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Regional variation in bycatches associated with king scallop (*Pecten maximus* L.) dredge fisheries

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Keywords

Pecten maximus, scallops, North-East Atlantic, bycatch, fisheries, dredging, scallop fisheries

Abstract

The biomass and composition of bycatch from king scallop dredge fisheries was assessed and compared between the English Channel, Cardigan Bay in Wales and around the Isle of Man. Bycatch composition varied significantly at localised, and broad, geographic scales. The mean proportion of scallop dredge bycatch biomass in the English Channel was 19% of total catch biomass. The proportion of bycatch was lower in Cardigan Bay (15%) but notably higher around the Isle of Man (53%). The proportion of individual bycatch species in dredge catches were low, therefore scallop dredging is unlikely to cause a substantial increase the population mortality of individual commercially fished species beyond that caused by the target fisheries for those species, or bycatches of other fisheries. The amount and mortality of organisms left on the seabed in the dredge path was not quantified in this study but should also be considered in management of the fishery. The discard rate of finfish and shellfish of commercial value from the king scallop dredge fishery in the English Channel was between 18-100%, with a higher rate of discarding occurring in the eastern English Channel compared to the west. The clear regional differences in bycatch composition and variation in the quantity of discards mean that an area by area approach to managing bycatch species is required in relation to the king scallop dredge fishery.

1. Introduction

Bycatch (the total catch of unwanted or non-target species) and discards (the proportion of organisms from a catch returned to the sea) are two of the most prominent issues currently under scrutiny in global fisheries management (Hall *et al.*, 2000; Kelleher, 2005). Most fishing gears are not completely selective for the target species. Therefore, non-target species are either retained as bycatch or returned to the sea as discards. Discarding occurs for a number of reasons such as lack of commercial value; high-grading (only retaining individuals of higher value *e.g.* larger individuals of a species); practical reasons (*e.g.* lack of space or suitable facilities for storage of the catch on board, or availability of processing facilities at the landing port); lack of quota or the correct licence required to land the species. Individuals of a target species that are below the minimum legal landing size also must be discarded. For these reasons fish that are fit for human consumption are often discarded, a practice that will be prohibited in the European Union by 2019 (Hall *et al.*, 2000; Davies *et al.*, 2009; Heath *et al.*, 2014).

1.1 Bycatch in scallop dredge fisheries

Organisms that are returned to the sea alive following retention in fishing gear may die from physical injuries obtained during the capture process, stress related symptoms or increased vulnerability to predation post-release (van Beek *et al.*, 1990; Chopin & Arimoto, 1995; Jenkins *et al.*, 2001; Veale *et al.*, 2001; Depestele *et al.*, 2014). Stress or physiological impacts caused by emersion and sorting on deck can also be fatal (Jenkins & Brand, 2001). Such impacts will vary depending on the susceptibility to capture and the survivability of bycatch species, which varies with morphological and physiological traits. In the case of scallop dredges, damage can occur on contact with the dredge on the seabed and when inside the dredge bag due to abrasion from other organisms or debris (Jenkins *et al.*, 2001). The catch efficiency of dredges for bycatch species is low and thus damaged individuals can remain on the seabed (Jenkins *et al.*, 2001; Gaspar *et al.*, 2003). Trophic impacts can be caused by removal of predators such as starfish and crabs, or through the supplementation of their diet from carrion left in the dredge tracks (Veale *et al*. 2000b). This can lead to shifts in community structure (Engel and Kvitek, 1998; Collie *et al*. 1997). Thus, fisheries may have individual, population and trophic level impacts on bycatch species (Berghahn, 1990; Ramsay *et al*., 1996; Collie *et al*., 1997, 2000).

1.2 Scallop fisheries around the UK

Scallops are currently the third most valuable species in the UK with landings worth £58.2 million in 2014 (MMO, 2015). Two species occur; the king scallop, *Pecten maximus* L. and the queen scallop, *Aequipecten opercularis*, however landings are dominated by king scallops, constituting *c*.75% of total landings (MMO, 2015). The main king scallop fisheries around the British Isles occur in the English Channel, Cardigan Bay (Wales), around the Isle of Man, off the south-east coast of Ireland, around the Channel Islands, the west and east coasts of Scotland and off Scarborough in the North Sea. King scallops are targeted using Newhaven or N-Viro™ dredges. Each dredge is typically 0.76 m in width with either 8 or 9 steel teeth that dig into the surface of the sediment to flick the scallops into the dredge belly (Howarth & Stewart, 2014). Vessels range from <10 m to >40 m Length Overall (LOA) and fish with up to 22 dredges each side (Szostek, 2015a).

On some vessels, king scallops are the only species retained, regardless of the commercial value of any bycatch species caught. However, species of high commercial value such as monkfish (*Lophius piscatorius*), Dover sole (*Solea solea*) and other flatfishes are sometimes retained. European Union fishery management rules currently apply to UK scallop fisheries and restrict retained bycatches to a maximum of 5% of the total catch weight of scallops. All retained bycatch must be counted against the relevant quota; species under the quota system and for which the vessel does not have access to quota must be discarded. Total fishing mortality of these commercially important species is therefore a combination of the effects of the target fisheries for these species, bycatch from fisheries that do not target the species (including the king scallop fishery) and unobserved mortality from contact with the gear on the seabed. Quantification of bycatch is fundamental to the implementation of EBFM (Ecosystem Based Fisheries Management) (Link, 2002). This approach has the goal of maintaining the entire ecosystem in a healthy and productive state such that eco-system over-fishing does not occur and trophic interactions are preserved (Hilborn, 2011). The European Marine Strategy Framework Directive (MSFD, 2008/56/EC) requires that, when considering fishing activities, the "*structure and functions of ecosystems are safeguarded and benthic ecosystems, in particular, are not adversely affected*". To achieve this, an improved understanding is required of the secondary effects of major fisheries (*e.g.* scallop dredging) on bycatch species.

There is also incentive for fishers in the European Union to reduce bycatch through the staged introduction of the landings obligation (discard ban) under the reformed Common Fisheries

Policy (CFP) that commenced in January 2015. This is intended to make fishing more sustainable through reducing the capture of low-value species and encouraging the utilisation of retained biomass that would normally be discarded (Mangi & Catchpole, 2013). This legislation will be enforced for all commercial fisheries by the end of 2019 and will extend to activities such as scallop dredging. Relatively little bycatch data exist for king scallop dredge fisheries around the UK or elsewhere in Europe and there has never been a formal assessment of bycatch on a broad geographic scale. There were three main objectives to the present study:

a) To quantify bycatch species that occur in the English Channel king scallop (*Pecten maximus*) fishery.
b) To assess geographic differences in bycatch species assemblages based on variation in environmental conditions at the scale of the English Channel.
c) To understand regional variation in king scallop dredge bycatch across ICES area VII, including king scallop fisheries across the English Channel and the Irish Sea.

2. Methods

2.1 Sampling

Sampling occurred between June 2012 and June 2013. Ten sampling trips were conducted on board eight commercial fishing vessels during normal commercial fishing operations. The aim was to sample the bycatch composition that occurred on a range of king scallop fishing grounds across the English Channel. These fishing grounds were identified from Vessel Monitoring System (VMS) data and semi-structured questionnaires undertaken with 49 skippers of vessels targeting king scallops as the main retained species. Precise sampling locations were dictated by where the skippers were fishing at the time. For example, no king scallop fishing occurs in the inshore eastern English Channel between March and December. Also, weather conditions (predominantly wind strength and direction) have a significant influence on the daily selection of fishing grounds (Szostek, 2015a). The total number of dredges used on the vessels varied between 10 and 34 (5 to 17 each side of the vessel), depending on vessel size. The following information was recorded for each haul sampled: co-ordinates at the start of each tow (the moment the fishing gear made contact with the seabed following deployment) taken from the vessel GPS system, average speed of tow (knots), duration of tow (minutes) and co-ordinates at the time of gear retrieval (when the skipper began to winch the gear from the seabed). For each haul the full contents of one, or two (if the dredges were less than *c*. 50% full) dredges were retained for sampling. A different dredge(s) was selected for sampling each time (*e.g.* alternating between port and starboard dredges, and from bow to stern) to account for random variation in dredge catching efficiency. On the largest vessel it was not possible to randomly sample the dredges due to safety and logistical reasons so the crew separated the contents of the first dredge (closest to the bow when on deck) for subsequent sorting. The volume of large rocks and broken shell (the proportion of the volume of a five stone fish basket, measured using a calibrated wooden stick) from each dredge sample was recorded. All king scallops from each sample were counted and their shell width (distance from anterior to posterior shell margin) measured to the nearest mm. Shell width was measured as opposed to shell height (distance from umbo to ventral shell margin) as this is how the crew differentiate between scallops above and below the minimum landing size (MLS). All remaining organisms from the dredge sample (*e.g.* sea urchins, crustaceans, starfish and fish species not of commercial value) were identified and the number of individuals counted. Body length was also recorded for individuals of commercially fished species and some non-commercial species. All fish, molluscs and crustacean species of commercial value from each haul (from all dredges, including the sampled dredges) were counted and body length measured. It was also noted whether these species were retained or discarded. In total, 99 hauls were sampled across the 10 sampling trips.

Additional data were obtained from the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) for king scallop observer trips that occurred in the English Channel between September 2011 and October 2012. Species for which length measurements were recorded during CEFAS observer trips were commercial finfish species and non-quota shellfish species of commercial value such as king scallops, lobster and whelks. The sampling methods employed in the present study and CEFAS surveys differed only in that during CEFAS observer trips, smaller benthic species (such as sea-urchins, starfish and small crustaceans) and fish species not of commercial value were combined with inert material (rock, broken shell, sand etc.) from the dredge sample and a total volume recorded as ‘benthos’. However, ‘benthos’ was not consistently recorded across all observer trips. Therefore, all records of ‘benthos’ were removed from the dataset and the CEFAS data were used only in the analysis of bycatches of fish and shellfish species of commercial value. A limited number of hauls that included records of species with no quantification (recorded only as ‘observed’) were also removed from the dataset. In total, data recorded from 308 hauls from 24 separate CEFAS observer trips were retained for analysis. The locations of all samples are shown in Figure 1.

