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Original Article

Residency and habitat use of European lobster (*Homarus gammarus*) within an offshore wind farm

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As offshore wind energy developments increase globally in response to climate change, it is important to gain an understanding of the effects they are having on the marine environment. Whilst there is growing information on the types of organisms present within these sites, our knowledge of how species interact with these sites is limited. For the first time we examined the movements and habitat utilization of a temperate decapod, the European Lobster *Homarus gammarus*, using acoustic telemetry within an offshore wind farm (OWF). Innovasea V9 acoustic transmitters were externally attached to 33 individuals (carapace length = 87–113 mm) at three turbine locations within an offshore wind farm in the Irish Sea. Individuals were found to exhibit high residency to the tagging sites, with over half of tagged lobsters present at the tagging sites for 70% of the study period. Individual home ranges and core territories were calculated using 95% and 50% kernel density, respectively. Home ranges ranged from 9313.76 to 23 156.48m^2 while core territories ranged from 1084.05 to 6037.38m^2. Over 50% of all detections were recorded within 35 m of the scour protection. These results suggest that particular areas of habitat within fixed-turbine OWFs provide a suitable habitat for lobsters. We postulate that this is likely the result of artificial reef effects arising from the addition of artificial hard substate into previously soft sediment dominated habitats. Therefore, future fixed-turbine OWF developments across Europe may provide potential fishery opportunities as a result of artificial reef effects.

Keywords: acoustic telemetry, homarus gammarus, offshore wind energy, residency, tracking.

Introduction

The expansion of offshore wind energy developments is a key mitigating measure in response to climate change and increasing energy demands. Commitments to move away from fossil fuels will see proposed developments across Europe, the United States, and East Asia, increasing global capacity from 48GW to over 300GW by 2030 (Lee & Zhao, 2021)). In the United Kingdom, there are currently over 3 000 offshore wind turbines in operation or under construction [75% and 24%, respectively (The Crown Estate, 2021)]. In an effort to achieve Net-Zero targets the UK Government and devolved administrations have set ambitious goals of increasing total installed capacity of offshore wind from 13.6 to 50 GW within the next decade (British Energy Security Strategy, 2022).

The continued expansion of offshore wind farms (OWFs) is expected to have significant direct and indirect impacts on the marine environment. Artificial noise, changes in sediment characteristics, electromagnetic fields, coastal darkening, and habitat alteration are some of the factors associated with OWF construction and operation (Nedwell *et al*., 2003; Öhman *et al*., 2007; Van Deurs *et al*., 2012; Degraer *et al*., 2020; Herbet-Read *et al*., 2022). Other users of the marine environment are also expected to be affected. OWF construction can reduce access to traditional fishing grounds forcing a displacement of fishing activities (Stelzenmüller *et al*., 2022). If fishing industries cannot adapt to this displacement, it has the potential to cause economic loss and impacts on coastal communities. (Stelzenmüller *et al*., 2021).

Across the UK and Europe, fixed-turbine OWF development often takes place in shallow (<30 m) sand-dominated habitats (Roach *et al*., 2018). During construction hard substrates are introduced into these areas in the form of monopiles and scour protection (Wilson and Elliot, 2009). These hard substrates can form de facto artificial reefs that become colonized by species usually found in association with areas of natural reef (Degraer *et al*., 2020). For example, monopiles and scour protection become dominated by fouling organisms such as mussels and barnacles, while commercially important species of fish and crustaceans occupy areas in and around these structures (Reubens *et al*., 2013; De Mesel *et al*., 2015; Krone *et al*., 2013). The introduction of these hard substrates and subsequent colonization has been found to induce changes in the marine environment, which may have positive and negative effects on local ecosystem functioning and is considered one of the most important effects on the marine environment generated by the construction of OWFs (Langhamer & Wilhelmsson, 2009; Andersson *et al*., 2010; Vaissière *et al*., 2014; Dannheim *et al*., 2020). While there is growing evidence on the abundance and diversity of crustaceans occupying artificial reefs created by OWFs, their behaviour and interactions in association with areas of scour protection within these sites have received scant attention.

The European lobster (*Homarus gammarus* (L.), hereafter referred to as lobster) is frequently reported within OWF sites (De Mesel *et al*., 2013; Roach *et al*., 2022). This commercially important species supports an industry valued at ∼£51 million in the UK and offers one of the highest average prices

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(£16/kg) of all species landed in the UK (Uberoi *et al.*, 2021). Clawed lobsters (*H. gammarus and Homarus americanus*) require shelter throughout their benthic life stages (Jensen *et al.*, 2000), and are often found in association with areas of hard substrate (Wiig *et al.*, 2013). As a result of these shelter requirements, *H. gammarus* have been found associated with artificial reef structures, where they display high site fidelity (Smith *et al.*, 1998). Lobsters have been observed to quickly colonize newly made artificial reefs where they remain resident for extended periods of time and have been observed to successfully spawn and molt (Collins *et al.*, 1994). These observations have led researchers to suggest artificial reefs provide sufficient resources for lobster survival, and providing construction takes place at an appropriate scale, present a potential stock enhancement technique (Bennet et al., 1980). To determine whether artificial reefs generated by the addition of scour protection within OWFs offer a similar suitable habitat for lobsters, a greater understanding of their interactions with these features is required.

Species movement characteristics are universally important to their ecology and play a major role in determining the structure and dynamics at population, community, and ecosystem levels (Nathan *et al.*, 2008). For example, movement is key in determining patterns of species distribution, patterns of change in genetic diversity, and influencing resource levels (Jeltsch *et al.*, 2013). The most common forms of movement include foraging, dispersal, and migration (Colbert *et al.*, 2012). Lobsters are known to forage over limited spatial scales, these movements are influenced by shelter requirements and thus limited to areas within relatively close proximity to shelter providing habitat (Karnofsky, 1989, Watson *et al.*, 1999). Therefore, lobsters will commonly select shelter within habitat where food is available locally (Jensen *et al.*, 2000). Dispersal involves the movement of individuals or multiple individuals away from one area to another, and is often influenced by population size, resource availability, and habitat quality (Croteau, 2010). *Homarus americanus* has been shown to exhibit a form of dispersal known as "demographic diffusion" where larger individuals avoid or leave areas of high population densities for areas of lower population density. Demographic diffusion is thought to be in response to competition for shelter (Steneck, 2006). Migration movements generally take place on a seasonal basis and occur over the largest spatial scale of the three main movement forms. While populations of *H. americanus* are capable of large (>80 km) offshore seasonal migrations, thought to be influenced by water temperatures, *H. gammarus* has been found to carry out relatively short migrations (0–45 km) (Cooper & Uzmann 1971, Haakonsen *et al.*, 1994, Smith *et al.*, 2001). The occurrence and scales at which these forms of movement take place are influenced by a combination of biotic (e.g. body size, generally larger individuals have greater physical advantages allowing them to travel greater distances (Travis *et al.*, 2012) and abiotic (e.g. changes in resource availability influence short to large scale movements across a range of taxa) factors (Murphy & Boone, 2022). An improved understanding of a species movement characteristics, and the factors affecting their movement provides a greater appreciation of how that species interacts with and impacts the surrounding ecosystem.

