Original submission to: ICES Journal of Marine Science

Manuscript; original article

Title: The effects of temporary exclusion of activity due to wind farm construction on a lobster (*Homarus gammarus*) fishery suggests a potential management approach.

Authors: Michael Roach[1, 2], Mike Cohen[2], Rodney Forster[3], Andrew S. Revill[4], Magnus Johnson[1]

1. School of Environmental Sciences; University of Hull, Cottingham Road, Hull, UK, HU6 7RX.
2. Holderness Fishing Industry Group; The Former Harbour Masters Office, Harbour Road, Bridlington, United Kingdom, YO15 2NR.
3. Institute for Estuarine and Coastal Studies; University of Hull, Cottingham Road, Hull, UK, HU6 7RX.
4. DONG Energy (UK); 5 Horwick Place, London, SW1P 1WG.

Mike Cohen; m.cohen@hfig.org.uk
Rodney Forster; R.Forster@hull.ac.uk
Andrew Revill; andy@revillnation.com
Magnus Johnson; M.Johnson@hull.ac.uk

Corresponding Author

Michael Roach, School of Environmental Sciences; University of Hull, Cottingham Road, Hull, UK, HU6 7RX.

Email: m.roach@2009.hull.ac.uk, Tel: (+44)7794542066

Abstract

Offshore wind farms form an important part of many countries strategy for responding to the threat of climate change but their development can conflict with other offshore activities. Static gear fisheries targeting sedentary benthic species are particularly affected by spatial management that involves exclusion of fishers. Here we investigate the ecological effect of a short-term closure of a European lobster (*Homarus gammarus* (L.)) fishing ground, facilitated by the development of the Westermost Rough offshore wind farm located on the north-east coast of the United Kingdom. We also investigate the effects on the population when the site is reopened on completion of the construction. We find that temporary closure offers some respite for adult animals and leads to increases in abundance and size of the target species in that area. Reopening of the site to fishing exploitation saw a decrease in catch rates and size structure, this did not reach levels below that of the surrounding area. Opening the site to exploitation also allows the fishery to recuperate some of the economic loss during the closure. We suggest that our results may indicate that temporary closures of selected areas may be beneficial and offer a management option for lobster fisheries.

Keywords: crustacean fisheries, offshore wind energy, rotational harvest, spatial management, static gear, temporary closure.

Introduction

Globally there has been an increase in energy provided from the wind industry, surpassing 63 GW in 2015, an 18% increase since 2014 (Global Wind Energy Council, 2015). Wind energy developments are often the most used tool by national governments to meet their energy demands from renewable sources, seeing an increase in offshore wind developments in recent years. Offshore wind developments are often located to exploit the optimum wind energy and be able to transmit the energy to shore. For example, the United States is estimated to have a 4000 GW capacity for wind energy (US Department of Energy 2012). The development of offshore wind farms can cause spatial conflicts with other sea users. For example, the eastern sea board of the US is prime location for both offshore wind energy and nationally important crustacean fisheries (Breton and Moe 2009, Brehme *et al.,* 2015;). Co-location of marine users and spatial management of resources is being observed in the UK; one of the world leaders in offshore wind exploitation (Hooper and Austen, 2014, Kota *et al.*, 2015).

UK government has a target of 15% of its energy from renewable sources by 2020 (European Commission, 2016). There are currently 25 offshore wind farms (OWF) operational or under construction within UK waters currently providing approximately 5% of the UK demand with a further 16 with development consent, (Crown Estates, 2017). There has been a steady increase in research into the impacts of OWF on the marine ecosystem. This increase in literature is largely review-based with the few empirical studies available, not being able to give a reliable assessment of the cumulative impact of offshore wind development (Lindeboom *et al.,* 2015). The current empirical studies have largely focussed on the impact to seabird interactions (15 out of 78 publications reviewed by Hooper *et* *al.*, (2017), marine mammals (Madsen *et al.,* 2006, Thomsen *et al.,* 2008, Bailey *et al.,* 2010, Brandt *et al.,* 2011), substrate and infauna disturbance (De Backer *et al.,* 2014, Coates *et al.,* 2014,Vandendriessche *et al.,* 2015) and fish populations (Wahlberg and Westerberg 2005, De Troch *et al.,* 2013, Bergman *et al.,* 2014, Stenberg *et al.,* 2015). Most empirical studies investigating effects on macrobenthic crustaceans form part of an environmental impact assessment or statutory monitoring programmes.

To date the majority of OWF constructed in European waters are located in shallow water (typically less than 30 m) on sand based substrates. The introduction of individual turbines and associated stone protection (used to protect monopole bases from sand scour), can introduce a new hard substrate habitat to an area. This can increase shelter and hard substrate habitat in areas that it may not have previously existed. This introduced habitat has been found to increase biodiversity and biomass of associated fauna in some areas (Lindeboom *et al.,* 2011, De Backer *et al.,* 2014, Stenberg *et al.,* 2015). Krone *et al.*, (2017) observed over 5000 *Cancer pagurus* on individual monopoles with scour stone protection, which was more than double that found on monopoles without scour stone protection. However, this was observed in areas characterised by sandy substrate, the effect of scour stone protection on areas characterised by rock and cobble is yet to be understood. Using studies from sites that are not comparable to each other to understand effects of OWF installations can lead to misunderstanding of the processes involved (Lindeboom *et al.,* 2015).

OWF and individual turbines can act as fish aggregation devices, providing a refuge for fish species from predation and exploitation, although the effects can be spatially limited to the OWF (Griffin *et al.,* 2016). An OWF can act as a quasi-marine protected area (MPA) or no take zone (NTZ). This can be due to exclusion during construction or operation, to all fishing vessels or the physical presence of the turbines excluding certain gear types such as mobile gear (Bergman *et al.*, 2014; Krone *et al.*, 2017). There is potential for co-location of fisheries and OWF developments, however these are predominantly static fisheries (Christie *et al.,* 2014, Hooper and Austen 2014, Stelzenmüller *et al.,* 2016). The effects of OWF on mobile benthic megafauna that are targeted by static gear fisheries are little understood (Hooper and Austen 2014; Lindeboom *et al.,* 2015). The potential of spill-over effects of MPA/NTZ can be difficult to ascertain (Moland *et al.,* 2013, Smyth *et al.,* 2015, Vandendriessche *et al.,* 2015), the temporal scale of studies can often not be of sufficient duration to observe the spill over. However Goñi *et al.,*(2010) and Hoskin *et al.,*(2011) observed spill-over effects of different lobster populations within a closed area over a period of 10 and 4 years respectively. *Homarus gammarus* have been shown to have strong site fidelity and defined home ranges (Bannister and Addison, 1998; Smith *et al.*, 1998; Moland *et al.*, 2011) although there is a seasonal migration to deeper water during the colder months. Any spill-over effects of closed areas are likely to be only observed locally or during immigration/emigration from the site. The implementation of an MPA/NTZ has often been met with resistance by commercial fisheries. The potential for positive ecological and possible economic effects of closed areas are often met with scepticism from the fishing industry. This is due to the implementation of surveys not reflecting the way fishermen operate and the fact that data are not in the public domain (Hooper and Austen 2014, Hooper *et al.,* 2015).

The spill over effect can lead to the process of ‘fishing the line’, where fishing intensity is increased on the boundaries of a closed area (Kellner *et al.,* 2007).

Spatial displacement of effort into another area can increase pressure on fisheries and lead to increased competition among fishers. This is especially the case in static gear fisheries where individual fishers can have a strong fidelity to specific sites (Hart *et al.,* 2002, Turner *et al.,* 2013). The implementation of closed areas can often be considered by industry and some in the scientific community to be conducted for political purposes as opposed to ecological. The use of MPA's as a fisheries management tool should be treated as a rigorously designed experiment with accurate cost/benefit analysis (Kaiser 2005, Caveen *et al.,* 2014). During construction of OWF the fishing industry are often excluded from the area for safety reasons; this can have a potential short-term positive effect on the local population due to the removal of fishing mortality.

Here we investigate the short-term effects of construction of an OWF on a commercially exploited European Lobster (*Homarus gammarus*, Homaridae (L.) subsequently referred to as lobster) population. We also highlight the effects of reopening the site to exploitation on completion of the OWF construction and their use as a potential management tool. The study also highlighted the potential positive effects of the fishing industry engaging in research of OWF effects.