2.2 Data Analysis

2.21 Environmental variables

Szostek *et al*. (2015) found that the environmental variables tidal bed shear stress, depth, mean sea bed temperature (T_{mean}) and interannual temperature range (T_{range}) explain much of the environmental variation between the major king scallop fishing grounds across the English Channel. Values for these four parameters were obtained for all sample locations in the English Channel (see Szostek *et al*. 2015b for data sources). Non-parametric multivariate analyses of the environmental data were performed in PRIMER v.6 (Clarke & Gorley, 2006). A draftsman plot was used to identify significant autocorrelation between each pair of environmental variables. The dataset was normalised and a resemblance matrix was produced using Euclidean distance. A Principal Component Analysis (PCA) was performed to establish which of the environmental variables explained the greatest variation among sites. To identify environmentally distinct regions a CLUSTER analysis with SIMPROF testing identified significant groupings of sites (all samples from the same trip were grouped as a site) based on the similarity of their environmental variables, at a significance level of P = 0.05. ANOVA testing was used to determine if there were significant differences in the proportion of bycatch biomass between groups of sites, following testing of the assumptions of ANOVA (normal distribution of residuals and homogeneity of variance). The BIOENV procedure was used to investigate which environmental variables gave the highest correlation with bycatch species composition. In this way we were able to determine whether environmental variation could be used to provide insights into the quantity or identity of bycatch species in king scallop fisheries that occur in different areas.

2.22 Present study

Published data on standard length/weight relationships was used to calculate the total biomass of each species for which a length measurement was taken. Tow length was calculated by multiplying the duration of the tow by the average speed recorded for the tow. Area swept was calculated as the total width of the dredges multiplied by tow length. The total biomass of each species per tow was then calculated, by raising the biomass recorded to the total number of dredges (if from a sub-sample) and all values were standardised to kg km^{-2}. For the species for which only abundance data were collected, the mean weight of an individual was calculated from data obtained during scientific surveys (Szostek *et al*. 2015b). Total biomass per tow was estimated using these values and then standardised to kg km^{-2}. As each trip occurred in one localised area of the seabed, the mean biomass of each species retained per trip was calculated by pooling the data from all hauls per trip. These values were used to ascertain the proportion of the catch weight that was contributed by each species.

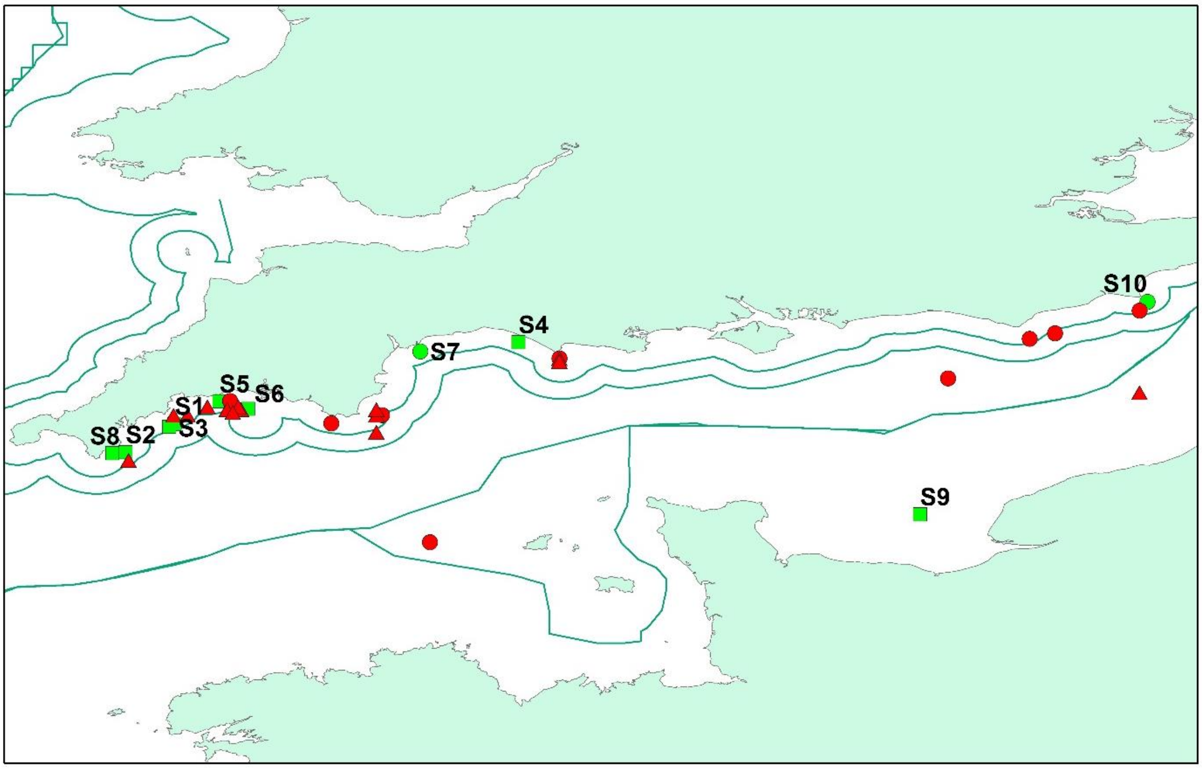


Figure 1: Location of the 34 sites sampled for king scallop dredge bycatch in the English Channel. Sites sampled by the author are indicated by green squares (spring/summer) and green circles (autumn/winter) and labelled S1-S10. Sampling took place on board commercial fishing vessels between June 2012 and June 2013. Sites from CEFAS observer trips that occurred between September 2011 and October 2012 are indicated by red triangles (spring/summer) and red circles (autumn/winter). The 6 and 12 NM limits are shown along the UK coast, as well as the boundary between UK and French territorial waters.

The bycatch species data were aggregated to genus level, as this may be more appropriate for detecting anthropogenic changes in community composition (Warwick et al. 1988a, b), and square-root transformed to down-weight the influence of highly abundant or rare taxa. Using PRIMER, a resemblance matrix was created and used to generate an MDS (multi-dimensional scaling) plot to visualise clusters of sample sites based on their similarity in bycatch species composition. ANOSIM tests were used to ascertain whether samples grouped by the similarity in environmental parameters, season (‘winter’: October to March, or ‘summer’: April to

September), or sample trip, had significantly different species composition. A SIMPER analysis was used to identify typical species for the each group of sites identified from the analysis of environmental variables.

In order to calculate size-weight (total wet weight) relationships for *P. maximus* the exponential relationship of weight with shell height and shell width was determined using data on king scallop size-weight relationships from a previous study (Szostek *et al*. 2015b). Geographic differences in growth rates and allometry occur for *P. maximus* (Chauvaud *et al.*, 2012; G. Campbell, unpubl. data) Therefore, separate equations were determined for ICES sub-areas VIId and VIIe. The relationship between *P. maximus* shell width and total wet weight in sub-area VIIe (western English Channel) is described by the equation: $y = 0.0003\,L^{2.8178}$ ($R^2 = 0.96$) (n=411) and in sub-area VIId (eastern English Channel) by the equation $y = 0.0006\,L^{2.6183}$ ($R^2=0.88$) (n=502). CEFAS data included measurements of *Pecten maximus* shell height, rather than shell width. The relationship between *P. maximus* shell height and total wet weight in area VIIe is described by the equation: $y = 0.0002\,L^{2.9676}$ ($R^2 = 0.95$) (n=411) and in area VIId by the equation $y = 0.0004\,L^{2.7724}$ ($R^2 = 0.89$) (n=502).

2.21 CEFAS data

The total number of species in the CEFAS observer data was 45 (restricted to finfish and commercially important shellfish species), compared to 74 species recorded in the present study, in which all species were identified and recorded, regardless of commercial value. To enable a comparison of CEFAS observer data with data collected in the present study, the latter was constrained to the species recorded in the CEFAS dataset. The mean biomass of each species per trip (kg km^{-2}) was used to compare the species composition across the sampling data and CEFAS data. An MDS plot was used to visualise groupings of sites based on their similarity in bycatch species composition and ANOSIM was used to test for significant differences in the species composition of finfish and shellfish of commercial value between environmentally distinct regions.

2.24 Comparison with other fisheries

The observed patterns in bycatch were compared with bycatches in other important king scallop fisheries in ICES area VII, in Wales and around the Isle of Man. King scallop dredge bycatch data from Cardigan Bay, Wales and the Isle of Man territorial waters were obtained from the Fisheries and Conservation Science Group, Bangor University (see Figure 2). These data were gathered during surveys on the *RV Prince Madog*, using standard Newhaven king scallop dredges. The dataset encompassed 20 survey sites within 12 nautical miles of the Isle of Man (IM) coastline that were identified as king scallop fishing grounds from a high frequency of VMS records (Shepperson *et al.,* 2014). Consultation with a local fisherman (M. Roberts, *FV Harmoni*, pers. comm.) identified important king scallop fishing grounds in Cardigan Bay (CB) and resulted in data from 57 sample sites being included in the analysis. Data from IM were collected between May 2012 and February 2013 and data from CB were collected between June 2012 and August 2014. In the IM and CB datasets only one tow was conducted at each site, each year, therefore a single value of biomass was used for each site, as opposed to mean values that were calculated from multiple tows at sites in the English Channel. However, if there were data for the same sample site from more than one year for the IM and CB datasets, the mean biomass value across years was used. Information on tow length and area swept (total width of the dredges used) was used to calculate biomass of king scallops and bycatch species, standardised to kg km^{-2}. MDS and ANOSIM statistical tests were used to investigate differences in bycatch assemblage at different geographic scales. The number of sample sites, sampling approach and analyses performed in each area are summarised in Table 1. ANOVA testing was used to ascertain if bycatch biomass varied significantly between locations, after the assumptions of normal distribution of residuals and homogeneity of variance in the dataset were checked.

