issues associated with the sparse nature of observer data. Further, the mixed nature of demersal fisheries in this area and their complex spatial structure [12] make the Celtic Sea an ideal area to make use of such a data sharing exercise to help better identify spatial patterns in fish distributions.

A unique tri-national dataset was created by combining observer data from Irish, French and British vessels operating in the Celtic Sea for the first time. This dataset was then used to identify areas where catches of species subject to TAC (total allowable catch), for both the above and below minimum conservation reference size (MCRS) components of the catch, were consistent over time. This use of consistent patterns in the catch, rather than simply calculating mean values from observer data over multiple years, is a novel way of approaching hotspot mapping. The resultant maps can be used to identify hotspots of catches that fishermen may want to better target or avoid to optimise catches under the landing obligation. Further to the development of this methodology an interactive app was developed so that fishermen can extract tailored information, ultimately helping to inform where to fish to reduce bycatch and reduce the risk of choke events [22]. If this approach does prove useful to them, it may also increase their motivation to share their own data and potentially increase the accuracy and/or increase the temporal resolution of the results.

2. Methods

2.1 Data

Data collected by onboard observers working on Irish, British and French demersal vessels operating in the Celtic Sea between 2010 and 2015 were used in the analyses. Data were collected by each member state as part of the EU data collection framework (Council regulation (EC) No 199/2008). The exact structure of each nation's observer programme does vary with the selection of vessels being stratified by gear type for the British fleet, by metier in France and stratified by area of operation (ICES Vlab, VIIa or VIIb-k) in Ireland with the selection probability of Irish vessels being proportional to their landings in the same quarter of the previous year [23–26]. Onboard sampling protocols also vary between each national observer programme although in each case components of both the discarded and retained catches are sampled, weighed and measured to allow estimates of total catches and discards to be made at fleet level [23–25,27]. In most instances every individual within a sub sample, of known weight, from each haul is identified and measured, with records of the total catch weight of the associated haul also being taken. For our analysis, this sub-sample data collected as part of each observer programme were raised to haul level, based on the total catch weight, using length-weight keys for each species sampled. This procedure was done at a national level, according to each research centres protocols, prior to the data being amalgamated into one dataset. Despite some differences in these raising procedures, each nation produced a dataset with catch weights being assigned to individual hauls, for which there was information on the start and

end positions, in addition to tow duration, thus allowing all three datasets to be merged and analysed together as described in section 2.2

Observer data were specifically used as it is the only reliable source of information on the component of catches that are discarded at sea, providing biological data on the whole catch and not just fish and shellfish later landed. In addition meta-data such as the position and duration of hauls, gear and mesh size used, vessel type and vessel size are all collected by observers. It is acknowledged that within mixed fisheries in particular the interactions that exist between fishing units and across species should not be ignored when utilising and interpreting fisheries data [28]. As such we consider it important to consider fleet segments separately with regard to spatial catch patterns. Due to the resolution of observer data, data from individual metiers were too sparse for our analyses so in the first instance we concentrated on data collected on-board TR1 (mixed whitefish) vessels and TR2 (*Nephrops*) vessels as defined by EU regulation, to test our hotspot mapping methodology. These gear types can be defined as those operating bottom trawls, Danish seine nets and similar towed gear with cod end mesh sizes between 70mm and 100mm for TR2 vessels and above 100mm for TR1 vessels, but excluding beam trawls in both cases [29]. Details of the sampling structure within these two categories and how different gear types are represented within them are further detailed in Table 1 and Table 2. Preliminary analysis indicated that for both vessel categories the area fished by sampled vessels was representative of the fishing effort of the fleet, as shown by examining VMS data, although the relationship between the spatial sampling effort of observers and fleet wide fishing patterns was closer for TR2 vessels compared to TR1 vessels (supplementary material; S1).

Table 1 here.

Table 2 here.

2.2 Mapping Methodology

The geographical midpoint of all hauls were calculated as the mean of the Euclidean distance between the start and end point of each fishery operation and catch data assigned to this point. Catch data were then assigned to 0.2 by 0.2 degree grid cells to ensure individual vessel and national data could not be identified. The proportion of the haul by weight (kg) for both the below and above MCRS component of the catch for key demersal species subject to a TAC (cod, haddock, whiting, hake, megrim, monkfish, saithe, pollack, plaice, ling and sole) was calculated. Mean annual

proportion values, based on total catches, were calculated for each grid cell and grid cells were subsequently binned into five categories based on 20% intervals ($0 \geq 20\%$, $20 \geq 40\%$, $40 \geq 60\%$, $60 \geq 80\%$, $80 \geq 100\%$), with an additional category being used to identify where grid cells contained zero catch within a year. A final, amalgamated map for 2010 through to 2015 was created for each species and size component grouping (either $<$ or $>$ MCRS) by identifying grid cells that were consistently within the same binned category over multiple years. Thus areas that display variability over multiple years were removed from the maps, with just those grid cells that are consistent over time remaining (Fig. 1).

