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Temporal variation in environmental conditions and the structure of fish assemblages around an offshore oil platform in the North Sea

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ABSTRACT

This study reports temporal variations in the environmental conditions and the structure of fish assemblages observed in the vicinity of an offshore oil platform and the surrounding seafloor in the North Sea. Multi-seasonal sampling was conducted at a typical large steel jacketed facility, using mid-water fish traps at three different depths (i.e., 10, 50 & 100 m). Commercially important gadoids such as saithe *Pollachius virens*, haddock *Melanogrammus aeglefinus* and cod *Gadus morhua* were the most abundant species, however, the species composition and the relative abundances of the species varied with depth, season and between years. Comparisons with a large-scale bottom trawl survey data suggested highly dynamic and species-specific interactions between fish movements, changing environmental conditions and the physical presence of an offshore platform. Given the number of platforms currently installed across the North Sea, there is a need to identify biological mechanisms behind such dynamic interactions.

1. Introduction

Fundamental information on the utilisation patterns of seafloor features by different fish species in the North Sea has become increasingly important due to: (1) discovery of fish hot spots around seafloor features such as cold-water corals (Costello et al., 2005; Roberts and Hirshfield, 2004), wrecks (Leewis et al., 2000) or artificially installed hard substrate/structures (Baine, 2001; Bohnsack and Sutherland, 1985; Wilhelmsson et al., 2006); (2) evidence of the degradation of seafloor habitats by destructive fishing methods (Kaiser et al., 2002; Turner et al., 1999); (3) increasing concerns over the state of fish stocks of commercial importance under conventional fishery management (Cook et al., 1997; Myers and Worm, 2003; Pikitch et al., 2004). There are currently over 500 offshore installations extracting oil and gas from the continental shelf across the North Sea. These facilities represent the major man-made constructions installed on the seabed, adding substantial components of seafloor heterogeneity to the normally flat, featureless and soft sedimentary surroundings, and therefore understanding their impact is of paramount importance.

Initially, marine policy issues surrounding the offshore activities were focused mainly on the effects of newly installed production facilities on fisheries because of the potential for them to generate negative effects either by increasing local pollution levels resulting from hydrocarbon extraction or by making some fishing areas inaccessible for fishing vessels. However, recent studies have suggested that the physical presence of such platforms, together with associated subsea infrastructure such as pipelines, wellheads and manifolds, may in fact have beneficial effects for fisheries because they may function as artificial reefs that attract marine life (Stachowitsch et al., 2002; Whomersley and Picken, 2003), and thereby lead to increased numbers of economically important fishes around the structures (Love and Westphal, 1990; Stanley and Wilson, 1991, 1997; Fabi et al., 2004; Love and York, 2005; Love et al., 2006; Jablonski, 2008).

There is a growing body of evidence to confirm that a variety of fish species aggregate around artificial hard structures in marine environments worldwide (Bohnsack and Sutherland, 1985; Picken and McIntyre, 1989; Aabel et al., 1997; Stanley and Wilson, 1997; Baine, 2001; Løkkeborg et al., 2002; Soldal et al., 2002; Fabi et al., 2004; Love and York, 2005; Wilhelmsson et al., 2006). In the North Sea, for example, acoustic measurements from an oil platform showed large aggregations of mackerel, cod and saithe in the close proximity of the structure (Soldal et al., 2002), and fishing experiments with gillnet along transects from two North Sea platforms showed well defined gradients in which enhanced fish density declined sharply outside 100–300 m distance from the

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structures (Løkkeborg et al., 2002).

While such elevated abundance of fish around offshore structures has been repeatedly demonstrated, the temporal patterns in the utilisation of such structures by different fish species have not yet been examined in the North Sea. Characterizing the temporal dynamics of fish assemblages and environmental conditions in association with offshore artificial structures is of great interest in the context of marine resource management because they may provide important insight into the overall impacts of the extensive offshore anthropogenic activities on fish distribution and their stock population dynamics at wider spatial scales. Currently, many offshore petroleum fields are approaching the end of their commercial lives and the focus is now shifting towards the fate of obsolete oil facilities, or a process known as decommissioning, since alternative disposal options may make significant differences in environmental effects and economic consequences. In contrast, there is a major expansion of marine renewable energy developments primarily in the shallow coastal waters worldwide (Inger et al., 2009; Boehlert and Gill, 2010). Marine ecosystems are thus expected to change rapidly in response to increasing anthropogenic influences and this creates a demand for better understanding how the spatio-temporal variation in the distribution of fish assemblages is related to the physical presence of offshore structures and how other environmental processes in turn affect the strength and dynamics of the fish-habitat dependencies in relation to any changes in the number and/or the distribution of offshore man-made structures.

Historically, most of the available literature on the ecology of fish populations surrounding oil/gas platforms comes from either in the Gulf of Mexico or off the coast of California in the USA. The Gulf of Mexico, for example, accommodates the largest concentration of offshore platforms (~4500) anywhere in the world (Parente et al., 2006) and hosts an extensive recreational fishery that relies on these offshore structures (Stanley and Wilson, 1991). For this reason, fishery-dependent data on the occurrence and seasonal abundance of selected fish species around oil/gas platforms have been readily available in this region (Stanley and Wilson, 1991) as well as off the coast of California (Love and Westphal, 1990). However, any fishery or survey vessels are currently not permitted to operate closer than 0.5 km to each oil/gas platform in the North Sea due to stringent safety regulations (500 m safety zones). For similar reasons, fishing directly from any operational platforms is normally banned. However, the Miller platform (Fig. 1) ceased production in 2007 and has since been used as a search and rescue helicopter base, which resulted in providing a unique opportunity to undertake a direct study on the relationships between fish populations and the physical presence of offshore platform in the North Sea.

Offshore platforms are thought to provide unique marine habitats in that they vertically stretch throughout the entire water column from the seafloor to the sea surface in remote offshore environments. These structures could be expected to attract various species, ranging from benthic, demersal to pelagic fishes within a single location. Using mid-water fish traps at three different water depths, this article firstly reports on the temporal dynamics of fish assemblages and the prevailing environmental conditions observed around a typical offshore oil platform in the North Sea. Subsequently, a subset of a large-scale bottom trawl survey data was extracted and compared with the fish trap data in order to investigate how temporal changes in the relative abundances of the same fish species observed at the platform could be linked to those observed at nearby control locations (surrounding soft-bottom seafloor) as well as at the entire North Sea region during the corresponding study period, using the IBTS (International Bottom Trawl Survey) and oceanography databases derived from ICES (International Council for the Exploration of the Sea). This comparative analysis was conducted under the assumption that, when the number of fish caught is recorded over time, change in catch per unit effort (CPUE) of the target fish species would be proportional to change in the abundance of the fish. Thus if the platform habitat is utilized by fish in the same way as the surrounding open seafloor over time, the temporal pattern of CPUE at the platform would also be proportional to or synchronized with that of CPUE at the surrounding control locations because the temporal dynamics observed at the platform would be merely a reflection of temporal changes in the relative abundance of fish individuals present at the surrounding areas. Based on the results from these analyses, together with the relevant literature, implications for the ecological impacts of the presence of the offshore platforms on North Sea fish populations are discussed.

2. Material and methods

2.1. Study site

The study was carried out at BP's Miller platform situated in the central northern part of the North Sea (58°43′19.70″N, 01°24′07.40″E) which lies within ICES statistical rectangle 46F1 (Fig. 1a and b). The platform was installed in 1991 in a water depth of approximately 103 m on an unconsolidated sandy seafloor. The platform has a large steel jacket structure (eight-legged) weighing approximately 18,600 t with a size of 71 × 55 m at the base, tapering to 71 × 30 m at the top. It provides a complex open lattice structure and a large surface area throughout the entire water column. The platform ceased production in September 2007 and currently hosts a Search and Rescue helicopter base for provision of offshore rescue and recovery operations for the central North Sea area. The platform is therefore maintained with minimum on-board personnel, and although illuminated during the night, the levels of noise and discharge of food waste were much reduced compared to those of operational platforms, representing one of the typical obsolete platform structures found in the region.

2.2. Data collection

2.2.1. Sampling at the Miller platform

Multi-seasonal fish sampling was conducted at the Miller platform from October 2010 for two years using three fish traps attached to a single mooring rope which was anchored to the bottom at one end, and tethered to the lower deck of the platform at the other (Fig. 2). Each fish trap consisted of one vertical aluminium axial section and four aluminium square frames that were covered with two sheets of trammel netting (1.2 m height × 2.7 m width) (Fig. 3). A trammel net is similar to a gillnet, which can be used to catch demersal, benthic and pelagic species, and a sheet of trammel net comprised three layers of net - an inner panel of netting with a small mesh size (51 mm) and two outer layers with a larger mesh size (305 mm). Fish may therefore be gilled, caught by the gills, or may be entangled in bags or pockets of the inner netting of this trap. Each fish trap was baited with approximately 700 g of fresh mackerel (*Scomber scombrus*: entire individuals chopped in pieces). The mooring fish sampling system was deployed with a ballast weight attached at the bottom and the three fish traps attached at depths of approximately 10, 50 and 100 m from the sea surface (Fig. 2). Floatation devices were connected to the rope to maintain the mooring system in suspension throughout the water column (Fig. 2).

The top two fish traps (i.e., 10 m and 50 m) were equipped with a temperature sensor (SBE 39, SeaBird Electronics) recording water temperature (°C) at 10 min intervals. The bottom trap (i.e., 100 m)