Advances in underwater tracking technology have provided insight into previously unobserved processes associated with the movement characteristics of a wide range of taxa (Crossin *et al.,* 2017). Remote tracking technologies, such as acoustic telemetry allow for continuous data collection over extended periods of time providing more informed estimates of movement characteristics compared to active tracking or underwater observations (Barrett, 1995). These technologies have been used to provide novel insights into lobster behaviour. With studies suggesting that although lobsters are capable of long-range movements, the majority of individuals are resident to specific areas (Watson *et al.*, 2009, Moland *et al.*, 2011; Skerrit *et al.*, 2015). Lobster movement has been investigated using acoustic telemetry, but the movement characteristics of lobsters in association with artificial structures, including OWFs, has received little attention. Here, we used acoustic telemetry to provide the first evidence for how *H. gammarus* interacts with the scour protection layer and surrounding habitat within an OWF development.

Materials and methods

Study site

The study was conducted at Gwynt y Môr wind farm (Figure 1a), 14 km off the North Wales coastline within Liverpool Bay, UK (53°28′08.3″N 3°35′02.9″W). Gwynt y Môr was constructed between 2011 and 2015 and comprises 160 turbines over an area of 80 km^2. The distance between the turbines is ~720 m. Water depth at the site varies between 16 and 28 m. In total, 45% of turbines are surrounded by a continuous layer of scour protection made up of rocks and boulders extending a maximum of 25 m from the base of the turbine (~1964 m^2). The base of the turbine covers <0.5% of total area at each turbine location. The total surface area of scour protection surrounding turbines is ~14 700 m^2. The habitat surrounding the scour protection is made up of gravel and sand sediment (CMACS, 2005). Gwynt y Môr has never been closed to fishing activities. At the time of the study there was one potting vessel, three sportfishing vessels and two scallop dredgers known to operate at the site on a regular basis (J Andrews 2021, pers. comm).

Data collection

Acoustic telemetry was used to monitor lobster positions from the 26th of June to the 10th of October 2021. The study took place over this period to avoid the scallop dredging season and potentially losing equipment moored to the seafloor. Six Innovasea VR2W receivers (69 kHz) were deployed at each of three turbine locations with each receiver deployed 100 m away from the turbine. The arrangement of receivers at each turbine was restricted by the presence of energy export cables. Consequently, the receivers were not evenly distributed around the turbine location (Figure 1b–d). However, the modified distribution of receivers at each turbine location did not compromise our ability to detect signals across the study sites. Receivers were moored 2 m above the seafloor using a polypropene line and a subsurface buoy. This line was connected to a 100 kg weight to limit receiver movement. A V9 range test/reference tag was directly attached to a 100 kg weight and moored 50 m away from the central turbine location at each site. For the first 7 days of the study this transmitter emitted signals every 7 seconds in order to determine the distance at which receivers could accurately detect

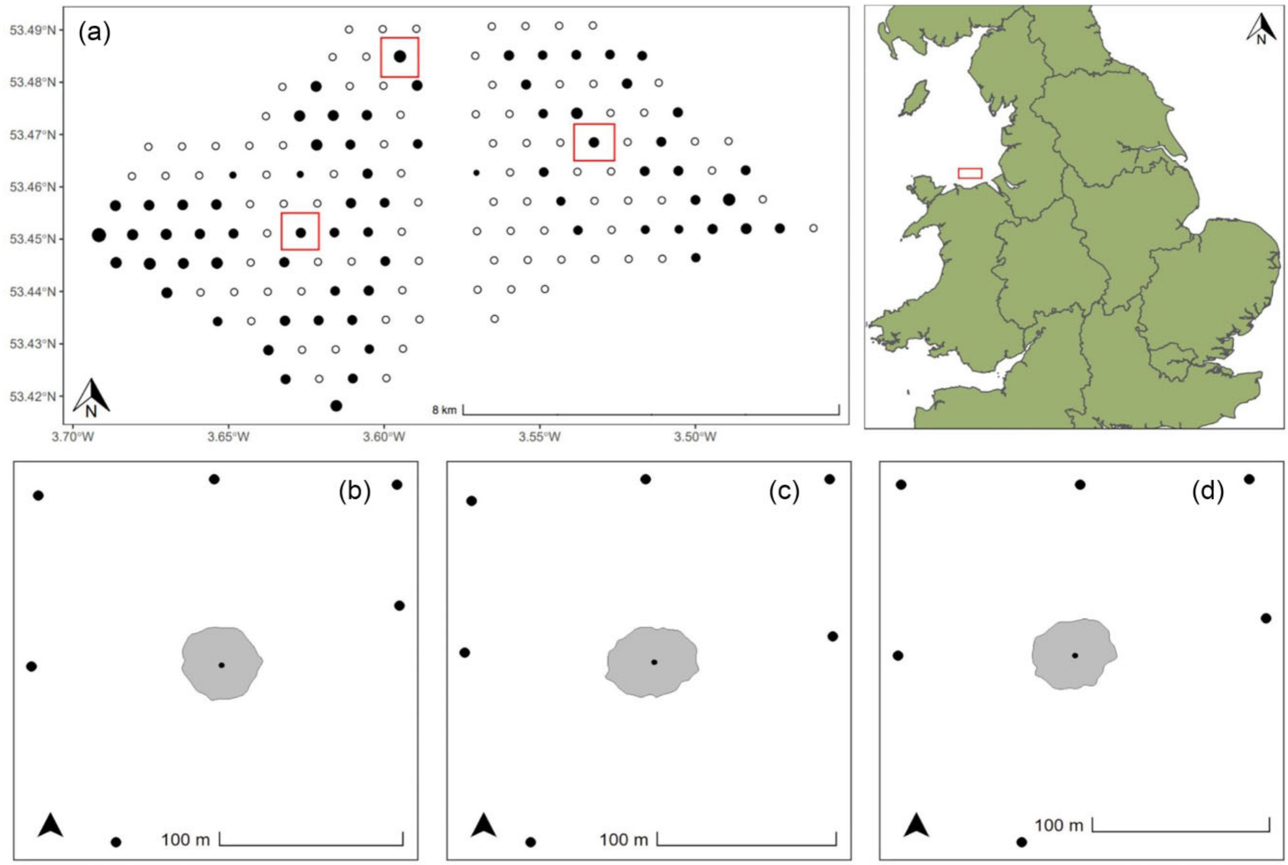

Figure 1. (a) Turbine layout at Gwynt y Môr wind farm including three study locations. Turbines with scour protection are represented by •, those without are the size of this represents the amount of scour at each turbine location. (b), (c), and (d) depict positions of acoustic receiver (•) and area of hard substrate (grey) at site 1, 2 and 3 respectively.

signals. Thereafter, the reference tag emitted signals randomly between 500 and 700 seconds to provide detections that allowed the movement of any receivers to be accounted for (control transmitter).