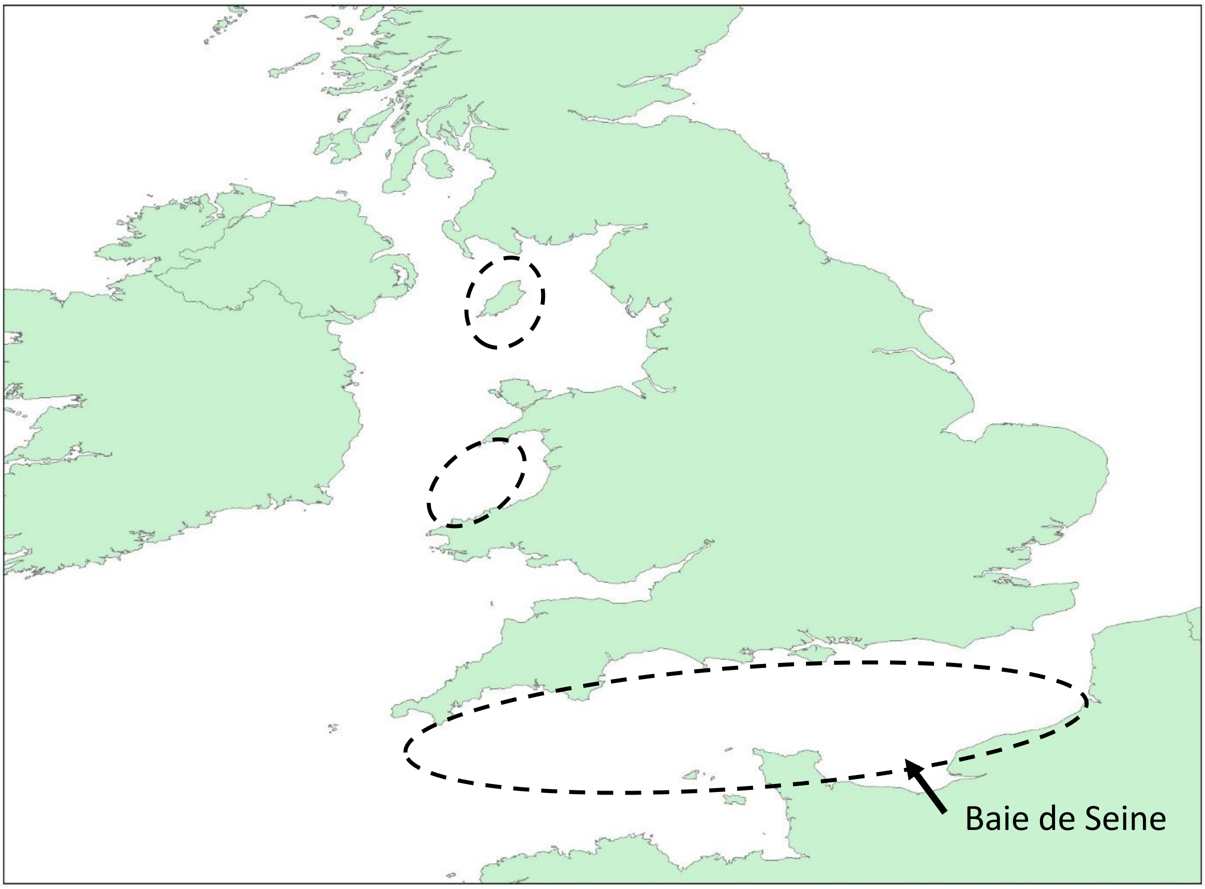


Figure 2: Broad sample locations around the British Isles, indicated with dashed lines. Isle of Man (top); Cardigan Bay (middle), English Channel (bottom). The location of the Baie de Seine is also indicated.

Table 1: Summary of the number of sites sampled, sampling approach and the data analyses performed for each area included in the study.

Location	number of sites sampled	Sampling approach	Data analyses
English Channel (present study)	10	Sub-sample of entire catch	Species diversity & composition, correlation with environmental variables, discards
English Channel (CEFAS data)	14	Sub-sample of finfish and commercial species only	Species diversity & composition, correlation with environmental variables, discards
Cardigan Bay, Wales	57	Sub-sample of entire catch	Species diversity & species composition
Isle of Man	20	Entire catch sampled	Species diversity & species composition

3. Results

3.1 Present study

3.11 Environmental variables

Using data for sites sampled in the present study, the first axis of the PCA analysis (PC1) explained 64% of the environmental variation between sites across the English Channel and the second axis (PC2) a further 26%. PC1 was composed of a similarly weighted combination of T_{range} and T_{mean} in one direction and depth in the opposite direction. PC2 was mainly influenced by bed shear stress. A SIMPROF test revealed three environmentally distinct groups of sample sites in the English Channel at the p=0.05 level. The first group (referred to as 'Shallow') included the four shallowest sites (two in Lyme Bay and two in the eastern English Channel), the second group (referred to as 'Far west') the two most westerly sites and the third group (referred to as 'West') the remaining four sites in the western English Channel (Table 2, Figure 1). The BIOENV analysis indicated that mean seabed temperature and depth best explained the variation in species composition between sites (ρ=0.625, p=0.002).

Table 2: Groups of sample sites in the English Channel based on their similarity in four environmental parameters, identified by a SIMPROF analysis. Groups are significantly different at the p=0.05 level.

Site	SIMPROF group	ICES sub-area	bed shear stress (N m^{-2})	mean seabed temperature (ºC)	mean temperature range (ºC)	depth (m)
S4	Shallow	VIIe	0.49	12.06	10.37	25
S7	Shallow	VIIe	0.13	12.04	10.36	16
S9	Shallow	VIId	0.92	12.30	10.76	26
S10	Shallow	VIId	0.42	11.83	11.64	29
S2	Far west	VIIe	0.62	10.69	7.79	70
S8	Far west	VIIe	0.80	10.69	7.79	32
S1	West	VIIe	0.11	11.34	8.28	58
S3	West	VIIe	0.12	11.24	8.27	60
S5	West	VIIe	0.08	11.50	8.67	45
S6	West	VIIe	0.12	11.50	8.80	49

3.12 Catch composition

From the samples gathered in the present study, inert material (broken shells, rock, sand, gravel) dominated the weight of catches, with a mean proportion of 75-92% of the total weight. *Pecten maximus* contributed 6-20% of the total catch weight and bycatch varied from <1% to 8% of the total weight of the contents of the dredges.

Of the living biomass retained by the dredges, bycatch species contributed between 8 and 37% to the catch weight, depending on the location, with a mean of 19% across all trips. The highest proportion of bycatch at a single site occurred in the east of Lyme Bay (site S4). The data met the criteria for ANOVA testing (normal distribution of residuals, homogeneity of variance) and the proportion of bycatch between the three habitat groupings was similar (ANOVA: $F_{2,7}$=0.237 p=0.80) (Figure 3). The mean number of species retained per tow across all trips was 10.1 (±3.8) (Table 3).

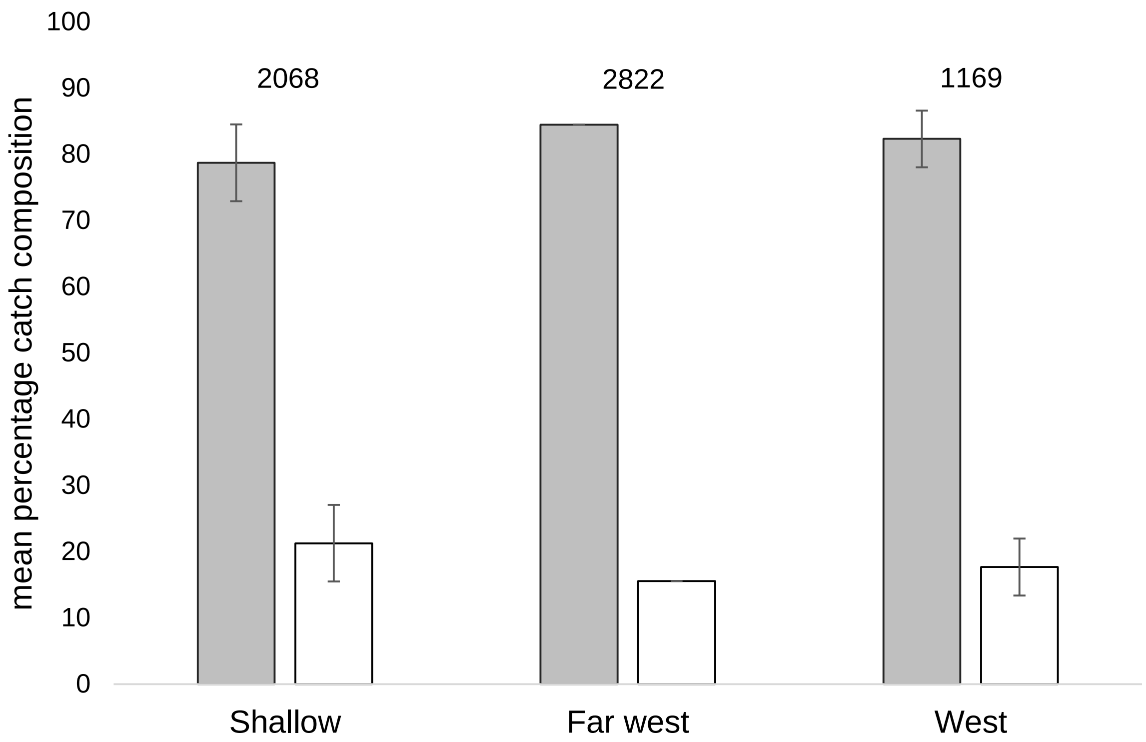


Figure 3: The percentage composition (biomass) (±S.E.) of *P. maximus* (grey bars) and bycatch species (white bars) in king scallop dredge catches from three groups of sample sites in the English Channel (Shallow; Far west; West). The Far west group contains only two sites; therefore calculation of standard error was not possible. Numbers above the bars represent the mean total biomass of catches in each group (kg km^{-2}).

Table 3: Mean total number of species and total biomass (of *P. maximus* and all bycatch species) from each survey trip. Mean and standard error values (S.E.) are given.

