Progress in Oceanography 117 (2013) 130–139

Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

Fishing and the oceanography of a stratified shelf sea

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ARTICLE INFO

Article history:
Available online 24 June 2013

ABSTRACT

Fishing vessel position data from the Vessel Monitoring System (VMS) were used to investigate fishing activity in the Celtic Sea, a seasonally-stratifying, temperate region on the shelf of northwest Europe. The spatial pattern of fishing showed that three main areas are targeted: (1) the Celtic Deep (an area of deeper water with fine sediments), (2) the shelf edge, and (3) an area covering several large seabed banks in the central Celtic Sea. Data from each of these regions were analysed to examine the contrasting seasonality of fishing activity, and to highlight where the spring-neap tidal cycle appears to be important to fishing. The oceanographic characteristics of the Celtic Sea were considered alongside the distribution and timing of fishing, illustrating likely contrasts in the underlying environmental drivers of the different fished regions. In the central Celtic Sea, fishing mainly occurred during the stratified period between April and August. Based on evidence provided in other papers of this Special Issue, we suggest that the fishing in this area is supported by (1) a broad increase in primary production caused by lee-waves generated by seabed banks around spring tides driving large supplies of nutrients into the photic zone, and (2) greater concentrations of zooplankton within the region influenced by the seabed banks and elevated primary production. In contrast, while the shelf edge is a site of elevated surface chlorophyll, previous work has suggested that the periodic mixing generated by an internal tide at the shelf edge alters the size–structure of the phytoplankton community which fish larvae from the spawning stocks along the shelf edge are able to exploit. The fishery for *Nephrops norvegicus* in the Celtic Deep was the only one to show a significant spring-neap cycle, possibly linked to *Nephrops* foraging outside their burrows less during spring tides. More tentatively, the fishery for *Nephrops* correlated most strongly with a localised shift in the tidal current polarisation, suggesting that the muddy seabed required by *Nephrops* is controlled by rotational constraints on the extent of the bottom boundary layer.

1. Introduction

Shelf and coastal waters provide about 90% of global fish catches (Pauly et al., 2002). The existence of high densities of commercially exploitable fish on the shelf can be linked to several factors. Rates of primary production in shelf seas are typically three times higher compared to the open ocean (Simpson and Sharples, 2012), with a high diversity of primary producers utilising nutrient inputs from rivers and from across the shelf edge from the open ocean. Bottom-up explanations for variability in fish stocks link physical perturbation of phytoplankton production to changes in a fishery (Tenore et al., 1995; Ware and Thomson, 1991). However, the physics of the environment can also affect fish distributions without primary production as a mediator. Fronts in shelf seas are often sites of high fishing, possibly attributable to increases in primary production at the fronts or to small-scale frontal circulation increasing the densities of prey and so attracting aggregations of predators (Munk et al., 1995; Sambrotto et al., 2008; Sims and Quayle, 1998). The interaction between the larger-scale patterns of circulation in shelf seas and the life histories of fish has been shown to be important in maintaining stocks (e.g. Hill et al., 1996; Lough and Manning, 2001; Reid, 2001). Seabed topography, on a range of spatial scales, has been implicated in enhancing primary production or concentrating prey (e.g. Genin, 2004). However, these links between the details of the shelf environment, the distribution of fish species and the areas that are fished are not always well understood. At a time when managers are moving towards more spatially explicit governance of our oceans, with the creation of marine protected areas (MPAs) and large areas

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http://dx.doi.org/10.1016/j.pocean.2013.06.014
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being licensed for marine renewable energy installations, it is imperative that we understand better the fundamental links between oceanographic processes and fishing activity.

The introduction of the Vessel Monitoring System (VMS) in the late 1990s has provided a valuable source of data with which to examine fishing vessel activity (e.g. Murawski et al., 2005; Witt and Godley, 2007). Vessel position (GPS) and speed data are typically transmitted once every hour or every 2 h, with these data collated and controlled by national agencies. These data have proved useful for assessing the spatial distribution of fishing (Jennings and Lee, 2012), and to inform on the design and implementation of marine protected areas (Hall-Spencer et al., 2009; Murawski et al., 2005), and the estimation of retained fish catches (Aanes et al., 2011). Knowing where fishing vessels go also provides a means to link the fishing activity to the oceanographic environment, though the use of VMS data in this context is less well developed. VMS data have shown how the fishing pressure exerted over a shelf sea is not spatially uniform (e.g. Jennings and Lee, 2012; Witt and Godley, 2007). Maps of fishing activity can also show correlations with seabed habitat type (Stelzenmuller et al., 2008) and oceanographic features (Williams et al., 2010). Such correlations reflect the knowledge of the environment that fishing crews have acquired, although fishing patterns will also be influenced by a range of other factors, such as fuel price, market demands, quota and weather constraints. In the Celtic Sea, our own experience suggested that the fishing vessel activity in the vicinity of Jones Bank, North West Bank and Labadie Bank was very high, as suggested by the loss of a significant proportion of the oceanographic moorings deployed on Jones Bank during preliminary work in 2005. This anecdotal evidence of fishing activity in the vicinity of seabed banks, along with observations of the distinct physical oceanography of these areas (Sharples et al., this issue) provided the underlying rationale supporting the work presented in this Special Issue.

This contribution focuses on the distribution of fishing activity revealed by VMS data within the Celtic Sea, providing a novel assessment of how the oceanographic characteristics of a whole shelf sea may lead to consistent patchiness in the fishing effort. The spatial and seasonal distribution of fishing was examined in relation to seabed features and to the regional oceanographic environment as revealed by satellite imagery and whole-shelf transects of the oceanography. We also considered fishing over individual banks in the Celtic Sea to determine whether or not fishing activity focuses on these small scale features that our work has shown to have a distinct physical environment compared to flatter seabed areas (e.g. Palmer et al., 2013). There are significant contrasts in tidal currents over the spring-neap cycle in the Celtic Sea, with spring tidal flows being typically twice those at neap tides (Sharples, 2008). Similar contrasts occur at the shelf edge, with a large spring-neap change in the structure of the internal tide (Sharples et al., 2007). The physical data from the JC025 cruise indicated marked spring-neap variability in currents and turbulence over the banks in the central Celtic Sea (Palmer et al., 2013). We also analysed the VMS data to assess whether or not the spring-neap tidal cycle has an influence on when and where fishing takes place.

