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Sustainable co-location solutions for offshore wind farms and fisheries need to account for socio-ecological trade-offs

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Abstract

The spatial expansion of offshore wind farms (OWFs) is key for the transition to a carbon free energy sector. In the North Sea, the sprawl of OWFs is regulated by marine spatial planning (MSP) and results in an increasing loss of space for other sectors such as fisheries. Understanding fisheries benefits of OWF and mitigating the loss of fishing grounds is key for co-location solutions in MSP. For the German exclusive economic zone (EEZ) of the North Sea we conducted a novel socio-ecological assessment of fisheries benefits which combines exploring potential spill-over from an OWF with an experimental brown crab (*Cancer pagurus*) pot fishery and an economic viability analysis of such a fishery. We arrayed a total of 205 baited pots along transects from an OWF located near the island of Helgoland. After a soaking time of 24 h we retrieved the pots and measured the carapace width (mm), weight (g), and sex of each individual crab. To conclude on cumulative spill-over potentials from all OWFs in the German EEZ and drivers of passive gear fisheries we analysed vessel monitoring system (VMS)-data and computed random forest regressions. Local spill-over mechanisms occurred up to distances of 300 to 500 m to the nearest turbines and revealed an increasing attraction of pot fishing activities to particular OWFs. This corresponds to the observation of constantly increasing fishing effort targeting brown crab likely due to both a growing international demand and stable resource populations at suitable habitats, including OWFs. Our break-even scenarios showed that beam trawlers have the capacities to conduct during summer an opportunistic but economically viable pot fishery. We argue that particularly in the North Sea, where space becomes limited, integrated assessments of the wider environmental and socio-economic effects of planning are crucial for a sustainable co-location of OWFs and fisheries.

1. Introduction

The advancement of offshore wind farms (OWFs) is a response to increasing energy demands and a key pillar in the global transition to a carbon-free power sector (GWEC, 2019). In a European comparison, the North Sea region is designating the largest total surface area (20 000 km^2) to the current and future development of offshore renewables (Stelzenmüller et al., 2020). Hence, the North Sea ecosystem is exposed to progressing human pressures (Halpern et al., 2019), while facing drastic effects of climate change (Holt et al., 2012) on food web structure and functioning (Lynam et al., 2017), and the composition of fish communities (Dulvy et al., 2008; Engelhard et al., 2014; Frelat et al., 2017). This highlights the urgent need for an integrated marine management approach accounting for complex interlinkages and feedbacks in coupled human and natural systems (Visbeck, 2018). The spatial expansion of offshore renewables increasingly steers a debate regarding local and cumulative environmental and socio-economic effects for other human activities. Thus, within a given area OWF and fisheries are often mutual exclusive evolving in a reallocation of fishing activities to other areas (Stelzenmüller et al., 2015). Depending on the adaptive capacities of the affected fishing fleets, this could result in economic losses or even socio-cultural impacts for fishing communities (Stelzenmüller et al., 2020). Marine spatial planning (MSP) is an integrated management process that allocates human uses at sea according to planning activities (Zaucha and Gee, 2019). MSP should promote Blue Growth while maintaining ecosystem health, mitigate spatial use conflicts (Santos et al., 2020), and create synergies between sectors through the promotion of co-location solutions (Jentoft and Knol, 2014; Kyvelou and Ierapetritis, 2019). The terms “co-location”, “co-use” or “multi-use” are often used synonymously, but require a careful consideration of the spatial, temporal, provisional, and functional dimensions of the connectivity of uses (Schupp et al., 2019). In the North Sea region, national MSP processes foresee divergent measures regarding the co-location of fisheries and OWFs. While in the UK fishing with bottom contacting gear in OWFs is permitted, fishing activities are currently prohibited in OWFs and the respective buffer zones in the German exclusive economic zone (EEZ) (Stelzenmüller et al., 2016). The marine spatial plan of the German EEZ of the North Sea, implemented in 2009, was one of the first legally binding plans regulating primarily the allocation of marine transport, development of offshore renewables or aggregate extraction by the means of priority areas. At present, the plan is being revised and the evaluation process needed to account for both changing political priorities and progress towards the achievement of planning goals (Stelzenmüller et al., 2021). In particular, the fishing sector calls for potential new regulations regarding a co-location of passive gear fisheries e.g. targeting brown crab (*Cancer pagurus*) in the proximity of OWFs. The revised draft plan comprises adaptations of shipping routes, an increase in priority areas for offshore renewables, the adoption of marine conservation areas, and a priority area for Norway lobster (*Nephrops norvegicus*) fisheries (www.bsh.de). Further the draft plan mentions the potential for passive gear fisheries within the safety zone up to a distance of 300 m to the OWF. Developing measures to mitigate economic losses for fisheries remains a key challenge for most MSP processes (Kularatna et al., 2019).