		No. of species		**Total biomass (kg m^{-2})**	
Group	**Trip**	**Mean**	**S.E.**	**Mean**	**S.E.**
Shallow	S4	10.1	0.8	2818.4	253.1
Shallow	S7	7.9	0.7	1828.6	194.4
Shallow	S9	13.8	1.1	1585.2	195.4
Shallow	S10	9.2	0.8	1521.3	74.4
Far west	S2	4.2	0.8	1973.2	221.2
Far west	S8	12.8	0.9	3617.2	173.9
West	S1	7.3	1.1	1255.2	92.8
West	S3	7.3	0.8	1534.9	142.4
West	S5	17.2	0.6	1352.0	75.0
West	S6	11.0	1.8	461.1	32.7

Of the 74 taxa (see S1) identified across all sampling trips, *P. maximus* accounted for on average 81% of catch biomass, while a further 16 species contributed to the top 99% of the mean catch biomass across sites (Table 4). The queen scallop, *Aequipecten opercularis,* had the second highest mean biomass, and was the only species that constituted on average >5% of the total catch weight across all sampling trips (Table 5).

Table 4: Mean biomass of the species that contributed to the top 99% of biomass caught across all sites sampled in the present study (S1-S10). Species of commercial value in the English Channel are indicated by an asterisk. Cum.% = cumulative percentage of bycatch. No. sites = number of sites at which the species occurred.

Species	**Common name**	**No. sites**	**Mean biomass (kg km^{-2})**	**Mean% of catch**	**Cum.%**
Pecten maximus	king scallop*	10	1476.3	81.0	81.0
Aequipecten opercularis	queen scallop*	8	130.2	6.1	87.1
Marthasterias glacialis	spiny starfish	7	83.0	3.5	90.6
Maja squinado	spiny spider crab*	8	27.0	1.4	92.0
Sepia officinalis	cuttlefish*	5	26.3	1.3	93.3
Cancer pagurus	brown crab*	10	16.0	1.1	94.4
Lophius piscatorius	monkfish*	7	15.8	1.0	95.4
Asterias rubens	common starfish	6	20.7	1.0	96.4
Luidia ciliaris	seven-armed starfish	7	13.7	0.8	97.3
Buccinum undatum	common whelk*	6	6.7	0.3	97.6
Ostrea edulis	common flat oyster*	1	5.4	0.3	97.9
Raja clavata	thornback ray*	4	5.0	0.2	98.1
Solea solea	Dover sole*	8	3.2	0.2	98.3
Scyliorhinus canicula	small spotted catshark	7	3.5	0.2	98.5
Scophthalmus maximus	turbot*	2	2.7	0.2	98.7
Pleuronectes platessa	plaice*	6	2.4	0.2	98.8
Echinus esculentus	common sea urchin	6	1.8	0.1	99.0

Table 5: Species that contributed >5% to the total biomass in king scallop dredge catches during at least one sample trip, from a total of 10 sample trips in the eastern and western English Channel (S1-S10). Numbers represent the percentage contribution to the overall catch biomass and those >5% are highlighted in bold. Species of commercial value in the English Channel are indicated by an asterisk (*). S.E. = standard error.

	Shallow				**Far west**		**West**					
Common name	**S4**	**S7**	**S9**	**S10**	**S2**	**S8**	**S1**	**S3**	**S5**	**S6**	**Mean**	**S.E.**
*P. maximus**	**55.0**	**79.2**	**70.3**	**82.0**	**72.6**	**72.3**	**76.4**	**83.4**	**66.4**	**73.6**	**73.1**	2.6
A. opercularis	**28.4**	0.0	2.6	1.4	0.3	0.0	3.4	2.2	**19.3**	2.5	**6.0**	3.1
M. glacialis	0.0	0.3	0.0	0.0	2.8	**17.0**	**5.8**	**6.0**	2.6	**7.2**	4.2	1.7
*C. pagurus**	0.5	1.3	0.1	0.9	**8.8**	0.8	4.8	0.5	1.8	3.2	2.3	0.9
*L. piscatorius**	0.3	0.0	0.0	0.0	**7.8**	0.5	2.2	2.3	0.6	4.2	1.8	0.8
*S. officinalis**	0.0	0.0	0.4	3.9	0.0	**7.8**	0.0	0.0	0.6	0.4	1.3	0.8
A. rubens	3.0	0.7	**5.2**	0.9	0.4	0.0	0.0	0.0	0.3	0.0	1.0	0.5
*S. maximus**	0.0	0.0	0.0	0.7	**6.6**	0.0	0.0	0.0	0.0	0.0	0.7	0.7

The three groups of sample sites (Shallow, Far West, West) identified in the SIMPROF analysis as being environmentally distinct (ANOSIM: R=0.632, p=0.001, Table 6, Figure 4) also had significantly different bycatch species composition. The MDS plot had a stress value of 0.18, which indicates a good 2-dimensional representation of the differences between the three groups (Clarke & Warwick, 2001). Within group similarity in bycatch species composition was relatively high (67, 64 and 64% for the groups Shallow, Far West and West, respectively), which suggests that the bycatch assemblages were strongly differentiated across the English Channel. There was no overall significant difference in bycatch species composition between season (R=0.016, p=0.38); however the lack of temporally repeated samples and the inherent variability between all sites mean this result should be interpreted with caution.

Bycatch species contributing to the top 95% of biomass in the Shallow group were *A. opercularis*, *A. rubens*, *M. squinado*, *S. officinalis*, *C. fornicata* and *B. undatum*. In the Far west group, species contributing to the top 95% of biomass were *M. glacialis* and *L. piscatorius,* although the Similarity/Standard Deviation (Sim/S.D.) values were low (<0.5), meaning that the biomass of these species was not consistent across sites within the group. In the West group, *A. opercularis*, *M. glacialis*, *L. ciliaris*, *L. piscatorius*, *C. pagurus* and *M. squinado* dominated the top 95% of biomass. The Sim/SD values for all these species were <1.3 meaning that the variation in biomass of the species between sites within the group was high.

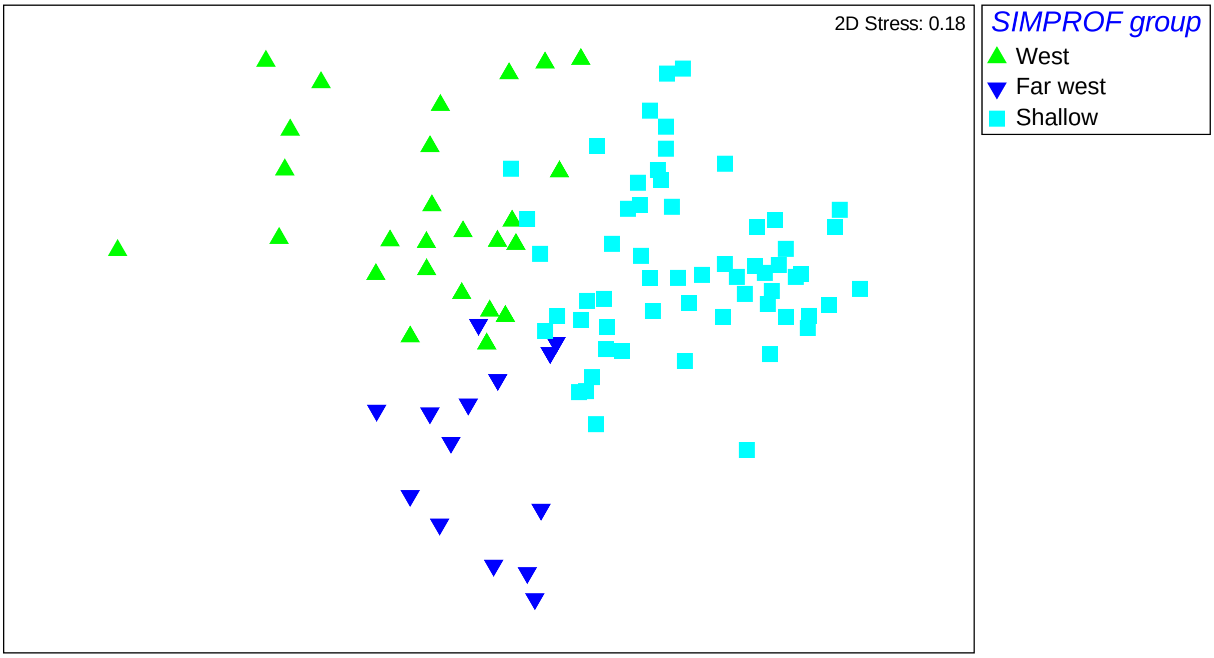


Figure 4: Multi-dimensional scaling plots of the similarity in bycatch species biomass between sample sites (S1-S10) (square-root transformed data) in king scallop dredge catches across the English Channel. Each individual symbol represents a sampled haul from a single tow. Symbols represent the three groups of environmentally distinct sample sites identified by SIMPROF analysis.

Table 6: Results from SIMPER and ANOSIM analysis for the dissimilarity in bycatch species composition between environmentally distinct groups of sites (Shallow (S1, S3, S5, S6); Far West (S2, S8); West (S4, S7, S9, S10)).

Groups	Dissimilarity (%)	R statistic	p-value
West, Far West	47	0.668	0.001
West, shallow	47	0.649	0.001
Far West, Shallow	45	0.452	0.001

3.2 CEFAS data and present study combined

3.21 Environmental variables

When assessing the environmental variation between sample sites from the present study and the CEFAS dataset combined, the first axis of the PCA (PC1) explained 70% of the environmental variation between sample sites, and the second axis (PC2) a further 21%. A CLUSTER analysis with SIMPROF testing revealed six groupings of sites based on significant differences in their environmental parameters at a significance level of 5% (Table 7). BIOENV showed that a combination of all four environmental variables best explained the variation in species composition between sites (ρ=0.368, p=0.001).