Methodology

Site Description

The Holderness coast lobster fishery is the largest lobster fishery in the UK, representing approximately 20% of national lobster landings. Landings of European lobster, into the regions' main port of Bridlington in 2015 were 405 tonnes with an estimated first sale value of £4.2 million (Marine Management Organisation 2015). The fishery in the area targets lobster almost exclusively using static creels generally baited with mackerel. Creels are immersed for varying periods depending on the fisher, but generally 2 – 3 days.

The Westermost Rough wind farm, constructed in 2014/15 at a cost of £800 million, and is located within the Holderness fishery, situated within one of the fisheries main target areas. The site was one of the first to be located on a rock and cobble substrate. The Westermost Rough OWF extends from 7.7 km off the coast to 13.3 km offshore and is approximately 35 km^2 in area (Figure 1). It consists of 35, 6 MW turbines and associated substation, located in a depth of water ranging from 15 - 23 metres. The substrate is predominantly rock and cobble with sand patches, the area was subjected to boulder removal prior to the construction phase.

The study was conducted using a fishing industry managed research vessel, the R.V. Huntress. The study was a collaboration between the local fishery; The Holderness Fishing Industry Group (www.hfig.org.uk) and the OWF developer, DONG Energy.

Sampling Methods

There were two sites chosen to assess the effects of the construction of the Westermost Rough OWF, one site in the OWF (treatment (subsequently referred to as the wind farm)) and a site to the north of the OWF (control) (Figure 1). The sites were restricted in their spatial distribution within the OWF due to the process of the construction of the OWF. The site was agreed with the developer as the area that could be surveyed without disruption to the sampling protocol. The control site was located 1 km to the north of the OWF. The prevailing current drifts north/south, any effects of the construction should not have been observed. This site was also selected due to the substrate reflecting that within the OWF. There were further spatial restrictions of the control site due to displacement of fishing gear from the OWF to the surrounding area, care was taken to avoid gear conflict.

Sampling strings consisting of 30 creels were deployed both within the wind farm and the control. The strings consisted of 25 standard commercial creels with a 70 mm mesh and 96.5 cm base; and 5 creels with a 30 mm mesh and a 76.2 cm base. All creels were exempt from local byelaws ordering the use of escape gaps. The smaller mesh creels were used to sample catch that may escape the larger mesh creels. On every haul, each creel was baited with two mackerel 'frames', which are commonly used in the region to target lobsters. Each string was secured at either end with a 20 kg anchor and marked with a surface marker buoy. The gear configuration mirrored that of the commercial fishing strings in the area.

A baseline survey was carried out prior to the wind farm construction, taking into account the spatial restrictions that were predicted once the construction began. The survey was timed to target the lobster fishery between June and September of 2013, maintaining a mean immersion period of 3.0 days (s.d. +/- 1.34 days) and all creels from both the control and treatment were processed on every survey day (n = 24 hauls each site). Following the before/after, control/impact (BACI) approach (Carstensen *et al.,* 2006, Hoskin *et al.,* 2011, Moland *et al.,* 2013, Vandendriessche *et al.,* 2015) sampling was mirrored in June to September of 2015 for the first-year post build of the wind farm. The immersion period of the creels in 2015 was 3.9 days (s.d. +/- 2.1 days) and all creels from both the control and treatment were processed on every survey day (n = 23 hauls each site). Variation in immersion periods to the baseline survey was due to inclement weather. There was no survey during 2014 as the site was under construction.

During the baseline survey of 2013 both the wind farm and control were subjected to fishing exploitation for the entire period. During construction, the wind farm was closed to fishing exploitation for a period of 20 months during 2014/15, until the middle of August 2015 (13/08/2015). This was part way through the 2015 sampling period, with 13 sample days when the site was closed and 11 sample days when the site was open to exploitation. For the entire survey periods in both 2013 and 2015 there were no restrictions to fishing exploitation in the control site and the main management of effort in the area was based on minimum landing size (87 mm carapace length (CL)) of the catch.

Abundance of lobster was recorded from each creel. Sex, condition, ovigerous status and size (CL) was recorded for the aggregated catch within each string. All animals were returned to sea after recording. The survey was timed and designed to assess the effects of the wind farm construction on the region's most valuable fishery, this study reports lobster status only.

Data Analysis

Analysis was conducted on the overall differences in size and catch rates between the baseline (2013) and the first-year post build (2015). Because the previously closed site was re-opened to fishing during the 2015 sampling regime, analysis was also conducted on the status of the wind farm (open/closed to fishing exploitation).

Size distribution

Differences in size frequency for both between years and between statuses of the wind farm (open and closed) were analysed using the two-sample Kolmogorov Smirnov test. Empirical cumulative distribution (ECDF) plots were generated to demonstrate the proportion of lobsters between the two sites that are less than each observed length (Thomas *et al*., 2015). Generalised Linear Mixed Models (GLMM) are used when the data are not normally distributed and when there is the potential for pseudo-replication (Zuur and Ieno, 2016). Due to the limitations of survey sites, the size data not conforming to normality (Kolmogorov Smirnov, $p < 0.05$) and the variability in the number of lobsters sampled on each day (range = 13 – 137 (2013), 44 – 179 (2015)), GLMM was deemed a more suitable analysis. We therefore applied a GLMM in which the relative catch probability of the lobsters entering the pots within each site was the response variable, carapace length (size) of lobster as the fixed effect and haul (survey day) was used as a crossed random intercept. A binomial error was applied due to the response variable being the relative catch probability of lobsters entering pots within each site. Sex, ovigerous status and condition of the lobsters were investigated as factors within the model but were rejected due to either insignificance ($P > 0.05$ (Sex and Condition)) or unsuitable factors to include (Ovigerous status). Soak time was investigated whether it should be included as an offset within the model. There was a poor relationship ($R^2 < 0.1$ on all occasions) between the daily abundance of lobsters within each string and the soak time they were subjected to. Soak time was also negated for the between sites comparison within the survey design, as both sites were subjected to the same soak time on all occasions. It was decided that soak time was not required to be offset within the GLMM. Therefore, the simplest model was the best description of the relative catch probability of lobsters of each size entering the strings/pots between the two sites/status of the wind farm (open/closed);

$$\Pr\{\frac{Test}{Test + Control}\} = 1/(1 + e^{-(\text{haul} + \beta_1 \text{ x length} + \beta_2 \text{ x length}^2)})$$

GLMM was applied using the lme4 package in R statistical software (Bates *et al.,* 2015). This follows an accepted methodology described by Holst and Revill, (2009), analysing differences in catch composition at length between tests and controls (Van Marlen *et al.*, 2014; Vogel *et al.*, 2017).

Validation of each GLMM model was conducted checking that the normality of the standardised residuals conformed to a normal distribution (Shapiro Wilkes, $p > 0.05$) (Thomas *et al.,* 2015) and also comparing the GLMM results to the 2-sample Kolmogorov Smirnov analysis. GLMM results were also presented graphically, allowing for inference as to where within the distribution the significance lay.

Catch comparison

Catch per unit of effort (CPUE) was determined as the total number of lobsters caught in a string (Davies *et al.,* 2015). Landings per unit of effort (LPUE) was determined as the total number of lobsters per string that were above the minimum landing size (87 mm CL) and of a good enough quality (i.e. not missing limbs and no visible signs of disease) to be landed to market. The CPUE and LPUE data conformed to a normal distribution (Kolmogorov Smirnov, $p > 0.05$) but the variances could not be considered equal (F test, $p < 0.05$). A Welch's t-test assuming unequal variances was applied to the CPUE and LPUE to analyse the differences in site, year and wind farm status (open/closed).

Results

A total of 1440 creels (720 at each site) were hauled during the baseline data collection in 2013 (n = 24 survey days) recording 6051 lobsters. During the 2015 post build survey (n = 23 survey days) 1380 creels (690 at each site) were hauled and 8734 lobsters were recorded.