2. Methods

VMS data were available for the period 2002–2007 in UK waters (supplied courtesy of the UK Department for Environment Food and Rural Affairs) and between May and December 2005 for Irish waters (supplied by the Irish Naval Service). Both data sets included time-referenced vessel positions and unique vessel identifiers for all European Union registered fishing vessels >15 m length. The time interval between reported vessel positions was generally 1 or 2 h. Vessels use a range of fishing gears including otter trawl, beam trawl, gillnets and pots. This information was not used as it was only supplied for UK vessels in UK waters, but it did indicate a full range of fishing methods being used. The UK data contained information from typically 850–1500 vessels each year. The 2005 data from Irish waters contained data from 826 vessels.

All VMS data were first sorted into time-ordered position listings for each vessel. Vessel speed was calculated using the distance travelled between adjacent positions in this listing, and the time between the positions. The Irish VMS data also included information on vessel course and speed, though with numerous missing values. For consistency between the UK and Irish datasets, all vessel speeds were calculated directly from the position information. A simple criterion of a critical speed of 5 knots was used to separate vessel activity into "fishing" (speeds $\leqslant$ 5 knots) and "transit" (speeds > 5 knots), similar to Hiddink et al. (2007).

Bathymetry for the Celtic Sea was taken from the Olex database (Fig. 1; www.olex.no). A regional analysis of the VMS fishing information was carried out over the whole Celtic Sea (Fig. 1) in order to determine the distribution of fishing activity. This large-scale spatial analysis was applied to UK and Irish VMS data between 1st May and 30th September 2005, partially because this corresponds to the time period over which most fish landings occur and also because of the limited data from Irish waters. Information describing the regional oceanographic environment came from two sources. Satellite imagery (sea surface temperature and sea surface chlorophyll concentration) was provided by the NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS) based at the Plymouth Marine Laboratory and the University of Dundee. Sections of temperature and chlorophyll concentration across the Celtic Sea were available from three cruises. One section was acquired during cruise JC025 (RRS *James Cook*, July 2008, the main source of data for this Special Issue) between the shelf edge and Jones Bank. Sections from the shelf edge, through the Celtic Sea and into the Irish Sea were available from cruises JR98 (RRS *James Clark Ross*, July 2003) and D352 (RRS *Discovery*, June 2010). The oceanographic structure of this region is largely determined by the barotropic and, at the shelf edge, baroclinic tides interacting with the seasonal air–sea heat flux (e.g. Simpson and Sharples, 2012). Partitioning of the region by these physical processes into mixed, seasonally-stratifying and shelf edge waters is consistent between years.

To quantify seasonal and tidal contrasts in fishing activity in different regions of the Celtic Sea a set of sample boxes were defined encompassing data from within the UK sector (Fig. 1), and informed by the regional VMS fishing activity pattern (described later in Section 3.1). Boxes i–iv were situated within the central Celtic Sea, with boxes i and iii covering two major seabed banks (Jones Bank and Northwest Bank) and boxes ii and iv covering areas of flat seabed adjacent to the banks. This separation between bank and adjacent nearby flat areas was used to determine whether or not the very localised physics over the banks (Palmer et al., 2013) had any effect on the fishing. Box v covered the area of the Celtic Deep in the north-eastern Celtic Sea, and box vi covered the edge of the continental shelf. The number of vessels observed to fish within each of the boxes is shown in Table 1, along with the total amount of vessel time spent fishing normalised by the box area. The total number of vessels visiting each box initially looks high; however ranking vessels in order of their contribution to fishing in each box (e.g. Fig. 2) indicated that most of the fishing in each box was dominated by relatively few vessels. The number of vessels responsible for 50% of the fishing time within each box is also shown in Table 1, which serves to highlight the typical site-fidelity of fishers.

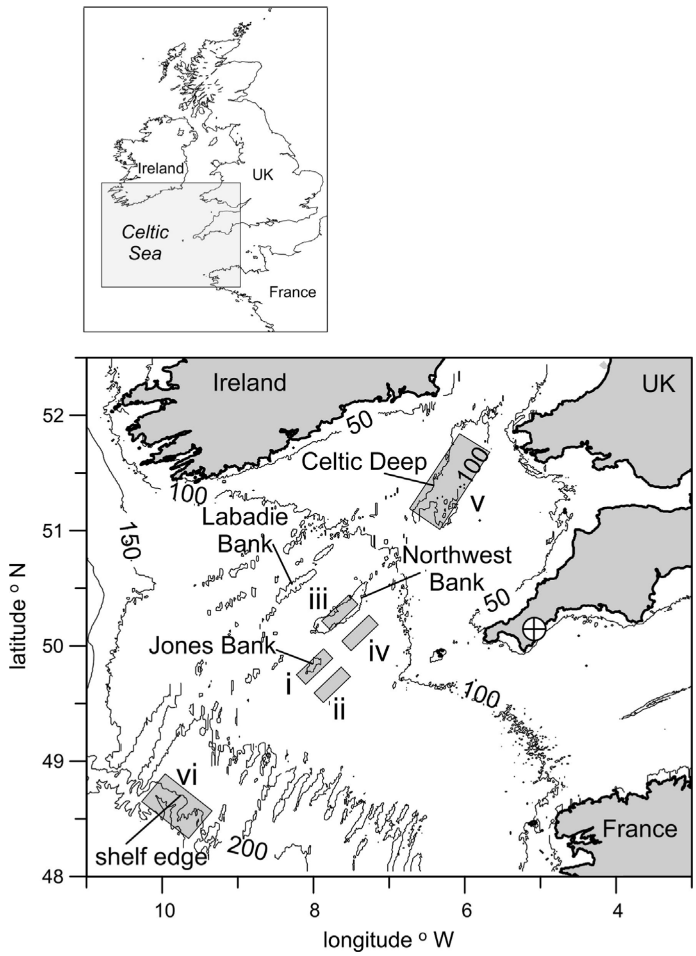

Fig. 1. Location map for the Celtic Sea region covered by the UK and Irish VMS data. Bathymetry is based on the Olex data, sub-sampled to 1 km resolution from the original database. The shaded boxes are used in the VMS analyses. In the central Celtic Sea box i is over Jones Bank, iii is over Northwest Bank and boxes ii and iv are over flat regions adjacent to the banks. In the northern Celtic Sea box v is situated over the Celtic Deep, and in the south box vi lies along the shelf edge (coincident with the 200 m isobath). The crossed circle marks Falmouth, used for information on the spring-neap tidal timing.