Table 7: Results from a CLUSTER analysis of the similarity in environmental parameters at all sampling sites

Group	**Sites**	**Location**
FB_mid	C28, S1, S3	Falmouth Bay (mid)
FB_east	C10, C11, C12, C19, C25, C27, C7, S5, S6	Falmouth Bay (east)
SB_EC	C16, C17, C18, C20, C3, C22	Start Bay and mid-eastern English Channel
FB_west_WC	C23, C24, C4, S2, S8	Falmouth Bay (west), mid-western English Channel, Start Bay
LB_Portland	C13, C26, C14	Lyme Bay (Portland)
LB_EC	C1, C6, S10, S4, S7, S9, C2, C5	Lyme Bay and eastern English Channel

3.22 Catch composition

When considering only finfish and shellfish bycatch species of commercial value, using the combined survey and CEFAS datasets, the same five bycatch species of commercial value that were identified using only the data from the present study had the highest mean biomass across all sample sites (*Aequipecten opercularis*, *Maja squinado*, *Lophius* sp., *Sepia officinalis* and *Cancer pagurus*). The percentage dissimilarity in species composition between groups ranged from 3-48% and species composition was significantly different between six pairs of environmentally distinct groups (Table 8). An MDS plot indicated that sites in the middle and eastern parts of Falmouth Bay (FB_mid; FB_east) had more similar species composition than other sites, and sites from Lyme Bay were clustered together (LB_Portland; LB_EC) (Figure 5). A stress level of 0.2 for the MDS plot indicates a useful 2-dimensional representation of the similarity between samples (Clarke & Warwick, 2001). The location of these groups of sample sites are indicated by matching symbols in Figure 6. .

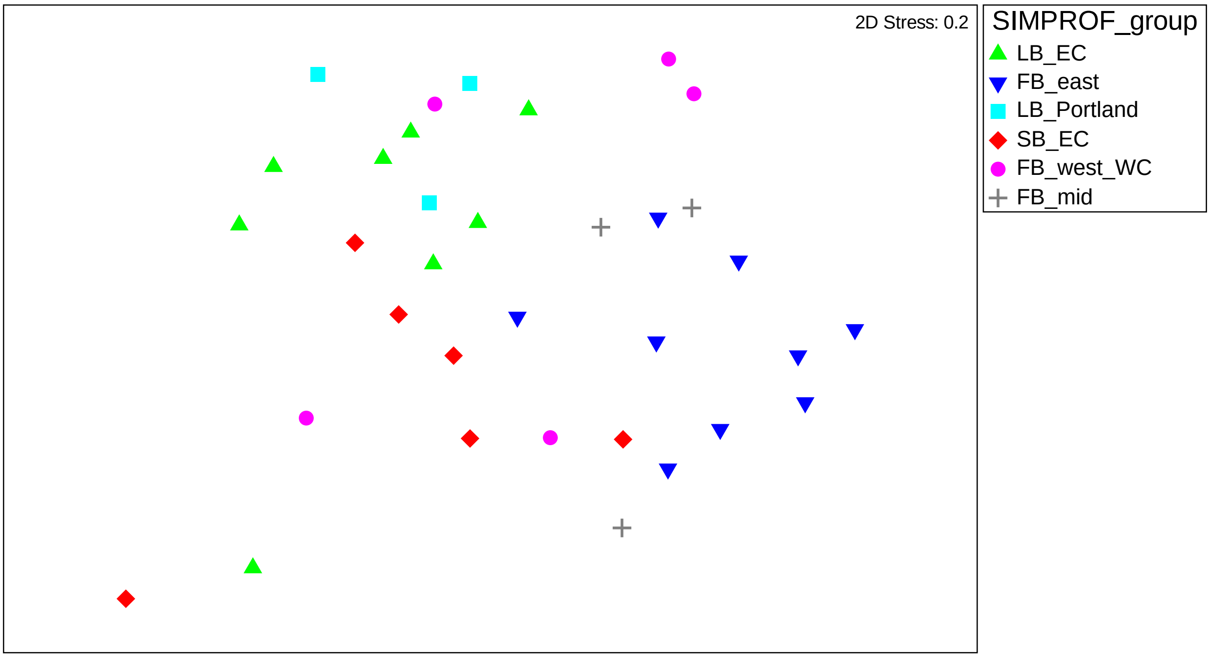


Figure 5: Multi-dimensional scaling plots of relative similarity in biomass of finfish and shellfish species of commercial value (square-root transformed data) in king scallop dredge catches across the English Channel. Each symbol represents data pooled from one sample site. Symbols represent environmentally distinct groups of sample sites.

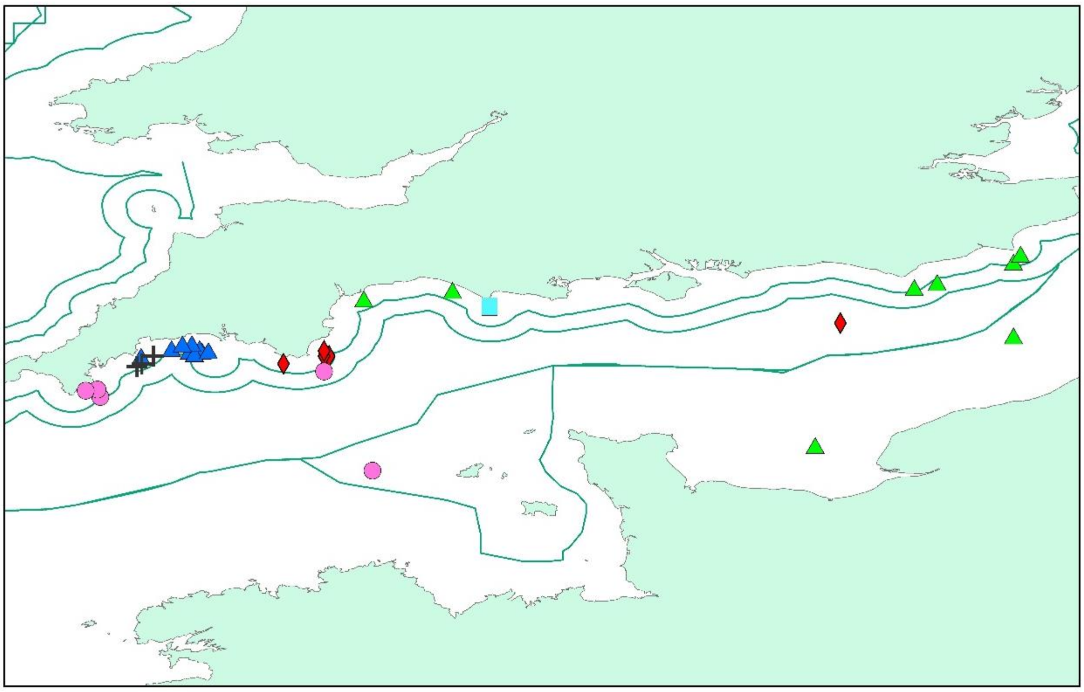


Figure 6: Sample sites from the present study and CEFAS that were environmentally distinct (SIMPROF analysis). Each symbol represents a sample site and symbols represent groups: LB_EC (green triangles); FB_east (blue triangles), LB_Portland (blue squares); SB_EC (red diamonds); FB_west_WC (pink circles); FB_mid (grey crosses).

Table 8: P-values from ANOSIM testing for the dissimilarity in species composition of finfish and shellfish species of commercial value between environmentally distinct groups of sample sites. Significant p-values are in bold text.

	FB_east	SB_EC	FB_west_WC	LB_Portland	LB_EC
FB_mid	0.264	0.202	0.821	0.100	0.055
FB_east		**0.005**	**0.008**	**0.005**	**0.001**
SB_EC			0.413	0.083	**0.027**
FB_west_WC				0.482	**0.033**
LB_Portland					0.285
LB_EC					

3.3 Discards

Based on data from the present study and CEFAS data, the mean biomass of discarded king scallops below the minimum landing size (110 mm in sub-area VIId and 100 mm in sub-area VIIe) ranged from 1.5 – 52.9% per trip. The mean proportion discarded was 20% in ICES sub-area VIId (eastern English Channel) and 27% in ICES sub-area VIIe (western English Channel) respectively (Figure 7a). The lowest amount of undersized king scallop discards occurred at a site in eastern Lyme Bay.

In total, across all sample sites, twenty different bycatch species were retained, at the discretion of the skipper (each species was not retained on every trip). Individuals of commercially fished species that were below the minimum landing size for that species and all other (non-commercial) species were always discarded. The mean proportion of finfish and shellfish of commercial value (excluding king scallops) discarded during a trip ranged from 18-100%. The mean biomass of finfish and shellfish of commercial value (excluding king scallops) retained per haul across all trips was 36 kg km^{-2} (Figure 7b). The mean biomass discarded per trip was significantly higher in the eastern English Channel (sub-area VIId, 135 kg km^{-2}) than the western English Channel (sub-area VIIe, 66 kg km^{-2}), ($t=2.05$, d.f=32, $p=0.048$). However, there were fewer samples from the eastern English Channel and there was a large degree of variation in discarded biomass between samples in the eastern English Channel, therefore the statistical significance of the latter result should be interpreted with caution. The higher discard biomass in the eastern English Channel was largely attributed to the species *Pleuronectes platessa*, *S. officinalis* and *M. squinado*.