To avoid the local peak period of ecdysis, lobsters used in the study were caught and released in two phases. Two parlour pots baited with salted ballan wrasse (*Labrus bergylta*) were deployed at site 1, 2, and 3 over two weeks and checked every three days. Captured lobsters over minimum landing size [90 mm carapace length (CL)] were stored on land within commercial holding tanks under ambient conditions (Mermaid Seafoods, Llandudno, UK), and any lobsters that displayed signs of nearing ecdysis were removed from the investigation. Prior to release, lobsters were sexed, measured (CL) and assigned a unique identifier code (T1–T33). Single Innovasea acoustic transmitters (Model V9-2 L, length–27.5 mm, weight in water–4.5 g) were attached to the carapace of each individual using cyanoacrylate and epoxy resin (Figure 2). Lobsters were then returned to the same turbine location from which they had been caught. Lobsters at each site were released one after another with a maximum of 10 mins between each release. Each individual was carefully lowered to the surface of the water before release to minimise trauma. In the first phase 24 lobsters were released [site 1 = 9 lobsters, (22/6/21)] [site 2 = 8, site 3 = 7, (23/6/21)]. In the second phase nine lobsters were released (site 1 = 3 lobsters, site 2 = 3, and site 3 = 3) on the 3/9/21. The CL of all tagged lobsters ranged from 86 to 113 mm [mean male CL = 97 mm (n = 22), mean female CL = 92 mm ($n = 11$)]. Signals from the animal transmitters were repeated after a random delay between 120 and 240 seconds. Given reported walking speeds of *H. gammarus* (0.6 m/min) this delay provides high resolution spatial data while limiting the number of signal collisions (O'grady et al., 2001).

Figure 2. Innovasea V9 acoustic transmitter attached to carapace of European lobster (*H. gammarus*) using cyanoacrylate glue and epoxy resin.

The probability of successful transmissions from animal transmitters to each receiver is influenced by objects obstructing the line of sight between transmitters and receivers. Therefore, in the present study we assumed a reduced number of detections if lobsters took shelter within crevices of the scour protection and line of sight to all receivers was be obstructed. To ensure normal activity had resumed after capture only positions collected 48 h after release were included in the analysis (Skerritt *et al.*, 2015).

Data analysis

All data manipulation and statistical analyses were conducted using R version 4.1.0 (R Core Team, 2021). Prior to analysis any false detections caused by transmitter signal collisions were removed (spurious detections). In addition, detections from animal transmitters were compared to that of sync transmitters to avoid using data from transmitters that may have become dislodged from lobsters (Skerrit *et al.*, 2015).

Residency

In order to quantify the presence of the lobsters at each site over time residency scores were calculated for each tagged lobster. The residency score is expressed as the proportion of days each tagged lobster was detected at tagging sites during the entire study period. The score (R) was calculated by dividing the number of days a lobster was detected (LD) by the number of days for the total study period (TD):

$$R = \mathrm{LD}/\mathrm{TD}.$$

Home-range

The Vtrack package (Campbell *et al.*, 2012) was used to estimate centers of activity (CoA) for each lobster (Simplfendorfer *et al.*, 2002). CoA provide geographic positions for each individual based on weighted means of the number of signal receptions at each receiver location during a specified time bin. The optimal time bin was calculated as 60 min following Villegas-Rios *et al.* (2013). Robust position estimates are calculated when lobsters are detected by multiple receivers, therefore any detections that were received by less than three receivers were removed before calculating CoA. To further ensure that data was representative of lobster's movements, any individual with <100 CoA points was also omitted from further analysis (Ruebens *et al.*,). To investigate the areas used by tagged lobsters during the study a kernel density estimator from the adehabitat*HR* package (Calenge, 2006) was used to calculate the utilization distribution (UD) of each lobster. The UD describes the intensity of area use of an animal's location over time (Worton, 1989). The home range of each tagged lobster was defined as the smallest area containing 95% of the UD (UD_{95}). Home range includes the total area used by each lobster in its normal activities of foraging and mating (Burt, 1943). To investigate the area's most frequently used within each lobster's home range, a core territory was defined as the smallest area containing 50% of the UD (UD_{50}). A total, 50% of the UD represents the area most intensely used within the home range (Moland *et al.*, 2011). Kernel bandwidth [the smoothing parameter ($h0$)] was standardized [we found a common smoothing parameter that produced meaningful plots for all individuals and avoided over-smoothing ($h0 = 10$)] using visual analysis of successive trials (Läuter *et al.*, 1988) to order to carry out unbiased comparison between individuals and sites (Fieberg, 2007; Skerrit *et al.*, 2015).

Habitat use

During the study, tagged lobsters could be either within the scour protection or move outside the detection range of the receiver network, both of which would result in limited animal detections. These "absence periods" were used to further describe the habitat use and movement characteristics of tagged lobsters. A lobster was considered absent if no detections were recorded over a 60-min period. Based on the proximity of the final CoA position prior to an absence period, the lobster was considered as either: (1) within scour protection; (2) outside the receiver network. The average maximum recorded error from the control tags deployed at each site was 21.43 m. If the last CoA position for an animal was <21.43 m from the edge of scour area the absence was considered to be a result of the lobster entering the scour protection and visa versa for CoA positions >21.43 m from the edge of the scour protection. The mean time spent within scour was calculated for each individual and all individuals at each site.

Statistical analysis

To investigate the effect of tagging site, sex of lobster, and lobster CL on residency scores, $\mathrm{UD}_{95}/\mathrm{UD}_{50}$ values and within scour/outside receiver network absence periods the following statistical approaches were applied.