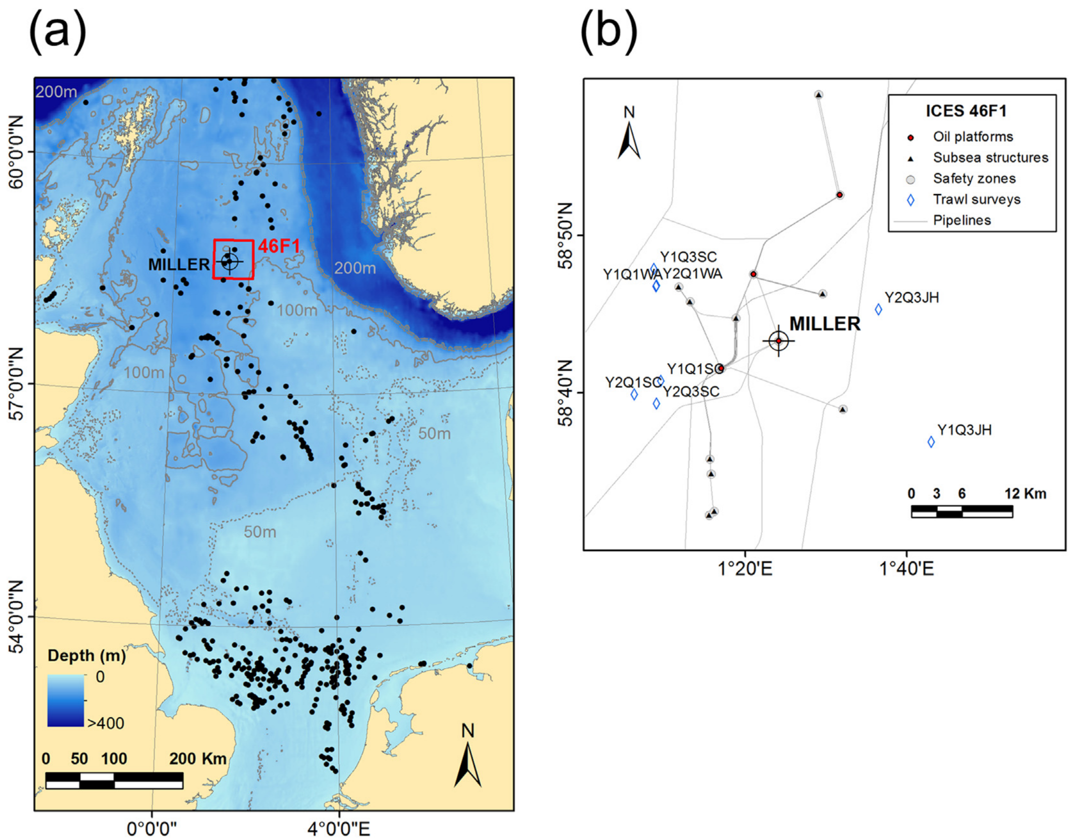

Fig. 1. (a) Map of the North Sea showing the locations of offshore oil/gas platforms (the filled black circles) (Source: OSPAR, 2012). The circle and cross symbol indicates the location of the Miller platform and the red square defines the area of ICES statistical rectangle 46F1. (b) Map of ICES 46F1 showing the locations of offshore platforms, pipelines, subsea structures and associated 500 m safety zones. Blue diamond symbols represent locations of trawl surveys conducted in the IBTS operations between Q1 2011 and Q3 2012 (Codes as in Table 1).

was equipped with a current meter with temperature and pressure sensors (Aquadopp Current Meter, Nortek) measuring water temperature (°C), pressure (dbar), current speed (m/s) as well as current direction (degree) at 10 min intervals.

Sampling was conducted four times a year covering all seasons (Q4: autumn; Q1: winter; Q2: spring; Q3: summer) over two years (Y1 and Y2). For each sampling, the mooring fish traps were deployed for >12.5 h (typically from late in the afternoon through night till the following morning-noon) so that each soak time could cover at least one tidal cycle, and this procedure was replicated three times on consecutive days per season. All the sampling was conducted when the wind speed was <25 knot (wave height < 3–4 m) for safety reasons. Upon retrieval of the fish traps, all the fish samples were sorted, identified and enumerated, and body size (total length in cm) was recorded for all individuals captured in the sampling. Based on the duration of soak time, relative abundance of each fish species caught per trap was standardised to catch per unit effort described as the number of fish individuals caught per 12.5 h ($CPUE_{MILLER}$).

2.2.2. Data extraction from the IBTS and ICES database

A subset of fish data was extracted for ICES statistical rectangle 46F1 (nearby control sites, Fig. 1 and Table 1) and for the whole North Sea region, using a large-scale bottom trawl survey data derived from the IBTS database (http://www.ices.dk/Pages/default.aspx). The IBTS has been providing independent indices of fish distribution and relative abundance in the North Sea, using a bottom-trawl net (GOV trawl - mesh size at the opening: 200 mm; mesh size at the codend: 20 mm; details for the specification of the GOV-trawl can be found in ICES, 2010) which has been fully standardised amongst the participating nations since 1983. The survey grid is based on an ICES statistical rectangle of approximately 30 × 30 nautical miles (0.5° latitude × 1° longitude), each of which is normally sampled by the ships of two different nations per survey (two hauls per rectangle). The whole survey area comprises a total of around 160 ICES statistical rectangles across the North Sea, and the survey normally takes place twice a year for the first quarter (Q1: winter) and the third quarter (Q3: summer). At each station, the trawl net is towed for approximately 30 min and the catch is sorted and enumerated to determine the relative abundances and length distributions for all fish species caught. The catch per species is standardised to catch per unit effort described as the number of individuals caught per 1 h tow ($CPUE_{IBTS}$). Details on the sampling methods and protocols are available in the IBTS survey manual (ICES, 2010). In addition, a subset of data for spatio-temporal variations in both surface and bottom temperatures for the whole North Sea region were extracted using ICES oceanographic database (http://www.ices.dk/Pages/default.aspx).

2.3. Data analysis

2.3.1. Fish associated with Miller platform

For the catches at the Miller platform, temporal changes in fish relative abundance, species composition and species richness were examined across seasons (Q1-Q4) and years (Y1 and Y2) using univariate analyses. The general relationships between fish relative abundance, species composition and water temperatures were examined in relation to seasons, years as well as water depths using

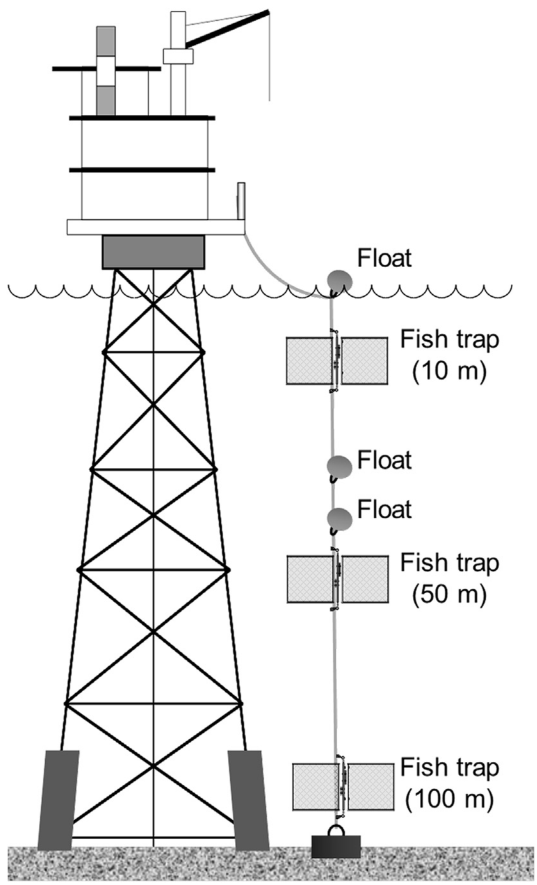

Fig. 2. Schematic diagram of the mooring fish sampling system deployed from the Miller platform.

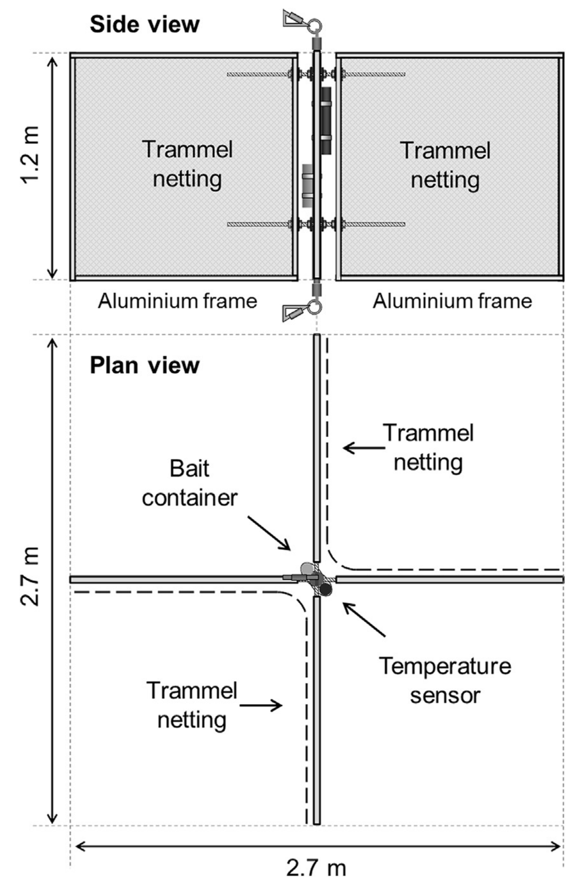

Fig. 3. Schematic diagram of the baited fish trap unit employed in this study.

univariate analyses. For the prevailing environmental conditions, changes in temperature between seasons and years were examined for each of the three depths separately, using univariate analyses. Two-way ANOVA (analysis of variance) and post hoc Tukey's test were performed to make statistical comparisons of the temperature data for the three different depths (i.e., 10, 50 and 100 m) where two factors were season and year. In addition, trends in bottom current speed and direction were examined using polar plots per deployment. All statistical analyses were performed using R version 3.0.0 package (R Development Core Team, 2013).

2.3.2. Fish associated with Miller platform in relation to ICES 46F1

Because the sampling gear employed at the Miller platform (i.e., baited fish trap with trammel netting) was different from that of the bottom trawl survey (i.e., GOV trawl), $CPUE_{MILLER}$ obtained at the Miller platform could not be directly compared with $CPUE_{IBTS}$ for ICES 46F1. However, if the North Sea offshore structures are utilized by fish in the same way as the surrounding open seafloor nearby, the temporal pattern of $CPUE_{MILLER}$ would be proportional to or synchronized with that of $CPUE_{IBTS}$ for ICES 46F1 since changes in the number of fish individuals observed at platforms would be merely a reflection of changes in the relative abundances of fish individuals at nearby surrounding areas. Likewise, body size distribution of each fish species caught at the Miller platform would be similar to that in the trawl surveys at ICES 46F1 at corresponding seasons. To examine these, temporal changes in fish mean relative abundances and their body size distributions were presented in bar plots and box plots, respectively, for the catches from the Miller platform as well as from the trawl surveys at ICES 46F1. With respect to the body size distribution, the results should, however, be interpreted with due caution because there may be a potential size bias in fish individuals caught by the baited fish trap when compared with the trawling methods. This is because, firstly, certain size classes may be present but may not be susceptible to baiting, and secondly the codend of the trawl net had a smaller mesh size than the inner net of the baited fish trap – the minimum size of fish caught by the fish trap was 17 cm in this study, and the 0-group of any fish species would not therefore be expected to be caught by this fish trap.

For the fish data obtained at the Miller platform, two-way ANOVA and post hoc Tukey's test were also performed to assess the temporal effects of both season and year on the relative abundance and body size data for saithe *Pollachius virens* and haddock *Melanogrammus aeglefinus*, which were the two

Table 1
Summary information of the IBTS trawl operations conducted at ICES statistical rectangle 46F1 between Q1 2011 and Q3 2012. (Y1 = Year1; Y2 = Year 2; Q1 = Winter; Q3 = Summer).