Table 1
Number of vessels fishing in each of the analyses boxes i–vi for UK VMS data in years 2002–2007; n = total number of vessels detected fishing, n_{50} = number of vessels responsible for 50% of the fishing in the box. Fishing activity within each box is normalised by the box area.

Box	Location	Area (km^2)	n						n_{50}						Fishing activity (d km^{-2})					
			2002	2003	2004	2005	2006	2007	2002	2003	2004	2005	2006	2007	2002	2003	2004	2005	2006	2007
i	Jones Bank	460	30	55	74	64	67	57	3	7	6	8	8	6	0.06	0.18	0.34	0.40	0.37	0.26
ii	SE Jones Bank	460	29	57	74	73	60	51	3	6	9	10	8	8	0.04	0.13	0.20	0.14	0.17	0.13
iii	Northwest Bank	460	27	31	67	59	56	47	1	4	3	4	4	3	0.09	0.06	0.17	0.34	0.32	0.21
iv	NE Jones Bank	460	31	52	91	80	66	52	6	5	10	9	9	6	0.05	0.22	0.43	0.46	0.35	0.19
v	Celtic Deep	3100	116	121	217	223	227	197	13	12	30	26	27	26	0.33	0.42	0.78	1.01	0.98	0.78
vi	Shelf edge	2000	149	152	164	177	171	133	17	16	18	19	21	18	1.07	1.23	1.31	1.17	0.83	0.99

3. Results

3.1. Regional analysis

The regional pattern of fishing activity was illustrated by collating all UK and Irish VMS data between May and September 2005 (Fig. 3). Fishing activity was clearly focused over specific areas. By far the highest fishing activity occurred in the Celtic Deep and along the shelf edge. Fishing in the Celtic Deep particularly targets *Nephrops norvegicus* (ICES, 2011), where a locally deep basin with muddy seabed sediments provides habitat for this bottom-dwelling lobster. At the shelf edge fishers target a range of species, including spawning stocks of mackerel, horse mackerel, hake, blue whiting and anchovies (Reid, 2001). Lower, but still significant, fishing occurred within the central Celtic Sea. Here most of the fishing activity was in a region where water depths are 100–125 m, over the field of seabed features that includes the Labadie, Jones and Northwest Banks. This area of fishing activity appeared

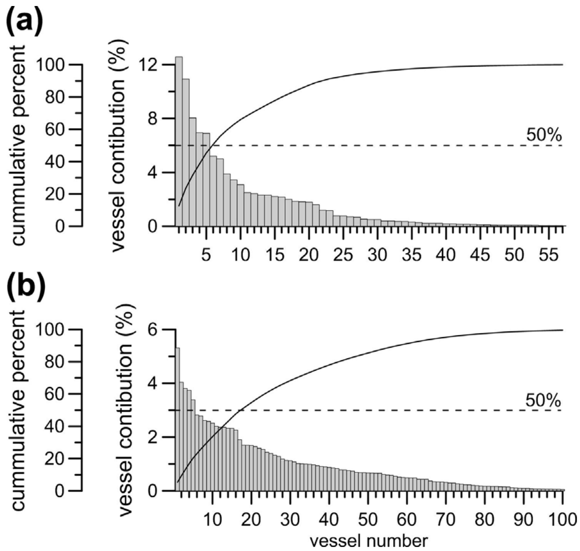

Fig. 2. Ranked vessel contributions to total fishing (bars) and the cumulative fishing activity (lines) for (a) Jones Bank in 2007, box i, and (b) the shelf edge in 2007, box vi.

very clearly defined, separated from the high fishing regions of the Celtic Deep and the shelf edge by areas where negligible fishing occurred. A similar analysis of the UK data in other years (not shown) showed that the relative horizontal distribution of fishing activity was consistent within UK waters with that shown in Fig. 3, although the absolute fishing rates varied.

There is no suggestion in Fig. 3 that fishing occurred just over individual banks; instead effort was spread over and between banks fairly uniformly. Using the data in Table 1 from within the sample boxes i–iv within the central Celtic Sea, it is clear that there was no significant preference for an individual bank compared to adjacent flat regions of shelf (Table 2). There were, however, significant differences between the mean fishing activity within the central Celtic Sea (0.22 ± 0.13 d km^{-2} averaged over boxes i–iv) and the activity in the Celtic Deep and at the shelf edge (Table 2). Average fishing activity at the shelf edge was five times greater than within the Celtic Sea, and in the Celtic Deep fishing activity was greater than in the central Celtic Sea by a factor of 3.3.

Table 2
Mean fishing activity within sample boxes i–vi, over banks (collated boxes i and iii) and over flat seabed (collated boxes ii and iv). Means ± 1 standard deviation are calculated from data in Table 1.

Box	Location	Mean fishing activity ± 1 s.d. (d km^{-2}) 2002–2007
i	Jones Bank	0.27 ± 0.13
ii	SE Jones Bank	0.14 ± 0.05
iii	Northwest Bank	0.20 ± 0.12
iv	NE Jones Bank	0.28 ± 0.16
i, iii	Banks	0.23 ± 0.12
ii, iv	Flat	0.21 ± 0.14
v	Celtic Deep	0.72 ± 0.28
vi	Shelf edge	1.10 ± 0.17

3.2. Seasonal patterns of fishing

Analysis of the seasonal distribution of fishing activity in the Celtic Deep, the central Celtic Sea (collated data for boxes i–iv) and the shelf edge (Fig. 4) showed marked differences in how fishing was carried out through the year. The Celtic Deep (Fig. 4a) showed very little seasonality, with a slight reduction in fishing in the early part of the year followed by consistent fishing from about April through to December. Much more marked seasonality was evident in the central Celtic Sea (Fig. 4b), where the bulk of the fishing occurred during spring and summer, with much less fishing in autumn and winter. There was also a distinct seasonality in the fishing at the shelf edge, but skewed and shifted in phase compared to the central Celtic Sea. Very little fishing occurred in April–June, followed by a sharp increase in July–August and a slow reduction in fishing through to the next spring.