Empirical knowledge on ecological and socio-economic implications of co-location solutions for OWF and fisheries is still sparse. The construction of OWFs comprising activities such as piledriving or removal of soft bottom habitats has caused a decrease of abundance of pelagic fish by 50 % and effected the behaviour and physiology of fish (Lüdeke, 2015; Methratta, 2020). Over time the introduction of hard substrates leads to changes in species compositions (Stenberg et al., 2015), food web structures and complexity (Mavraki et al., 2020). Fisheries benefits of OWFs could result from small and meso-scaled ecological effects such as an increase of biomass, abundance and size of fisheries resources around piles and turbine scour protections (Dannheim et al., 2019; Methratta and Dardick, 2019; Reubens et al., 2013) and a subsequent spill-over into the surrounding waters. While the spill-over of biomass and related fisheries benefits have been extensively studied for many marine protected areas (MPA) (Edgar et al., 2014; Vandeperre et al., 2011), the spill-over effects in the context of OWFs remain largely uncharted. In the southern North Sea, a spill-over of biomass might be expected for target species such as European edible crab or brown crab, brown shrimp (*Crangon crangon*), and European lobster (*Homarus gammarus*) due to enlarged opportunities for shelter and increased food availability (Ashley et al., 2014; Krone et al., 2017; Krone et al., 2013a).

Hence, artificial reef structures such as monopiles with a scour protection led to local increases of brown crab biomass with an estimated increase of 320 % in the German Bight (Krone et al., 2017). Passive gear fisheries targeting decapods seem to be most feasible to be combined with OWFs (Hooper and Austen, 2014). In the southern North Sea, a growing interest in a brown crab pot fishery with distinct and persistent fishing grounds over time has been observed (Stelzenmüller et al., 2016). Between 2008 and 2016, overall yearly catches of brown shrimp of the EU fleet have increased from about 34 thousand tons to almost 50 thousand tons, with the value of landings increasing even more (STECF, 2018). These figures suggest that the demand for brown crab is growing, thus justifying also a closer view on this type of fisheries.

Yet, a quantification of potential fisheries benefits of OWFs due to emerging resources such as brown crab is pending. Quantifying fisheries benefits entails both a sound knowledge of local ecological processes and functions and an assessment of socio-economic constraints of the fishing vessels engaging in such a fishery.

Taking the German EEZ of the North Sea as an example, we contribute to the urgently needed empirical evidence of potential fisheries benefits of OWFs and reflect on sustainable co-location solutions of OWFs and pot fisheries. Our integrated approach combines for the first time an experimental brown crab fishery in the vicinity of an OWF with a supply balance and economic viability analysis for fishing vessels targeting brown crab. Further we explored the cumulative brown crab spill-over potential by analysing spatio-temporal trends in passive gear fisheries in the proximity of OWFs in the German EEZ with the help of vessel monitoring system (VMS) data and random forest regression.

2. Methods

To answer our research question if fisheries can benefit from man-made structures such as OWF and to understand the potential implications for co-locating OWFs and fisheries we structured our methodological approach along the following themes: i) empirical evidence of brown crab spill-over from OWFs; ii) attraction of international pot fishing vessels to OWFs indicating spill-over potential; iii) European supply and demand of brown crab from the North Sea; and iv) break-even scenarios for fishing vessels deploying occasionally pots to target brown crabs.

2.1 Experimental brown crab fishery around an offshore wind farm

Brown crabs are nocturnal animals and opportunistic feeders preying on bivalves, gastropods, barnacles, echinoderms, bristle worms, and other crustaceans (Klaoudatos et al., 2013). They reproduce in winter with planktonic larvae (1 mm) and live on habitats with coarse sediment, mud or sand preferably at depth varying from 6 to 40 m. The size (carapace width) at first sexual maturity (around 3 to 5 years of age) differs for males (~110 mm) and females (~127 mm) and varies regionally (Klaoudatos et al., 2013; Tonk and Rozemeijer, 2019). Regional stock assessments for the southern North Sea revealed stable population sizes in consecutive years and regional exploitation rates are lying within recommended boundaries to maintain maximum sustainable yields (MSY level proxy is 35 % of virgin spawner per recruit (SpR) (CEFAS, 2017). The minimum landing size (MLS) for crabs in the North Sea south of 56°N is 130 mm (CEFAS, 2017).