Beta regression

As residency scores are bounded from 0 to 1 and did not meet the normality assumptions of a linear model (K-S test $p < 0.05$) the effect of site, sex, and CL on residency scores was investigated with beta regression using the *betareg* package (Zeileis *et al.*, 2016). The following model structure was used:

$$R = \beta_0 + \beta_1\mathrm{ST} + \beta_2\mathrm{CL} + \beta_3\mathrm{SX},$$

where β_0 is the intercept, ST is a 3-level factor representing site, CL is the slope relating to CL, and SX is a 2-level factor describing sex. Model simplification was carried out systemically until the minimum adequate model was compared to the null model. As only fixed effects were used in each of the model's maximum likelihood tests were used to investigate the significance of predictor variables ($\alpha = 0.05$) (Verbyla, 2019).

Multiple linear regression

Multiple linear regression was used to investigate the effect of site, sex and CL on $\mathrm{UD}_{95}/\mathrm{UD}_{50}$ values and within scour/outside receiver network absences periods. The following general model structure was used:

$$x = \beta_0 + \beta_1\mathrm{ST} + \beta_2\mathrm{CL} + \beta_3\mathrm{SX},$$

Where x represents either UD_{95} value, UD_{50} value, within scour absence period or outside receiver network absence period. β_0 is the intercept, ST is a 3-level factor representing site, CL is the slope relating to CL, and SX is a 2-level factor describing sex. Model assumptions were investigated using visual examination of diagnostic plots. UD_{95} and UD_{50} values were found to be normally distributed. "Within scour" and "outside of array" absences periods were found to be non-normally distributed, therefore, to meet the assumptions of normality and heteroscedasticity a log transformation was applied to this data prior to modelling.

Model simplification was carried out systemically until the minimum adequate model was compared to the null model. As only fixed effects were used in each of the model's maximum likelihood tests were used to investigate the significance of predictor variables ($\alpha = 0.05$) (Verbyla, 2019).

Table 1. Summary of acoustic monitoring data for 31 tagged lobsters (*** indicates data was collected for lobster that was recorded at a site other than release location). CL = carapace length.

Tag ID	Tag number	Sex	CL (mm)	Date released	Number of detections	Days detected	Days at liberty	Residency (%)
Site 1								
T1	63 583	female	100	22/06/2021	64 884	50	61	44
T2	63 584	female	91	22/06/2021	135 096	80	80	72.22
T3	63 585	male	88	22/06/2021	88 412	87	87	78.7
T4	63 586	male	85	22/06/2021	4526	40	92	35.19
T5	63 587	female	92	22/06/2021	123 976	110	110	100
T6	63 588	male	105	22/06/2021	95 756	110	110	100
T7	63 589	male	90	22/06/2021	98 651	110	110	100
T8	63 590	female	86	22/06/2021	107 380	110	110	100
T9	63 591	male	97	22/06/2021	88 421	110	110	100
T25	63 607	male	94	03/09/2021	1715	11	21	25
T26	63 608	female	113	03/09/2021	163	4	4	5.56
T27	63 609	female	94	03/09/2021	7972	5	5	8.33
Site 2								
T16	63 598	male	110	23/06/2021	90	4	27	1.85
T17	63 599	female	87	23/06/2021	153 792	110	110	100
T18	63 600	male	90	23/06/2021	148 549	110	110	100
T19	63 601	male	90	23/06/2021	42 466	38	37	33
T20	63 602	male	94	23/06/2021	33 932	110	110	100
T21	63 603	female	88	23/06/2021	37 768	62	63	55.56
T22	63 604	male	110	23/06/2021	127 416	110	110	100
T24	63 606	male	96	23/06/2021	113 546	110	110	100
T31	63 613	male	93	03/09/2021	3526	5	5	8.33
T23	63 605	female	88	07/07/2021	1112	25	27	37.04
T32	63 614	male	108	03/09/2021	55 204	38	38	100
Site 3								
T10	63 592	female	95	23/06/2021	78 796	50	50	44.44
T11	63 593	male	95	23/06/2021	79 665	82	82	74.07
T12	63 594	male	110	23/06/2021	148 624	107	112	97.22
T13	63 595	male	100	23/06/2021	85 110	104	110	94.44
T14	63 596	male	95	23/06/2021	14 136	23	23	19.44
T15	63 597	male	95	23/06/2021	201 741	122	112	100
T23	63 605	female	88	23/06/2021	9940	15	44	37.04
T30	63 612	male	104	03/09/2021	762	1	1	2.78
T33	63 615	male	100	03/09/2021	884	3	39	2.78
T31	63 613	male	93	21/09/2021	115	4	4	8.33

Results

Detections trends

After filtering for spurious detections, a total of 2 174 155 raw detections were recorded from tagged lobsters. The highest number of detections were recorded at site 1 (816 726) followed by site 2 (716 165) and then site 3 (619 485). The total number of detections recorded for each lobster ranged from 158 to 202 113[(Median (*Mdn)* = 64 884, 95% CL (61 397, 71 438); n = 31] and daily detections for individual lobsters ranged from 1 to 2 559 [*Mean (M)* = 1034.67 ± 14.40 SE; *n* = 31]. Higher numbers of total detections were recorded for lobsters tagged and released in the first phase (*M* = 87 585 ± 10 893 SE; *n* = 24) compared to those tagged and released in the second phase (*M* = 7507 ± 6018 SE; *n* = 9).

Residency

Residency was high for most individuals; 55% of tagged lobsters were detected for ≥70% of the total study period, with 39% of all tagged lobsters detected for 100% of the entire study period (Table 1). The mean number of days all lobsters were detected was 63 ± 7.9 SE. In total, 40% of all tagged individuals were still present at their original tagging sites at the end of the study (Figure 3). Maximum likelihood testing found no significant difference between the beta regression model including all possible interaction terms as predictor values of residency scores and the null model ($X^2 = 0.46$, $p = 0.97$). Indicating site, sex, or (CL) did not have a significant effect on residency scores. Three lobsters were detected moving between tagging sites, T23 was released at site 3 before being detected at site 2 14 days after release, where it remained for 27 days before no further detections were recorded. T29 was released at site 2, and then detected at site 3, 18 days later where it remained for 4 days before not being detected again within the receiver network. Sites 2 and 3 were positioned over 4.5 km away from each other. T26 was caught by a commercial fisherman at a turbine 0.7 km away from its release site (site 1). The average number of tagged lobsters recorded at each site per day ranged from 2 to 10, the average per day throughout the entire study period was 6.10 ± 0.09 SE (Figure 4).