3.3. Spring-neap patterns

Different components of the marine ecosystem are able to respond to changes in the environment or in food supply on different time scales. Phytoplankton specific growth rates, typically 0.5–2 d^{-1}, are fast enough for them to respond to variability in the physical environment of a few days. In tidally energetic shelf seas the spring-neap cycle of tidal mixing can drive cycles in nutrient fluxes that phytoplankton nutrient uptake and growth can take advantage of (e.g. at the shelf edge, Sharples et al., 2007; at tidal mixing fronts and within the seasonal thermocline, Sharples,

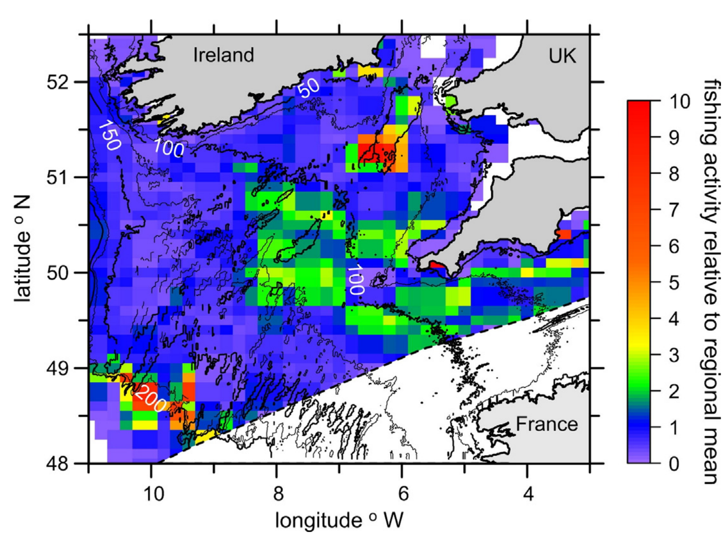

Fig. 3. Regional distribution of fishing activity in UK and Irish waters of the Celtic Sea based on VMS data May–September 2005. Activity is illustrated relative to the mean over the whole region (0.03 d km^{-2}). Bathymetry is based on the Olex database. No data were available from French territorial waters.

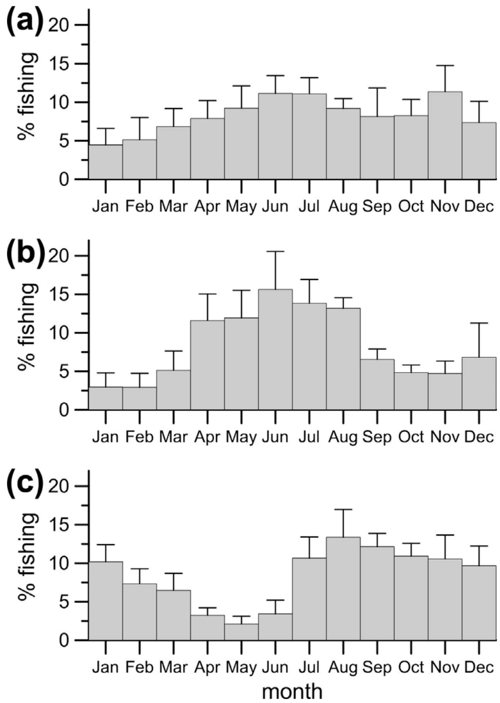

Fig. 4. Seasonal distribution of fishing activity based on UK VMS data in years 2002–2007. (a) Activity in the Celtic Deep (box v in Fig. 1). (b) Activity over the central Celtic Sea (boxes i–iv in Fig. 1). (c) Activity at the shelf edge (box vi in Fig. 1). Fishing activity is expressed as% of the annual mean. Error bars are 1 standard deviation about the mean over years 2002–2007.

2008). The mesozooplankton grazers, however, have reproduction cycles that last from a few weeks to months. So while a fortnightly pulse of primary producer biomass may trigger zooplankton reproduction, advection and dispersion by currents over the reproduction time scale of zooplankton will decouple zooplankton biomass from the phytoplankton (e.g. Abraham, 1998; Kiørboe, 1993). The fish species targeted by fishers in the Celtic Sea are generally long-lived species with reproduction cycles much longer than either the phytoplankton or the zooplankton (e.g. Martinez et al., 2013), and so we would not expect fishing activity to respond to spring-neap cycles in primary production. However, fishing activity may respond more directly to the spring-neap cycle if the contrasts in tidal flow and turbulence lead to changes in the distributions or behaviour of fish which may affect catchability.

Analysis of UK VMS data for 2007 was carried out to assess whether or not there was any spring-neap tidal contrast in fishing activity in the region. Data for the Celtic Deep (box v), the banks (boxes i and iii) and the flat regions (boxes ii and iv) of the central Celtic Sea, and for the shelf edge (box vi) were analysed for the timing of fishing activity relative to the nearest spring tide in 2007. Tidal height and time information was extracted for Falmouth (see Fig. 1) using the POLTIPS tidal prediction package (http://www.pol.ac.uk/appl/poltips3.html). VMS data were then analysed by recording the number of days between each fishing activity data point and the time of the nearest spring tide, and collating the information to quantify the proportion of total fishing activity occurring on each day of the spring-neap cycle (Fig. 5). The Celtic Deep data indicated a strong springs-neaps contrast in fishing activity, with about 75% of the fishing occurring ±3 days about neap tides and a significant minimum in fishing around spring tides (Fig. 5c). By contrast, the shelf edge showed a very flat distribution of fishing activity through the springs-neaps tidal cycle; there was no significant departure from the 6.6% activity per day expected as an average over a 15 day period. Fishing in the central Celtic Sea (Fig. 5a and b) showed a rather more confused pattern in relation to the spring-neap tidal cycle. Both the banks (Fig. 5a) and the flat regions (Fig. 5b) had a weak suggestion of lower fishing near spring tides, although there was little indication that there was any significant contrast between the banks and flat regions. Further analyses of fishing activity against the spring-neap cycle for other years (not shown) indicated that the Celtic Deep and the shelf edge patterns were very robust, while the patterns over the central Celtic Sea are more variable between years. Analysis and presentation of fishing activity data for individual vessels was not undertaken, as there are constraints on such use of VMS data in terms of confidentiality. However, an assessment of individual vessels that contributed to most of the fishing over the central Celtic Sea did show that a spring tide reduction in fishing activity was strong for some vessels and completely absent for others. This is likely a result of what gear is being used and which species are being targeted by the different vessels.