The German EEZ covers a significant surface area that is known for an increased brown crab density in the southern North Sea (CEFAS, 2017). Estimates for the Dutch North Sea (which borders the German EEZ to the west) indicated a potential of 100 brown crabs per km^2 (Tonk and Rozemeijer, 2019). The international fishing activities in the German EEZ targeting brown crab with baited pots remain of marginal economic relevance and have been persistently limited to distinct areas between April and November (Klaoudatos et al., 2013; Stelzenmüller et al., 2016). Considering the characteristics of this fishery, we conducted experimental fisheries with baited pots targeting brown crabs along transects near the OWF Meerwind Süd/Ost. The OWF is in operation since 2015 and is located approximately 20 km off the island of Helgoland (Figure 1). The site encloses 80 turbines (monopiles with scour protection) at depths varying between 22 m and 27 m on sandy bottoms (see Figure 1). In 2019 (June and August) we positioned a total number of 205 pots baited with fresh mackerel (*Scombrus scombrus*) along transects at distances of approximately 50 m, 500 m, 1000 m and 1500 m to the nearest wind turbine on the eastern border of the wind farm. In total, we arrayed 41 pot fleets (five pots per fleet) with a tow length of 30 m between individual pots and 15 kg of ground weight at both sides. The actual mid-points of the respective fleet positions are shown in Figure 1. After a soaking time of approximately 24 h we retrieved the pots and measured the carapace width (mm), weight (g), and sex of each individual crab. We marked each animal with a bio-marker to enable a recognition of recaptures and released it in the direct proximity of the sampling stations. Further, we recorded at the 41 stations the water depth (m), sea surface temperature, bottom temperature, wind and weather conditions. For the subsequent statistical analysis, we standardised for each station the total biomass (kg), total number (N), sex ratio (male/female), and total biomass for brown crabs of the size classes < 130 mm and ≥ 130 mm for a soaking time of 24 h. For each of the 41 pot fleets we calculated size-based indices such as the minimum, maximum, and mean carapace width (mm) and its respective standard deviation. We computed linear regressions with distance to the nearest wind turbine (m) as explanatory variable to determine significant spatial trends in size, sex ratio and biomass.

2.2 Cumulative spill-over potential from offshore wind farms

We analysed spatio-temporal patterns of international pot fisheries to explore changes of patterns in fishing effort in the proximity of OWFs, suggesting a local spill-over mechanism of brown crab. Further, we evaluated the cumulative spill-over potential for the currently existing OWFs in the German EEZ. For this we compiled international VMS data from 2012 to 2019 comprising the vessel registration number, vessel position, and speed of fishing vessels with lengths greater than 12 m for the German North Sea. We first removed duplicated pings, pings with assigned speed values > 25 kn, and harbour pings except the last one using the VMStools package (Hintzen et al., 2012) for the software R 3.6.3 for statistical computing (R Core Team, 2019). Next, we matched vessel registration numbers of VMS data with the European fleet registry and filtered for vessels reporting pots as their primary or secondary fishing gear. We adopted the approach by Kroodsma et al. (2018) to identify continuous vessel tracks and exclude fragmented vessel tracks. Hence, we calculated geographical and temporal distances for each consecutive VMS ping of the same vessel and summed up half of the time from the previous to the current and the current to the following ping, respectively. We neglected pings with temporal intervals < 120 min, because it represents the longest interval for transmitting VMS signals among included flag nations. Next, we identified continuous data segments among vessel data pieces by assigning a new segment number when the geographical or temporal distance between consecutive pings was > 50 nm or 24 h. We kept only segments with a total number of pings ≥ 4. From the remaining pings assigned to fishing segments, which reflected individual fishing trips, we filtered in a last step only pings indicating fishing. We separated fishing from steaming pings with the *activityTacsat* function from the VMStools package. Note that we determined peaks for steaming and fishing speeds manually by inspecting speed histograms of each vessel and year before running the *activityTacsat* algorithm. To enable analyses of spatio-temporal fishing patterns, we calculated for each VMS ping the distance to the nearest boundary of an OWF with the sf package (Pebesma, 2018) for R. With the help of Arc Map (10.5.1) we associated the name of the nearest OWF, depth (m), and median grain size to each retained VMS ping. This enabled us to calculate total hours fished by summing up the time steps for different aggregation levels, such as month, year, distance range to the nearest OWF (km), depth range (m), vessel, or nearest OWF.

In a next step, we selected OWFs to which fishing effort could be associated in four successional years and grouped those by the year they went in operation (2012 and 2015). This allowed us to explore the spatial patterns and intensity of pot fishing activities in the vicinity of those OWFs. To further explore the relationship between the fishing intensity (annual total hours fished) by the respective vessels and the explanatory variables (year, proximate OWF, distance to turbine, depth and median grain size) we applied random forest (RF) regressions (Breiman, 2001) with the R package randomForest (Liaw et al., 2015) for fishing activities at distances < 15 km to the nearest OWF. RF is a supervised machine learning technique based on regression tree methodology. It predicts a response variable from a number of explanatory variables by recursively subdividing a dataset into subgroups (Hastie et al., 2009). Partitions are achieved by two means: (1) a random selection of explanatory variables to grow each tree and (2) each tree is based on a different random data subset, created by bootstrapping. We divided the data in a training subset (70 %; in-bag data) to develop the tree and prediction rules, whereas the out-of-bag data (30 %) provided estimates of the generalization error. The rank importance of each explanatory variable was measured as the change in mean square error estimated by leaving a variable out of the model. We further computed partial dependence plots to explore the relationships between individual explanatory variables and annual fishing effort.