Size Distribution

The size frequency distributions of lobsters differed significantly between the two years (Kolmogorov Smirnov, $D = 0.10$, $p < 0.001$). The windfarm in 2015 showed a larger proportion of lobsters at a larger size (>100mm CL) than sampled in 2013 (Figure 2a & b), there was a greater proportion of lobsters from the MLS (87mm) – 96 mm CL in sampled in 2013. There was a broader size range, 39 – 126 mm CL in 2015 as opposed to 56 – 114 mm CL in 2013. The empirical cumulative distribution function (ECDF) plot (Figure 2c) demonstrates that the greatest difference in distributions were between 75 & 92 mm CL. This was supported by the GLMM plot (Table 1, Figure 2d), which demonstrates that there was a greater proportion of lobsters sampled over 70 mm CL in 2015 than in 2013.

During the wind farm closure in 2015 (prior to 13/08/2015) the size distribution of lobsters in the control site (Figure 3b) had a narrower distribution (39 -117 mm CL) than within the wind farm (40 – 126 mm CL) and there was generally a greater proportion of lobsters within the wind farm than within the control site (Figure 3a). The size distribution of lobsters within the wind farm was significantly different to both the control site (Kolmogorov Smirnov, $D = 0.32$, $p = < 0.0001$) and the baseline data (Kolmogorov Smirnov, $D = 0.14$, $p < 0.0001$) (Figure 3a & b). Although Figure 3c shows that the size of lobsters within the wind farm (red) differed from the baseline (black and grey) and the control (blue) between 60 – 107 mm CL, Figure 3d shows that the distribution was split approximately at the MLS (vertical line). The graphical representation of the GLMM (Table 1) shows that there was a greater proportion of lobsters below the MLS in the control site and the inverse in the wind farm.

There was a decline in the proportion of lobsters above MLS in the control site after the wind farm had been opened to fishing (Figure 4a) in comparison to the period when the wind farm was closed (Figure 3a) (Kolmogorov Smirnov, D = 0.07, $p < 0.05$). This was also reflected within the wind farm site (Figure 3b & 4b) (Kolmogorov Smirnov, D = 0.28, $p < 0.0001$). The sampling period post opening of the wind farm to fishing demonstrated a greater proportion of lobsters within the wind farm in comparison to the control site (Kolmogorov Smirnov, D = 0.11, $p < 0.0001$). Although there was a difference in the cumulative distribution between the wind farm and the control site between 70 – 100 mm CL, both sites also showed a difference from the baseline data (Figure 4c). GLMM analysis (Table 1) shows that after opening of the site to fishing there was a greater proportion of lobsters below MLS in the control site as opposed to the wind farm (Figure 4d). There was no significant difference in the proportion of lobsters above MLS between the two sites post opening of the site.

Catch and landings per unit of effort between years

Mean CPUE (Table 2) was significantly greater in 2015 for both sites than in 2013 ($p < 0.01$ (Table 4)), however did not differ significantly between control and wind farm within the same year ($p > 0.05$ (Table 4). Mean LPUE (Table 2) was also significantly greater in the wind farm in 2015 than 2013 and it was also significantly greater in the wind farm than the control site in the year 2015 ($p < 0.01$ (Table 4)).

The control site showed no significant difference in mean LPUE between sample years ($p > 0.05$ (Figure 5 & Table 4)). The greatest ratio between CPUE & LPUE (0.25) was within the wind farm during the year 2015, this was when the wind farm was closed for a period during the sampling regime (Figure 5).

Influence of wind farm opening

After the wind farm opened to fishing exploitation, mean CPUE (Table 3) within the wind farm reduced significantly ($p < 0.001$ (Table 5)), this was not the case in the control site ($p > 0.05$ (Table 5)). Mean CPUE (Table 3) was also significantly greater prior to the wind farm being opened to fishing exploitation ($p < 0.001$ (Figure 6 & Table 5)). Mean LPUE (Table 3) was significantly greater in the wind farm when it was closed than the control site during the same period and once the wind farm was opened to fishing ($p < 0.001$ (Table 5)). Mean LPUE (Table 3) was significantly greater in the control site when the wind farm was closed than the period when the area was open to fishing exploitation ($p < 0.05$ (Figure 6 & Table 5)). The greatest ratio of LPUE against CPUE (0.33) was during the period when the wind farm was closed to fishing, indicating a higher proportion of high quality lobsters that were not being exploited (Figure 6).

Discussion

Size distribution

The exclusion of fishing effort within the OWF was observed to have an effect on the size distribution of lobsters within the area. There was a greater total number of lobsters observed during the post-build survey than during the baseline survey ($n = 2683$ difference). Within the wind farm, there was a greater proportion of lobsters, greater than MLS observed in 2015 than in 2013 (Figure 2). The absence of fishing exploitation within the wind farm during construction acted as a NTZ, protecting lobsters greater than the MLS. There is potential for spill-over effects of an MPA/NTZ (McClanahan and Mangi 2000, Smyth *et al.,* 2015), this can be observed locally for species with reduced movement patterns. (Moland *et al.,* 2011). When a NTZ is created it has been reported to initially show an increase in lobster abundance and biomass (Hoskin *et al*., 2011, Wootton *et al*., 2012, Davies *et al*., 2015). The increase in the proportion of larger lobster (> 100 mm CL) reported in Figure 2 and the overall higher number of lobsters observed was expected due to the closure of the site when compared to the baseline data.

Prior to the wind farm being opened, the size distribution of lobsters within the wind farm was significantly different to the control site and the wind farm baseline distribution (Figure 3). The density of lobsters can be influenced by the availability of shelters within a habitat (Ball *et al.,* 2001, Steneck 2006). The size of lobsters within a population has also been demonstrated to be limited by the size and number of shelters available (Bushmann and Atema 1997, Debuse *et al.,* 1999). The addition of scour stone protection to the base of each monopole could potentially increase the available habitat and shelters for lobsters. The Westermost Rough OWF site was subjected to boulder removal prior to construction so the additional habitat creation may have been negated by the boulder removal. As the difference in size within the wind farm was described by lobsters over 75mm CL (Figure 3d), the absence of fishing effort in the site is most likely to have greater influence than the habitat change.

Opening of the site to fishing exploitation led to a rapid, short-term increase in fishing mortality in the wind farm in comparison to the surrounding area. After the wind farm was reopened to fishing the previously unfished population of larger lobsters was reduced by intensive fishing over a short period. This reduction however did not drop below that reflected by the control site which was subjected to exploitation for the entire period. The proportion of lobsters above MLS did not differ between the wind farm and the control site in the period after opening to fishing (Figure 4d). However, there was a greater proportion of smaller lobsters observed in the control site than within the wind farm (Figure 4d). The presence of a greater abundance of larger lobsters may have deterred the smaller lobsters from the wind farm (Steneck 2006, Émond *et al.,* 2010). Their immigration into the site once lobsters above MLS were again being exploited may not have occurred during the timeframe of the survey. The smaller lobsters may have also been displaced into areas surrounding the wind farm due to inter-specific competition for resources (Wahle *et al.,* 2013) which was reflected in the control site (Figure 3b & 4b). This indicates potential overspill effects, however, of the pre-recruits rather than recruits into a fishery. There are also influences in catch dynamics of a creel, smaller lobsters can use creels as shelter from predation. The greater abundance of larger lobsters in the area that were subsequently caught in the survey creels, may have deterred the smaller lobsters from entering the creels (Jury *et al.,* 2001). This interaction could have skewed the data to present a population biased in favour of larger lobsters. Alternatively the construction of the OWF and associated disturbance may have had a greater effect on the smaller, less robust lobsters (Rodmell and Johnson, 2002). As the fishing pressure returns to a stable state, again removing lobsters above MLS, it’s likely that smaller lobsters will again be observed within the area.

Catch and landings per unit of effort

The increase in lobster abundance observed in 2015 was reflected by the CPUE, showing a significant increase in catch rate of lobsters for both sites in 2015. There was no significant difference in catch rates of lobsters between the wind farm and control site in 2015 (Figure 5). Indicating that the difference between the years was due to natural variation and not just the closure of the wind farm. The LPUE, i.e. the number of lobsters of good quality per string that were above the MLS of 87 mm CL also showed a significant increase within the wind farm between years and with the control site in 2015. Wootton *et al.,* (2012) & Davies *et al.,* (2015) both observed a greater prevalence of injury and disease in lobsters within an NTZ. The increased LPUE observed in this study, indicating a greater abundance of lobsters without injury above MLS, suggests that this was not the case here. This could be attributed to the period of closure, as this site was only closed for 20 months in comparison to 2 and 5 years in their respective studies. The area may not have been closed long enough for true competition of resources that can result in increased occurrences of injuries.