In addition to calculating the proportion of each species in the catch by weight and producing maps based on these data the above mapping procedure was repeated using a second metric of catch per unit effort (CPUE). CPUE (kg hr^{-1}) was calculated from the original datasets by dividing the total weight of both below and above MCRS TAC species caught in each haul by the total haul duration. Again, mean annual values were calculated for each grid cell and subsequent values were divided into five equal quantiles, following the removal of zero catches. An additional amalgamated map was created for the whole time period studied by identifying grid cells that were consistently within the same quantile over multiple years.

In addition to determining annual catch patterns, seasonal patterns were investigated by sub setting the observer data into four datasets based on the quarter of the year in which fishing operations took place. Mean quarterly values per grid cell for each individual year were calculated as before again being binned or assigned to quantiles with amalgamated quarterly maps being produced for both proportion and CPUE data. All analyses were undertaken in R 3.4.3 [30].

Fig 1 here.

2.3 Comparison with mean data

The gridded hotspot maps produced, identifying where catch composition remained consistent over time, were compared with a map based solely on mean catch values to determine the effectiveness of this new methodology. The original dataset was stratified by year and then randomly split into two main subsets, a training dataset including 90% of the total observations and a test dataset containing the remaining 10% of the data.. The gridded mapping procedure, as described in section 2.2, was performed using the training data. Individual data points in the test dataset were also

categorised based on the quantile they fell into. Additional maps for the < and > MCRS components of each TAC species were produced by calculating the overall mean proportion by weight and mean CPUE for all hauls in each grid cells using the training data. The quality of all of these mapping procedures was then assessed using the test data. Nearest neighbour analysis was run to identify the closest grid cells in each map to individual data points in the corresponding testing dataset. Test dataset points closer to the edge of the mapped area than to populated grid cells were removed from the analysis. For each map agreement between the categories of the catch in the testing dataset and that of the closest grid cell were calculated. Cohen's Kappa was calculated using the psych package in R [31] for each map in comparison with the testing dataset, as this statistic calculates the proportion of agreement after chance agreement has been removed [32,33]. The above methodology was repeated 1000 times for each map comparison and respective mean Cohen's Kappa values and associated standard deviations were calculated.

2.4 Interpolation

The resultant gridded hotspot maps show where consistent proportions or volumes of certain species within the catch are likely to be found over multiple years. This provides valuable information to inform where to target fishing activities and optimise catches in relation to available quotas. To provide a more user friendly end product the gridded maps were interpolated using inverse distance weighting using gstat in R [30,34]. Due to the grid structure of the data a number of suitable interpolation techniques were compared prior to the final interpolation technique being applied. Proximity polygons, nearest neighbour analysis and inverse distance weighting techniques were validated against a test dataset and the root mean square error (RMSE) was calculated for each method [35]. The inverse distance weighting interpolation consistently produced the lowest RMSE values for each interpolated map and thus this method was used throughout our analyses. Interpolation was also applied to the grids at this stage, rather than on the raw data prior to gridding, to ensure data from annual maps could be overlapped on the same scale, allowing for the retention of consistent data as previously described.

2.5 App Development

To produce a user friendly and interactive tool for use by stakeholders an app, which is available at <https://shiny.marine.ie/discardless/>, was developed using Shiny and Leaflet in R [36,37]. Layers were extracted from the interpolated maps based on the original bin and quantile categories. These were converted to spatially referenced shape files and saved separately. The use of interactive maps allows users to define vessel category (TR1, TR2) and time period of interest (Annual Data, Quarter

1, Quarter 2, Quarter 3 or Quarter 4) as well as the species they wish to target or avoid. For each species selected, the user can specify whether they are interested in avoiding the below or above MCRS component of the catch, or both of these. The user is then able to toggle the levels of catch they either wish to target or avoid, selecting either the minimum proportion of the selected species or minimum level of CPUE of interest (Fig. 2). Multiple target and non-target species can be selected at once and semi-transparent map layers are displayed on an interactive map, identifying where selected levels of catch are likely to occur.

Fig 2 here.