2.3 European supply and demand of brown crab from the North Sea

To gain an overview of the European supply and demand of brown crab from the North Sea we calculated supply balances by accounting for the domestic supply (catches + import) and the amount of apparent consumption (available raw material of brown crab). Hence, we adopted the approach of the European Market Observatory for Fisheries and Aquaculture Products and calculated the apparent consumption of brown crab as national catches + import – export (t) (EUMOFA, 2019a). For catches we included all brown crabs caught by a country's fleet, independently from the area of landing and we extracted respective catch data as net weight (t) from Eurostat (www.appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do; fish_ca_main). To balance the data we converted net weights into live weight equivalents using the conversion factors provided by EUMOFA (EUMOFA, 2019b). We defined international trade as imports and exports (Eurostat, 2016). However, differences in concepts and definitions of the countries, as well as dissimilar reference periods due to transport times led to asymmetries between data the importer of one country and the exporter of another country. Therefore, we used only data on import to show the interactions between the major actors within Europe. Since the international trade of brown crab comprised mainly the UK, Ireland, France and Spain, we focused on those countries and we defined the remaining countries as "others". In addition, we considered export data to China. We further simplified the trade between the main countries by offsetting when a trade was < 5 t, and when the trade volume between major actors and "others" was < 100 t.

2.4 Economic viability of an occasional brown crab fishery

An increasing stock of brown crab might provide fishing opportunities also for vessels which regularly target on other species. We identified German beam trawlers with a length of about 24 m targeting mainly brown shrimp as being capable to conduct a brown crab fishery. Entering a pot fishery would require only modification of on-board equipment, but no quota acquisition. Here we assessed the economic viability of this option based on the assumption that a brown crab fishery would take place only at times when a brown shrimp fishery is regarded inefficient, thus when the only alternative option would be to stay in the port. To assess the specific contribution margin we disregarded fixed costs and considered only fishing costs directly linked to a brown crab fishery. We derived the cost structure of German beam trawlers (18 and 24 m) targeting brown shrimp from the annual economic report on the EU fishing fleet, AER (STECF, 2019a) (Table 3). In a subsequent step, we modified the cost and effort data in case the fleet segment is deploying pots targeting brown crab (Table 3). Further, we anticipated a total investment of 65,000 € for pots, winch, containers and vessel modification (pers. comm. Christian Janhsen). The useful life of these assets is set to five years, resulting in an annual depreciation of 13,000 €. Variable costs (excluding personnel costs) were estimated at 330 € per day. Personnel costs were estimated at 22 % of the revenue (crew share).

Based on these figures, we computed the daily break-even revenue (BER). When assuming that neither fixed costs nor opportunity costs apply and interest rates are disregarded due to their low level, only variable costs and annual depreciation (DEP) for the investment in equipment for crab fishing has to be considered for the break-even analysis. Then the BER is the sum of DEP and the variable costs. The sum of depreciation and variable costs (excluding personnel costs) was increased by the crew share to account for personnel costs in the break-even case.

Garrett et al. (2015) reported prices of up to 4 € per kg brown crab landed in Spain and France with catches of specialized vivier vessels varying between 13 to 14 tons a week (in 2013). However, vivier vessels are highly specialized and retrofitted beam trawlers are unlikely to achieve comparably high catch rates. The 2018 AER revealed that average prices (2008 - 2017) for brown crab landings varied significantly between countries (STECF, 2018). The prices were highest in Denmark (3.31 €/kg), followed by the UK (1.60 €/kg) and Ireland (1.23 €/kg). In contrast, German vessels sold only at 0.66 €/kg. Therefore, we calculated break-even scenarios for prices ranging from 0.66 to 3 € per kg landed brown crab.