Year	Season	Date	Ship	Trawl location		Depth (m)	Code
				Lat	Lon		
Y1	Q1	2011-01-29	WAH3	58.7792	1.1452	111	11Q1WA
		2011-02-06	SCO3	58.6792	1.1567	120	11Q1SC
	Q3	2011-07-12	JHJ	58.6150	1.7150	116	11Q3JH
		2011-07-31	SCO3	58.7975	1.1407	110	11Q3SC
Y2	Q1	2012-02-01	SCO3	58.6648	1.1013	115	12Q1SC
		2012-02-16	WAH3	58.7800	1.1467	110	12Q1WA
	Q3	2012-07-09	JHJ	58.7550	1.6067	108	12Q3JH
		2012-07-10	SCO3	58.6553	1.1473	126	12Q3SC

numerically most dominant species (For haddock, only Q3 and Q4 data were used in the ANOVA analysis since haddock individuals were mostly absent in Q1 and Q2 at the Miller platform). Prior to the statistical analysis, the relative abundance data ($CPUE_{MILLER}$) were log-transformed to approximate the normal distribution and stabilise the variance. The statistical analyses were performed using R version 3.0.0 package (R Development Core Team, 2013).

2.3.3. Fish associated with Miller platform in relation to the whole North Sea region

Using the IBTS data sets, maps for the distribution and abundance of major fish species observed at the Miller platform were produced for the whole North Sea region at corresponding seasons from 2011 Q1 to 2012 Q3. On average 349 georeferenced data points ($CPUE_{IBTS}$ per haul per species) by season across the North Sea were interpolated to produce each map. Similarly, the data sets for spatio-temporal variations in both surface and bottom temperatures across the North Sea were obtained using ICES oceanographic database from which a total of respective 5641 and 4649 sample points (on average respective 1410 and 1162 data points per season across the North Sea) were extracted. In order to produce a smooth estimated surface for both fish and temperature distributions over the spatial extent of the study area, the subset of the extracted data points by season for each of the variables were interpolated using Inverse Distance Weighting (IDW) on ESRI ArcGIS 10.0.

3. Results

3.1. Fish associated with Miller platform

The string of three fish traps was deployed 24 times (= 72 trap cycles) over the 2 year duration of this study (Table 2). A total of six fish species were identified: 4 species from the family Gadidae, saithe *P. virens*, haddock *M. aeglefinus*, cod *Gadus morhua* and poor cod *Trisopterus minutus*, 1 Lotidae, tusk *Brosme brosme* and 1 Pleuronectidae, long rough dab *Hippoglossoides platessoides*. The commercially important species, saithe, haddock and cod were most frequently caught (Fig. 4a). Both tusk and poor cod were also regularly, but to a lesser extent, caught, and only one individual of long rough dab was caught in April 2012 (Table 2) (Fig. 4a). There were marked changes in species composition and their relative abundances ($CPUE_{MILLER}$) between seasons as well as years (Fig. 4a). Between 3 and 5 species were constantly recorded during the study period, except for the winter months in January in both years where only saithe was caught (Fig. 4b). Saithe was the only species present in all seasons throughout the study period, but their relative abundances ($CPUE_{MILLER}$) were markedly higher in Y1 when compared with those in Y2 in the corresponding seasons (Fig. 4a). In contrast, haddock were caught only in the summer and autumn months and they essentially disappeared in the winter and spring months with only a single individual caught in April 2011 (Fig. 4a).

Fig. 5 shows the relationships between fish relative abundances ($CPUE_{MILLER}$), water depths (m) and water temperature (°C) per deployment for each season. There was marked variation in both fish species composition and their relative abundances between seasons as well as years when compared with those between deployments. In addition, at any time of the year, most fish were caught from the bottom depth at 100 m where the water temperatures were the coldest (Fig. 5).

Temperatures at all the three water depths showed an indication of annual cycle, and there were significant differences between temperatures in different seasons as well as years (Fig. 6) (Table 3). Minimum temperatures at all depths were recorded mostly in Q2 (spring) with average values of 6.7 °C–7.5 °C (Fig. 6). The large-scale temperature changes also occurred in the upper (10 m) and middle (50 m) water column in Q3 (summer) and Q4 (autumn) where temperatures rose up to 12.9 °C and 11.5 °C, respectively (Fig. 6a and b). In contrast, the bottom temperatures at 100 m remained relatively constant throughout the year between 6.7 °C and 8.5 °C (Fig. 6c). Overall, temperature values obtained in Y2 at all three depths were significantly warmer than those obtained in Y1 in most of the corresponding seasons (Fig. 6) (Table 3), which coincided with the marked reduction in fish catches at the Miller platform (Fig. 4a).

The patterns of seabed currents observed during each deployment are summarised in Fig. 7. On average, the observed bottom water speeds at the Miller field was 0.055 m/s, but the seabed currents varied substantially from deployment to deployment (maximum: 0.232 m/s; minimum: 0.001 m/s), and there was no noticeable relationship between fish catches and the property of bottom water currents at least for saithe and haddock. However, the pattern of water currents may have had some influence on the catches of both tusk and poor cod, as these species were only caught when the prevailing currents were oriented northeast to southwest direction along which the platform was located (Fig. 7b, n, p and x).

3.2. Fish associated with Miller platform in relation to ICES 46F1

Changes in the relative abundances of five fish species regularly caught at the Miller platform ($CPUE_{MILLER}$) (Table 2) were presented in connection with the comparative trawl survey data at ICES rectangle 46F1 for Q1 and Q3 ($CPUE_{IBTS}$) (Table 1) during the corresponding study period (Fig. 8). At the Miller platform, saithe was caught in relatively high numbers in almost all deployments with a noticeable declining trend observed from Y1 to Y2 (Fig. 8a). In contrast, saithe was either absent or caught in very small number in the trawl catches at nearby reference locations at 46F1 (Fig. 8f). At the Miller platform, haddock showed distinctive seasonal patterns mostly occurring in warmer months in Q4 and Q3, and their relative abundances also showed a declining trend towards the end of the study period (Fig. 8b). In contrast, haddock was caught much more steadily in the IBTS trawl survey in both Q1 and Q3, and the change in their relative abundance did not exhibit any declining trend in the nearby stations (Fig. 8g). Both cod and tusk occurred three times out of eight sampling seasons at the Miller platform (Fig. 8c and d). In the IBTS, cod was more regularly caught both in Q1 and Q3 (Fig. 8h), whereas tusk was not caught at all in any trawl catch in nearby reference locations at 46F1 during the study period (Fig. 8i). Poor cod was caught repeatedly at the Miller platform as well as in the IBTS trawl survey (Fig. 8e and j), but their catches remained generally small in both sampling methodologies.

Body size distributions of the major fish species caught at the Miller platform were also presented with the comparative data obtained in the trawl surveys at 46F1 conducted at corresponding seasons (Fig. 9). Both saithe and tusk were mostly caught only at the Miller platform, but body size distributions of haddock, cod and poor cod showed that at any season individuals caught at the Miller platform were generally larger when compared with those caught in nearby reference locations in the trawl surveys.

Amongst fish individuals caught at the Miller platform, saithe showed statistically significant differences in their relative abundances ($CPUE_{MILLER}$) between seasons as well as years with the values in Y1 significantly higher than those in Y2 in the corresponding seasons (Table 4) (Fig. 8a). There were also significant differences in their body size distributions between seasons as well as years (Table 5) (Fig. 9a). For example, in the first year, the catches of saithe were dominated by smaller individuals in Q4 and Q2, but this trend was significantly reversed in Q1 and Q3. In the second

Table 2
Summary results of the multi-seasonal fish sampling at the Miller platform with total catch from the 3 depths per deployment (N = ind./deployment) and relative abundance (CPUE = ind./12.5 h) by species. (Rep# = Replicate number; P. cod = Poor cod; L.R. dab = Long rough dab; Q4 = Autumn; Q1 = Winter; Q2 = Spring; Q3 = Summer).

Year	Season	Date	Rep#	Soak time (hh:mm)	Saithe		Haddock		Cod		P. cod		Tusk		L.R. dab	
					N	CPUE	N	CPUE	N	CPUE	N	CPUE	N	CPUE	N	CPUE
Y1	Q4	2010-10-08	1	18:20	7	4.77	2	1.36	0	0	0	0	0	0	0	0
		2010-10-09	2	18:00	2	1.39	5	3.47	0	0	1	0.69	1	0.69	0	0
		2010-10-11	3	23:20	4	2.14	4	2.14	0	0	0	0	0	0	0	0
	Q1	2011-01-14	1	15:30	14	11.29	0	0	0	0	0	0	0	0	0	0
		2011-01-18	2	16:50	12	8.91	0	0	0	0	0	0	0	0	0	0
		2011-01-20	3	17:20	12	8.65	0	0	0	0	0	0	0	0	0	0
	Q2	2011-04-17	1	17:50	3	2.10	1	0.70	1	0.70	0	0	0	0	0	0
		2011-04-19	2	17:30	2	1.43	0	0	0	0	1	0.71	1	0.71	0	0
		2011-04-20	3	17:20	2	1.44	0	0	0	0	0	0	0	0	0	0
	Q3	2011-07-01	1	15:00	1	0.83	2	1.67	1	0.83	0	0	0	0	0	0
		2011-07-02	2	15:20	5	4.08	2	1.63	0	0	0	0	0	0	0	0
		2011-07-04	3	15:10	8	6.59	4	3.30	1	0.82	0	0	0	0	0	0
Y2	Q4	2011-10-14	1	22:30	1	0.56	1	0.56	1	0.56	0	0	0	0	0	0
		2011-10-16	2	19:00	3	1.97	1	0.66	0	0	0	0	0	0	0	0
		2011-10-17	3	22:50	2	1.09	3	1.64	1	0.55	0	0	0	0	0	0
	Q1	2012-01-15	1	17:30	5	3.57	0	0	0	0	0	0	0	0	0	0
		2012-01-16	2	17:50	4	2.80	0	0	0	0	0	0	0	0	0	0
		2012-01-17	3	17:10	5	3.64	0	0	0	0	0	0	0	0	0	0
	Q2	2012-04-06	1	19:20	3	1.94	0	0	0	0	1	0.65	0	0	0	0
		2012-04-07	2	18:00	0	0	0	0	0	0	0	0	0	0	0	0
		2012-04-08	3	16:20	0	0	0	0	0	0	0	0	0	0	1	0.77
	Q3	2012-07-08	1	18:10	1	0.69	0	0	0	0	0	0	0	0	0	0
		2012-07-09	2	16:10	1	0.77	1	0.77	0	0	0	0	0	0	0	0
		2012-07-10	3	14:50	1	0.84	1	0.84	0	0	0	0	1	0.84	0	0

year, however, there was no marked variation in their body size composition between seasons although the overall catches were mainly dominated by smaller individuals in comparison with those individuals caught in Q1 and Q3 in the first year (Fig. 9a) (Table 5). Haddock individuals caught at the Miller platform also showed significant differences in their relative abundances between seasons and years (Fig. 8b) (Table 4), but their body size composition did not vary significantly between seasons or years although there was significant interactive effect between season and year which influenced the body size composition of haddock (Fig. 9g) (Table 5).