Home-range and habitat use

After filtering CoA points for individuals with ≥100 calculated positions, a total of 25 lobsters were carried forward for further analysis (male = 16 female = 9, CL = 85–110 mm, site 1 = 10, site 2 = 8, site 3 = 7).

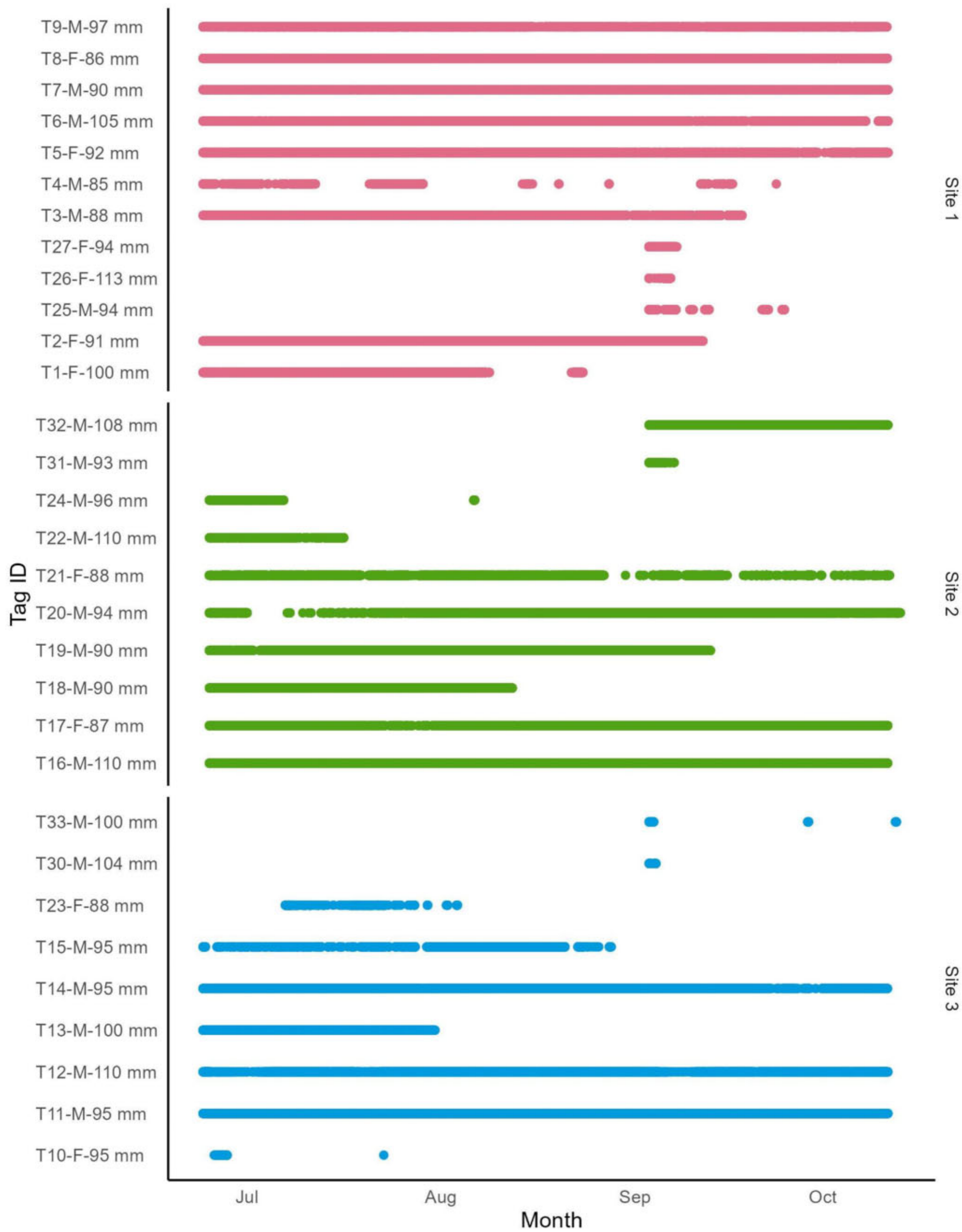

Figure 3. Overview of detections from all tagged lobsters. Each line represents the detections of one individual. Tag labels (y-axis) are in the format "Tag Id-Sex-CL."

Home range and core territory estimates were variable between individuals, UD_{95} for all tagged lobsters ranged from 9313.76 to 23 156.48 m^2 ($M = 15\ 240.41 \pm 979.77$ m^2 SE; $n = 25$), and UD_{50} for all tagged lobsters ranged from 1084.05 to 6037.38m^2 ($M = 2702.31 \pm 227.34$ m^2 SE; $n = 25$) (Supplementary Material, Table 2). Multiple linear regression suggested that while site and CL did not have a significant effect on UD_{95} values, UD_{95} varied significantly between males and females ($F_{1,19} = 4.45$, $R^2 = 0.15$, $p = 0.04$), with males ($M = 16059.66m^2 \pm 875.03$ SE; $n = 16$) having larger UD_{95} values than females ($M = 13783.97m^2 \pm 1161.26$SE; n = 9).

Similarly, multiple linear regression suggested that while site and CL did not have a significant effect on UD_{50} values, UD_{50} varied significantly between males and females ($F_{1,22} = 4.69$, $R^2 = 0.13$, $p = 0.04$), with males ($M = 2943.35 \pm 289.46$ m^2 SE; $n = 16$) having larger UD_{50} values than females ($M = 2273.79 \pm 339.91$ m^2 SE; $n = 9$). However, the low R^2 scores for both the UD_{95} and UD_{50} model suggests factors not included within the analysis may have had greater contributions these differences than the sex of the lobsters.