3. Results

3.1 Spatial pattern of experimental brown crab catches

We sampled a total number of 792 brown crabs (males: 655; females: 137) with carapace width ranging from 69 to 225 mm and an overall mean width of 152 mm (+/-26.4 mm) (Appendix A). The frequency distribution of the respective carapace width (mm) for male and female with the corresponding mean width (females: 135 mm (+/- 21.92 mm); males: 156 mm (+/- 25.87 mm) is shown in Appendix A. We observed an overall sex ratio of 4.8 in favour of males. Out of the 137 females a total number of 39 (29 %) were below the size of first sexual maturity (127 mm; Tonk and Rozemeijer, 2019). In contrast, only a total number of 22 (3.4 %) of the 655 males were below the respective size of first sexual maturity (110 mm; Tonk and Rozemeijer, 2019). The frequency distribution indicates a normal distribution of carapace width of female, but a slightly skewed distribution for females. In addition, the frequency distribution shown in the Appendix A shows that the majority of the caught brown crabs were above the MLS of 130 mm. Our experimental set up led to a mean catch per unit effort (cpue) of 9 kg·24h^{-1} (+/- 3 kg·24h^{-1}) at distances between 213 and 2650 m to the wind turbines. The prevailing conditions in terms of sampling depth, surface and bottom temperature were relatively constant with a mean depth of 23 m and bottom temperatures of approximate 14 °C in June and 18 °C in August. Overall, we found a significant decrease of catches in biomass, numbers, males and individuals ≥ 130 mm with increasing distance to the turbines (Table 1 and Figure 2). Although the trend was statistically not significant (p-value of 0.13, see Table 1), we found the highest cpue of brown crabs < 130 mm up to a distance of 300 m to the turbines, pointing to the functioning of turbines with scour protection as potential nursery areas of brown crab. Our results revealed clear differences in spatial patterns of female cpues and maximum carapace width between the stations sampled in June and August (Figure 2). Hence, in August cpues of females almost doubled at distances ranging from 600 to 1100 m. This was on a par with increases of both minimum width and cpues of brown crabs < 130 mm at corresponding distances. Hence, these results indicate a clear shift in carapace width fractions of females within only a couple of weeks during summer time.

3.2 Cumulative spill-over potential from offshore wind farms

We identified a total number of 32 993 VMS pings affiliated to pot fishing within the German EEZ and adjacent coastal waters (2012 to 2019). From those pings, 91 % were connected to UK vessels, 5 % to Irish vessels, 2 % to German vessels, and the remaining 2 % showed an equal share of fishing between Polish and Danish vessels. Only six vessels (5 UK vessels, 1 Irish vessel) made up for 97 % of the overall detected pot fishing activities. Effort peaked during the summer months across all years and increased by 400 % from 2012 to 2019 (Appendix B). Comparing the annual fishing effort at various distance classes (< 5 km, 5-10 km, 10-20 km, 20-30 km, and > 30 km) to the nearest OWF (km) revealed that annual fishing effort increased across all distances to the OWF (Figure 3). Further, over time most effort was allocated at distances > 30 km to the nearest OWF, while at distances < 5 km the effort increased from 2017 onwards to levels which were comparable to other distance classes. Figure 3 revealed that the annual fishing effort was general highest at depths ranging from 30 to 40 m. The retained OWFs being in operation since 2012 comprise DanTysk, Global Tech I, Meerwind Süd/Ost, Nordsee Ost, Riffgat and Trianel Borkum (Figure 4, top). The fishing activities associated to Dan Tysk and Gobal Tech I took constantly place at distances beyond 30 km reflecting rather the increased suitability of the naturally prevailing habitats. Interestingly, the fishing effort associated to Meerwind Süd/Ost increased over time and converged towards the OWF, where we conducted our experimental brown crab fishery. The same observation holds for Nordsee Ost and Riffgat. The OWFs being in operation since 2015 encompassed Amrumbank West, Borkum Riffgrund 1, Gode Wind 01 and 02, Nordsee One and Sandbank. The observed fishing patterns around Gode Wind 01 and Gode Wind 02 could indicate a displaced pot fishery which now benefits from fishing in the closer proximity of an OWF (Figure 4, bottom). One striking observation was that the fishing activities around Borkum Riffgrund 1 occurred after the OWF has been constructed, indicating a potential fishery benefit through spill-over of brown crab.

Based on the observed patterns of the pot fishing activities in the proximity of the OWF and the results of our experimental pot fisheries, we defined four archetypes of spatial patterns of pot fishing activities in the vicinity of an OWF (Figure 5). Figure 5 shows that a potential spill-over effect of brown crab could manifest in increased catches up to a distance of 5 km from OWFs (dark green zone). Thus, recurrent pot fishing activities taking place at such distances might indicate spill-over effects. On the contrary, we assumed that spill-over effects would not manifest at distances greater than 10 km to an OWF. The archetypes distinguish cases where e.g. previous pot fisheries have been displaced from an OWF area and recurred within a distance of 5 km, hence indicating rather suitable habitats for brown crabs. We described also a model where pot fisheries took place in the OWF proximity only after the OWF has been constructed, pointing to potential spill-over mechanisms.