3.3. *Fish associated with Miller platform in relation to the whole North Sea region*

Based on the IBTS trawl survey database, spatio-temporal changes in the distribution and abundance of the major fish species observed at the Miller platform were examined for the whole North Sea region (Fig. 10). The spatial patterns varied markedly between species, although the degree of temporal variations exhibited within each species generally remained low but rather species specific. For example, distribution of saithe was generally constrained in the northern North Sea along the edge of the Norwegian Deep, yet this northern-oriented trend appears more pronounced in Q1 as the densities of saithe became mostly zero (absent) around the northern central North Sea where the Miller platform was also located (Fig. 10a and c) when compared with Q3 (Fig. 10b and d). Haddock showed almost identical patterns of occurrence in the northerly area of the North Sea across seasons with some noticeable declining trends in their abundances observed from Y1Q1 to Y2Q3 (Fig. 10e, f, g and h). At the Miller platform, haddock were caught mostly in the summer and autumn months (Fig. 8b), but such strong seasonality, however, was not evident in their temporal pattern in the surrounding areas in the northern North Sea. Cod showed a wider geographical range distributed throughout the North Sea with higher occurrence and catch rate mainly observed along a broad zone stretching from northeast archipelago of Scotland to northern Denmark (Fig. 10i, j, k and l) but with some large areas of absence or very low abundance recorded in the shallow waters around east of Scotland and southern North Sea in Q3 seasons. Tusk was repeatedly caught at the Miller platform in this study, but this species was rarely caught in the large-scale bottom trawl surveys and only limited number of survey catch was thus recorded in each season (Fig. 10m, n, o and p). Poor cod appeared distributed only western part of the North Sea mainly concentrated along northeast archipelago of Scotland down through to the east coast of southern England (Fig. 10q, r, s and t), and the highest and lowest abundances were observed in Y2Q3 and Y1Q3, respectively.

Temporal variations in water temperatures recorded at the Miller platform (Fig. 6) were generally consistent with the North Sea regional trends (Fig. 11). In both surface and bottom waters, temperatures were generally higher in Y2 than in Y1 in the respective Q1 and Q3 seasons throughout the North Sea, although temperature values in Y2Q3 in bottom waters observed around the east coast of Scotland became locally colder than those observed in Y1Q3. This region coincided with the area where marked increase in fish catches of poor cod was recorded (Fig. 10r and t) (Fig. 11f and h). In terms of the vertical distribution of temperature, the water column was stratified during Q3 summer seasons, with markedly higher temperatures observed in the southern North Sea and a thermocline located in the region of around 50 m water depth (Fig. 11b, d, f and h). After the summer months, the strong stratification of the water mass disappeared, and there was little variation in water temperatures throughout the water column in the winter months in Q1 (Fig. 11a, c, e and g).

4. Discussion

This study investigated temporal variation in the environmental conditions and the occurrence of fish assemblages in the vicinity of the Miller oil platform as well as the surrounding environment in the North Sea. Commercially important fish such as saithe *P. virens*, haddock *M. aeglefinus* and cod *G. morhua* were the most abundant species caught by the fish traps, and both tusk *B. brosme* and poor

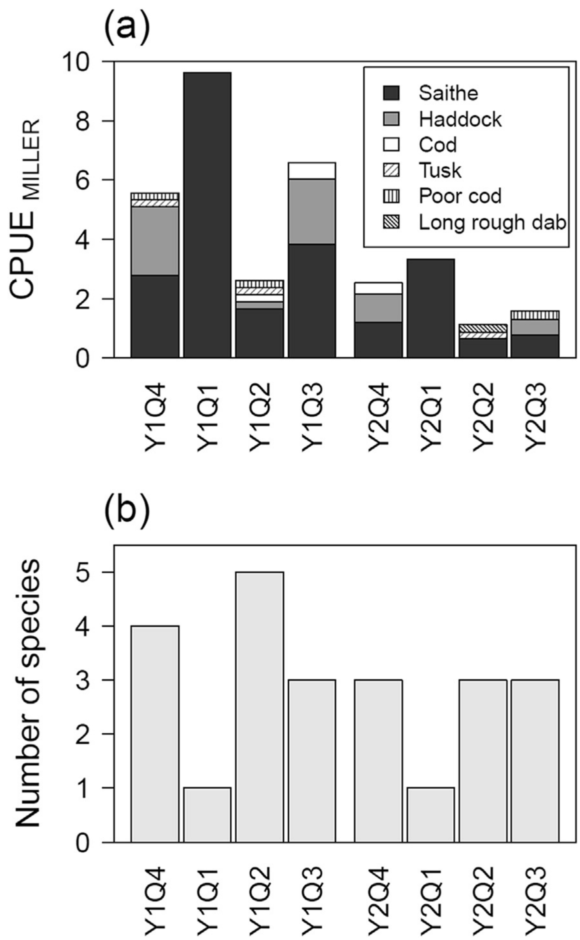

Fig. 4. (a) Changes in fish species composition and their mean relative abundances expressed in $CPUE_{MILLER}$ over time observed at the Miller platform. (b) Changes in the number of fish species recorded over time observed at the Miller platform. (Y1 = Year1; Y2 = Year 2; Q4 = Autumn; Q1 = Winter; Q2 = Spring; Q3 = Summer).

cod *T. minutus* were also regularly observed at the study site. With respect to the physical conditions at the Miller platform, temperatures at all the three water depths (i.e., 10 m, 50 m & 100 m) showed a distinctive indication of annual cycle with the degree of changes differed depending on the depth. These changes in temperatures at the Miller platform were consistent with seasonal patterns observed in the northern part of the North Sea where the water column is generally well mixed in winter, but horizontal thermal stratification occurs in summer, typically at a depth of around 50 m (e.g. Umgiesser et al., 2002; this study). Further, the patterns of seabed currents varied substantially from deployment to deployment, yet at any time of the year, the majority of fish individuals were caught from the bottom depth at 100 m where the water temperatures were the coldest. Overall, there were marked changes in fish species composition and their relative abundances between sampling depths, seasons as well as years at the Miller platform, suggesting highly dynamic interactions occurring between fish movements, changing environmental conditions and the physical presence of an offshore platform.

The composition of fish species observed in this study was consistent with the earlier research studies conducted around offshore platforms in this region. For example, Soldal et al. (2002) investigated the relationship between fish and one of North Sea oil platforms using acoustics, and demonstrated a presence of large aggregations of cod and saithe in close proximity to the structure. Løkkeborg et al. (2002) also conducted fishing experiments with gillnet along transects from two of North Sea platforms and showed well defined gradients in which enhanced fish density of both cod and saithe declined sharply outside 100–300 m distance from the structures. Further, Picken and McIntyre (1989) and Aabel et al. (1997) reviewed the interactions between fishes and a variety of North Sea offshore platforms and showed coherent patterns of associations between individuals of gadoids, particularly cod, haddock and saithe, and the physical presence of the offshore structures. Tusk is known to be strongly associated with natural reef and wreck habitats (Costello et al., 2005), but in the North Sea, this species has also been commonly found on offshore platforms particularly where structural complexity is high (Guerin, 2009). Poor cod has also been found at other offshore platforms in the North Sea (Guerin, 2009), and two other species of the same genus, namely Norway pout *Trisopterus esmarkii* and pouting *Trisopterus luscus* have been reported to be associated with offshore structures (Aabel et al., 1997; Guerin, 2009; Reubens et al., 2013). It is also not uncommon to find flatfish in association with the offshore platforms in the North Sea (Valdemarsen, 1979; Aabel et al., 1997; Guerin, 2009; Martínez, 2012). It should, however, be noted here that, with respect to the occurrence of fish species, a consistent feature across the literature on offshore platforms is that the return of ecological information is highly dependent on the sampling method employed. In this regard, the number of fish species recorded at the Miller platform in this study may well be conservative because the baited fish trap is thought to be selective sampling which may have underestimated the number of fish species present - only a subset of species may have been attracted by the bait. Thus the results from the relevant literature that used less-selective sampling methods such as trawling, large-scale passive gill-netting, ROVs and underwater cameras, revealed that other fish species such as ling *Molva molva*, pollock *Pollachius pollachius*, *Trisopterus* spp. (e.g., Norway pout), redfish (*Sebastes* spp.), wolffish *Anarhichas lupus*, and some species of flatfish (Pleuronectiformes) are also commonly observed around the offshore oil/gas platforms across the northern and central part of the North Sea (Valdemarsen, 1979; Aabel et al., 1997; Løkkeborg et al., 2002; Guerin, 2009; Martínez, 2012).

Amongst these oil-platform-associated fish species in the North Sea, cod, haddock and saithe have been known to show coherent patterns in their local distributions where significantly higher number of individuals can be found in the immediate vicinity of individual structures when compared with surrounding open soft-bottom areas (Valdemarsen, 1979; Aabel et al., 1997; Løkkeborg et al., 2002; Soldal et al., 2002). Further, both saithe and tusk were readily caught at the Miller platform in this study, yet their relative abundances obtained from large-scale bottom trawl surveys conducted in nearby locations showed distinctively different temporal patterns where the densities of these species were recorded as mostly zero or very low at corresponding seasons as well as years. This is likely to be attributed to the fact that the IBTS trawl tracks are mainly limited to "trawlable" open and soft bottom seafloor due to the design of the survey gear, whereas the distribution of saithe and tusk are more strongly associated with structurally complex habitats with hard substrate such as reefs and rock outcrops. Similarly, Wieland et al. (2009) found that, using several standardised fishing methods, the catch rates of cod were substantially higher on gravel or rough stone bottom as well as at ship wrecks than on smooth sand bottom in the north-eastern North Sea. Thus, the earlier studies together with the consistent occurrences of the same fish species observed at platform in this study suggest that the installation of offshore oil/gas platforms and associated subsea infrastructures have provided substantial components of seafloor heterogeneity (i.e., unique habitat) which have