2.6 Simulation Study

A modelling approach was adopted to assess how successful the mapping app could be at assisting an Irish demersal trawler to avoid choke species if it had been used in the Celtic Sea in 2015. Haddock has been identified as a key choke species for Irish TR1 vessels due to the restrictive quotas available for this species [38], with the early fulfilment of haddock quotas preventing further fishing for less quota restricted species [22]. Haddock and whiting are two species that are frequently found to co-occur within the demersal fishery but haddock quotas are often substantially lower than those available for whiting in Ireland. During January 2014 for example, 2 tonnes of haddock were available per Irish vessel operating in ICES areas VIIb-k, VII, IX and X compared with 25 tonnes of whiting in VIIb-k [39]. Thus we used the app to highlight areas where haddock catches were likely to be low and >MCRS whiting catches were likely to be high to identify where best to fish to avoid choking on haddock and extend fishing opportunities for whiting under the LO. From this map six scenarios were examined; 1. Unrestricted Fishing (fishing could take place anywhere in the area bound by 14°W, 3°W, 50°N and 53°N), 2. Fishing in areas with low CPUE of < MCRS haddock (avoiding juvenile haddock), 3. Fishing in areas with low CPUE of > MCRS haddock (avoiding marketable haddock), 4. Fishing in areas with low CPUE of haddock (outside of scenarios 2 and 3 combined, so avoiding both sizes of haddock), 5. Fishing in areas with high CPUE of > MCRS whiting, 6. Fishing in areas with high whiting and low haddock CPUE (where 5 does not overlap 4).

The tri-national observer dataset for TR1 vessels operating in 2015 was used to create interpolated base maps of CPUE (kg h^{-1}) for both below and above MCRS haddock and whiting catches. For each of the scenarios, points were randomly sampled (with replacement) from the appropriate area, as

detailed above. Sampling of points within each area was stopped once a haddock quota of two tonnes had been reached and the whiting caught at this time was recorded. The mean number of hours fished prior to the haddock quota being reached was also inferred. This modelling exercise was repeated 1000 times for each scenario and resultant mean simulated catch values and fishing times were calculated.

3. Results

The hotspot maps, an example of which can be seen in Figure 2, have been created for the above and below MCRS component of the catch for all demersal species subject to a TAC. To better focus comparison and analysis of the results this paper will focus on three key species; haddock, whiting and cod. Both haddock and whiting have been recognised as “choke” species [40] in the Celtic Sea with the perception from multiple member states that catches for these species exceed TAC [41]. Further current ICES advice states that when the MSY approach is applied there should be zero catch or TAC zero in the Celtic Sea and western English channel for cod in 2019 [42]. With particularly low cod quota share available for the UK as well as Ireland in this region in addition to the latest TAC zero advice cod also poses a significant choke risk for all vessels operating in the Celtic Sea [42,43]. Examples of how the information in these maps compares and contrasts for these species are described below.

3.1 Comparison with mean data

The results in Table 3 show that there was generally greater agreement between the hotspot maps we developed for both TR1 and TR2 vessels and a subset of original data points than compared with maps based on mean values from 2010 to 2015 for all maps tested. For TR1 vessels the greatest agreement between the test dataset and our maps was for above MCRS whiting for proportion data (0.43 ± 0.06) and below MCRS whiting for CPUE data (0.41 ± 0.06). Thus for these size classes of whiting the consistencies in catch patterns are most reflected in real-catch data. For TR2 vessels there was greater agreement between the mean proportion data and test data than the hotspot maps for > MCRS whiting, but in all other instances there is greater agreement with the hotspot maps. The below MCRS haddock hotspot map showed the greatest agreement with test data for all proportion maps for the TR2 vessels (0.51 ± 0.06). The greatest agreement between all maps was observed for the >MCRS haddock CPUE hotspot map for TR2 vessels (0.53 ± 0.1). In terms of the two

catch metrics there is a 50% split between the proportion and CPUE hotspot maps having greatest agreement with the raw data.

Table 3 here.

3.2 TR1 vs TR2 vessels

Hotspot maps for TR1 and TR2 vessels were constructed separately and Figure 3 shows how the maps identifying areas with consistent levels of above MCRS haddock CPUE compare for these vessel types. There are similarities between these two maps with both having a large area of the median category of CPUE in the Irish Sea above 52°N. Similarly to the west of Ireland TR1 vessels consistently catch the largest amounts of haddock centred along 52.5°N, with TR2 vessels having an area with high haddock catches at 52.7°N. Unlike TR1 vessels there is a large area where TR2 vessels are likely to have catches with the highest haddock CPUE centred around 51.5°N and 7.5°W. The hotspot map for TR2 vessels also shows an area with very low catches between 50-50.5°N and 8-8.5°W that is not evident for TR1 vessels.

Fig 3 here.

3.3 CPUE vs Proportion

Fig 4 here.

Both CPUE (kg hr^{-1}) and proportion by weight in the catch were used as metrics to identify hotspots of key TAC species. Figure 4 shows an example of how these two metrics compare for above MCRS haddock in the Celtic Sea. There are areas with consistently high levels of haddock CPUE within the catch throughout the region with substantial hotspots to the west of Ireland centred around the coordinates 52.5°N 11.0°W (Fig 4.A). There are very few areas where catches of above MCRS haddock consistently constitute at least 20% of the catch (Fig4.B). High proportions of haddock are identified closer in towards the coast than with the CPUE data although some patterns are similar between the two maps along the west coast of Ireland at around 52.8°N 9.6°W and along the south

west coast at 52.1°N 7.2°W. Less relief is evident on the map representing the proportion of haddock (Fig4.B) as few catches were identified with greater than 60% of haddock in the catch.