In total, 92% of the UD_{95} area either partially or fully included scour protection (Figure 5). At site 1 the mean UD_{95} area represented 57.85% of the total receiver array area in which CoA points and (therefore UD_{95}) was derived, at site 2 this was 44.77%, and at site 3 54.36%. UD_{50} areas were often focused around the area of scour protection at each site (Figure 5) with 52% of all lobsters UD_{50} overlapping with scour protection. The mean

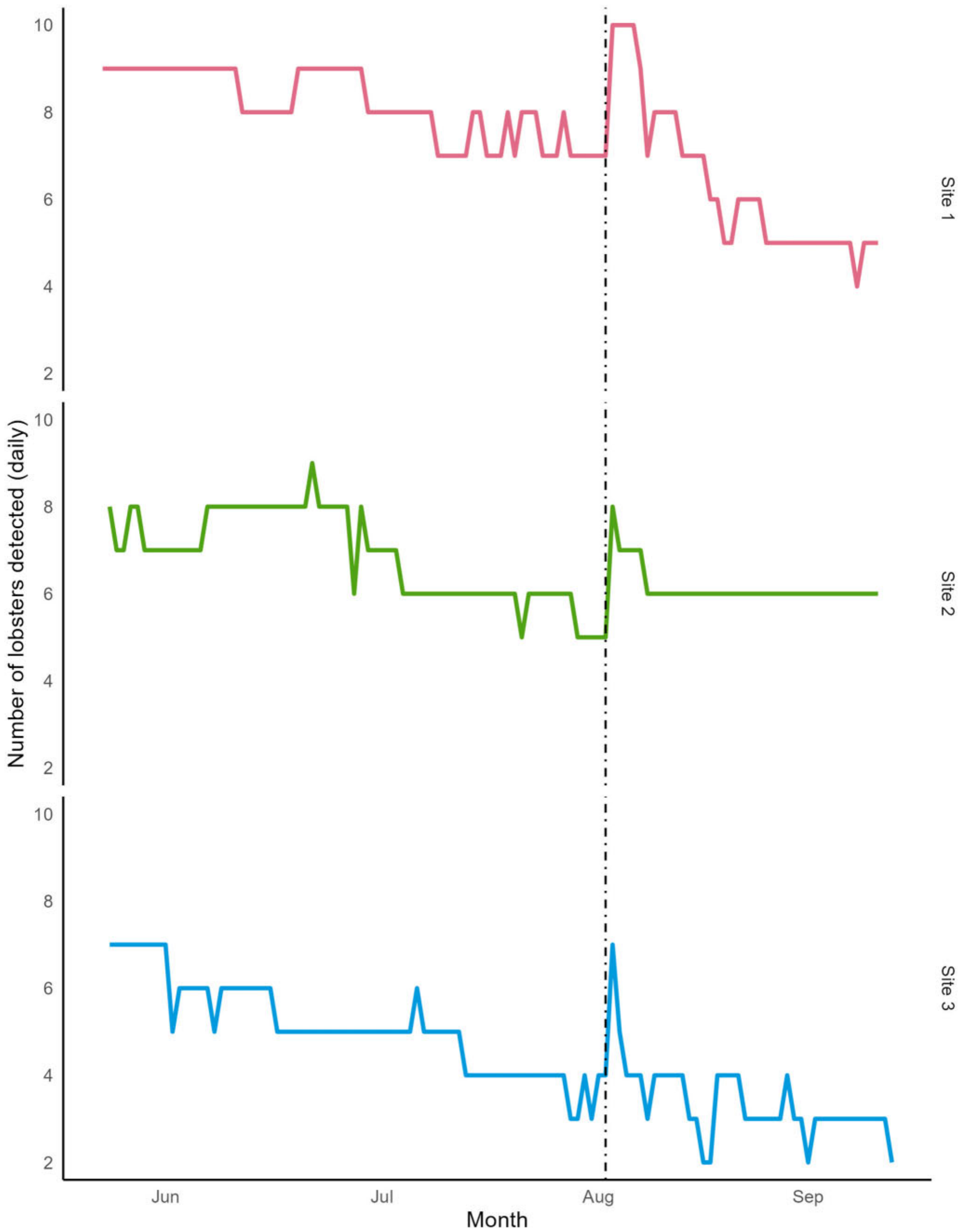

Figure 4. Number of lobster record per day throughout study period. Dashed line indicates 2nd release of tagged lobsters.

distance that lobsters were recorded from the edge of the scour protection was 34.40 ± 0.12 m^2 SE. More than 50% of all CoA positions were within 35 m of the edge of the scour. Very few detections were recorded at distances >90 m away from the edge of the scour (Supplementary Material, Table 3).

Absence periods longer than 1 h were recorded for 25 tagged lobsters (male = 16, female = 9). A total of 499 "within scour" absence periods were estimated across all sites. The duration of these periods ranged from 2 to 187 h, with a mean duration of 6.66 ± 0.53 h SE across all sites. The mean estimated time spent outside the receiver array represents 0.4% of the mean number of hours lobsters were present at the tagging site. At site 1 the mean duration was 5.11 ± 0.36 h SE, whilst at site 2 mean duration was 6.65 ± 1.06 h SE, and at site 3 mean duration was 9.75 ± 1.66 hrs SE. The mean absence duration for males was 7.46 ± 0.53 h SE and, for females the mean absence duration was 4.50 ± 0.44 h SE. The total time lobsters were estimated to spend within the scour throughout the total time each individual was detected ranged from 2–785 hrs (M = 146.18 ± 39.47 hrs SE; n = 24). Maximum likelihood tests found no significant differences between the multiple regression model including all possible interaction terms site and the null model (X^2 = 0.56, p = 0.74). Suggesting neither of these predictor variables had a significant effect on "within scour" time.

Spatial extent of movements

A total of 1829 "outside of array" absence events took place across all sites. The duration of these absence events across all sites ranged from 2 to 720 h (M = 6.27 ± 0.54 SE;