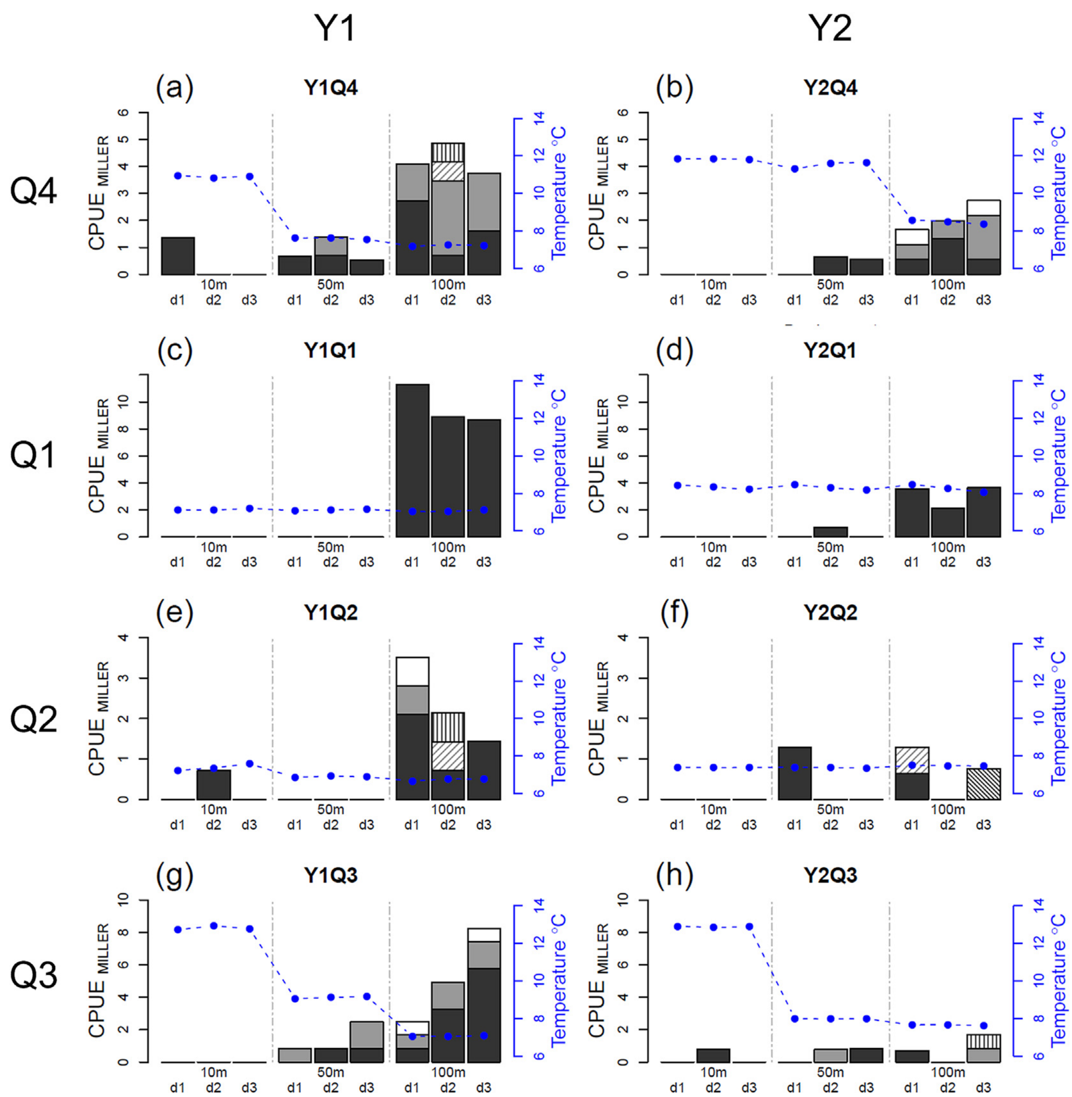

Fig. 5. The relationships between fish species composition, relative abundances and water temperatures across three different depths (10, 50 and 100 m) and deployments (d1, d2 and d3). (Fish species symbols and seasonal codes as in Fig. 4).

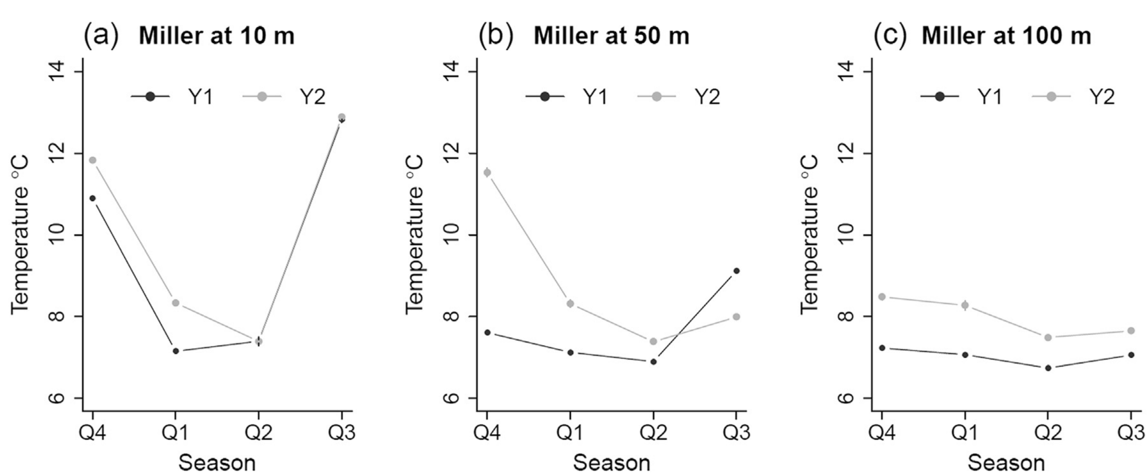

Fig. 6. Changes in mean water temperatures (±S.E.) across seasons and years at the Miller platform: (a) 10 m water depth; (b) 50 m water depth; (c) 100 m water depth. (Seasonal codes as in Fig. 4).

Table 3
Results of 2-way ANOVA, testing effect of year and season on water temperature data at 10, 50 and 100 m depths at the Miller platform. Statistically significant differences for all possible combinations of year/season pairs were derived from the post hoc Tukey's test (*** = p < 0.001; ** = p < 0.01; * = p < 0.05; n.s. = not significant; Y1 = Year1; Y2 = Year 2; Q4 = Autumn; Q1 = Winter; Q2 = Spring; Q3 = Summer).

Depth	Factor	df	MS	*F*	p	Tukey HSD
10 m	Year	1	1.79	223.9	<0.001***	Y1 < Y2***
	Season	3	43.64	5449.4	<0.001***	Q4 > Q1***, Q4 > Q2***, Q3 > Q4*** Q2 < Q1***, Q3 > Q1***, Q3 > Q2***
	Year × Season	3	0.55	68.3	<0.001***	
	Within samples	16	0.01			
50 m	Year	1	7.49	955.0	<0.001***	Y1 < Y2***
	Season	3	6.69	852.7	<0.001***	Q4 > Q1***, Q4 > Q2***, Q3 < Q4*** Q2 < Q1***, Q3 > Q1***, Q3 > Q2***
	Year × Season	3	6.67	850.3	<0.001***	
	Within samples	16	0.01			
100 m	Year	1	5.43	669.5	<0.001***	Y1 < Y2***
	Season	3	0.65	80.4	<0.001***	Q4 > Q1*, Q4 > Q2***, Q3 < Q4*** Q2 < Q1***, Q3 < Q1***, Q3 > Q2**
	Year × Season	3	0.16	20.1	<0.001***	
	Within samples	16	0.01			

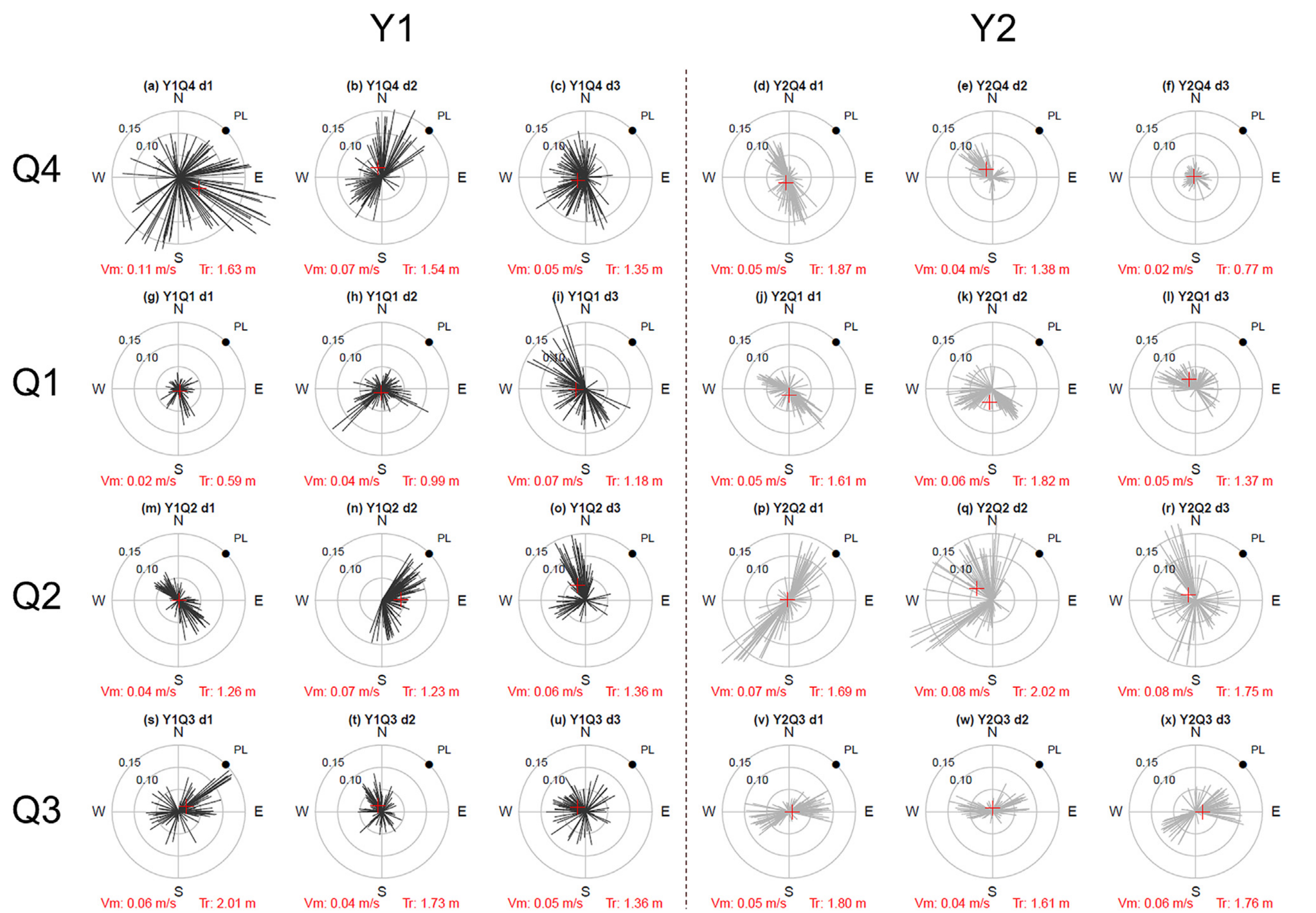

Fig. 7. Polar plots for the patterns in the bottom water currents with the speed and direction indicated by each vector for each deployment. PL indicates the direction of platform in relation to the sampling location, V_m shows mean velocity (m/s), T_r represents the maximum tidal range (m) recorded and the red cross denotes the centroid of values per deployment. (Seasonal codes as in Fig. 4).

been capable of attracting populations of these fish species and thereby function as artificial reefs potentially acting as a network of *de facto* marine protected zones (de Groot, 1982; Osmundsen and Tveterås, 2003).