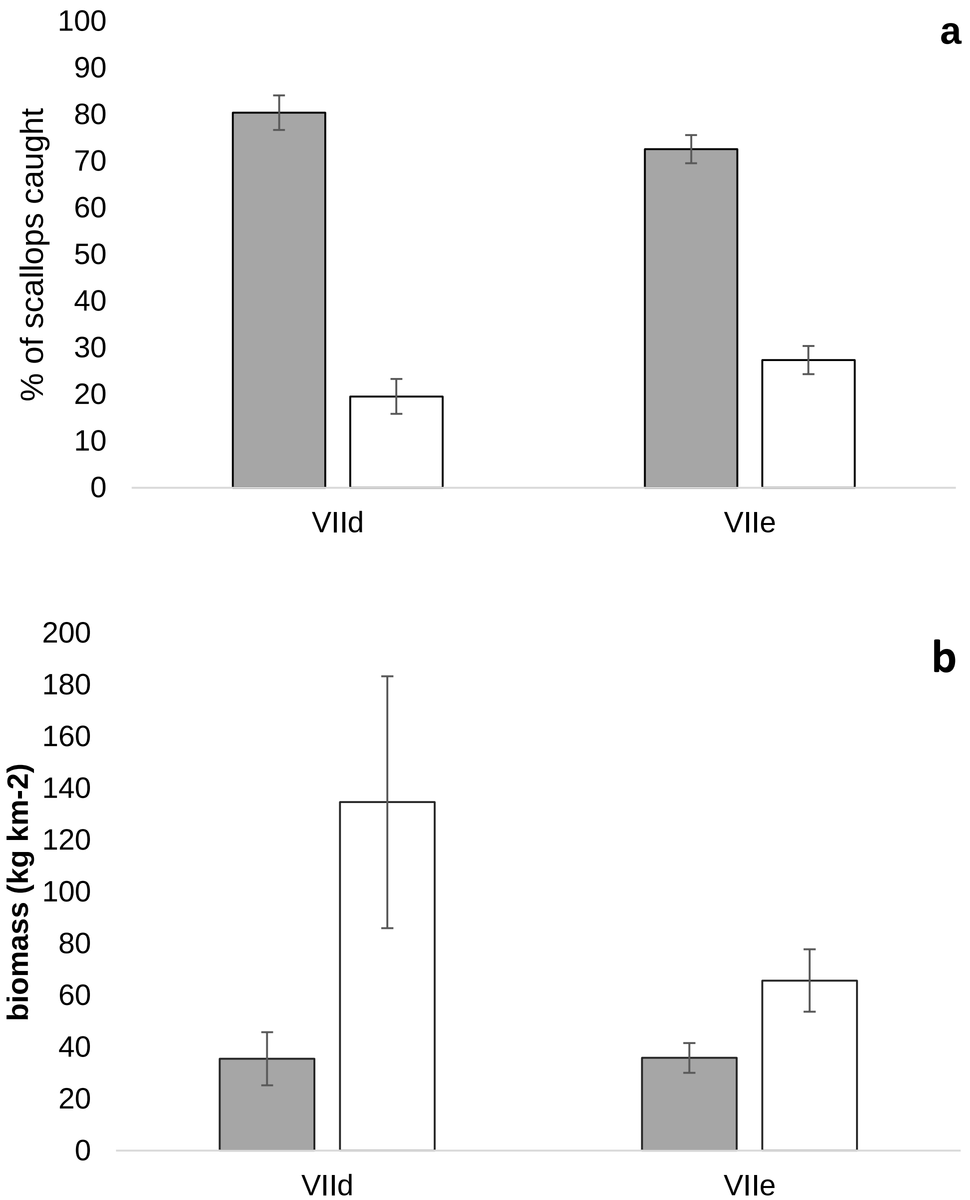
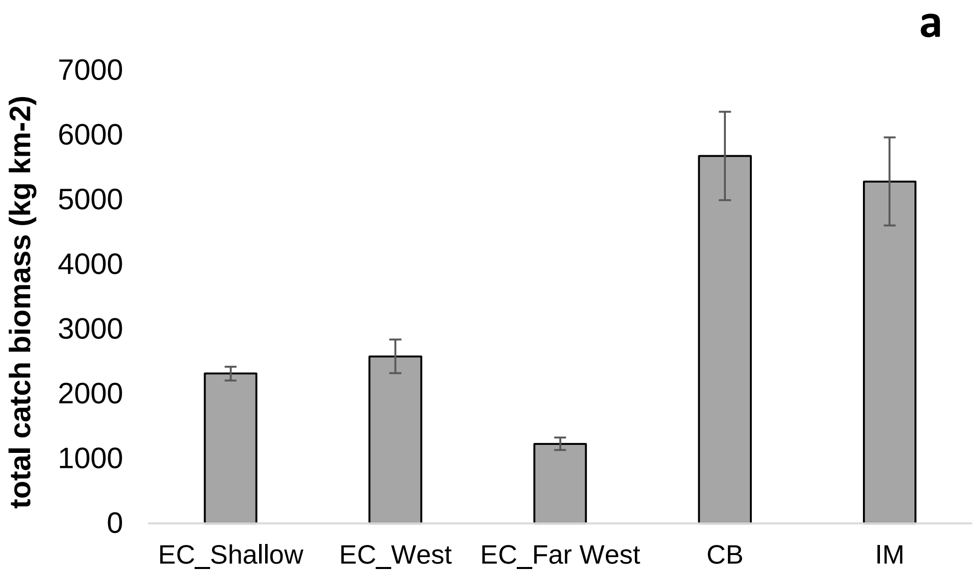


Figure 7: a) Mean proportion (±S.E.) of *P. maximus*, b) Mean biomass (kg km^{-2}) (±S.E.) of finfish and shellfish of commercial value (excluding king scallops) that were retained (grey bars) or discarded (white bars) in king scallop dredge catches in the eastern (ICES sub-area VIId) and western (ICES sub-area VIIe) English Channel. Combined data from the present study and CEFAS sampling trips.

3.4 Large-scale geographic variation

There was no significant difference in king scallop dredge bycatch species composition from three geographically distinct areas around the Isle of Man; the south, east, and west (ANOSIM: r=0.149, p=0.054), therefore Isle of Man samples were pooled and then compared with catches from Cardigan Bay and the three groups of sample sites from the English Channel. The data met the assumptions for ANOVA (normal distribution of residuals and homogeneity of variance) and the mean biomass of dredge catches was significantly different between all five locations (ANOVA: $F_{4, 82}$=11.29, p<0.001). Total catch biomass was greatest in Cardigan Bay (CB) (Figure 8a), although the highest species diversity (Margalef index) occurred in catches around the Isle of Man (Figure 8b). The lowest catch biomass occurred in the English Channel bycatch assemblage 'West' (see Figure 3, Table 3). Bycatch species composition was significantly different between all five areas (ANOSIM: R=0.58, p=0.001). All pairwise comparisons of the bycatch composition from the five locations resulted in R values between 0.216 and 0.877 and all had a significant p-value of <0.002. A low R-value (<0.3) between the English Channel group 'Far West' and CB indicates significant overlap in the bycatch species composition of these two areas. Within group similarity ranged from 37% in the English Channel 'West' group to 51% in CB. Dissimilarity between groups ranged from 61% (CB/IM) to 88% (CB/Far West).

Pecten maximus contributed the highest proportion of biomass to catches in all areas. Sim/SD values for *P. maximus* were >1.3 in all areas meaning that biomass was consistent between samples within areas. Cardigan Bay dredge catches were characterised by a higher proportion of king scallops (85% of catch biomass) than all areas of the English Channel and the Isle of Man, with just three further species contributing to the top 90% of biomass. These species were *M. squinado* and *Asterias rubens* that accounted on average for 4% and 3% of catch biomass respectively and *C. pagurus* that contributed 1.5% of catch biomass. In the Isle of Man, *P. maximus* accounted for an average of 47% of catch biomass. Five species that contributed to the top 80% of bycatch biomass around the Isle of Man include *A. opercularis* (13%) and *A. rubens* (11%), with *Raja naevus*, *Echinus esculentus* and *Eledone cirrhosa* contributing on average 4%, 4%, and 3% respectively. Although a number of finfish and shellfish species of commercial value were present in both Cardigan Bay and the Isle of Man, catches were low, with no single species contributing >2% to catch biomass. *A. rubens* contributed consistently catch biomass in all areas of the Isle of Man, but not in Cardigan Bay. Eleven species were responsible for the top 80% similarity within groups, across all sample areas, of which six are commercially fished (Table 9). Typical species for each of the five areas, identified by the SIMPER analysis, are given in S2.



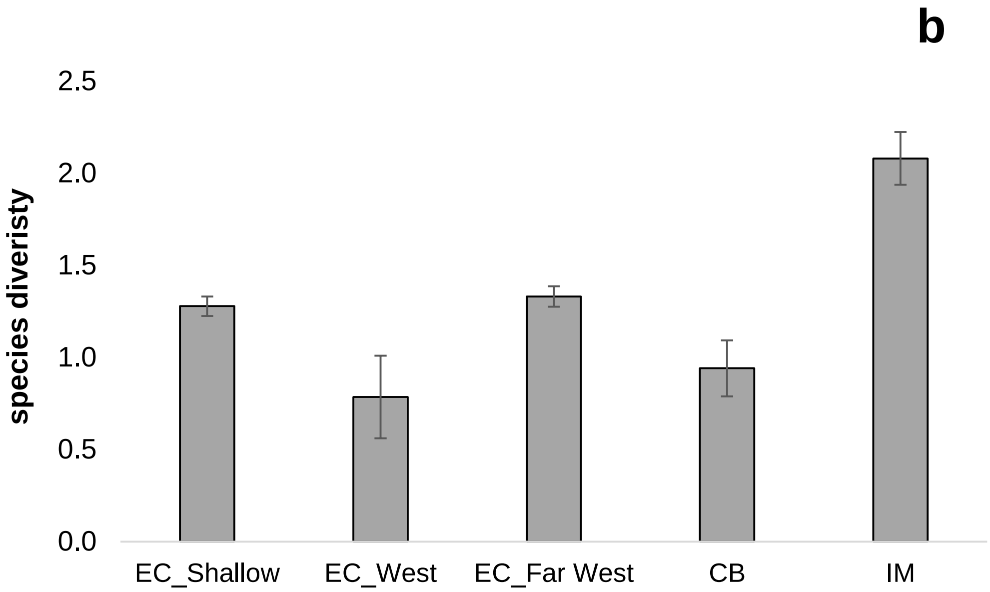


Figure 8: a) mean total catch biomass; b) mean species diversity (Margalef index), in king scallop dredge catches from five areas: the English Channel (EC_Shallow, EC_Far West, EC_West), Wales (CB) and the Isle of Man (IM). Error bars represent one standard error of the mean.

Table 9: Species contributing to the top 80% within group similarity in king scallop dredge bycatch at sites in the English Channel, Cardigan Bay and the Isle of Man. Species of commercial value are indicated by an asterisk.