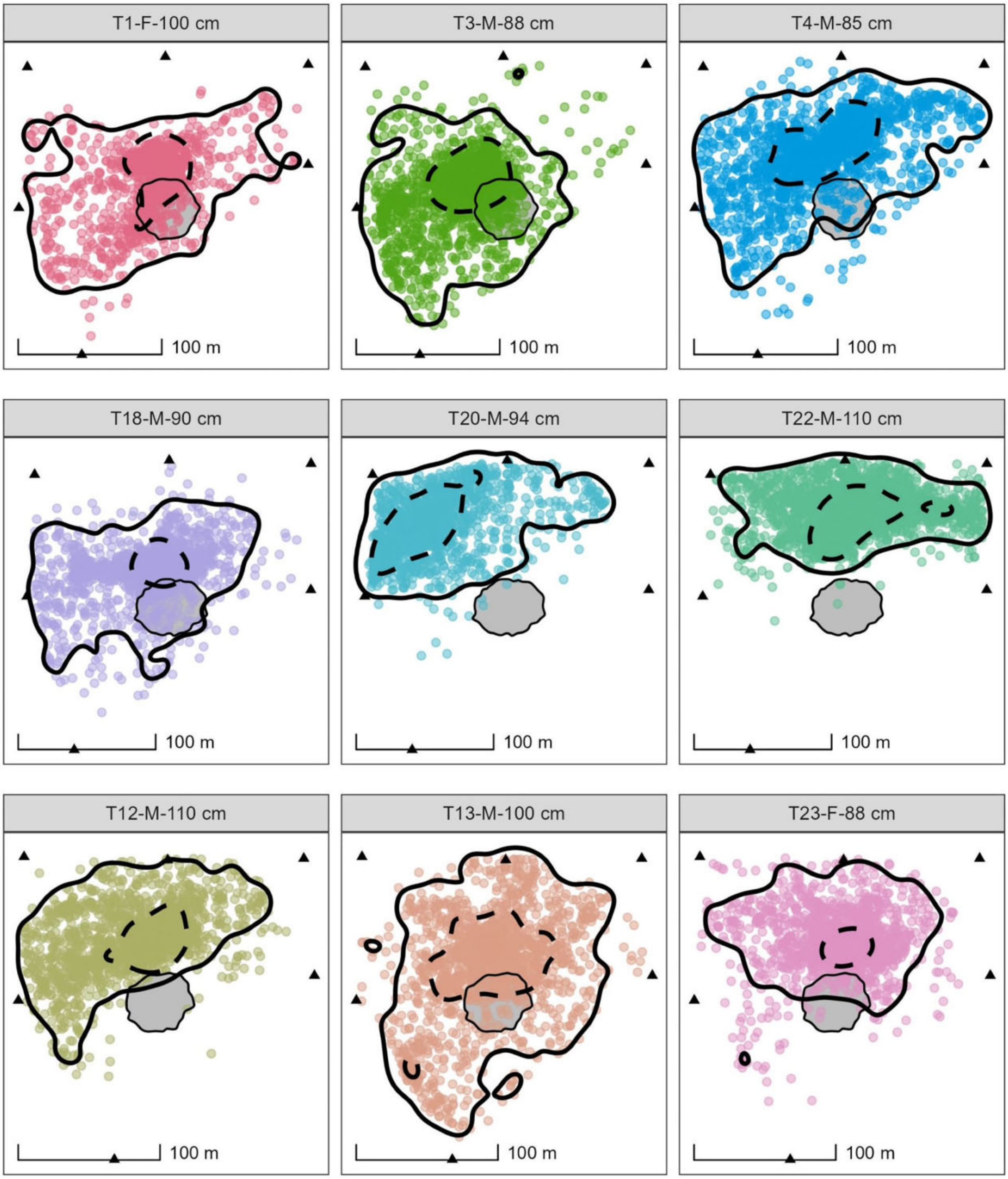

Figure 5. Example COA points (•), UD95 areas (solid line), and UD50 areas (dashed line) in relation to area of scour protection (grey) for nine representative lobsters from each of the three study sites (site 1 = T1, T3, T4; site 2 = T18, T20, T22; and site 3 = T12, T13, T23). Tag labels are in the format "Tag Id-Sex-CL."

$n = 24$). At site 1 the mean duration was 6.10 ± 0.67 h SE, at site 2 the mean duration was 5.67 h ± 0.34 SE, and at site 3 the mean duration was 7.75 ± 2.15 h SE. Maximum likelihood tests found no significant difference between the multiple regression model including all possible interaction terms and the null model ($X^2 = 0.41$, $p = 0.83$). Suggesting neither site, sex, or CL had a significant effect on "outside of array" time. The total time lobsters were estimated to spend outside of the receiver array throughout the entire study ranged from 58 to 1562 h ($M = 481.20 \pm 71.90$ h SE; n = 24).

Discussion

We report the first study of crustacean movements within an OWF in the UK, and the first insight into the movement patterns and habitat use of lobsters within an OWF. Tagged lobsters displayed high residency to tagging sites with UD_{95} and UD_{50} areas often found in association with the habitat surrounding the turbines. Repeated excursions away from and returning to the UD_{95} and UD_{50} areas were recorded, as well as movements between different turbines. Although in some cases lobsters moved away from study sites and were not detected/recaptured at other turbine locations. These results suggest lobsters utilize a range of substate types within OWFs but are likely to be resident to areas where artificial hard substrates are present. However, future work is required to gain a greater understanding of the factors driving this behaviour.

Residency

Despite the relatively small size of our study sites (~$0.03km^2$), 55% of tagged lobsters were present at tagging sites for 70% of the study period, and high numbers of detections were recorded daily. The high residency index (RI) for most tagged lobsters indicates that tagged lobsters occupied a limited area within the tagging sites. Similar levels of residency were reported for *H. gammarus* within the Skagerrak Strait, where 95% of tagged lobsters showed strong site fidelity to a $1km^2$ marine reserve and 50% of lobsters were resident to small marine protected areas ($0.5–1km^2$) after almost a year (Moland *et al.*, 2011; Brockstedt *et al.*, 2013). Lobster movements are influenced by habitat characteristics, with lobsters likely to move more in areas with suboptimal conditions, including a lack of suitable shelter (Watson et al., 1999). Therefore, the high residency levels recorded in this study suggest the habitat within each tagging site presented suitable conditions, including the presence of suitable shelter habitat. As lobsters are known to occupy shelter in a variety of habitats, including crevices in both natural rock and artificial structures it is possible that tagged lobsters with a UD_{50} area closely associated with the scour protection may have been using the scour protection within the study sites for shelter (Jensen *et al.*, 2000).

The average number of lobsters recorded per day at each tagging site suggests the habitat within these sites can support multiple lobsters for periods of time similar to the duration of this study. There were, however, fluctuations in the number of tagged lobsters detected at each site over the duration of the study, and instances of tagged lobsters being detected or caught at different turbine locations. These results may have been influenced by limited carrying capacities of the habitat present at each tagging site. Shelter and food availability are key drivers of movement patterns in clawed lobsters (Smith *et al.*, 2001, Watson et al., 1999) *H. americanus* will leave areas of high lobster density where there is intense competition for resources (Steneck, 2006). We tentatively suggest this response was influencing changes in the mean number of lobsters detected per day in the present study, with the possibility that non-tagged lobsters were moving into the study sites increasing competition for shelter and food, causing tagged lobsters to move to other areas of scour protection within the OWF. We acknowledge however, that interactions between tagged lobsters or a number of other abiotic and/or biotic factors may have also influenced these results.

Home-range

Home range and core territory estimates obtained from UD_{95} and UD_{50} values were variable across individuals, with the largest UD_{95} value 2.4 times greater than the smallest, and the largest UD_{50} value 5.5 times greater than the smallest. This variability reflects the hypothesis that individual "personality-traits" (e.g. activity, boldness, and exploratory behaviour) could influence movement and space use (Fraser *et al.*, 2001; Spiegel *et al.*, 2017). Similar levels of variability in individual *H. gammarus* home range estimates have been reported elsewhere (Moland *et al.*, 2011; Skerrit *et al.*, 2015).