However, this study also showed that there were substantial changes in species composition and their relative abundances observed not only between sampling depths, but also between seasons as well as years at the Miller platform. For example, haddock were caught mostly in the summer and autumn months and they essentially disappeared in the winter and spring months. Such strong seasonality, however, was not observed in their temporal pattern obtained from large-scale bottom trawl surveys conducted in nearby locations at corresponding seasons. Haddock also showed significant variation in their relative abundances between years, and where they were present, their body size distributions at the Miller platform were mostly larger than those caught at nearby surrounding open seafloor. The strong seasonal occurrences and some variation in their body size composition exemplified by haddock indicate that individuals observed around the Miller platform in different seasons and locations were likely to

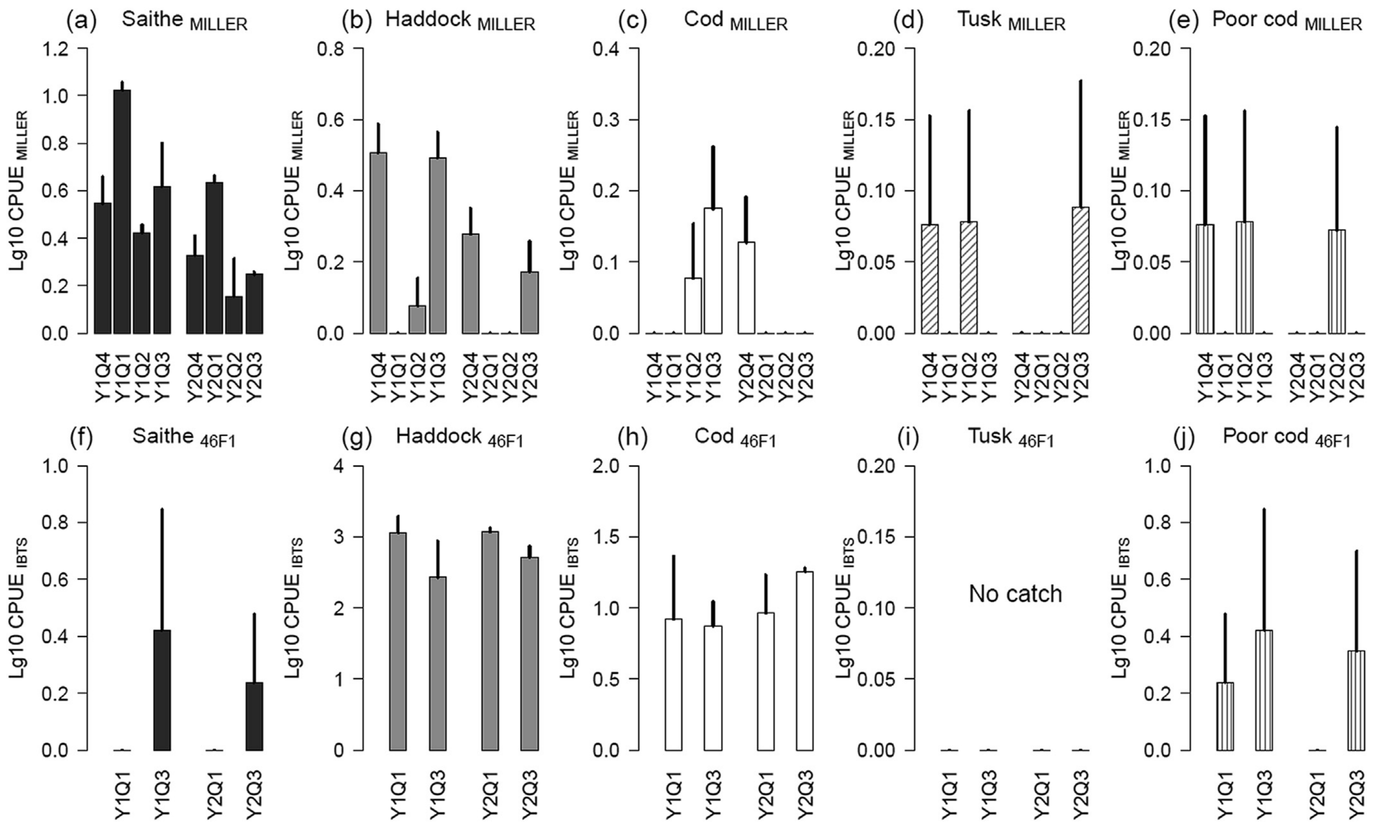

Fig. 8. Temporal changes in the log10-transformed CPUE (+S.E.) of the major fish species observed at the Miller platform (a = Saithe; b = Haddock; c = Cod; d = Tusk; e = Poor cod) with comparative trawl survey data taken from the IBTS at 46F1 (f = Saithe; g = Haddock; h = Cod; i = Tusk; j = Poor cod). (Fish species symbols and seasonal codes as in Fig. 4).

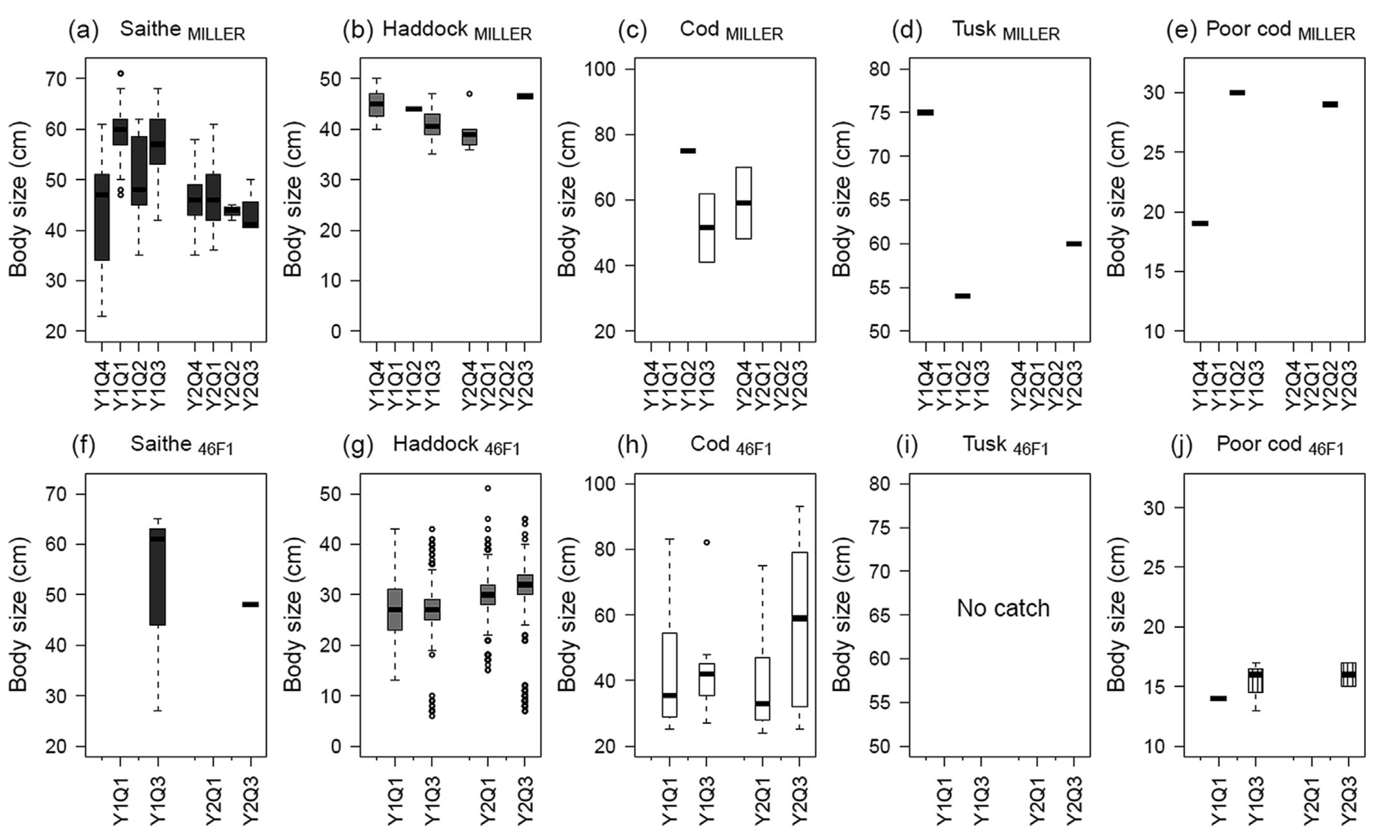

Fig. 9. Temporal changes in body size distributions of the major fish species observed at the Miller platform (a = Saithe; b = Haddock; c = Cod; d = Tusk; e = Poor cod) with comparative trawl survey data taken from the IBTS at 46F1 (f = Saithe; g = Haddock; h = Cod; i = Tusk; j = Poor cod). (Fish species symbols and seasonal codes as in Fig. 4).

Table 4
Results of 2-way ANOVA, testing effect of year and season on log10-transformed $CPUE_{MILLER}$ for saithe and haddock caught at the Miller platform. Statistically significant differences for all possible combinations of year/season pairs were derived from the post hoc Tukey's test (Symbols and codes as in Table 3).

Species	Factor	df	MS	*F*	p	Tukey HSD
Saithe	Year	1	0.576	19.0	<0.001***	Y1 > Y2***
	Season	3	0.324	10.7	<0.001***	Q4 < Q1**, Q2 < Q1***, Q3 < Q1***
	Year × Season	3	0.010	0.3	0.801 (n.s.)	
	Within samples	16	0.030			
Haddock	Year	1	0.228	12.7	<0.01**	Y1 > Y2**
	Season	1	0.011	0.6	0.459 (n.s.)	
	Year × Season	1	0.006	0.4	0.567 (n.s.)	
	Within samples	8	0.018			

Table 5
Results of 2-way ANOVA, testing effect of year and season on body size data (total length: cm) for saithe and haddock caught at the Miller platform. Statistically significant differences for all possible combinations of year/season pairs were derived from the post hoc Tukey's test (Symbols and codes as in Table 3).

Species	Factor	df	MS	*F*	p	Tukey HSD
Saithe	Year	1	1566	26.1	<0.001***	Y1 > Y2***
	Season	3	716	11.9	<0.001***	Q4 < Q1***, Q3 > Q4**, Q2 < Q1*
	Year × Season	3	256.9	4.3	0.007**	
	Within samples	90	60.0			
Haddock	Year	1	11.5	0.9	0.357 (n.s.)	
	Season	1	13.7	1.1	0.315 (n.s.)	
	Year × Season	1	125.8	9.7	0.005**	
	Within samples	22	13.0			

represent part of a number of interconnected subpopulations over wider space and time. Furthermore, saithe showed significant differences in their body size distributions between seasons as well as years, suggesting that there was a series of turnover of individuals in the utilisation of the platform by different age groups across seasons and years and their residence time and movement could therefore be regulated at seasonal and/or inter-annual scales. However, movement of fish individuals in association with offshore platforms can be complex and variable over different temporal scales. Using acoustic tagging system, Jørgensen et al. (2002) examined the residence time and movement of cod at an offshore platform in the North Sea, and found that around 50% of the tagged individuals remained in the direct vicinity throughout the 3-month period, while some individuals were registered at the neighbouring platform and approximately 14% of individuals were still detected at the study site 12-month later. Other acoustic and fishing studies conducted around North Sea platforms have found evidence of diel and seasonal changes in the abundance in fish assemblages around the structures (Løkkeborg et al., 2002; Soldal et al., 2002).