After the wind farm was opened to fishing the CPUE reduced significantly within the wind farm when compared to when the site was closed. It also differed significantly to the control site after opening (Figure 6 & Table 5). This demonstrates the effect of opening the area to exploitation after a period of closure. The mean LPUE however, after opening of the wind farm did not differ significantly to the control site (Figure 6 & Table 5). This indicates that although effort was high, within a relatively short period (6 weeks survey period after opening), the landings fishermen were getting within the site reflected the surrounding area.

It has been demonstrated that periodic (Murawski *et al.,* 2000) or permanent (Bergman *et al.,* 2014) closure of areas to exploitation can enhance commercial fisheries. Closure of areas can allow the larger, more fecund lobsters to contribute to the spawning stock without fishing pressure (Moland *et al.,* 2010, Leal *et al.,* 2012). Periodically closing and reopening of the site has the potential to offset the possible detrimental effects of a permanent NTZ as observed by Wootton *et al.,* (2012) & Davies *et al.,* (2015). Economic loss to the fishery of a closed area may be offset by the increased earning potential once the site has been opened. Figure 6 demonstrates a 22% increase in LPUE in comparison to the control site. This however was only a short-term effect as the LPUE within the wind farm reflected the control site during the period of the survey (six weeks after opening).

There is the potential for OWFs with their easily identifiable delineation to be used as a stock management tool for lobster fisheries. Combined with other suitable and easily identifiable sites, rotational closures could protect spawning stocks whilst offsetting economic loss and detrimental effects of permanently closed areas (Cohen and Foale, 2013).

Conclusion

This study has demonstrated the short-term effects on size distribution, CPUE and LPUE of offshore wind farm construction on a commercially important lobster fishery. The construction of the OWF created a temporary NTZ during the construction period which resulted in an increase in larger, good quality lobsters in comparison to both the baseline data and control sites. The opening of the wind farm during the sampling period has highlighted that exploitation levels immediately following reopening of a site are high but quickly return to reflect surrounding areas. This study, whilst spatially limited has also presented a BACI approach to monitoring effects of OWF construction. Presenting a high number of individuals sampled, that represented the main fishing season for lobsters in the area. The collaboration between industry and developers has led to a study using industry data collection, that enables a high number of lobsters sampled, to aid in addressing a current gap in the literature. Subsequent monitoring of the site will highlight any longer-term effects of the OWF construction and its operation on the local lobster stocks when fishing exploitation is stable. Opening of the site during the sampling period has also highlighted the potential for OWF sites to be used as a stock management tool for periodic closures.

Acknowledgements

We would like to thank DONG Energy for funding the research and encouraging industry/developer collaboration. The crew of the R.V. Huntress for extensive sea time and advice on local fisheries and Rebecca Skirrow for assistance with data recording.

References

Bailey, H., Senior, B., Simmons, D., Rusin, J., Picken, G., and Thompson, P. M. 2010. Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals. Marine Pollution Bulletin, 60: 888–897.

Ball, B., Linnane, A., Munday, B., Browne, R., and Mercer, J. P. 2001. The effect of cover on in situ predation in early benthic phase European lobster *Homarus gammarus*. Journal of Marine Biological Association, 81: 639–642.

Bannister R.C.A, and Addison, J. T. 1998. Enhancing lobster stocks : a review of recent european methods , results , and future prospects. Bullitin of Marine Science, 62: 369–387.

Bates, D., Mächler, M., Bolker, B. M., and Walker, S. C. 2015. Fitting linear mixed-effects models using lme4. Journal of Statistical Software, 67: 1–48.

Bergman, M. J. N., Ubels, S. M., Duineveld, G. C. A., and Meesters, E. W. G. 2014. Effects of a 5-year trawling ban on the local benthic community in a wind farm in the Dutch coastal zone. ICES Journal of Marine Science, 71: 1088–1099.

Brandt, M. J., Diederichs, A., Betke, K., and Nehls, G. 2011. Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. Marine Ecology Progress Series, 421: 205–216.

Brehme, C. E., McCarron, P., and Tetreault, H. 2015. A Dasymetric Map of Maine Lobster Trap Distribution Using Local Knowledge. The Professional Geographer, 67: 98–109.

Breton, S. P., and Moe, G. 2009. Status, plans and technologies for offshore wind turbines in Europe and North America. Renewable Energy, 34: 646–654.

Bushmann, P. J., and Atema, J. 1997. Shelter sharing and chemical courtship signals in the lobster *Homarus americanus*. Canadian Journal of Fisheries & Aquatic Sciences, 54: 647–654.

Carstensen, J., Henriksen, O. D., and Teilmann, J. 2006. Impacts of offshore wind farm construction on harbour porpoises : acoustic monitoring of echo- location activity using porpoise detectors (T-PODs). Marine Ecology Progress Series, 321: 295–308.

Caveen, A. J., Fitzsimmons, C., Pieraccini, M., Dunn, E., Sweeting, C. J., Johnson, M. L., Bloomfield, H., *et al.* 2014. Diverging strategies to planning an ecologically coherent network of MPAs in the North Sea: the roles of advocacy, evidence and pragmatism in the face of uncertainty. Advances in marine biology, 69: 325–370.

Christie, N., Smyth, K., Barnes, R., and Elliott, M. 2014. Co-location of activities and designations: A means of solving or creating problems in marine spatial planning? Marine Policy, 43: 254–261.

Coates, D. a., Deschutter, Y., Vincx, M., and Vanaverbeke, J. 2014. Enrichment and shifts in macrobenthic assemblages in an offshore wind farm area in the Belgian part of the North Sea. Marine Environmental Research, 95: 1–12.

Cohen, P. J., and Foale, S. J. 2013. Sustaining small-scale fisheries with periodically harvested marine reserves. Marine Policy, 37: 278–287.

Davies, C. E., Johnson, A. F., Wootton, E. C., Greenwood, S. J., Clark, K. F., Vogan, C. L., and Rowley, A. F. 2015. Effects of population density and body size on disease ecology of the European lobster in a temperate marine conservation zone. ICES Journal of Marine Science, 72: 128–138.

De Backer, A., Van Hoey, G., Coates, D., Vanaverbeke, J., and Hostens, K. 2014. Similar diversity-disturbance responses to different physical impacts: Three cases of small-scale biodiversity increase in the Belgian part of the North Sea. Marine Pollution Bulletin, 84: 251–262.

De Troch, M., Reubens, J. T., Heirman, E., Degraer, S., and Vincx, M. 2013. Energy profiling of demersal fish: a case-study in wind farm artificial reefs. Marine environmental research, 92: 224–33.

Debuse, V. J., Addison, J. T., and Reynolds, J. D. 1999. Effects of breeding site density on competition and sexual selection in the European lobster. Behavioral Ecology, 14: 396–402.

Émond, K., Sainte-Marie, B., and Gendron, L. 2010. Relative growth, life-history phases, and sexual maturity of American lobster (Homarus americanus). Canadian Journal of Zoology, 88: 347–358.

Energy, U. D. of. 2012. Energy efficiency & renewable energy.

Estates, C. 2017. Offshore wind energy; Project details.

European Commission. 2016. Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources.

Global Wind Energy Council. 2015. Global Wind Report 2015. 75 pp.

Goñi, R., Hilborn, R., Díaz, D., Mallol, S., and Adlerstein, S. 2010. Net contribution of spillover from a marine reserve to fishery catches. Marine Ecology Progress Series, 400: 233–244.

Griffin, R. A., Robinson, G. J., West, A., Gloyne-Phillips, I. T., and Unsworth, R. K. F. 2016. Assessing fish and motile fauna around offshore windfarms using stereo baited video. PLoS ONE, 11: 1–14.

Hart, P. J. ., Blyth, R. B., Kaiser, M. J., and Edwards Jones, G. 2002. Sustainable exploitation with minimal conflict: is it possible? *In* Who Owns the Sea.

Holst, R., and Revill, A. 2009. A simple statistical method for catch comparison studies. Fisheries Research, 95: 254–259.

Hooper, T., and Austen, M. 2014. The co-location of offshore windfarms and decapod fisheries in the UK: Constraints and opportunities. Marine Policy, 43: 295–300.