3.4 Below MCRS vs Above MCRS catches

Fig 5 here.

All species maps were created for two size categories based on fish either below or above MCRS, allowing for a comparison of the distribution of these two size categories amongst and between species. When comparing whiting catches the largest volumes of above MCRS fish are caught in an area centred around the coordinates 51.1°N 6.85°W (Fig. 5B). The majority of points with the greatest CPUE of below MCRS whiting are also encompassed within this area. Areas with high CPUE of below MCRS whiting do, however, cover a much smaller area compared to the above MCRS component of the catch. There is an additional area centred at 53.0°N 10.0°W where high levels of both below and above MCRS whiting catches are recorded. Small distinct hotspots, representing the highest CPUE category, cover a total area of less than 651km² for below MCRS catches compared to 4204km² for the above MCRS catches in the same CPUE category. There are also a few distinct patches identified as having a high likelihood of high above MCRS catches where there are no below MCRS catches identified, namely along the 52.5°N latitude line and just off of the south west coast of Ireland.

3.5 Seasonal variation

Seasonal variation in catches can be identified by examining amalgamated quarterly rather than annual data. When comparing areas where there are likely to be consistent levels of CPUE of above MCRS cod, over each quarter, seasonal patterns can be seen (Fig.6). Throughout the year the higher cod catches are mainly concentrated within area VIIg. Moving from quarter one to quarter two, there is a southward expansion in the areas within the two highest CPUE categories whilst the extent of the medium catch categories retracts in from the west. During the third quarter of the year the extent of all but the lowest CPUE layer of the map expand to cover larger areas, extending up the west coast of Ireland. In the final quarter of the year these layers retract again with the areas with the highest cod CPUE moving towards the south west of ICES area VIIg and north of VIIf.

Fig 6 here.

3.6 Species Comparison

The same metrics (CPUE or proportion) can be used to compare the likelihood of different species co-occurring. The area with consistent proportions of haddock in the catch over multiple years in the Celtic Sea for example is much greater than that of whiting (Fig.7). No areas are identified as having consistent proportions of whiting in the catch south of the 52.5°N latitude line and west of the 9°W longitude line (Fig.7B). There is a distinct chance of catching haddock in this area, with some hotspots of up to 60% of haddock being identified here (Fig.7A). There is, however, overlap of the haddock and whiting map extents, especially within ICES area VIIg. Overall there are relatively small areas being noted as consistently having at least 20% of haddock and whiting in the catch (approximately 5280km² compared to 3215km² respectively).

Fig 7 here.

3.7 Shiny App

All of the maps produced provide useful information that can be compared in numerous ways depending on the user's interests and objectives. Providing the maps in an interactive app thus provides the opportunity to pick those layers of interest to easily compare and contrast. Figure 2, for example, shows the overlap of four different layers. The first two are species that fishers might wish to target. Both above MCRS cod and whiting have been selected as the target species, with the level of CPUE being set to include the top 40% of catches identified during the mapping analysis. Below MCRS haddock and whiting are selected as the non-target species, with the layers highlighting the three highest levels of CPUE identified. The resultant overlap of all of these layers is displayed within an interactive map layer. Although there are overlaps between all four of the layers there are distinct areas that highlight where just the target species are likely to be found (in light and dark green in Fig.2). For example there is an extensive area in the north east of the Celtic sea between the coasts of Ireland and Wales where high levels of both above MCRS cod and whiting were found with no below MCRS catches of these two species.

3.8 Simulation Study

In our modelling exercise, when examining the mean whiting catch at the point the monthly haddock quota is reached for an Irish vessel operating in the Celtic Sea region, the lowest amount of whiting was caught in Scenario 1 when fishing was unrestricted (Fig. 8B, mean=1710kg). As a consequence of a very restrictive quota, the whiting catch at the point of the haddock choke was also restricted for scenario 2 before slightly increasing for scenarios 3 and 4 successively. Interestingly the whiting catch at the point of the haddock choke peaks at Scenario 5 (mean=2609kg), when solely high whiting areas are being targeted compared to the slightly lower whiting catches in scenario 6 where fishing was restricted to the areas where high whiting catches are not overlapped with the high haddock catches (mean=2441kg). When examining the time fished at the point the haddock choke was reached the whiting catch patterns are reflected for the first 4 scenarios, with the time increasing from 38 hours of fishing within the month at scenario 1 to 59 hours within the month at scenario 4 (Fig.8B). For scenarios 5 (high whiting) and 6 where fishing is targeting the high whiting, low haddock areas the time available for fishing is reduced to just 31 and 30 hours respectively, resulting in much more economical fishing than scenario 1 to 4.

Fig 8 here.