The random forest models of fishing effort around the two groups of OWFs (OWFs in operation since 2012 and 2015) explained 24 % (OWF2012) and 19 % (OWF2015) of the variance and revealed a rank importance of the variables potentially driving the allocation of fishing effort (Appendix C). The rank importance (% IncMSE), representing the increase of the mean squared error when a given variable is randomly permuted, showed that the fishing effort around the OWF being constructed until 2012 was mainly determined by the explanatory variables year, location (associated OWF), and depth. Hence, the allocation of fishing effort has not been triggered by the proximity of these OWFs. In contrast, the fishing effort around OWFs being in operation since 2015 showed a deviating rank importance with median grain size, distance to the OWF, and location (associated OWF) being the most important variables. This points to the fact, that fishing effort could have been attracted by those respective OWFs due to increased brown crab abundances.

3.3 European supply balances and economic viability analysis

Total brown crab catches from the North Sea ranged from 40 000 to 47 100 t between 2010 and 2017. The supply balance analysis showed that in 2017 brown crab catches of UK, Ireland, France and

Spain summed up to 43 373 t, whereby the UK alone contributed the largest share of 32 410 t (Figure 6). The UK exported nearly one third of the catches and, considering small amounts of imports, the national apparent consumption was 22 326 t. By far, Spain had the smallest share of catches (61 t), these are usually by-catches. Due to an import of 3 945 t of brown crabs the Spanish apparent consumption was 3 688 t. In contrast, in France the apparent consumption was nearly three times higher, based on domestic catches of 4324 t, and imports of 7481 t received in equal parts from the UK and Ireland. Export markets to Asia, especially to China, Hong Kong, Taiwan and Vietnam are constantly growing. In 2017 the UK exported 2722 t and Ireland 909 t brown crab to China.

Figure 7 illustrates the daily BER and corresponding catch for different price (€·kg^{-1}) scenarios for landed brown crab. The variable costs per day of a beam trawler (61 gross tonnes) targeting brown crab add up to 330 €·d^{-1} (61 × 5.4 €·d^{-1}; see Appendix D), excluding crew costs. With an annual depreciation of 13 000 € and crew costs as a 22 % share of the revenue the estimated crew costs result in 73 €·d^{-1} ((13.000 € × 0.22) + (330 €·d^{-1} × 0.22)) for the break-even case (Appendix D).

The annual BER is 403 € per day plus 16 667 €. Our break-even scenarios suggest that even in the case of high prices (3 € kg^{-1}) and a fishing period of 30 days per year the daily break-even catch is about 300 kg. If the price is about 1 € kg^{-1} and only ten fishing days can be assigned to brown crab fishing, then a daily catch of about 2.000 kg is necessary to cover variable costs and depreciation on crab fishing investment (Figure 7).

4. Discussion

We observed local spill-over mechanisms of brown crab from an OWF in the southern North Sea and demonstrated a patchy, but increasing attraction of pot fishing activities to OWFs. At the same time, we showed that the international fishing effort targeting brown crab enlarged gradually over the past years due to an increasing demand and stable resource populations at suitable habitats, including OWFs. Hence, we illustrate that under these conditions brown crab fisheries benefit from the rapid expansion of OWFs. The German fishing sector has not yet embraced these new fishing opportunities, but would have the capacities to conduct economically viable pot fisheries. We highlight that a comprehensive understanding of fisheries benefits due to the presence of OWFs requires combing knowledge about ecological effects on fisheries resources with socio-economic effects on the fishing fleets. Our study provides an urgently needed integrated assessment of socio-economic and ecological implications of MSP with offshore renewables and fisheries and sheds light on key requirements for an ecosystem-based planning approach.