Hooper, T., Ashley, M., and Austen, M. 2015. Perceptions of fishers and developers on the co-location of offshore wind farms and decapod fisheries in the UK. Marine Policy, 61: 16–22.

Hooper, T., Beaumont, N., and Hattam, C. 2017. The implications of energy systems for ecosystem services: A detailed case study of offshore wind. Renewable and Sustainable Energy Reviews, 70: 230–241.

Hoskin, M. G., Coleman, R. a., von Carlshausen, E., and Davis, C. M. 2011. Variable population responses by large decapod crustaceans to the establishment of a temperate marine no-take zone. Canadian Journal of Fisheries and Aquatic Sciences, 68: 185–200.

Jury, S.H., Howell, H., O'Grady, D.F., Watson III, W.H., 2001. Lobster trap video: in situ video surveillance of the behaviour of Homarus americanus in and around traps. Marine and Freshwater Research, 52: 1125–1132.

Kaiser, M. J. 2005. Are Marine Protected Areas a red herring or fisheries panacea? Canadian Journal of Fisheries and Aquatic Sciences, 62: 1194–1199.

Kellner, J. B., Tetreault, I., Gaines, S. D., and Nisbet, R. M. 2007. Fishing the Line near Marine Reserves in Single and Multispecies Fisheries. Ecological Applications, 17: 1039–1054.

Kota, S., Bayne, S. B., and Nimmagadda, S. 2015. Offshore wind energy: A comparative analysis of UK, USA and India. Renewable and Sustainable Energy Reviews, 41: 685–694.

Krone, R., Dederer, G., Kanstinger, P., Krämer, P., Schneider, C., and Schmalenbach, I. 2017. Mobile demersal megafauna at common offshore wind turbine foundations in the German Bight (North Sea) two years after deployment - increased production rate of *Cancer pagurus*. Marine Environmental Research, 123: 53–61.

Leal, M. C., Pochelon, P. N., Silva, T. L., Reis, A., Rosa, R., and Calado, R. 2012. Variable within-brood maternal provisioning in newly extruded embryos of *Homarus gammarus*. Marine Biology, 160: 763–772.

Lindeboom, H., Degraer, S., Dannheim, J., Gill, A. B., and Wilhelmsson, D. 2015. Offshore wind park monitoring programmes, lessons learned and recommendations for the future. Hydrobiologia, 756: 169–180. Springer International Publishing.

Lindeboom, H. J., Kouwenhoven, H. J., Bergman, M. J. N., Bouma, S., Brasseur, S., Daan, R., Fijn, R. C., *et al.* 2011. Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. Environmental Research Letters, 6: 35101.

Madsen, P. T., Wahlberg, M., Tougaard, J., and Tyack, P. 2006. Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs. Mar. Ecol. Progr. Ser., 309: 279–295.

McClanahan, T. R., and Mangi, S. 2000. Spillover of Exploitable Fishes from a Marine Park and Its Effect on the Adjacent Fishery Author. Ecological Applications, 10: 1792–1805.

Moland, E., Olsen, E. M., and Stenseth, N. C. 2010. Maternal influences on offspring size variation and viability in wild European lobster *Homarus gammarus*. Marine Ecology Progress Series, 400: 165–173.

Moland, E., Olsen, E. M., Andvord, K., Knutsen, J. A., and Stenseth, N. C. 2011. Home range of European lobster (*Homarus gammarus*) in a marine reserve : implications for future reserve design. Canadian Journal of Fisheries and Aquatic Sciences, 1210: 1197–1210.

Moland, E., Olsen, E. M., Knutsen, H., Garrigou, P., Espeland, S. H., Kleiven, A. R., André, C., *et al.* 2013. Lobster and cod benefit from small-scale northern marine protected areas: inference from an empirical before-after control-impact study. Proceedings. Biological sciences / The Royal Society, 280: 20122679.

Murawski, S. A., Brown, R., Lai, H. L., Rago, P. J., and Hendrickson, L. 2000. Large-Scale Closed Areas As a Fishery Tool in Temperate Marine Systems : the Georges Bank Experience. Bulletin of Marine Science, 66: 775–798.

Rodmell, D., and Johnson, M. 2002. The development of marine based wind energy generation and inshore fisheries in UK waters: Are they compatible? *In* Who owns the sea?, pp. 76–103.

Smith, I. P., Collins, K. J., and Jensen, a. C. 1998. Movement and activity patterns of the European lobster, *Homarus gammarus* , revealed by electromagnetic telemetry. Marine Biology, 132: 611–623.

Smyth, K., Christie, N., Burdon, D., Atkins, J. P., Barnes, R., and Elliott, M. 2015. Renewables-to-reefs? – Decommissioning options for the offshore wind power industry. Marine Pollution Bulletin, 90: 247–258.

Stelzenmüller, V., Diekmann, R., Bastardie, F., Schulze, T., Berkenhagen, J., Kloppmann, M., Krause, G., *et al.* 2016. Co-location of passive gear fisheries in offshore wind farms in the German EEZ of the North Sea: A first socio-economic scoping. Journal of Environmental Management, 183: 794–805.

Stenberg, C., Støttrup, J., van Deurs, M., Berg, C., Dinesen, G., Mosegaard, H., Grome, T., *et al.* 2015. Long-term effects of an offshore wind farm in the North Sea on fish communities. Marine Ecology Progress Series, 528: 257–265.

Steneck, R. S. 2006. Possible Demographic Consequences of Intraspecific Shelter Competition among American Lobsters. Journal of Crustacean Biology, 26: 628–638.

Thomas, R., Lello, J., Medeiros, R., Pollard, A., Seward, A., Smith, J., Vafidis, J., *et al.* 2015. Data Analysis with R Statistical Software A guidebook for Scientists. 103-112 pp.

Thomsen, F., Lüdemann, K., Kafemann, R., and Piper, W. 2008. Effects of offshore wind farm noise on marine mammals and fish. Bioacoustics, 17: 221–223.

Turner, R. a., Gray, T., Polunin, N. V. C., and Stead, S. M. 2013. Territoriality as a Driver of Fishers' Spatial Behavior in the Northumberland Lobster Fishery. Society & Natural Resources, 26: 491–505.

Van Marlen, B., Wiegerinck, J. A. M., van Os-Koomen, E., and van Barneveld, E. 2014. Catch comparison of flatfish pulse trawls and a tickler chain beam trawl. Fisheries Research, 151: 57–69.

Vandendriessche, S., Derweduwen, J., and Hostens, K. 2015. Equivocal effects of offshore wind farms in Belgium on soft substrate epibenthos and fish assemblages. Hydrobiologia, 756: 19–35. Springer International Publishing.

Vogel, C., Kopp, D., and Méhault, S. 2017. From discard ban to exemption: How can gear technology help reduce catches of undersized Nephrops and hake in the Bay of Biscay trawling fleet? Journal of Environmental Management, 186: 96–107.

Wahlberg, M., and Westerberg, H. 2005. Hearing in fish and their reactions to sounds from offshore wind farms. Marine Ecology Progress Series, 288: 295–309.

Wahle, R. A. W., Brown, C., and Hovel, K. 2013. The Geography and Body-Size Dependence of Top-Down Forcing in New England â€™ s Lobster-Groundfish Interaction. Bulletin of Marine Science, 89: 189–212.

Wootton, E. C., Woolmer, A. P., Vogan, C. L., Pope, E. C., Hamilton, K. M., and Rowley, A. F. 2012. Increased Disease Calls for a Cost-Benefits Review of Marine Reserves. PloS one, 7.

Zuur, A. F., and Ieno, E. N. 2016. A protocol for conducting and presenting results of regression-type analyses. Methods in Ecology and Evolution, 7: 636–645.

Table 1: GLMM parameters for both the comparison between years and the comparison between the control and wind farm, in relation to the status of the wind farm being subjected to fishing exploitation.

Treatment	Response	Intercept Variance	Parameter	Estimate	Standard Error
Wind farm	Between 2013 and 2015	0.755	β_0	0.215	0.347
			β_1	-0.009	0.004
Wind farm closed	Wind farm and control	0.031	β_0	6.678	0.385
			β_1	-0.081	0.005
Wind farm open	Wind farm and control	0.036	β_0	2.045	0.464
			β_1	-0.020	0.006

Table 2: Descriptive statistics of CPUE and LPUE of lobsters sampled at both sites of the Westermost Rough OWF during the 2013 and 2015 surveys.