English Channel	Cardigan Bay	Isle of Man
*Pecten maximus**	*Pecten maximus**	*Pecten maximus**
*Cancer pagurus**	*Asterias rubens*	*Asterias rubens*
*Aequipecten opercularis**		*Aequipecten opercularis**
Marthasterias glacialis		*Alcyonium digitatum*
Maja squinado		*Luidia ciliaris*
Luidia ciliaris		
*Solea solea**		
*Lophius piscatorius**		
*Microstomus kitt**		

4. Discussion

Understanding the quantity of bycatch and discards associated with a fishery is an important step in assessing the sustainability of that fishery. This understanding also helps to identify issues and drive initiatives that might reduce bycatch, if levels are considered unsustainable (*e.g.* Shephard *et al*., 2009). The results of this study provide an estimate of bycatch biomass and species composition typically associated with the king scallop dredge fishery across the English Channel. Using available data, we were also able to compare bycatches that occur in the English Channel against other important king scallop fisheries around the British Isles, which indicated that there is considerable variation in the amount of dredge bycatch in different localities. The results indicate that while bycatches are relatively low (<20% of catch biomass) in some areas, they are considerably higher (>50% of catch biomass) in other areas. This means that observer sampling programmes designed to monitor scallop dredge bycatch should be designed to capture both spatial and temporal variability at the appropriate scale. Nevertheless, the analysis presented here provides a basis for defining areas with similar bycatch characteristics that would inform the definition of 'bycatch sampling regions'.

4.1 King scallop dredge bycatch in the English Channel

Overall, 19% of the wet weight of king scallop dredge catches in the English Channel was comprised of bycatch. The proportion of bycatch (as a proportion of the total catch biomass) was similar across all areas sampled in the English Channel. Discards of finfish and shellfish of commercial value as a proportion of total bycatch were highest in the eastern English Channel. This was mainly due to a high biomass of discarded cuttlefish, plaice and spider crabs that were predominant in the bycatch in that location. The selectivity of the dredge gear allows small benthic organisms to be riddled out of the bottom of the dredge bag, through interconnecting steel rings of 7.5-9 cm diameter, therefore bycatches were dominated by larger benthic species, such as starfish, brown and spider crabs and larger demersal fish species. Individual bycatch species were present at consistently low levels, at <9% of total catch biomass. There were three exceptions to this; at two sites queen scallops contributed 19% and 28% to the catch biomass, and at one site the starfish, *M. glacialis*, contributed 17% to the total catch biomass.

Low catches of commercially fished species may relate to low local abundance of those species at a particular site (Craven *et al.*, 2013). However, in the present study, the boundaries of king scallop and demersal beam trawl fisheries overlap, particularly in the western English Channel. This overlap suggests a low catch susceptibility of demersal fish and other shellfish species of commercial value to the Newhaven scallop dredge. Incorporating the additional samples from the CEFAS data highlighted that in the English Channel, the biomass of bycatch in king scallop dredges is dominated by commercially important, rather than non-commercial species, with the exception of the spiny starfish, *Marthasterias glacialis*. The latter being the only species not of commercial value in the top eight species contributing to overall catch biomass in the English Channel. However, this was attributable to a single area; *M. glacialis* was prevalent in bycatches at sites within Falmouth Bay (western English Channel), with only one further record outside of Falmouth Bay.

Species of commercial value that dominated king scallop dredge bycatches in the English Channel (including samples from the present study and CEFAS data) were the spiny spider crab, monkfish, queen scallop, brown crab and cuttlefish. Non-commercial species that were also prevalent in catches were the common starfish (*Asterias rubens*), the seven-armed starfish (*Luidia ciliaris*), the sea urchin (*Echinus esculentus)* and the small spotted catshark (*Scyliorhinus canicula)*. Other taxa that were retained by the dredge were a number of flatfish and round fish species, starfish, echinoderms, small crustaceans, bivalves, hydroids and bryozoans. The individual proportion of these taxa in catches was low (generally <0.5% of catch biomass).

4.2 Broad-scale variation in king scallop dredge bycatch

Environmental and physical conditions at the seabed vary across a variety of spatial scales, which causes variation in the related species community composition. Bycatch assemblages in some fisheries are known to vary with depth, season and other abiotic factors (Probert *et al.,* 1997; Bergmann *et al.,* 2002; Rodrigues-Filho *et al.,* 2013). There was moderate correlation between the species resemblance matrix and the physical parameters of depth and mean seabed temperature. From sites in the English Channel sampled in the present study, bycatch species composition was significantly different between all but the two sample sites that were nearest each other. In the English Channel, three distinct bycatch assemblages were identified that related to the environmental parameters at the associated sample sites. At a broader geographic scale, across ICES area VII, significant differences in bycatch assemblage composition were found between king scallop fishing grounds in the English Channel, Cardigan Bay and around the Isle of Man. This is likely to be due to habitat differences between the three locations. The seabed on king scallop fishing grounds in the English Channel ranges from sand to gravelly sand habitats that support broadly similar benthic communities from east to west, which are dominated by species resilient to physical disturbance (Szostek *et al*., 2015b). Seabed habitats around the Isle of Man vary to a greater degree and include biogenic habitats such as horse mussel (*Modiolus modiolus*), *Sabellaria spinulosa* and maerl reefs (Hinz *et al*., 2010). Biogenic reefs are important for nutrient cycling and benthopelagic coupling and are of international conservation importance, designated as OSPAR priority habitats (www.ospar.org). They also provide structurally complex habitats that can support dense and diverse communities (Rees *et al*. 2008; Sanderson *et al*. 2008). Biogenic reefs are a refuge for juveniles of fish species such as cod, saithe and pollock (Kamenos *et al*., 2004) and provide settlement habitat for shellfish species including king scallop spat (Kent *et al*., 2016). The importance of biogenic reefs and their high vulnerability to bottom-towed fishing gears (Cook *et al*., 2013) is an important consideration for spatial management. *Modiolus* reefs are notably absent in the English Channel with the southern-most point of the species range occurring in the Humber and Severn estuaries. Around the Isle of Man, muddy substrates that support communities dominated by the Norway lobster (*Nephrops norvegicus*) and polychaete worms (Hinz *et al*., 2010) also occur, and contributing to the diversity of dredge bycatch around the Isle of Man are a greater number of fish species (Craven *et al*., 2013). In Cardigan Bay, the seabed habitats on which commercial scallop fishing occurs are dominated by unconsolidated sand, gravel and cobble sediments that do not support a diverse epifaunal community (Lambert *et al*., in prep). The increased variety of habitats, supporting a wider range of species, can explain the more diverse dredge bycatch in the waters around the Isle of Man compared to the English Channel and Cardigan Bay.

The intensity of fishing disturbance itself will alter bycatch assemblages at localised geographic scales over longer timescales. The intensity of long–term fishing effort negatively correlates with species richness, diversity and abundance around the Isle of Man (Veale *et al*., 2000a). This could be attributed to greater mortality of sensitive species, habitat homogenisation and the intermediate disturbance hypothesis (Connell, 1978). In the English Channel, scallop fishing effort is not significantly correlated with species diversity, biomass or abundance, with environmental factors being important drivers of community composition (Szostek *et al*., 2015b). The latter may be due to the timescales over which the commercial fishery has been in operation, resulting in altered communities that are dominated by species resilient to the effects of fishing. Trophic impacts can be caused by carrion left in the dredge tracks that can supplement the diet of predators such as starfish and crabs (Veale *et al*., 2000b). However, this is not a reliable food supply therefore benefits may not be observed at population level (Veale *et al*., 2000b). Predators can also be removed from the system through capture as bycatch, with impacts at lower trophic levels. This can lead to shifts in community structure through the proliferation of opportunistic species (Engel & Kvitek, 1998), or scavenging species (Collie *et al*., 1997). Damage from dredge fishing to essential fish habitat must also be considered in fishery management plans.

Many of the species contributing to the majority of dissimilarity in bycatch assemblage between the English Channel, Cardigan Bay and the Isle of Man, were present in all three areas but were not consistently abundant between samples in each area. This indicates that there is high variation in individual bycatch species relative abundances at localised scales, as well as larger spatial scales across the extent of the fishery. Small scale differences in the bycatch composition within Cardigan Bay are attributed to geographic variation rather than management area (Lambert *et al.*, 2014).

4.3 Temporal and spatial variation

Spatial and temporal variation is inherent in bycatch data (Allen *et al.*, 2002; Borges *et al.*, 2004; Craven *et al.*, 2013). Therefore, even with many samples covering a broad temporal and spatial scale, bias may hide patterns in the data and stratification of sampling effort cannot guarantee reliable samples (Rochet & Trenkel, 2005). Bycatch from scallop fisheries can vary with location, gear configuration, season, environmental and weather conditions and tow duration. Seasonal variations in fish and invertebrate abundance and behaviour are also likely to influence the prevalence of certain species in catches (Wilberg *et al.,* 2010). Identifying hotspots or certain times of year when bycatch species are more prevalent, or more susceptible to capture, can help inform management measures that could reduce these bycatches, such as the use of temporary closed areas or particular fishing gears.

In the present study there was a particularly high biomass of the common cuttlefish, *S. officinalis* in catches in the Baie de Seine (see Figure 1). Cuttlefish are a commercially valuable cephalopod species in the north-east Atlantic and the main fishing grounds are in the English Channel. The species is short-lived (typically no more than 2 years) and recruitment to the fishery peaks in autumn when juveniles migrate to offshore wintering grounds (Royer *et al.,* 2006). Sampling at the site in the Baie de Seine coincided with this time period. If the catch quantity of this species was of concern, management could restrict scallop dredging to times of the year when catchability is lower. Due to the lack of seasonal resolution, and the lack of samples from larger vessels in the current dataset, it is not possible to raise the dataset from the present study to the annual landings of the king scallop fleet in the English Channel. However, the mean contribution of cuttlefish to the overall catch in the Baie de Seine was 7.8%, therefore it is likely that the mean proportion of cuttlefish bycatch throughout the year would be less.