4.1 Spill-over and implications for co-locating fisheries and OWF

The environmental conditions across the experimental fishing sites around an OWF were fairly stable, however, they were not directly located on known suitable habitats for brown crabs. Therefore, we assume that the observed spatial patterns of enlarged catches and sizes of brown crabs closer to the monopiles with a scour protection reflect both the increased availability of suitable artificial habitats and a spill-over mechanism. Since we performed our sampling during summer time, it is however important to note that the catchability between male and female differed since egg carrying females are burying in soft sediments (Tonk and Rozemeijer, 2019). In close proximity (~ 300 m) to the foundations our catches of brown crab with a carapace width < 130 mm were highest, pointing to the potential functioning scour protections as nursery area. This agrees well with existing observations (Krone et al., 2017; Krone et al., 2013b), describing OWFs as nursery areas for brown crab and the importance of OWFs to enhance local populations. Our results emphasised also the importance of the increased water temperature, hence the timing of sampling. The measured minimum carapace widths at distances > 500 m to the turbines increased clearly from June to August, as well as the relative biomass of female crabs. In contrast, the maximum carapace widths sampled at such distances decreased from June to August. Thus, larger carapace widths could reflect individual growth. In addition, migration and therefore the mobility increases with increasing water temperatures which could explain the enhanced catches of females in August (Woll and Ålesund, 2006). The decreased catches of larger individuals in August could point to an increased fishing mortality. The latter is supported by our analysis showing increased fishing effort in the third quarter of a year with August as one of the months of highest pot fishing intensities. The observed spatial patterns and trends in catches and sizes are relevant when advising MSP processes on how to regulate a sustainable co-location of fisheries and OWF. Pot fisheries are well suited for co-location solutions since pots do not disturb the seabed (Kopp et al., 2020) and therefore the risk to damage cables or other OWF infrastructure is low. Co-location solutions could also comprise temporal regulations where for instance pot fisheries is permitted up to 200 - 300 m to the foundations during summer or regulations for gear setting to avoid ghost fishing in the case of lost gear. For an OWF this would give planning security in the sense that e.g. maintenance involving increased ship traffic could be scheduled to minimise collision risk due to increased shipping activities. To keep local brown crab populations stable in the long term, fishing activities might be restricted in the OWF buffer zone during the first and second quarter of a year, while in July and August fisheries is permitted. The implementation of co-location solutions could also address regulations for OWF regarding the type foundations and scour protections to maximise the potential ecological benefits (Dannheim et al., 2019). The joint engagement of sectors in developing co-location solutions in MSP is to some extent an analogy to co-designing adaptive management and marine conservation measures (Christie et al., 2016).

4.2 Understanding trends of fishing activities in the vicinity of OWF

We showed that OWFs, being in operation since 2015, attracted pot fishing activities. These might be caused by general increasing brown crab abundance together with the newly established local populations as a result of the suitable artificial habitats. On the other hand, an increased fishing effort could also be linked to an overall upsurge of demand. The particular OWF sites (since 2015) represent rather new habitats for brown crabs since they are not located close to the persistent pot fishery hot spots (Stelzenmüller et al., 2016). But these OWFs are located in closer proximity to the coast and important fishing ports, hence being more attractive fishing grounds from an economic cost-benefit perspective. Based on our results we defined archetypes of fishing patterns indicating both new fishing activities and recurrent pot fisheries, which has been displaced due to construction activities. Overall, our analysis illustrated cumulative effects of biomass spill-over and confirms rising fishing opportunities and fisheries benefits. Still, we demonstrate also that spill-over effects cannot be generally assumed for a given OWF. Future studies focussing on cumulative spill-over potential of OWFs should put more attention on additional factors, i.e. habitat and foundation types, and prevailing fishing effort of both passive and trawled gears. We assessed the cumulative spill-over potential with the help of VMS data. Separating fishing from steaming pings encompasses a remaining uncertainty with regards to the correct categorisation.

4.3 Trends of demand and supply for brown crab from the North Sea

The demand and supply of brown crab from the North Sea showed striking differences in the apparent consumption between countries. Results should be treated with care and be used in relative terms instead of absolute terms (EUMOFA, 2019b). But, these differences are likewise reflected by country specific processing chains of brown crab. Basic and advanced processing takes place in UK and Ireland, e.g. white, brown or mixed meat, fresh, frozen or canned and produced pates, paste or crab cakes. As opposed to France and Spain, where only little or even no substantive processing (e.g. cooked as whole, preparing of claws) is taking place. This mirrors apparent differences in the consumption behaviour. In the UK and Ireland processed products are being preferred, while in Spain and France fresh and unprocessed, even alive crabs are favoured. Hence, in France live crabs are an indicator for quality and freshness of crabs (Garrett et al., 2015). In Spain, consuming brown crab is often combined with social events or special occasions such as Christmas or weddings. Overall the increasing export to China suggests that brown crab remains a profitable fisheries resource. This is also confirmed by current research focusing on the optimisation of long-distance transports of living crabs, hence allowing those products to enter the Chinese market (Ben-Asher et al., 2020).