4. Discussion

Hotspot mapping provides useful information to allow the optimisation of fishing activity to better target certain species whilst avoiding unwanted and quota restricted catch. Observer data, collected from commercial fishing vessels, provides an ideal basis for such maps as these data include the discarded component of catches, in addition to landings. The sparse coverage of observer data and limited sampling of commercial vessels can present problems when trying to identify patterns in fish distributions. By combining data, for the first time, from three EU member states for commercial vessels operating within the Celtic Sea, we were able to produce maps highlighting where catches of TAC species show consistent patterns over multiple years. By adopting a new hotspot mapping methodology to utilise this unique dataset we have produced maps that provide more accurate data than just mean catch rates. Further by using the output of these maps in an interactive app we have produced a tool that can easily be used by stakeholders to help inform decisions on where to fish to reduce unwanted catches and potentially extend fishing opportunities under the Landing Obligation.

The unique hotspot mapping methodology developed in this paper identifies areas with consistent catches over time. There are some important assumptions made when using and analysing observer data. These include assuming observer data is representative of the entire fleet, especially with regard to differences in the observer program design between the UK, Ireland and France. There is the potential for additional variation between individual vessels, and the efficiency with which they may be able to avoid unwanted catches, that should be considered when utilising observer data. Observer data remains an important data source, however, as in instances where fisheries are not fully documented or audited using electronic monitoring systems it provides the only source of information on the component of the catch that is discarded at sea. The use of this data to identify consistent patterns in the catch, rather than mean values of observer data, is not only a novel way of approaching hotspot mapping but our analysis indicates that results from the hotspot maps generally more closely represent fishing data than mean maps. As previously highlighted by Gerritsen *et al.*, (2012) species composition of retained catches from demersal otter trawls in Irish waters show considerable spatial structure. Certainly the ability to highlight this structure and consistency with this hotspot mapping methodology, excluding areas with high variability in catch composition, presents stakeholders with data that better highlights where both those catches they want to target or avoid are likely to occur.

There is some variation between catch metrics, vessel type and species as to how well our hotspot maps represent fishing data collected by observers, in part due to how variable the data is between years for each of these variables. For TR1 vessels for example hotspot maps match observer data less well for the below MCRS components of the catch compared to >MCRS hotspot maps. This in part may be due to vessels successfully avoiding juvenile catches as these fish cannot be legally landed. With distinct nursery grounds for a number of commercially important species having been identified around the coast of the British Isles [45,46] it is possible to avoid large aggregations of small fish. This spatial avoidance coupled with larger mesh sizes in TR1 gears, allowing for the escape of juveniles [47,48], may further reduce the catches of undersize fish. Thus with smaller quantities of below MCRS fish being caught and recorded by observers it could be harder to identify areas with consistent catches. Further there could be greater variability in the data set concerning <MCRS catches over the period of study due to changes in gear selectivity as the mandatory use of a square mesh panel (SMP) for demersal fisheries in the Celtic Sea was introduced in 2012 [49]. The uncertainty associated with these maps should therefore be acknowledged and presented to final users and taken into consideration when informing decision making. Overall, however, this

methodology remains a strong tool to inform decision making to optimise catches under the restrictions presented by the Landing Obligation.

Vessels operating different gears and targeting different fisheries are likely to have different catch profiles [28,50]. When comparing separate hotspot maps created from TR1 and TR2 vessels there were apparent differences, although some overall patterns reflecting species distribution were seen in both. TR2 gears, with mesh sizes between 70 and 99mm, are usually used to target *Nephrops norvegicus* [29]. *Nephrops* fishing grounds are restricted spatially to areas with large scale mud patches, which allows for *Nephrops* to build their burrows, with a distinct seasonality also existing within the fishery [51–53]. This associated concentration of fishing activity in time and space for this gear type, compared with TR1 vessels which target mixed demersal fisheries, will likely contribute towards the main differences seen between these two sets of maps. The differences highlighted between these two maps indicate it is important to consider different fleet segments and ensure stakeholders targeting different fisheries are provided with the information most relevant to them. Further these differences highlight how the adoption of gears with greater selectivity may be more important for certain fisheries that are more spatially restricted, including those targeting *Nephrops*, as there are fewer options to relocate fishing activity to better optimise catches.

Two catch metrics were used to identify where similar catches are expected to occur over time. CPUE gives an indication of how the volume of a species in a catch varies. When trying to avoid non-target, quota restricted species it would make sense to avoid areas where there is increased probability of high CPUE catches. When targeting commercially exploited species stakeholders are likely to be drawn to areas with high CPUE due to the associated economic incentives [8,54,55]. It is also important to consider the proportion of the target species within the catch and how clean the catch is if bycatch is to be avoided. Thus it may be important to consider the information provided by both of these metrics. Our example comparing CPUE and proportion maps for above MCRS haddock shows how these two metrics compare and contrast. There is some agreement between the two maps as to where hotspots of haddock occur, and identifying these areas would be beneficial to best target fishing. There is certainly less relief in the maps based on proportion by weight and this is especially true of the below MCRS component of the catch where often there is never greater than 20% of the catch by weight. For these cases the CPUE map provides more detailed information as data categories are based on quantiles rather than pre-defined equal intervals. However, it would also be possible to define different intervals that provide more relief for

these examples, and this would be the type of information that stakeholders could provide to refine the app to best suit their needs.