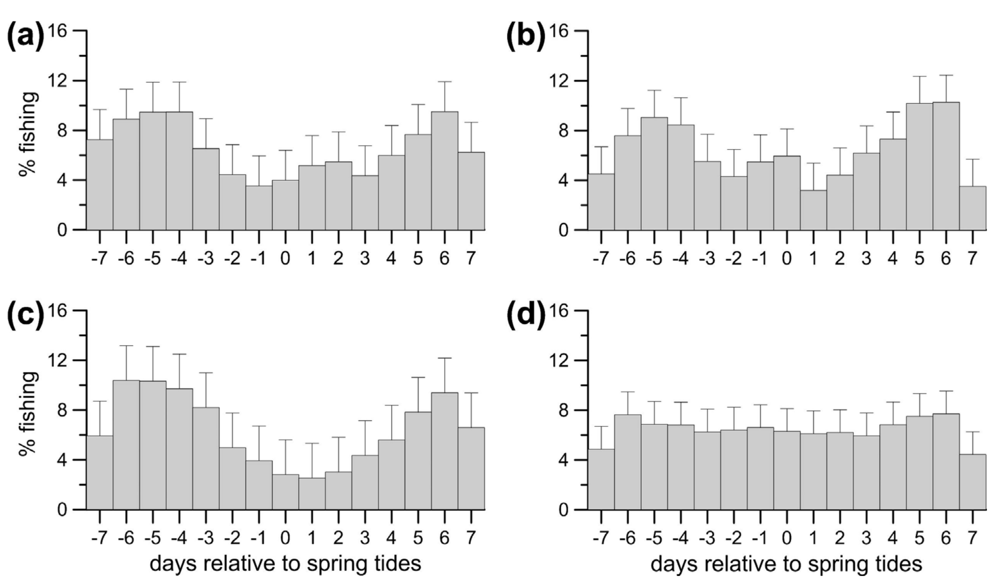

Fig. 5. Timing of fishing activity relative to spring tides. (a) Jones Bank and Northwest Bank (boxes i and iii), (b) flat shelf (boxes ii and iv), (c) Celtic Deep (box v), (d) the shelf edge (box vi). Analysis was carried out on UK VMS data for 2007. Error bars are 1 standard deviation about the mean. Note that over the 14.78 d spring-neap cycle, data for +7 and −7 days relative to spring tides can be combined.

4. Discussion

The regional analysis of fishing activity in the Celtic Sea suggests that fishing was focused in three main areas: (1) the Celtic Deep, (2) the shelf edge, and (3) a region in the central Celtic Sea with depths between 100 and 125 m and encompassing the field of large seabed banks. Comparison of the distribution of fishing activity (Fig. 3) with the bathymetry (Fig. 1), and also with regional oceanographic patterns (Fig. 6) can provide some insight into the possible links between fishing and the regional-scale physical characteristics of the Celtic Sea.

4.1. The Celtic Deep

N. norvegicus requires a cohesive mud seabed in order to dig the burrows within which it shelters from predators and strong currents (Cobb and Wahle, 1994). The Celtic Deep is one of the few areas of muddy sediments in the Celtic Sea (Connor et al., 2006), making it suitable habitat for *N. norvegicus* (Ellis et al., 2013). We suggest here that the existence of this mud patch, and thus the proximate cause of the fishery, is dependent on a particular characteristic of the tides over the Celtic Deep. Using the squared tidal current amplitude as an indicator of stress at the seabed, the Celtic Deep can be seen to be not significantly different from the areas to the west and northwest (Fig. 6a) where seabed sediments are sandier (Connor et al., 2006). Thus there does not appear to be a local reduction in bed stress within the Celtic Deep that might explain the area of fine sediment deposition. However, a significant physical contrast between the Celtic Deep and the waters immediately adjacent is that the area is a site of strongly anti-clockwise polarised tidal currents (Fig. 6b). There is a marked correspondence between the region of fishing and the area of anti-clockwise polarisation of tidal current ellipses in the southeast of the Celtic Deep (Fig. 6b) Such tidal current polarisation limits the vertical extent of turbulence above the seabed (Simpson and Tinker, 2009), which will limit the resuspension of sediments away from the seabed. While seabed sediment characteristics are vital to the existence of *N. norvegicus*, there also needs to be a supply or organic material to the seabed that can support the benthic ecosystem. In the north of the Celtic Deep lies a tidal mixing front (Bowers and Simpson, 1987), visible as the marked horizontal sea surface temperature gradient in Fig. 6c. Relatively high sea surface chlorophyll is associated with this front, with moderate concentrations of chlorophyll reaching over much of the Celtic Deep (Fig. 6d). Primary production rates in the photic zone in this area have been measured at 10–20 mg C m^{-3} d^{-1}, which is at the high end of the range seen in the Celtic Sea in summer (Hickman et al., 2012). The tidal ellipse polarisation also influences the position of this nearby front (Simpson and Sharples, 1994), resulting in an anti-clockwise baroclinic residual circulation during the stratified part of the year (Brown et al., 2003) which could play a similar role to the gyre observed over the *N. norvegicus* grounds in the western Irish Sea by providing a seasonal retention mechanism for *N. norvegicus* larvae (Hill et al., 1996). We suggest that the existence of *N. norvegicus*, and its associated fishery, in the Celtic Deep is primarily dependent on the polarisation of the tidal current ellipse allowing the cohesive mud habitat to be maintained. The relatively high rates of primary production on the stratified side of the nearby tidal mixing front then provides a source of organic material to the seabed, while the frontal circulation could aid retention of *N. norvegicus* larvae. Further work would need to identify the role of tidal polarisation in sediment dynamics, and could investigate how inter-annual variability in primary production and frontal structure might alter the *N. norvegicus* population and the fishery landings.