The majority of fish species observed at oil platforms do not appear to remain in these habitats for their entire life history, and they are more likely to undertake migration between habitats at varying temporal scales. At the Miller platform, the abundances of saithe and haddock were significantly higher in the first year where the water temperatures were significantly colder. The spatial and temporal dynamics of the water temperature are influenced by the vertical mixing and the horizontal thermal stratification processes, which could also affect the spatio-temporal dynamics of the North Sea ecosystem through modifying the availability of light and limiting nutrients for the surface primary productivity (Nielsen and St. Mary, 2001). Changes in water temperatures have therefore been shown to affect the distributional responses of many marine fish species in the North Sea (Daan et al., 1995; Attrill and Power, 2002; Perry et al., 2005; Dulvy et al., 2008). This suggests that fish individuals residing within a seemingly discrete habitat (e.g. oil platform, open seafloor) consist of only a subset of individuals from a larger population distributed across a wider expanse of space and time (Schroeder and Love, 2004) whose overall movements could be regulated by large scale environmental processes such as changes in the oceanographic conditions and the water temperatures. As has been demonstrated in the other parts of the world, it seems clear that different fish species have different utilisation patterns of an offshore platform which may also be influenced by physical factors such as temporal variation in temperature and oceanographic conditions as well as biological factors such as prey availability, species-specific sedentary/migratory behaviour and life cycle stages of individuals (e.g. Bohnsack and Sutherland, 1985; Stanley and Wilson, 1997; Schroeder and Love, 2004; Love et al., 2005, 2006; Page et al., 2007). To understand the true role of offshore platforms in the ecology of fish populations, it is vital to identify the biological mechanism behind such temporal movement patterns in association with large scale environmental drivers.

5. Conclusions

Increasing number of existing offshore platforms are approaching the end of their commercial lives and, to date, 7% of existing North Sea installations have already been decommissioned (Royal Academy of Engineering, 2013). Given the number of offshore platforms currently installed in the North Sea as well as the strong and consistent association between fish and these installations as demonstrated in this study, there is a need to identify relative roles of these artificial habitats in, for example, providing feeding and/or spawning grounds for mature/larger adults (Friedlander et al., 2014) or nursery grounds for juveniles (Love and York, 2005; Love et al., 2006), since the reproductive ability and early life history events of fish stocks are the crucial mechanisms for shaping long-term variations in recruitment and hence in the subsequent fish stock dynamics (Haddon, 2011). There are increasing concerns over the state of fish stocks (Cook et al., 1997; Myers and Worm, 2003; Pikitch et al., 2004), and the management of marine resources ultimately requires knowledge in the dynamic behaviour of spatially distributed marine populations and their life-cycle-related movements across heterogeneous habitats upon which overall fish stock dynamics is to be dependent (Gillanders et al., 2003; Kritzer and Sale, 2004; Botsford et al., 2009).

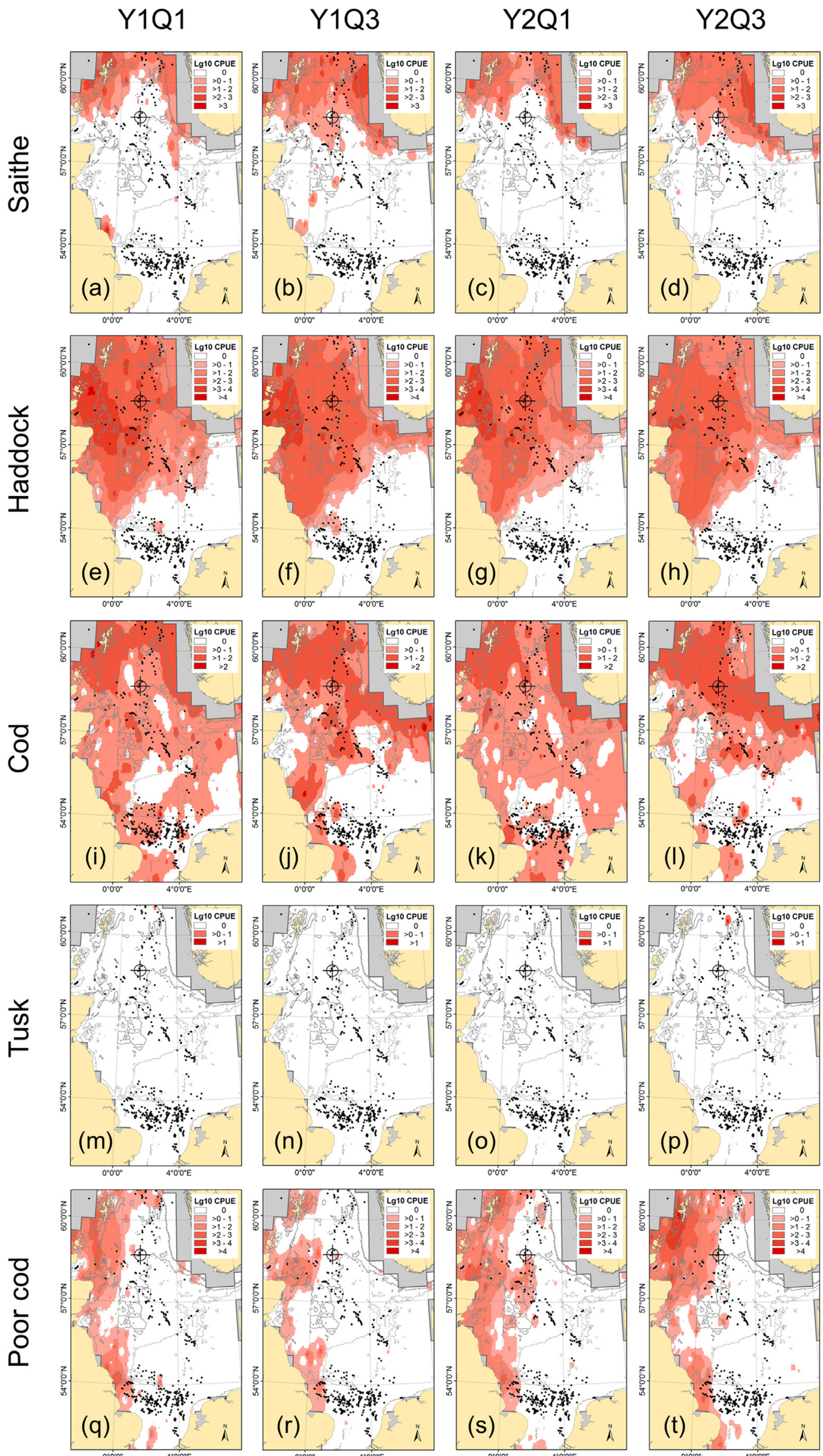

Fig. 10. Spatio-temporal changes in the log10-transformed $CPUE_{IBTS}$ of the major fish species observed at the Miller platform based on the IBTS database in the North Sea (a-d = Saithe; e-h = Haddock; i-l = Cod; m-p = Tusk; q-t = Poor cod). The grey shaded area indicates outside of the North Sea IBTS survey area. (Platform locations as in Fig. 1a and seasonal codes as in Fig. 4).

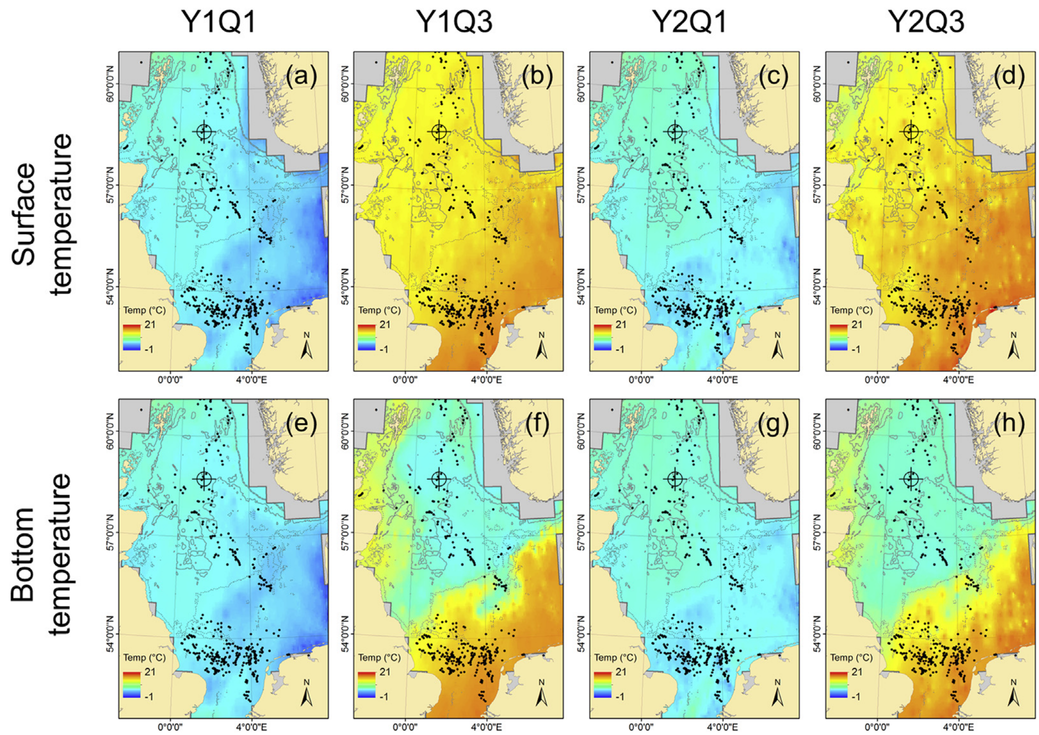

Fig. 11. Spatio-temporal changes in temperature distribution in surface waters (a–d) and bottom waters (e–h) in the North Sea. The grey shaded area indicates outside of the North Sea IBTS survey area. (Platform locations as in Fig. 1a and seasonal codes as in Fig. 4).

Further study is needed to better understand the influence of the physical presence of the offshore platforms on the life cycle, temporal movements and connectivity of fish populations as well as possible links between large scale ecological/environmental processes and distributional dynamics of fish populations. The results clearly indicate complex relationships between fish movements and the offshore platforms requiring long-term monitoring conducted at multiple locations over wider spatial coverage. Accumulation of knowledge on fish movement patterns and habitat connectivity over long time period will increase our ability to identify the true ecological consequences of different decommissioning alternatives as well as to facilitate effective spatial management of marine ecosystems in the North Sea.