Under the LO all catches of TAC species, regardless of size, will count against quotas [1]. Thus it will be important for fishers to avoid below MCRS fish as this component of the catch counts against quotas but provides no or limited income if landed. It has certainly been recognised that there is a positive relationship between depth and fish size for a number of demersal species [56–58]. Our examination of hotspot areas for <MCRS whiting catches indeed shows a concentration of catches in the shallower waters along the coast of Ireland. Areas with consistently high catches of >MCRS fish are much more widespread across the Celtic Sea area, and for whiting it is possible to identify areas to target large, marketable fish whilst reducing the chances of catching the smaller fish.

The hotspot mapping method presented identifies areas with consistent proportions or volumes in the catch over time. Obviously fish populations are mobile often displaying seasonal movements and migrations [59–61]. Examining how cod distributions vary with season certainly shows how important it is for stakeholders to consider the data provided in these maps at greater temporal resolution than just annually. Due to the resolution of observer data used in this work, quarterly data is currently the finest temporal resolution that the maps can be divided into. This still provides greater detail than solely presenting annual data and allows fishermen to consider how the dynamics of fish stocks over the course of a year requires seasonal adaptation to fishing practices. If, however, we had access to more reliable and consistent data collected by the fishers themselves, the maps could become more accurate and be presented with finer temporal and spatial resolution. Indeed there are a number of successful examples from fisheries around the world where near real-time information, provided by commercial vessels, assists industry in avoiding bycatch species. These include real-time closures to avoid cod in Scottish North Sea demersal fisheries, voluntary avoidance of chum salmon in the eastern Bering Sea and real-time closures to reduce juvenile saithe, haddock and cod discards in the Icelandic cod fishery [63–65]. Thus while the methodology we present here uses the best information currently available on discards in the Celtic Sea the resultant tools could be improved with greater provision of industry data. Such data provision could also aid in identifying environmental variability over time, especially under a climate change context, which may modify species distributions and resultant catch hotspots.

In the Celtic Sea, where there is a mixed demersal fishery and numerous species co-occur it is important to be able to highlight those areas where certain species are less likely to occur together

to allow fishermen to avoid quota restricted species. Haddock and whiting are two species that co-occur but for which there are often uneven quotas available, resulting in haddock being a key choke species, especially in Irish fisheries [38]. This example of a quota mismatch illustrates how the hotspot maps and resultant map app could be used to inform decisions to best target species for which there is quota available. Simulation modelling of fishing activity based on the mapping app indicates that just better concentrating fishing activity in areas with consistently high catches of the target increases whiting catches prior to the haddock quota being reached. The modelling does indicate, however, that the fishery would still become choked in a relatively short amount of time if efforts were made to maximise on whiting catches. Such restrictions on the Irish fishery were similarly observed by commercial vessels attempting to mitigate against the LO during challenge trials assessing the potential impact of this legislation on the Irish fleet [38]. The associated increases in whiting catches, however, means that fishing efforts could be much more economical, with lower fuel and operational costs being associated with bigger catches. This example focused on TR1 vessels which are often larger and more powerful with the ability to travel further to utilise all of the quotas available to them. For smaller vessels operating primarily in inshore areas it may not be possible to operate more economically when there is a need to travel further from a home port to avoid quota restricted species. However, whilst this is a simplified example of how one choke species might interact with one target for an Irish TR1 vessel it does illustrate that there is real potential for the hotspot maps to inform stakeholders on how to best target those species for which there is quota available.

It is clear that these hotspot maps can provide information that could be very useful if stakeholders are to make the most informed decisions when choosing where to fish whilst operating under the LO [4]. A suite of measures from gear adaptations through to the provision of spatial-temporal information will be required for the fishing industry to successfully reduce unwanted catches and meet the legislative requirements of the LO [66]. Indeed globally a number of initiatives exist where commercial data is used to inform vessel operations [14,63,64]. Working in an area without fully documented fisheries or the widespread adoption of electronic monitoring, however, we have utilised the available data to provide a much needed additional element to this suite. But to ensure this data is easily accessible and digestible it needs to be presented to industry in the appropriate format. Thus the interactive app was developed to allow stakeholders to pick and choose the information that is relevant to them at any one point in time. The hotspot maps and resultant modelling of fishing activity using the maps indicates that demersal fisheries are likely to be heavily restricted under the Landing Obligation due to choke species within this mixed fishery. By arming

industry with as much knowledge and information as possible, however, it is hoped fishing operations can be optimised with fisheries continuing to be profitable whilst operating under the LO. By continuing to develop this application alongside industry, collecting feedback and taking the needs of the final users into account, we envisage this tool could greatly assist in optimising decision making when faced with the challenged of operating in a mixed fishery.