Although no previous studies have estimated the home range of *H. gammarus* within an OWF or in association with artificial structures, estimates of home range within natural habitat varies significantly between studies. The present study estimated mean home range from UD_{95} as 15 240.41m^2. Previous reports of home range estimated from UD_{95} include, 19, 879, 170, 660, and 2,134m^2 (Moland *et al.*, 2011; Wiig *et al.*, 2013; Skerrit *et al.*, 2015). The variability in home range estimates between studies is influenced by the differences in spatial and temporal scales of the studies, tracking technologies, and varying environmental conditions. Differences in technology can provide contrasting levels of position accuracy, and lead to overestimated home range estimates (Skerrit *et al.*, 2015). Although increased study duration and study area provides greater opportunity to capture tagged individuals full range of movement, it is also important to note that home range estimates from acoustic telemetry are limited by the detectable range of transmissions, with the potential to underestimate home range as a result of a tagged individual moving beyond this detectable range. In the present study estimates of distance travelled outside of the array as generated by correlated random walk suggest tagged lobsters would on average travel ~28 m outside of the receiver array area before returning. Therefore, home range estimates in this study may have been limited by the total detectable range.

UD_{95} and UD_{50} values were found to be larger for males ($M\ UD_{95} = 16059.66\ m^2$, $M\ UD_{50} = 2943\ m^2$) than females ($M\ UD_{95} = 13783.97\ m^2$, $M\ UD_{50} = 2273\ m^2$), which is similar that observed by Skerrit *et al.* (2015) where male lobsters travelled further away from shelter than females. However, the reasons underlying these differences remain unclear.

Habitat use

We estimated 55% of all CoA points were within 35 m of the edge of the scour protection, and 68% of tagged lobsters UD_{50} areas either fully or partially overlapped the scour protection. Other, generally reef-associated mid- and high-trophic level species have been found within close proximity of areas of scour protection within OWFs across Europe. For example, off the Belgian coast lobsters have been found associated with scour protection at the Thortonbank OWF (De Mesel *et al.*, 2013) In the Netherlands, 97% of position fixes from acoustically tagged Atlantic cod (*Gadus morhua*) were found either overlapping or within 25 m of the scour protection (Reubens *et al.*, 2013). An average of 5000 edible crabs (*Cancer pagarus*) per area of scour protection were recorded within an OWF in the German Bight (Krone *et al.*, 2017). The presence of these species in association with scour protection within OWFs demonstrate the potential for artificial hard substrates and surrounding habitat within OWFs to support a range of species. This is likely a result of reef effects generated through the provision of habitat (Dannheim *et al.*, 2020).

Potential fishery opportunities

The results presented in this study suggest particular areas of habitat within OWFs have the potential to support resident populations of a commercially valuable species. Globally, artificial reefs have been constructed to enhance fishery resources and support fisheries management (Paxton *et al.*, 2020). With certain artificial reefs capable of providing sufficient resources for lobster to spawn and grow (Bennet et al., 1980, Collins *et al.*, 1994). Considering the potential negative impacts on certain sectors of the fishing industry as a result of future OWF construction the presence of this commercially important species within OWFs may present potential fishing opportunities that could form an important compensatory measure for fishers negatively impacted by the construction of OWFs (Stelzenmüller *et al.*, 2021, 2022). However, in order to move towards this concept, a number of challenges must be addressed. These challenges include, but are not limited to, the willingness of OWF operators to provide access for fishers, ensuring fishing activity does not risk damaging OWF assets, and evaluating the safety risks associated with carrying out fishing activities within a highly developed marine area. As a result of the species present, and the logistics of fishing within a highly developed marine area it is likely these fishing opportunities will be most suitable for static gear fisheries, particularly the potting sector. There is also the potential of increasing the amount or adapting the type of artificial hard substrates to support increased populations of commercially important species. If this is informed by concerted research efforts, there is potential to provide more suitable habitat to support increased biodiversity leading to greater populations of commercial valuable species within these sites. However, to avoid potential greenwashing, the impacts of increased or modified scour protection on the original biological community need to be investigated. As does the potential benefits for the fishing industry to ensure this form of mitigation has economic longevity.

Future work

While the results presented in this study suggest that lobsters make use of areas of artificial hard substrates within OWFs and in some cases, may be resident to these areas. The lack of a control site in this study means the factors driving this behaviour remain unclear. Therefore, future studies should seek to include control sites either lacking artificial hard substates or sites outside of the OWF. We expect that studies comparing lobster residency and home ranges from sites with and without hard substrates both within OWFs and areas outside of OWFs would be best designed to provide a greater understanding of how the presence of artificial hard substrates are influencing lobster movements and behaviour. Furthermore, future studies should seek to record lobster movements over greater spatial scales using larger receiver arrays, particularly focusing on movements between specific turbines as this may increase our understanding of intraspecific interactions and possible carrying capacities of lobsters within OWFs. Finally, considering food resources are expected to be one of the factors driving the presence of higher trophic organisms within OWFs (Dannheim *et al.*, 2020), future studies investigating the feeding habits of lobsters within OWFs may provide an increased understanding of the results presented in this study.

Conclusions

This study provides the first account of lobster habitat use and movements within an OWF. Tagged lobsters displayed high residency to tagging sites and were often re-detected at tagging sites after short to moderate absences periods, which are expected to be the result of lobsters either leaving the array area or sheltering within scour protection. The consistency in lobster residency and location of UD_{95} and UD_{50} areas across sites within this study suggest that lobsters found within OWFs across Europe can be expected to occupy similar areas within these sites, potentially sheltering within scour protection and making use of the surrounding habitat. The number of lobsters recorded within each tagging site throughout the study suggest the habitat within each site may present resources that can support multiple lobsters. However, observations of lobsters moving away from one area of scour to another suggest that these resources may only support a limited population size. While future work is required to gain a better understanding of the factors driving the behaviour of lobsters recorded in this study, ultimately, these results suggest the potential for artificial hard substrates and the surrounding habitat to support populations of *H. gammarus* within OWFs. As a result, future fixed-turbine OWF developments that include scour protection may lead to potential fishery opportunities.

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Supplementary Data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Conflict of interest

None declared.

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Data Availability Statement

The data underlying this article will be shared on reasonable request to the corresponding author.

Author Contributions

P.M. developed the main idea in correspondence with H.T. and D.W. H.T. conducted fieldwork, performed the analysis, and the writing. T.S., P.M., and D.W. provided expertise on the analysis and helped with writing.

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