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References

Aabel, J.P., Cripps, S.J., Jensen, A.C., Picken, G., 1997. Creating Artificial Reefs from Decommissioned Platforms in the North Sea: a Review of Knowledge and Proposed Programme of Research. Offshore Decommissioning Communications Project (London).
Attrill, M.J., Power, A.J., 2002. Climatic influence on a marine fish assemblage. Nature 417, 275–278.
Baine, M., 2001. Artificial reefs: a review of their design, application, management and performance. Ocean. Coast. Manag. 44, 241–259.
Boehlert, G.W., Gill, A.G., 2010. Environmental and ecological effects of ocean renewable energy development: a current synthesis. Oceanography 23, 68–81.
Bohnsack, J.A., Sutherland, D.L., 1985. Artificial reef research: a review with recommendations for future priorities. Bull. Mar. Sci. 37, 11–39.
Botsford, L.W., Brumbaugh, D.R., Grimes, C., Kellner, J.B., Largier, J., O'Farrell, M.R., Ralston, S., Soulanille, E., Wespestad, V., 2009. Connectivity, sustainability, and yield: bridging the gap between conventional fisheries management and marine protected areas. Rev. Fish. Biol. Fish. 19, 69–95.
Cook, R.M., Sinclair, A., Stefansson, G., 1997. Potential collapse of North sea cod stocks. Nature 385, 521–522.
Costello, M.J., McCrea, M., Freiwald, A., Lundälv, T., Jonsson, L., Bett, B.J., van Weering, T.C.E., de Haas, H., Roberts, J.M., Allen, D., 2005. Role of cold-water Lophelia pertusa coral reefs as fish habitat in the NE Atlantic. In: Freiwald, A., Roberts, J.M. (Eds.), Cold-water Corals and Ecosystems. Springer-Verlag, Berlin, Heidelberg, pp. 771–805.
Daan, N., Bromley, P.J., Hislop, J.R.G., Nielsen, N.A., 1990. Ecology of North sea fish. Neth. J. Sea Res. 26, 343–386.
de Groot, S.J., 1982. The impact of laying and maintenance of offshore pipelines on the marine environment and the North sea fisheries. Ocean. Manag. 8, 1–27.
R Development Core Team, 2013. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
Dulvy, N.K., Rogers, S.I., Jennings, S., Stelzenmüller, V., Dye, S.R., Sjkoldal, H.R., 2008. Climate change and deepening of the North sea fish assemblage: a biotic indicator of warming seas. J. Appl. Ecol. 45, 1029–1039.
Fabi, G., Grati, F., Puletti, M., Scarcella, G., 2004. Effects on fish community induced by installation of two gas platforms in the Adriatic Sea. Mar. Ecol. Prog. Ser. 273, 187–197.
Friedlander, A.M., Ballesteros, E., Fay, M., Sala, E., 2014. Marine communities on oil platforms in Gabon, West Africa: high biodiversity oases in a low biodiversity environment. PLoS One 9 (8), e103709.
Gillanders, B.M., Able, K.W., Brown, J.A., Eggleston, D.B., Sheridan, P.F., 2003. Evidence of connectivity between juvenile and adult habitats for mobile marine fauna: an important component of nurseries. Mar. Ecol. Prog. Ser. 247, 281–295.
Guerin, A.J., 2009. Marine Communities of North Sea Offshore Platforms, and the Use of Stable Isotopes to Explore Artificial Reef Food Webs (PhD thesis). University of Southampton.
Haddon, M., 2011. Modelling and Quantitative Methods in Fisheries, Second ed. Chapman & Hall/CRC, Boca Raton, Florida.
ICES, 2010. Addendum 1: IBTS Manual - Revision VIII. Manual for the International Bottom Trawl Surveys. The International Bottom Trawl Survey Working Group.
Inger, R., Attrill, M.J., Bearhop, S., Broderick, A.C., Grecian, W.J., Hodgson, D.J., Mills, C., Sheehan, E., Votier, S.C., Witt, M.J., Godley, B.J., 2009. Marine renewable energy: potential benefits to biodiversity? An urgent call for research. J. Appl. Ecol. 46, 1145–1153.
Jablonski, S., 2008. The interaction of the oil and gas offshore industry with fisheries in Brazil: the “Stena Tay” experience. Braz. J. Oceanogr. 56, 289–296.
Jørgensen, T., Løkkeberg, S., Soldal, A.V., 2002. Residence of fish in the vicinity of a

decommissioned oil platform in the North Sea. ICES J. Mar. Sci. 59, 288–293.
Kaiser, M.J., Collie, J.S., Hall, S.J., Jennings, S., Poiner, I.R., 2002. Modification of marine habitats by trawling activities: prognosis and solutions. Fish. Fish. 3, 114–136.
Kritzer, J.P., Sale, P.F., 2004. Metapopulation ecology in the sea: from Levins' model to marine ecology and fisheries science. Fish. Fish. 5, 131–140.
Leewis, R., van Moorsel, G., Waardenburg, H., 2000. Shipwrecks on the Dutch continental shelf as artificial reefs. In: Jensen, A., Collins, K., Lockwood, A. (Eds.), Artificial Reefs in European Seas. Kluwer Academic, Amsterdam, Netherlands, pp. 419–434.
Løkkeborg, S., Humborstad, O., Jørgensen, T., Soldal, A.V., 2002. Spatio-temporal variations in gillnet catch rates in the vicinity of North sea oil platforms. ICES J. Mar. Sci. 59, 294–299.
Love, M.S., Westphal, W., 1990. Comparison of fishes taken by a sportfishing party vessel around oil platforms and adjacent natural reefs near Santa Barbara, California. Fish. Bull. 88, 599–605.
Love, M.S., York, A., 2005. A comparison of the fish assemblages associated with an oil/gas pipeline and adjacent seafloor in the Santa Barbara Channel, southern California Bight. Bull. Mar. Sci. 77, 101–117.
Love, M.S., Schroeder, D.M., Lenarz, W.H., 2005. Distribution of bocaccio (Sebastes paucispinis) and cowcod (Sebastes levis) around oil platforms and natural outcrops off California with implications for larval production. Bull. Mar. Sci. 77, 397–408.
Love, M.S., Schroeder, D.M., Lenarz, W., MacCall, A., Bull, A.S., Thorsteinson, L., 2006. Potential use of offshore marine structures in rebuilding an overfished rockfish species, bocaccio (*Sebastes paucispinis*). Fish. Bull. 104, 383–390.
Martínez, I., 2012. Demersal Fish Assemblages around Sea Bed Features: Buzzard Oil & Gas Field Platform in the North Sea and Jones Bank, Celtic Sea (PhD thesis). University of Aberdeen.
Myers, R.A., Worm, B., 2003. Rapid worldwide depletion of predatory fish communities. Nature 423, 280–283.
Nielsen, M.H., St John, M., 2001. Modelling Thermal stratification in the North sea: application of a 2-D potential energy model. Estuar. Coast. Shelf Sci. 53, 607–617.
Osmundsen, P., Tveterås, R., 2003. Decommissioning of petroleum installations—major policy issues. Energy Policy 31, 1579–1588.
OSPAR, 2012. Update of the Inventory of Oil and Gas Offshore Installations in the OSPAR Maritime Area. OSPAR Commission, London (ISBN 978-1-909159-21-1).
Page, H.M., Dugan, J.E., Schroeder, D.M., Nishimoto, M.M., Love, M.S., Hoesterey, J.C., 2007. Trophic links and condition of a temperate reef fish: comparisons among offshore oil platform and natural reef habitats. Mar. Ecol. Prog. Ser. 344, 245–256.
Parente, V., Ferreira, D., dos Santos, E.M., Luczynskic, E., 2006. Offshore decommissioning issues: deductibility and transferability. Energ. Policy 34, 1992–2001.
Perry, A.L., Low, P.J., Ellis, J.R., Reynolds, J.D., 2005. Climate change and distribution shifts in marine fishes. Science 308, 1912–1915.
Picken, G.B., McIntyre, A.D., 1989. Rigs to reefs in the North Sea. Bull. Mar. Sci. 44, 782–788.
Pikitch, E.K., Santora, E.A., Babcock, A., Bakun, A., Bonfil, R., Conover, D.O., Dayton, P., Doukakis, P., Fluharty, D., Heheman, B., Houde, E.D., Link, J., Livingston, P.A., Mangel, M., McAllister, M.K., Pope, J., Sainsbury, K., 2004. Ecosystem-based fishery management. Science 305, 346–347.
Reubens, J.T., Braeckman, U., Vanaverbeke, J., Van Colen, C., Degraer, S., Vincx, M., 2013. Aggregation at windmill artificial reefs: CPUE of Atlantic cod (*Gadus morhua*) and pouting (*Trisopterus luscus*) at different habitats in the Belgian part of the North Sea. Fish. Res. 139, 28–34.
Roberts, S., Hirshfield, M., 2004. Deep-sea corals: out of sight, but no longer out of mind. Front. Ecol. Environ. 2, 123–130.
Royal Academy of Engineering, 2013. Decommissioning in the North Sea. Royal Academy of Engineering (London).
Schroeder, D.M., Love, M.S., 2004. Ecological and political issues surrounding decommissioning of offshore oil facilities in the southern California Bight. Ocean. Coast. Manag. 47, 21–48.
Soldal, A.V., Svellingen, I., Jørgensen, T., Løkkeborg, S., 2002. Rigs-to-reefs in the North Sea: hydroacoustic quantification of fish in the vicinity of a "semi-cold" platform. ICES J. Mar. Sci. 59, 281–287.
Stachowitsch, M., Kikinger, R., Herler, J., Zolda, P., Geutebrück, E., 2002. Offshore oil platforms and fouling communities in the southern Arabian Gulf (Abu Dhabi). Mar. Pollut. Bull. 44, 853–860.
Stanley, D.R., Wilson, C.A., 1991. Factors affecting the abundance of selected fishes near oil and gas platforms in the northern Gulf of Mexico. Fish. Bull. 89, 149–159.
Stanley, D.R., Wilson, C.A., 1997. Seasonal and spatial variation in the abundance and size distribution of fishes associated with a petroleum platform in the northern Gulf of Mexico. Can. J. Fish. Aquat. Sci. 54, 1166–1176.
Turner, S.J., Thrush, S.F., Hewitt, J.E., Cummings, V.J., Funnell, G., 1999. Fishing impacts and the degradation or loss of habitat structure. Fish. Manag. Ecol. 6, 401–420.
Umgiesser, G., Luyten, P.J., Carniel, S., 2002. Exploring the thermal cycle of the Northern North sea area using a 3-D circulation model: the example of PROVESS NNS station. J. Sea Res. 48, 271–286.
Valdemarsen, J.W., 1979. Behavioural Aspects of Fish in Relation to Oil Platforms in the North Sea. ICES CM, 1979/B: 27.
Whomersley, P., Picken, G.B., 2003. Long-term dynamics of fouling communities found on offshore installations in the North Sea. J. Mar. Biol. Assoc. U. K. 83, 897–901.
Wieland, K., Pedersen, E.M.F., Olesen, H.J., Beyer, J.E., 2009. Effect of bottom type on catch rates of North sea cod (*Gadus morhua*) in surveys with commercial fishing vessels. Fish. Res. 96, 244–251.
Wilhelmsson, D., Malm, T., Öhman, M.C., 2006. The influence of offshore windpower on demersal fish. ICES J. Mar. Sci. 63, 775–784.