Year	Site	Effort	Mean	s.d.
2013	Wind Farm	CPUE	63.14	34.68
2013	Control	CPUE	74.27	45.48
2015	Wind Farm	CPUE	93.30	32.14
2015	Control	CPUE	107.30	29.46
2013	Wind Farm	LPUE	11.51	6.75
2013	Control	LPUE	11.28	5.71
2015	Wind Farm	LPUE	23.39	16.68
2015	Control	LPUE	10.26	4.67

Table 3: Descriptive statistics of CPUE and LPUE of lobsters sampled at both sites of the Westermost Rough OWF before and after the wind farm was opened to fishing exploitation.

Status	Site	Effort	Mean	s.d.
Closed	Wind Farm	CPUE	113.08	29.31
Closed	Control	CPUE	107.08	35.44
Open	Wind Farm	CPUE	71.73	18.59
Open	Control	CPUE	107.55	22.98
Closed	Wind Farm	LPUE	36.83	10.43
Closed	Control	LPUE	12.08	4.23
Open	Wind Farm	LPUE	8.73	6.25
Open	Control	LPUE	8.27	4.47

Table 4: Results from Welch's 2 sample t test for the mean CPUE/LPUE data analysed between the control and treatment sites of the Westermost Rough OWF and between the baseline and post build surveys. The significant results are displayed in **bold.**

Factors analysed	Response	*P*	t	DF
Treatment between years	CPUE	**< 0.01**	**- 3.02**	**29.27**
Control between years	CPUE	**< 0.01**	**- 2.88**	**35.75**
Treatment between years	LPUE	**< 0.01**	**- 3.16**	**29.27**
Control between years	LPUE	n.s.	0.65	40.62
Treatment v Control in 2013	CPUE	n.s.	0.91	39.25
Treatment v Control in 2015	CPUE	n.s.	1.54	43.67
Treatment v Control in 2013	LPUE	n.s.	- 0.12	40.88
Treatment v Control in 2015	LPUE	**< 0.01**	**- 3.64**	**25.43**

Table 5: Results from Welch's 2 sample t test for the mean CPUE/LPUE data analysed between the status of the Westermost Rough offshore wind farm (OWF) in 2015, i.e. open or closed to fishing. The significant results are displayed in **bold.**

Factors analysed	Response	*P*	t	DF
Treatment between status of OWF	CPUE	**< 0.001**	**4.08**	**18.79**
Control between status of OWF	CPUE	n.s.	- 0.04	19.01
Treatment between status of OWF	LPUE	**< 0.0001**	**7.92**	**18.23**
Control between status of OWF	LPUE	**< 0.05**	**2.10**	**20.56**
Treatment when OWF was open	CPUE	**< 0.001**	**4.02**	**19.16**
Control when OWF was closed	CPUE	n.s.	- 0.45	21.25
Treatment when OWF was open	LPUE	n.s.	- 0.20	18.12
Control when OWF was closed	LPUE	**< 0.0001**	**- 7.62**	**14.53**

Figures

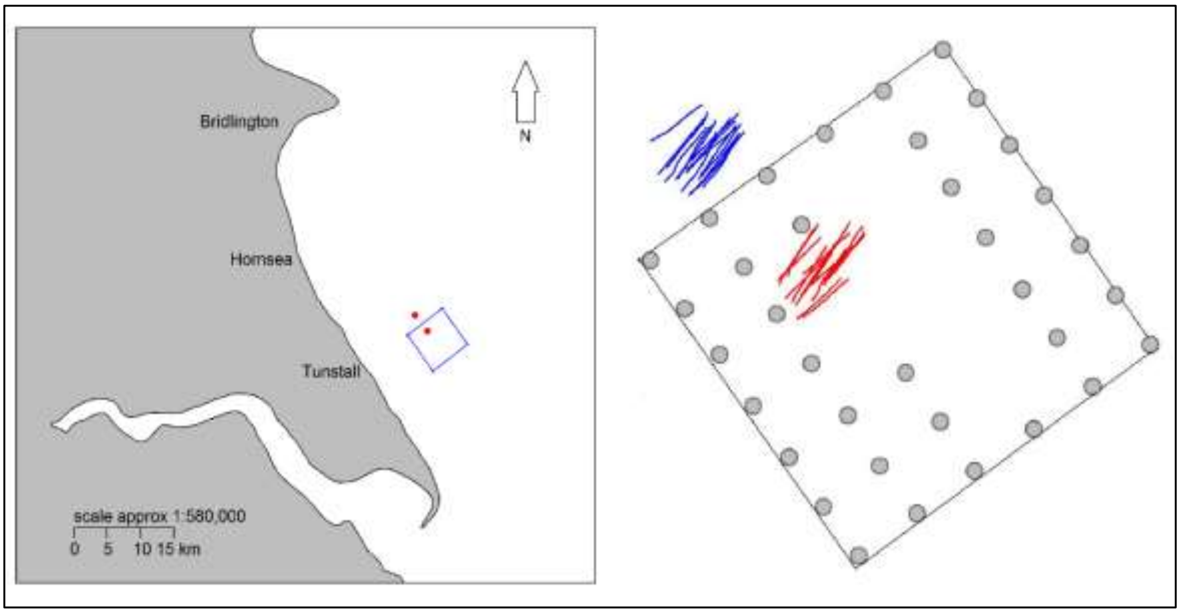

Figure 1: Location of the Westermost Rough OWF, the individual turbine locations marked in grey and the locations of the treatment strings (red) and the control strings (blue) to the North of the site.