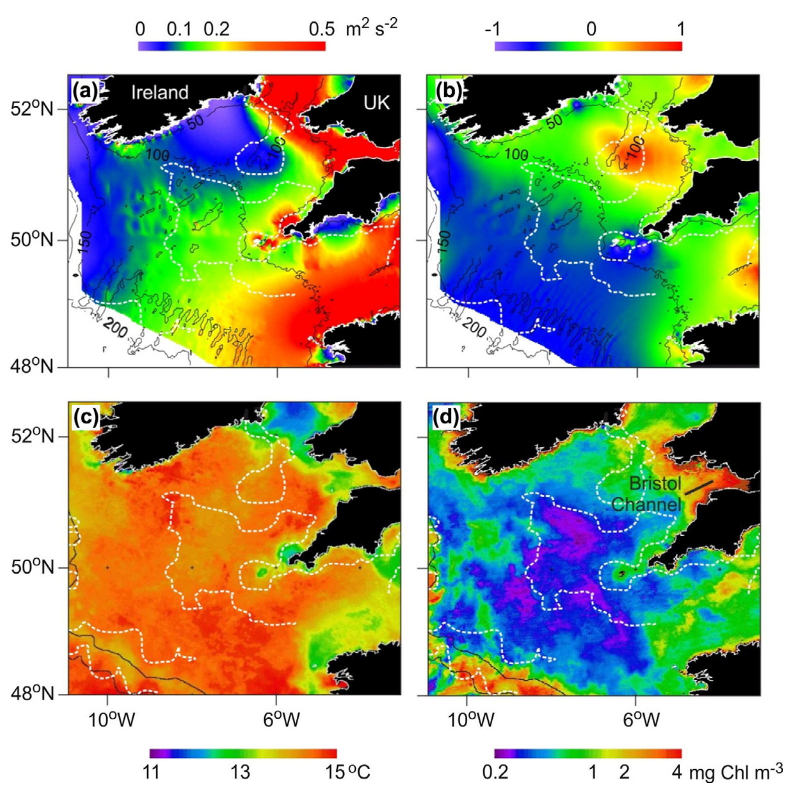

Fig. 6. (a) Squared M_2 tidal current amplitude (m^2 s^{-2}). (b) Polarisation of the M_2 tidal current ellipse; positive values indicate anti-clockwise rotation of the tidal current vector. (c) AVHRR image of sea surface temperature (°C). (d) MODIS image of sea surface chlorophyll (mg Chl m^{-3}). The dashed white contours surround the regions of high fishing activity, delineated as the 1× mean activity from Fig. 3. Data in (a and b) are from the POLCOMS model (Holt and James, 2001), with Olex bathymetry contoured every 50 m. Satellite images in (c and d) are 1 week composites, 9–15th June 2005, courtesy of NEODAAS Plymouth Marine Laboratory UK.

There was only weak seasonality to the fishing activity over the Celtic Deep (Fig. 4a), reflecting the year-round availability of *N. norvegicus* with fishing activity likely to be more dependent on other factors (e.g. weather, quota availability, market price and demand). However, there is a consistent pattern of lower fishing around spring tides compared to neap tides was clear (Fig. 5c). This pattern is robust both between seasons and over several years of VMS data. *N. norvegicus* is a relatively long-lived crustacean, so this tidal signal in the fishing activity will not be a response of *N. norvegicus* to frontal or thermocline cycles in primary productivity. Instead the reduced fishing at spring tides is likely to be a direct response to the lower availability of *N. norvegicus* outside their burrows. Catch rates of *N. norvegicus* are known to be generally higher during times of low water flow (Bell et al., 2006), because the animals are less active outside their burrows during times of strong currents.

4.2. The shelf edge

The shelf edge from the west of France (Bay of Biscay), round to the west of Ireland and west and north of Scotland is well known as a site used by spawning stocks of mackerel, horse mackerel, hake and blue whiting (Reid, 2001), with fishers also exploiting anglerfish and megrim. There are two aspects of the physics of the shelf edge that appear to support these dense fish stocks. The northward flowing slope current of warm water, set up by the interaction between the latitudinal heating gradient and the bathymetry of the shelf edge (Huthnance, 1984), is used by the migrating fish as they make for their spawning grounds along the shelf edge, and also provides a transport mechanism for larvae back towards the adult grounds (Reid, 2001). The shelf edge is also the site of locally enhanced vertical mixing of nutrients upward to the sea surface, driven by the internal tide (Pingree and Mardell, 1981; Sharples et al., 2007). This nutrient supply, identifiable in Fig. 6a as the band of cooler water over the shelf edge, has a strong spring-neap tidal signal with spring tide nitrate fluxes towards the surface being almost an order of magnitude greater than at neap tides. This flux supports increased primary production compared to waters adjacent to the shelf edge (Sharples et al., 2009). More importantly however, the site of shelf edge nutrient mixing has a very distinct phytoplankton community with generally larger celled phytoplankton and higher diatom numbers than found either on the shelf or in the adjacent NE Atlantic. These large-celled phytoplankton likely provide a vital food source for first-feeding fish larvae and larger zooplankton (Sharples et al., 2009). The surface chlorophyll signature indicating this mixing, primary production, and phytoplankton community (Fig. 6b) is coincident with the cool shelf edge surface water (Fig. 6a) and in summer is often visible along a 1500 km length of shelf edge from the Bay of Biscay round to the north of Scotland (Sharples et al., 2009).

The shelf edge fishing was strongly seasonal. There was a sharp increase in July, relatively high fishing maintained until January, and then a decrease to a minimum in the following April/May (Fig. 4c). Atlantic mackerel stocks migrate from their feeding grounds in the northern North Sea and the Norwegian Sea towards their spawning grounds west of Scotland and Ireland and southwest of the UK, and further south off northern Spain, through winter and spring (Reid et al., 1997; Uriarte and Lucio, 2001). The beginning of fishing activity is generally seen as a good indication of when the spawning stocks have arrived (Walsh et al., 1995). Seasonality of fishing along the Celtic Sea shelf edge thus likely reflects targeting of spawning stocks in the region as well as post-spawning fish returning to the north from the southern spawning area off Spain. In contrast to the Celtic Deep, there was no indication of any effects on fishing arising from the springs-neaps tidal cycle. While the primary production at the shelf edge is supported by the springs-neaps pulsing of nitrate towards the sea surface, the abundance of any particular fish species targeted by the fishing vessels is decoupled from the cycle of primary biomass. The lack of any springs-neaps variability in fishing activity also indicates that there was no other, more direct link, between any springs-neaps changes in behaviour or distributions of the targeted fish species and the ability of the fishing vessels to catch them.