Sampling in the present study is weighted towards summer sampling in the western English Channel, with fewer samples during winter and from the eastern English Channel. This is largely due to the difference in the total number of vessels that target king scallops in each area and the seasonality of king scallop dredging in the inshore eastern English Channel, which provided few sampling opportunities (Figure 2). The data does however indicate that overall, bycatch of commercially important and sensitive species is low compared to bycatch in other fisheries (Kelleher, 2005).

4.4 Discards

In terms of biomass, discards of bycatch were higher in the eastern English Channel. On average 73% of biomass from king scallop dredge catches in the English Channel was discarded, although non-commercial species accounted for the majority of the discarded biomass. Between 18 and 100% of bycatch species biomass of commercial value was discarded from king scallop dredge catches in the English Channel. A ban on the discarding of quota species, including pelagic (*e.g.* mackerel and herring) and demersal species (such as cod, haddock and whiting) is currently being phased in under the new CFP regulations (European Commission, 2013), meaning that by 2019 all bycatch species of commercial value may have to be landed. This will result in a significant increase in landed biomass for some fisheries (Catchpole *et al.,* 2008; Poos *et al.,* 2010). Commercially fished species accounted for 7% of total catch biomass in the English Channel king scallop fishery. Therefore, although the impacts of the new legislation will be less significant than for fisheries targeting quota species, there are still likely to be financial implications and logistical issues associated with the retention of discards in king scallop fisheries (Mangi & Catchpole, 2013).

The proportion of undersized king scallops is likely to be higher in areas that are fished heavily and/or have recently been harvested as the majority of king scallops over MLS will have been removed from the area. The present study revealed that undersized king scallops are caught more frequently in the western English Channel than in the eastern English Channel. This is probably largely attributable to slower growth rates observed in the western English Channel resulting in a larger proportion of the population being just below the minimum landing size. Fatal damage to king scallops can occur during dredging and varies between 2 and 20%, largely due to spatial variation in shell thickness (Beukers-Stewart & Beukers-Stewart, 2009). Intermediate damage may not be immediately fatal but could lead to an increased susceptibility to predation (Caddy, 1973; Jenkins & Brand, 2001). Damage to the mantle, similar to that caused during dredging, increases the likelihood of death within 30 days post-dredging (Gruffyd, 1972). The majority of damage that occurs is in the form of small chips on the perimeter of the shell that, although unlikely to cause immediate problems, can result in the redirection of energy from reproduction to repair, leading to lower reproductive output (Kaiser *et al.,* 2007). Mortality following dredging is greater in younger king scallops as their smaller size means they are more likely to be caught up in the mesh of the steel belly and they may be more susceptible to the effects of stress (Gruffyd, 1972; Maguire *et al.,* 2002). Due to the greater incidence of undersized discards in the western English Channel, improving gear efficiency to reduce the number of undersized individuals retained by the dredge (Lart *et al.,* 2003) would provide benefits to the stock.

4.5 Conclusions

Due to inherent variation in bycatch assemblages, coupled with seasonal variation in the abundance of certain species (*e.g.* Veale *et al.,* 2001), accurate estimates of bycatch can only be obtained through regular sampling, covering an appropriate spatial, temporal and seasonal scale. Distinct geographic areas, defined by physical and biological parameters should be incorporated into sampling plans. The results of this study indicate that overall bycatch in the English Channel king scallop fishery is lower than in other king scallop dredge fisheries that occur elsewhere in the British Isles. Based on the by catch rates reported, scallop dredgers have a limited capacity to inflict large scale mortalities on bycatch species of commercial value. However, we did not assess the quantity or mortality of organisms that come into contact with the dredge but remain on the seabed. Studies relating to this are limited, although Jenkins *et al*., (2001) concluded that there was wide variation in the response of different megafaunal taxa (including starfish and crabs) to damage and mortality following dredging activity. *Cancer pagarus* demonstrated higher levels of damage when not retained by the dredge and this is an important factor to account for when considering management of that species in relation to scallop dredging. Fisheries management should also take spawning periods and total fishing effort into account when considering dredge impacts.

The proportion of dredge bycatch in Cardigan Bay, Wales was slightly lower than that in the English Channel. However, dredge bycatch biomass was considerably higher around the Isle of Man (on average 53% of catch biomass). Scallop dredge bycatch species composition varies with localised and broad spatial scales, which is attributed to differences in physical and environmental conditions as well as seasonal variations in species abundances, catch susceptibility or gear configuration. Management options that reduce bycatch will become increasingly important in the future with the advent of the EU landing obligation. Such measures may include: using improved fishing gears that reduce bycatch and impacts on organisms that are not retained by the dredge; seasonal management restrictions to remove fishing impacts during times when certain species are more vulnerable to capture; avoiding sensitive habitats such as biogenic reefs and reducing overall fishing effort.

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S1: Species recorded during CEFAS dataset and author sampling trips.

Species	CEFAS data	Author data	Species	CEFAS data	Author data
Aequipecten opercularis	Y	Y	*Lophius piscatorius*	Y	Y
Agonus cataphractus		Y	*Luidia ciliaris*		Y
Alcyonidium diaphanum		Y	*Lutraria lutraria*		Y
Alcyonium digitatum		Y	*Maja squinado*	Y	Y
Ammodytidae sp.	Y		*Marthasterias glacialis*		Y
Anseropoda placenta		Y	*Merlangius merlangus*	Y	
Aphrodita aculeate		Y	*Microchirus variegatus*	Y	Y
Arnoglossus imperialis		Y	*Microstomus kitt*	Y	Y
Arnoglossus laterna		Y	*Mullus surmuletus*	Y	
Aspitrigla cuculus	Y		*Mustelus asterias*	Y	
Astarte sulcate		Y	*Mytilus edulis*		Y
Asterias rubens		Y	*Octopus vulgaris*		Y
Astropecten irregularis		Y	*Ophiura spp.*		Y
Atelecyclus rotundatus		Y	*Ostrea edulis*	Y	Y
Blennius gattorugine	Y		*Pagurus spp.*		Y
Blennius ocellaris	Y		*Palliolum tigerinum*		Y
Botryllus schlosseri		Y	*Papillicardium papillosum*		Y
Buccinum undatum	Y	Y	*Pecten maximus*	Y	Y
Buglossidium luteum	Y	Y	*Pegusa lascaris*	Y	
Callionymus lyra	Y		*Phrynorhombus norvegicus*		Y
Callionymus spp.		Y	*Pisidia longicornis*		Y
Cancer pagarus	Y	Y	*Pleuronectes platessa*	Y	Y
Chelidonichthys cuculus		Y	*Pollachius pollachius*	Y	
Chelidonichthys lucerna	Y	Y	*Porania pulvillus*		Y
Ciona intestinalis		Y	*Porcellana platycheles*		Y
Crepidula fornicate		Y	*Psammechinus miliaris*		Y
Crossaster papposus		Y	*Raja brachyura*	Y	
Diplecogaster bimaculata	Y		*Raja clavata*	Y	Y
Dromia personata		Y	*Raja montagui*	Y	
Ebalia spp.		Y	*Raja naevus*		Y
Echinus esculentus		Y	*Raja undulata*	Y	Y
Eledone cirrhosa		Y	*Sardina pilchardus*	Y	
Ensis spp.		Y	*Scophthalmus maximus*	Y	Y
Eunicella verrucosa		Y	*Scophthalmus rhombus*	Y	Y
Gadus morhua	Y		*Scyliorhinus canicula*	Y	Y
Galathea spp.		Y	*Sepia officinalis*	Y	Y
Henricia sanguinolenta		Y	*Sepiola atlantica*		Y
Hippoglossoides platessoides		Y	*Solea solea*	Y	Y
Homarus gammarus	Y		*Spatangus purpureus*		Y
Hyperoplus lanceolatus	Y		*Syngnathus acus*		Y
Inachus spp.		Y	*Syngnathus spp.*		Y
Laevicardium crassum		Y	*Tapes rhomboides*		Y
Lepidorhombus whiffiagonis	Y	Y	*Torpedo marmorata*	Y	
Leucoraja naevus	Y		*Trigloporus lastoviza*	Y	Y
Limanda limanda	Y		*Trisopterus luscus*	Y	
Liocarcinus spp.		Y	*Trisopterus minutus*	Y	Y
Lipophrys pholis		Y	*Zeus faber*	Y	Y
Loligo vulgaris		Y			
Lophius budegassa	Y				

S2: Typical species found in scallop dredge bycatch in each of the five areas. Species with notably high abundance (a) or those unique to an area (*) are listed.

	English Channel - Shallow	English Channel - Far West	English Channel - West	Cardigan Bay	Isle of Man
Ascidians					*Ascidia conchilega**
Bivalves	*Ostrea edulis**			*Glycymeris glycymeris*[a]	*Arctica islandica** *Anomia* sp.[a]
Bryozoans				*Flustra foliacea*[a] *Bugula flabellate** *Chartella* sp.* *Alcyonidium diaphanum*[a]	
Cephalopods	*Sepia officinalis**				*Loligo vulgaris*[a] *Eledone cirrhosa*[a]
Crustaceans				*Maja squinado*[a] *Necora puber** *Homarus gammarus*[a]	
Echinoderms					*Echinus esculentus*[a] *Solaster endeca** *Crossaster papposus*[a] *Stichastrella rosea** *Echinocardium cordatum*[a]
Fish/Sharks/Rays	*Arnoglossus laterna** *Scophthalmus maximus** *Scophthalmus rhombus**	*Lepidorhombus whiffiagonis** *Leucoraja naevus**	*Arnoglossus imperialis**	*Ammodytes* sp.[a] *Blennius ocellaris** *Chelidonichthys lucerna**	*Raja* sp.[a] *Taurulus bubalis**
Gastropods				*Capulus ungaricus**	*Neptunea antiqua*[a] *Colus* sp.[a]
Hydroids				*Abietinaria abietina*[a] *Hydrallmania* sp.[a]	
Soft corals					*Alcyonium digitatum*[a]
Sponges				*Halichondria* sp.*	*Haliclona* sp.[a]

847