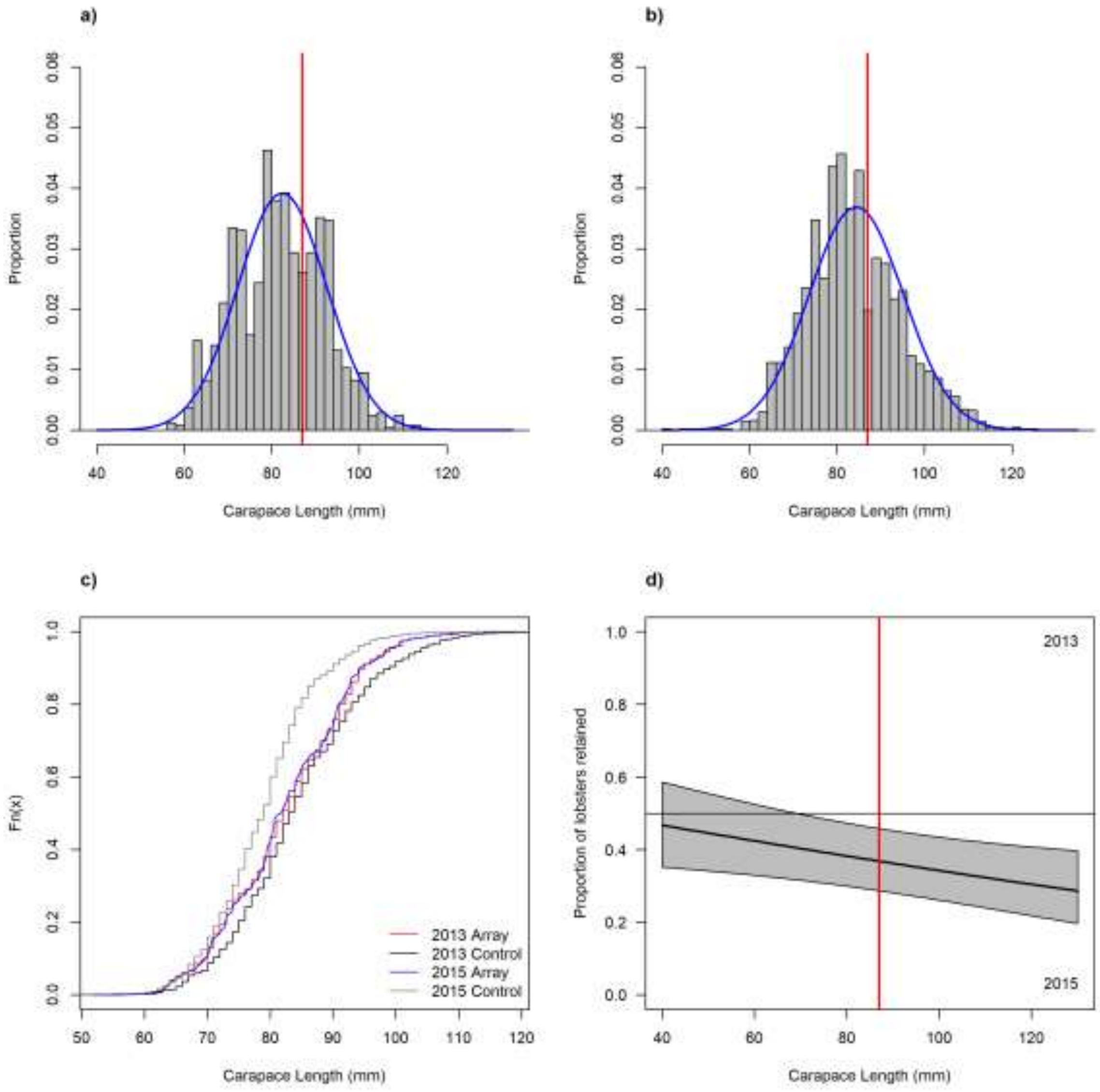

Figure 2: Size distributions of lobsters sampled within the Westermost Rough OWF for the baseline survey in 2013 (a) and the first-year post build survey in 2015 (b), both plots fitted with the density curve of the distribution and the bins set to 2mm carapace length. (c) Empirical cumulative distribution function (ECDF) for the sampled lobsters for the wind farm and control site in 2013 (red and black) and the wind farm and control site in 2015 (blue and grey). (d) Plot derived from GLMM modelling of the proportion of the lobsters sampled at each size in 2013 (top box) and 2015 (bottom box). The grey shaded areas represent the 95% confidence intervals and the bold black line the mean value. The central horizontal line

represents the 0.5 (50%) value, points overlapping this line indicate that there was no significant difference in the proportion of that sized animal between the two years. A value of 0.75 indicates that 75% of the lobsters sampled at that size were sampled in 2013 and the other 25% were sampled in 2015. This applies to all subsequent plots derived from GLMM analysis. The vertical line on all plots represents the minimum landing size of lobsters in the fishery which is 87mm carapace length. This applies to all subsequent plots reported.

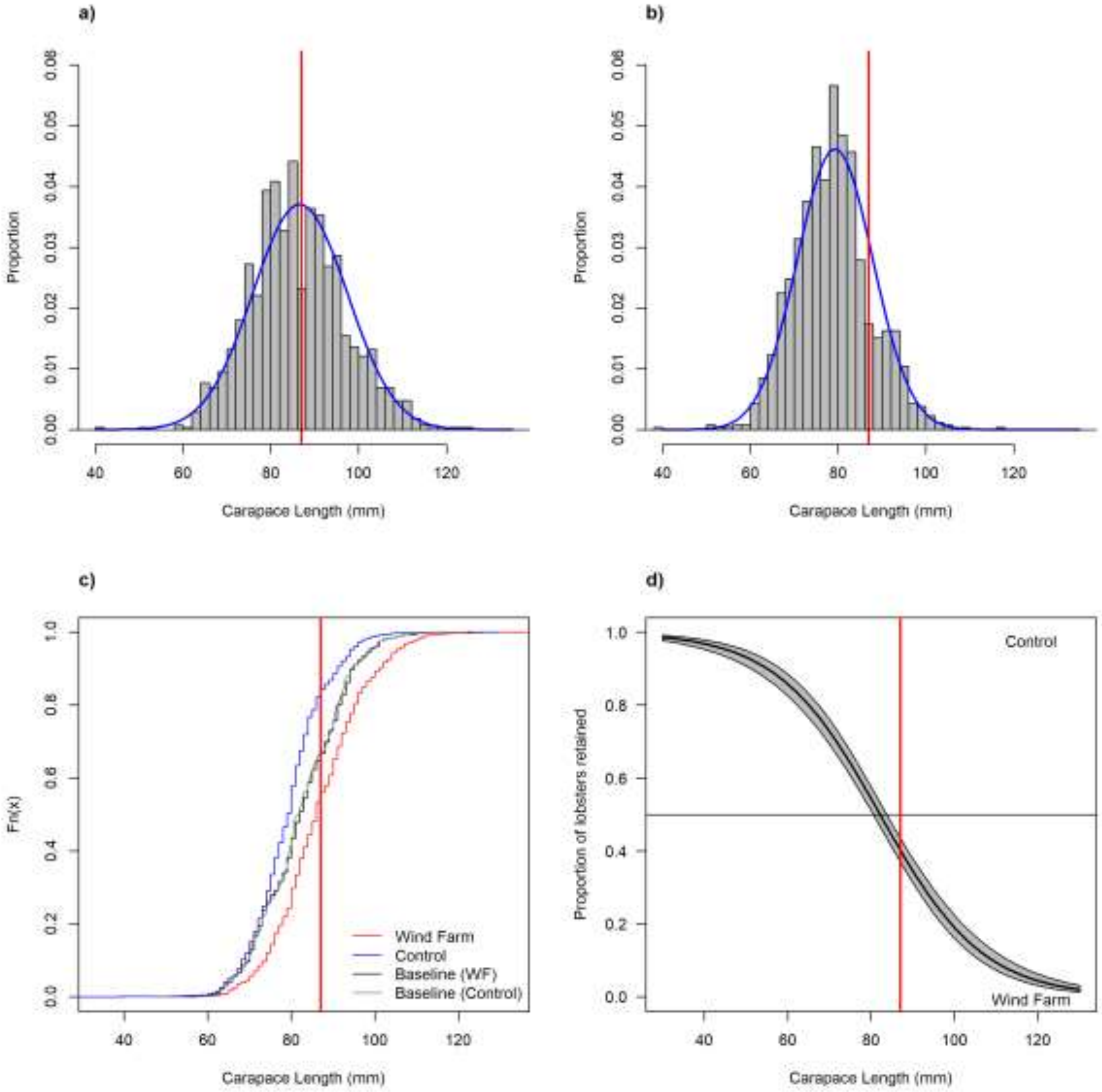

Figure 3: Size distributions of lobsters sampled at the Westermost Rough OWF for both the wind farm site (a) which was closed to fishing for the period and the control (b) which was subjected to fishing throughout the period. ECDF plot for the period before the wind farm site was opened to fishing showing the wind farm (red), control (blue) and baseline for the two sites (black (wind farm), grey(control) (c) and plot derived from GLMM analysis for both the control and wind farm site (d) for the period before the wind farm was opened to fishing.