4.3. The central Celtic Sea

The region of significant fishing vessel activity in the central Celtic Sea was coincident with a field of large seabed banks surrounded by water depths between 100 and 125 m. There was no clear surface temperature or chlorophyll signal that marks this area as different from the adjacent waters with negligible fishing activity (Fig. 6c and d). Instead the main contrast in the physics of this region compared to the non-fished areas adjacent to it was the occurrence of internal lee waves and associated strong internal mixing located over the banks (Palmer et al., 2013). The vertical turbulent fluxes of nitrate into the thermocline driven by breaking lee waves at spring tides was observed to reach over 50 mmol m^{-2} d^{-1}, a factor of 25 times greater than the fluxes at neap tides over the banks (Tweddle et al., 2013) and fluxes over flatter shelf regions (e.g. Sharples et al., 2001; Rippeth et al., 2009). The dye release experiments showed that this mixing-influenced water was advected and dispersed away from the sources of the turbulence (Inall et al., 2013). Estimates of the effect on the phytoplankton indicated that primary production rates within a patch of this bank-influenced water could be doubled to 0.5 g C m^{-2} d^{-1}, compared to 0.25 g C m^{-2} d^{-1} without the lee wave influence (Davidson et al., 2013). The combination of the advection and dispersion away from a bank with the response time of the phytoplankton nutrient uptake and growth was suggested to lead to half of the additional carbon fixation occurring away from the site of the mixing (Davidson et al., 2013).

Analysis of the VMS data showed that the fishing activity was broadly spread through the region of the banks without any clear indication that an individual bank might be favoured compared to the flatter regions immediately adjacent to it (e.g. Table 2). The fishery is targeting a broad range of large- and small-bodied demersal and pelagic fish, as well as cephlapods and shellfish (see Martinez, 2013, for a complete description). All of these species are long-lived compared to the time scales of primary production and so we would not expect to see patchiness in fish abundance, or fishing activity, to be driven by mixing and increased primary production at individual banks. While there were some spring-neap contrasts seen in fish species and distributions over and adjacent to the banks (Embling et al., 2013), evidence for a spring-neap tidal control on fishing activity within the central Celtic Sea was equivocal, tending to be vessel-dependent and showing no consistent pattern. Higher resolution VMS data could yield better information on the role of offshore banks for particular métiers. For instance, the gillnet fleet is known to operate over tidal cycles as strong tides can reduce the height of the net, which can influence catches and also cause gear damage (Millner, 1985; Stewart, 1988), and gillnet catches of some organisms are also known to be greater during neap tides (Clarke and King, 1985; Tregenza et al., 1997).

The broad mixture of target species and the observed spatial and temporal patterns of fishing activity suggest that the advantage to the fishing vessels arises from an integrated effect of the mixing over several banks rather than a localised response to the mixing signature seen over an individual bank. Further support for a correspondence between fishing and water that has been influenced by the mixing over banks is provided by considering long transects of temperature and chlorophyll structure through the Celtic Sea (Fig. 7). Increased chlorophyll concentrations in the bottom tidally-mixed layer are a useful indicator of the water column having recently (days to weeks) experienced enhanced mixing at the thermocline, which transfers biomass from the subsurface chlorophyll maximum down into the bottom layer (e.g. Sharples et al., 2001). Considering the locations marking the region of increased fishing based on the VMS data in the central Celtic Sea, each of the three transects in Fig. 7 showed that the fishing region was located within the area influenced by strong internal mixing as indicated by the increased bottom layer chlorophyll concentrations. While chlorophyll is not necessarily a good tracer for productivity, it is also noted that the regions of bank-influenced water in the transects of Fig. 7a and b also had greater chlorophyll concentrations within the thermocline. Similar observations over individual banks are shown in Sharples et al., this issue. The general pattern of fishing seen in Fig. 3 for the central Celtic Sea appeared offset towards the east and southeast from the main banks, which is consistent with the offset expected as a result of the mean flows driven by prevailing south-westerly winds. Also, the seasonality of fishing in the central Celtic Sea was pronounced (Fig. 4b), with most fishing occurring between April and August. This is consistent with the seasonality often seen in zooplankton biomass in shelf seas (e.g. Kiørboe, 1993) and with the seasonal timing of the stratification that supports the lee waves.

The implication of the results summarised above is that the key relevant contrast between the area of seabed banks and the non-fished regions of flatter shelf to the south and west is the strongly enhanced turbulent supply of nutrients to the phytoplankton over and near the banks. We suggest that the enhanced primary production generated by this nutrient supply and dispersed over the area of banks supports the fishery.

The targeted fish species range from planktivores up to large predators and so they are not directly dependent on phytoplankton as a food source. Making a link between fishing and an increase in primary production requires a correlated response in the zooplankton concentrations, providing a trophic connection between the phytoplankton and the fish. Noting again that zooplankton reproduction time scales are longer than those for phytoplankton growth, we first assess whether or not the residence time of the water within the fished region over the banks is sufficient to lead to an increase in zooplankton concentrations. The fished area was about 150 km in extent along the direction of the drift expected from prevailing westerly and south-westerly winds. Modelled mean flows in the Celtic Sea are generally much less than 5 cm s^{-1} (Holt et al., 2001). The storm-driven eastward flow observed during the research cruise in 2008 was about 4 cm s^{-1} (Inall et al., 2013), which provides an indication of the strongest mean flows to be expected. Assuming a range of likely mean currents in the region of 1–5 cm s^{-1}, this suggests an average residence time of bank-influenced water within the fished region of approximately 2–12 weeks which would be sufficient for mesozooplankton reproduction and development leading to higher mesozooplankton abundances within the area of bank-influenced water. During the cruise in 2008 net hauls for zooplankton biomass showed no localised contrasts in concentrations over and adjacent to Jones Bank, consistent with the lack of any contrasts in fishing activity on such scales. However, a larger-scale acoustic survey incorporating both the bank region and the deeper, flatter shelf to the south indicated higher zooplankton numbers over and adjacent to Jones bank compared to the deeper shelf to the southwest (Embling et al., 2013). Thus the residence time estimate and the zooplankton observations provide supporting evidence for the necessary trophic link between the primary production and the fish.