Acknowledgements

This work has been funded by the European Union's Horizon 2020 research and innovation programme under Grant Agreement DiscardLess No 633680.

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A.

B.

C.

CPUE Map Comparison

Season

Annual

Vessel type

TR1

Target Species

Target Species #1

Whiting

Target Species Size #1

Above MCRS

Max CPUE to target #1

Target Species #2

Cod

Target Species Size #2

Above MCRS

Max CPUE to target #2

Non-Target Species

Non-Target Species #1

Whiting

Non-Target Species Size #1

Below MCRS

Max CPUE to avoid #1

Non-Target Species #2

Cod

Non-Target Species Size #2

Below MCRS

Max CPUE to avoid #2

A.

B.

Legend
MIN ■ ■ ■ ■ MAX

A.

Legend
MIN MAX

B.

Legend
 0>20% 20>40% 40>60% 60>80% 80>100%

A.

B.

Legend
MIN MAX

Legend
MIN MAX

A.

B.

Legend

A.

B.

A.

B.

C.

D.

E.

F.

A.

B.

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Figure 1. Diagram showing the steps in the map production process. (A. Individual binned maps created for each year; B. Amalgamated map for all years identifying grid cells within consistent binned categories over multiple years; C. Final interpolated map)

Figure 2. A screenshot of the shiny app developed to allow stakeholders to select the size, species and quantity of fish they would like to target and/or avoid during different seasons. The resultant map displays layers representing where to target or avoid fishing operations to optimise catch composition

Figure 3. Interpolated maps identifying area with consistent levels of >MCRS haddock CPUE over multiple years (2010-2015) for A. TR1 vessels and B. TR2 vessels

Figure 4. Interpolated maps identifying A. Areas with consistent levels of >MCRS haddock CPUE over multiple years (2010-2015) and B. Areas with consistent proportion of >MCRS haddock in the catch by weight over multiple years (2010-2015) for TR1 vessels

Figure 5. Interpolated maps identifying areas with consistent levels of whiting CPUE over multiple years (2010-2015) for A. Below MCRS fish and B. Above MCRS fish for TR1 vessels

Figure 6. Interpolated maps identifying areas with consistent levels of CPUE for above MCRS cod over multiple years (2010-2015) for each quarter of the year for TR1 vessels

Figure 7. Interpolated maps identifying areas with consistent levels of the proportion of above MCRS A. Haddock and B. Whiting in the catch over multiple years (2010-2015)

Figure 8. A. Map from shiny app showing overlap of layers for target and non-target species, B. Mean whiting catch at the point 2 tonne haddock quota is reached, C. Hours fished prior to haddock quota being reached, from modelling fishing of the Irish fleet under 6 different spatially restricted fishing scenarios (1. Unrestricted fishing, 2. Low <MCRS haddock CPUE (outside of orange map layer), 3. Low > MCRS haddock CPUE (outside of red map area), 4. Low haddock CPUE (outside of 2 and 3), 5. High whiting CPUE (inside green area), 6. High whiting and low haddock CPUE (where 5 does not overlap 4))

Supplementary Figure 1: Scatterplots examining the relationship between the number of observer hauls identified within $0.2^\circ \times 0.2^\circ$ grid cells in the Celtic Sea and the number of VMS pings associated with fishing activity (as defined by vessel speed) in the corresponding $0.2^\circ \times 0.2^\circ$ grid cell for A. TR1 vessels ($R^2 = 0.53$, $p < 0.001$, $f = 97.36$, $df = 1$) and B. TR2 vessels ($R^2 = 0.94$, $p < 0.001$, $f = 1005$, $df = 1$) for data collected between 2010 and 2015.

Supplementary Figure 2: Empirical distributions for the mean catch per unit effort data (kg per hour) from amalgamated grid cells for TR1 vessels for A. <MCRS haddock, B. >MCRS haddock, C. <MCRS cod, D. >MCRS cod, E. <MCRS whiting & F. >MCRS whiting

Supplementary Figure 3: Empirical distributions for the mean catch per unit effort data (kg per hour) from amalgamated grid cells for TR2 vessels for A. <MCRS haddock, B. >MCRS haddock, C. <MCRS cod, D. >MCRS cod, E. <MCRS whiting & F. >MCRS whiting