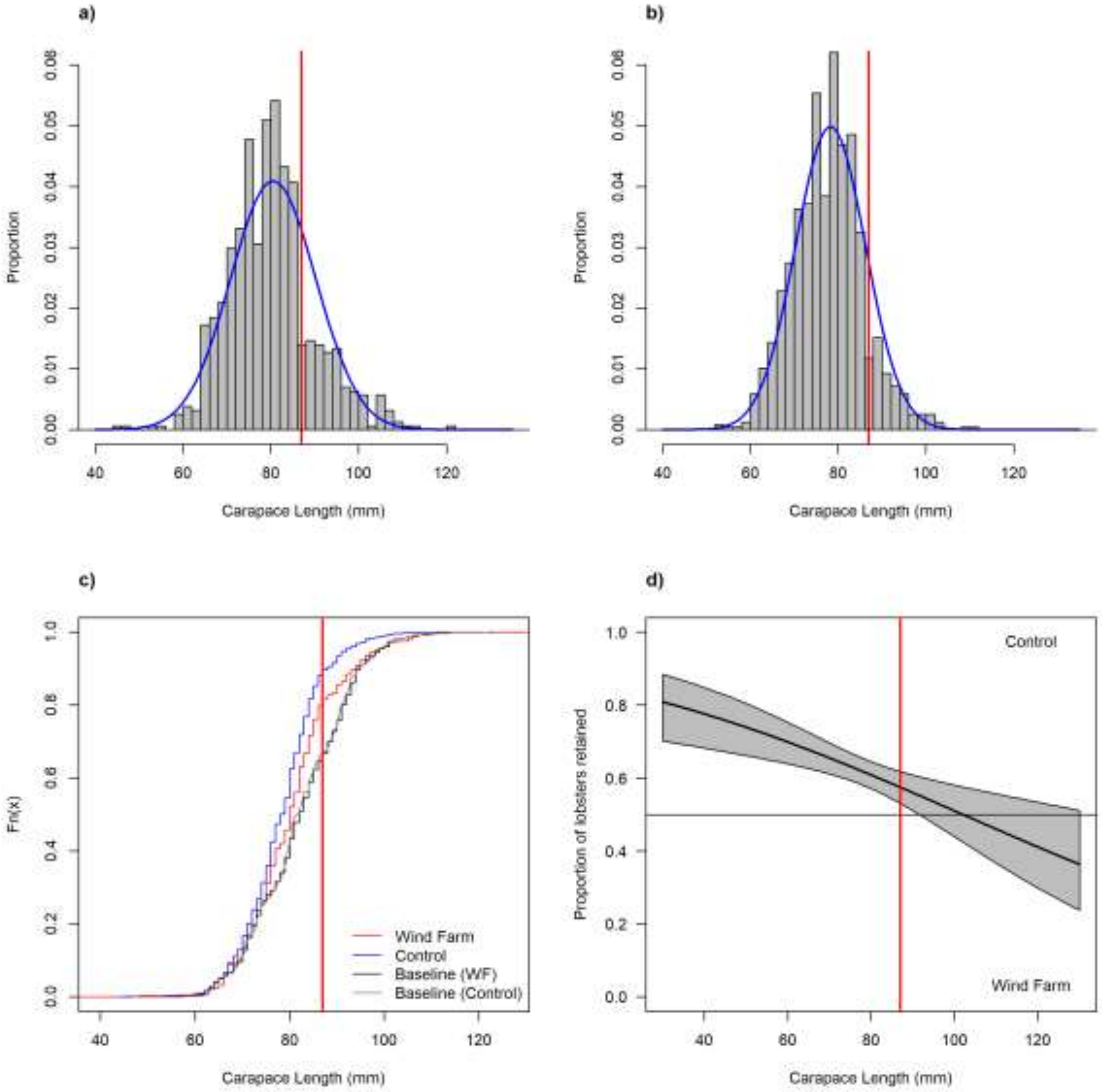

Figure 4: Size distributions of lobsters sampled at the Westermost Rough OWF for both the wind farm site (a) after the site was opened to fishing and the control (b) which was subjected to fishing throughout the period. ECDF plot for the period after the wind farm site was opened to fishing showing the wind farm (red), control (blue) and baseline for the two sites (black (wind farm), grey(control) (c) and plot derived from GLMM analysis for both the control and wind farm site (d) for the period after the wind farm was opened to fishing.

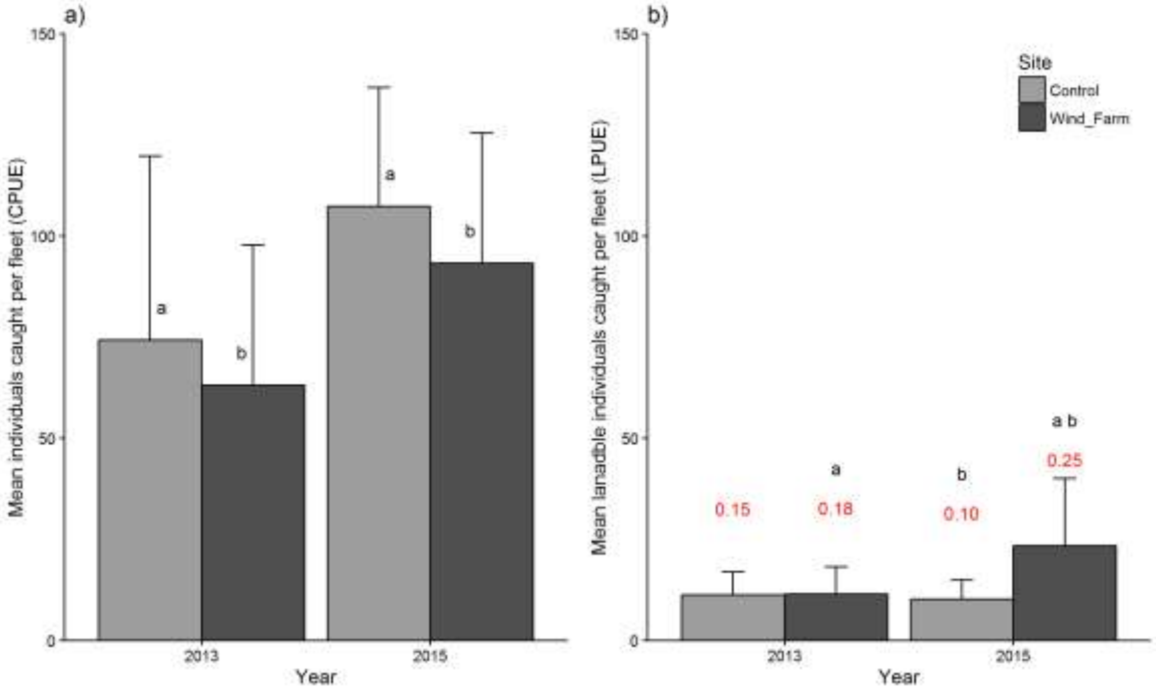

Figure 5: Mean catch per unit effort (a) and landings per unit effort (b) for the wind farm (dark grey) and the control site (light grey) for the baseline survey (2013) and the first-year post build survey (2015). The top of the bars represents the mean CPUE/LPUE and the error bars the standard deviation of the data. The values above the LPUE bars represent the ratio between CPUE and LPUE. The letters above the bars indicate the factors that showed a significant difference. This applies to all subsequent bar plots reported.

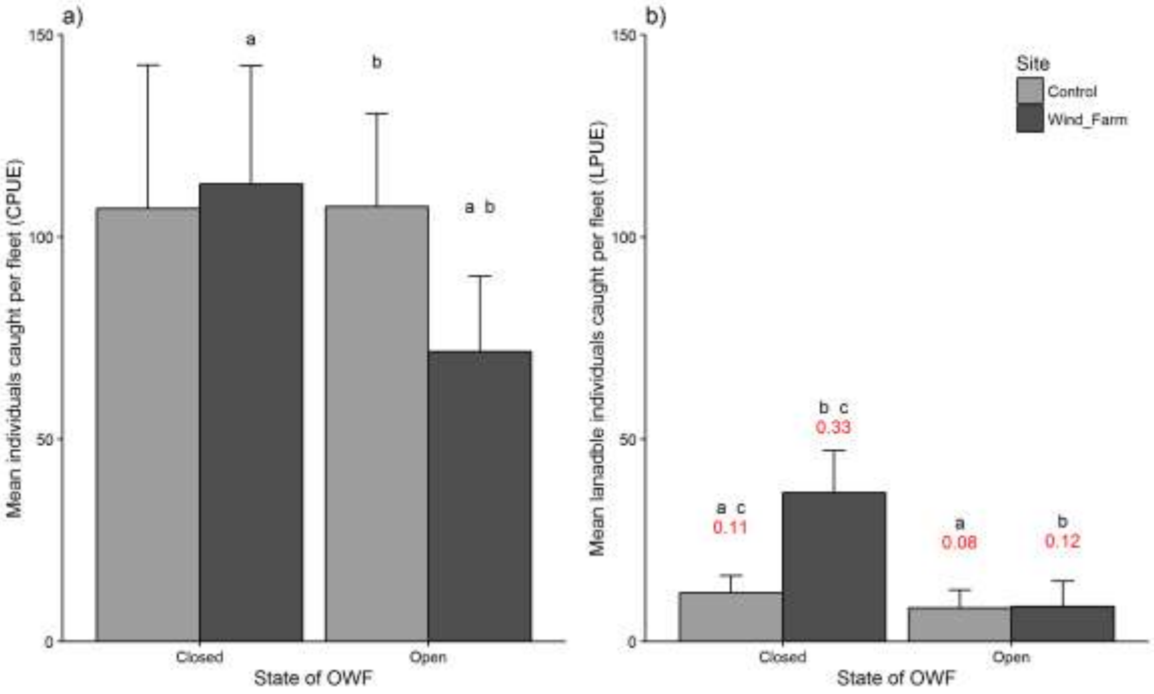

Figure 6: Mean CPUE (a) and LPUE from the wind farm (dark grey) and the control site (light grey) before and after the wind farm was opened to fishing exploitation.