It is interesting to consider likely links between surface temperature and/or surface chlorophyll in the satellite images and the distribution of fishing activity (Fig. 6c and d). Such satellite data is

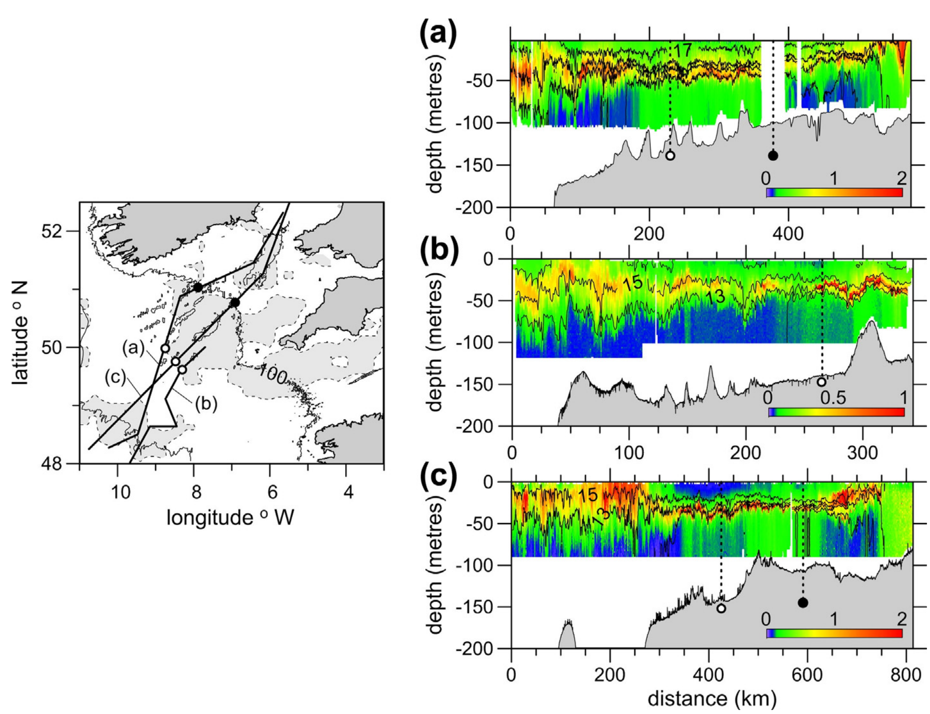

Fig. 7. Towed CTD transects of temperature (line contours, every 2 °C) and chlorophyll concentration (colours, mg Chl m^{-3}) from the shelf edge into the Celtic Sea, from cruises (a) JR98 (RRS *James Clark Ross*, July 2003 (Hickman et al., 2012)), (b) JC025 (RRS *James Cook*, July 2008) and (c) D352 (RRS *Discovery*, June 2010). All chlorophyll fluorometers were calibrated against water samples collected during each cruise. Note that the chlorophyll scale has been skewed to highlight the low chlorophyll in the bottom waters. The location map shows the transect routes, with Olex bathymetry contoured at 100 and 200 m. The shaded patches on the map indicate regions of high fishing activity, delineated as the 1× mean activity from Fig. 3. Open and filled circles on the map mark the southern and northern limits, respectively, of the mid-Celtic Sea region of increased fishing activity along each transect. These limits are marked with dashed lines on the transects (a–c).

often strongly correlated with fish distributions (e.g. Zainuddin et al., 2006). These links can be informative in understanding the underlying environmental controls on fish distributions, but making such links in shelf waters can be problematic. For instance, in Fig. 6d high values of surface chlorophyll close to the Irish coast, and in particular in the Bristol Channel, are likely contaminated with suspended sediments and dissolved organic material in these shallow, tidally energetic waters influenced by river inputs. However, away from the coastal influence the only strong correlation we see between sea surface chlorophyll or temperature and fishing activity is at the shelf edge. There the band of chlorophyll seen in satellite imagery in summer is indicative of where the phytoplankton community is responding to the internal tide-driven supply of nutrients (Sharples et al., 2009). In the central Celtic Sea there is no correlation between fishing activity and satellite imagery because the phytoplankton response to bank-driven nutrient fluxes occurs about 30 m below the sea surface within the base of the thermocline. Such sub-surface biological signals have been found to correlate with the patchy distributions of marine predators (Scott et al., 2010).

5. Summary

Analysis of Vessel Monitoring Data has provided a picture of the regional scale distribution of fishing activity through a temperate shelf sea system. The pattern of fishing showed the most heavily fished area was along the edge of the continental shelf, where a strong internal tide mixes nutrients towards the sea surface, increasing primary productivity and, perhaps more importantly, altering the species structure of the phytoplankton community. Another area of high fishing activity was in the Celtic Deep, a localised depression where a fine sediment substrate provides habitat for *N. norvegicus*. The processes underpinning this fishing area are less well understood. We hypothesise that the muddy substrate is linked to the overlying patch of anti-clockwise polarised tidal currents which affect the extent of turbulent mixing above the seabed, with the baroclinic circulation of the tidal mixing front potentially aiding larval retention and the primary production within and close to the front providing a supply of organic material to the seabed. A large area of fishing occurred over several banks within the Celtic Sea. The cumulative effect of several banks generating patches of increased nutrient fluxes into the photic zone, combined with dispersion of the mixing-influenced water away from the banks in the mean flows, potentially leads to an increase in primary production over a wide area. The timescales of advection within this area are sufficient to allow larger zooplankton to respond to this primary production, which would provide an advantage to planktivorous fish and their predators. Further work focused on the contrasts primary production between the area of banks and the deeper shelf, as well as on the zooplankton as the trophic link between the primary production and the fish is necessary to fully justify these suggested mechanisms. On a smaller scale, banks did not appear to be favoured by fishers (all vessels combined) compared to closely adjacent flat regions, although individual vessels or métiers may operate around such grounds more regularly.

The results here underline the range of potential links between the physics of the marine environment and the distribution of fishing pressure. A simple link from the physics through to primary and secondary production and so on to fish appears to be relevant only in one of the three main fishing areas of the Celtic Sea. Elsewhere we need also to consider the characteristics of the tidal flow and their affects on sediment deposition, baroclinic flows and primary production associated with a tidal mixing front, and the role of interior mixing by an internal tide in controlling the structure of the phytoplankton community. Satellite imagery of sea surface temperature and chlorophyll correlates with fishing activity in some regions, though such correlation does not provide insight into the primary causes underlying the distribution of fishing. The combination of a detailed understanding of oceanographic processes and of human fishing behaviour can reveal direct linkages between the underlying environment and the locations and times where fishing is most targeted. This knowledge can contribute to improved assessment of which areas that can tolerate intensive fishing and which would better serve the marine environment as Marine Protected Areas or for locations of marine energy extraction. Understanding these links will also be valuable in assessing the sensitivity of different fish stocks to changes in ocean processes driven by a warming climate.

Acknowledgements

This work was supported by funding from the NERC Oceans 2025 Programme, and the joint NERC-DEFRA Grant NE/F001983/1. The UK Department for Environment Food and Rural Affairs, and the Irish Naval Service kindly supplied the Vessel Monitoring System data. Thanks also to Katrien van Landeghem (Bangor University), and funding from the British Society for Geomorphology, for help with the Olex data (courtesy of Olex AS).

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