TR1 Gears (bottom trawls, Danish seines and similar towed gears with mesh sizes $\geq 100\text{mm}$)									
Quarter	Gear Type	Ireland		France		UK		Total hauls	Total trips
		Hauls	Trips	Hauls	Trips	Hauls	Trips		
Q1	OTB	292	29	76	8	32	9	400	46
	OTT	196	19	354	28	37	3	587	50
	SSC	87	8	-	-	-	-	87	8
	SDN	-	-	21	1	-	-	21	1
Total Q1		575	56	451	37	69	12	1095	105
Q2	OTB	416	31	166	12	17	8	599	51
	OTQ	22	2	-	-	-	-	22	2
	OTT	398	33	395	30	19	1	812	64
	PTB	5	1	-	-	2	1	7	2
	SSC	142	11	-	-	-	-	142	11
	SDN	-	-	63	4	-	-	63	4
Total Q2		983	78	624	46	38	10	1645	134
Q3	OTB	388	35	315	23	18	7	721	65
	OTT	298	24	478	41	42	4	818	69
	SSC	32	4	-	-	-	-	32	4
	SDN	-	-	99	6	-	-	99	3
Total Q3		718	63	892	70	60	11	1670	144
Q4	OTB	259	24	276	28	35	11	570	63
	OTT	112	11	296	24	30	3	438	38
	SDN	15	1	-	-	-	-	15	1
	SSC	12	3	-	-	-	-	12	3
Total Q4		398	39	572	52	65	14	1035	105

Table 1: Table detailing the number of hauls sampled, and trips in which they occurred in the TR1 data set used to construct hotspot maps. Numbers detailed based on country, quarter and gear type (OTB=Bottom Otter Trawl, OTQ= Otter Quad Trawl, OTT= Otter Twin Trawl, PTB= Bottom Pair Trawl, SSC= Scottish Seine, SDN= Danish Seine)

TR2 Gears (bottom trawls, Danish seines and similar towed gears with mesh sizes 70mm < 100mm)									
Quarter	Gear Type	Ireland		France		UK		Total hauls	Total trips
		Hauls	Trips	Hauls	Trips	Hauls	Trips		
Q1	OTB	137	15	114	33	73	34	324	82
	OTQ	223	15	-	-	-	-	223	15
	OTT	204	27	57	7	48	15	309	49
	SDN	-	-	28	2	-	-	28	2
Total Q1		564	57	199	42	121	49	884	148
Q2	OTB	169	22	190	57	96	40	455	119
	OTQ	109	9	-	-	-	-	109	9
	OTT	372	38	132	17	91	22	595	77
	SDN	-	-	13	3	-	-	13	3
Total Q2		650	69	335	77	187	62	1172	208
Q3	OTB	153	18	305	69	107	42	565	129
	OTQ	83	9	-	-	-	-	83	9
	OTT	179	19	51	7	27	5	257	31
	SDN	-	-	43	3	-	-	43	3
Total Q3		415	46	399	79	134	47	948	172
Q4	OTB	78	11	163	37	95	39	336	87
	OTQ	40	4	-	-	-	-	40	4
	OTT	132	14	112	6	82	20	326	40
	SDN	-	-	30	5	-	-	30	5
Total Q4		250	29	305	48	177	59	732	136

Table 2: Table detailing the number of hauls sampled, and trips in which they occurred in the TR2 data set used to construct hotspot maps. Numbers detailed based on country, quarter and gear type (OTB=Bottom Otter Trawl, OTQ= Otter Quad Trawl, OTT= Otter Twin Trawl, SDN= Danish Seine)

	Proportion data				CPUE data			
	TR1		TR2		TR1		TR2	
	Hotspot	Mean	Hotspot	Mean	Hotspot	Mean	Hotspot	Mean
Haddock >MCRS	0.22±0.06	0.20±0.05	0.43±0.01	0.19±0.05	0.27±0.06	0.19±0.04	0.53±0.10	0.17±0.04
Haddock <MCRS	0.25±0.06	0.13±0.04	0.51±0.06	0.31±0.05	0.32±0.07	0.001±0.09	0.38±0.07	0.07±0.09
Cod >MCRS	0.37±0.06	0.14±0.04	0.17±0.06	0.09±0.04	0.37±0.06	0.18±0.03	0.24±0.07	0.13±0.03
Cod <MCRS	0.27±0.06	0.21±0.04	0.26±0.07	0.15±0.04	0.22±0.08	-0.01±0.08	0.19±0.08	0.01±0.09
Whiting > MCRS	0.43±0.06	0.39±0.05	0.16±0.06	0.21±0.05	0.31±0.07	-0.01±0.08	0.27±0.07	0.14±0.04
Whiting < MCRS	0.25±0.06	0.16±0.04	0.27±0.06	0.16±0.05	0.41±0.06	0.26±0.04	0.16±0.07	0.05±0.09

Table 3: Table to show mean Cohen's kappa values ($\pm$ SD) for agreement between test subset of observer data and results from two mapping methodologies for TR1 and TR2 vessels (mean per 0.2 x 0.2 degree grid cell and for our hotspot mapping methodology) for proportion by weight maps and CPUE maps. Results are displayed for below and above MCRS haddock, cod and whiting.