4.4 Economic trade-offs of brown crab fisheries

A break-even analysis based on assumed catches and revenues allows for a first assessment of economic opportunities for pot fisheries. German beam trawlers with a length of about 18 - 24 m usually targeting brown shrimp could take advantage of brown crab fishing opportunities. These vessels almost exclusively target brown shrimp. This fishery is characterized by substantially fluctuating catches and prices and, as a consequence, shows highly volatile profitability (STECF, 2019b). Our break-even scenarios for German beam trawlers indicated that fishing on brown crab can be a promising alternative to staying in the port in times when brown shrimp fishery is unprofitable. Going one step further and combining our results from the experimental pot fishery with the break-even analysis suggests that a catch of at least 300 kg·d^{-1} could be achieved when approx. 150 pots are deployed, assuming an average catch of 10 kg per fleet of 5 pots. Such a catch seems feasible and to be profitable it would require at least 15 days of fishing. On average in summer the brown shrimp fishery is unprofitable since the main fishing seasons is between March and July (Schulte et al., 2020). Therefore, German beam trawlers would have the adaptive capacity to target brown crab for a limited time in summer to compensate socio-economic losses or even generate additional revenues. Comparing roughly the value of the international landings of other species from the wider experimental fisheries study area (STECF, 2018; ICES rectangles 37F7 and 38F7) revealed that brown crab ranked third (~2.6 Mio €) after brown shrimp (~8.2 Mio €) and sprat (*Sprattus sprattus*; ~6.4 Mio €). Hence, the value of these brown crab landings were almost three times higher than the one of sole (*Solea solea*). This underlines the local potential for this fisheries resource.

5. Conclusions

The development of offshore renewables such as OWF in the North Sea is spurring the conflict potential with other sectors and in particular with fisheries. When space becomes limited, it is key for MSP to understand adaptive capacities of fishing fleets to offset the increasing loss of fishing grounds and accessibility of resources. Expected long term fisheries benefits of OWF as well as the fear of further losses of fishing resources due to e.g. climate change, Brexit, or further spatial constraints and regulations are the main reasons for the fishing sector to call for a more integrated regulation through MSP. For the German EEZ of the North Sea we illustrated that a brown crab fishery in the vicinity of OWF as a second pillar could be economically viable and could lower the susceptibility to risk by diversifying fishing activities. Our integrated assessment approach exemplifies that co-location solutions between these sectors should be built on a sound knowledge of ecological processes such as spill-over mechanisms as well as socio-economic constraints of respective fishing fleets. We argue that co-location solutions should follow the example of a cross-sectoral co-design of management options. Our results showed also that spill-over potentials of brown crabs differ according to the environmental setting of an OWF, therefore a bottom-up or micro-planning for co-location solutions would be most effective to establish sustainable co-location solutions. This could also entail measures for future OWFs regarding the design of foundations with scour protection to support e.g. settlement of benthic communities or the decommissioning of OWFs. Advising MSP processes on long-term adaptive capacities of fisheries requires more future research on the ecological effects of OWF including studies on local and regional shifts of food webs. Taken together we conclude that MSP processes with offshore renewables and fisheries require integrated and evidence-based assessments of the wider environmental and socio-economic effects of the plan and its measures.

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Table 1: Results of the linear regression models as intercept, coefficient (b), degrees of freedom (df), R square (R^2), adjusted R square (R^2 adj), value of the F statistic (F), and p-value for the different response variables and time periods (June & August = 41 stations; June = 21 stations) with distance to the nearest turbine (m) as explanatory variable. Significant models (p-value < 0.05) are indicted in bold. Note that the sampling positions in August comprised only stations with a minimum distance to the nearest turbine > 500 m.

Response variable	**Period**	**Intercept**	**b**	**df**	**R^2**	**R^2adj**	**F**	**p-value**
Cpue (kg·$24h^{-1}$)	June &August	13.16	-0.01	31	0.26	0.24	11.13	**0.00**
Cpue (N·$24h^{-1}$)	June &August	18.96	-0.01	31	0.16	0.14	6.09	**0.02**
min width (mm)	June &August	101.77	0.02	31	0.06	0.03	1.85	0.18
max width (mm)	June &August	215.31	-0.04	31	0.38	0.36	18.75	**0.00**
Cpue $_F$ (kg·$24h^{-1}$)	June &August	0.83	0.00	31	0.01	-0.03	0.16	0.69
Cpue $_M$ (kg·$24h^{-1}$)	June &August	12.85	-0.01	31	0.41	0.39	21.33	**0.00**
Cpue $_{\geq 130\ mm}$ (kg·$24h^{-1}$)	June &August	13.32	-0.01	31	0.39	0.37	20.13	**0.00**
Cpue $_{< 130\ mm}$ (kg·$24h^{-1}$)	June &August	0.72	0.00	31	0.00	-0.03	0.00	0.96
Cpue (kg·$24h^{-1}$)	June	12.28	0.00	19	0.11	0.06	2.36	0.14
Cpue (N·$24h^{-1}$)	June	19.39	-0.01	19	0.19	0.15	4.54	**0.05**
min width (mm)	June	106.77	0.00	19	0.01	-0.04	0.21	0.65
max width (mm)	June	199.39	0.00	19	0.01	-0.04	0.15	0.70
Cpue $_F$ (kg·$24h^{-1}$)	June	0.78	0.00	19	0.00	-0.05	0.04	0.85
Cpue $_M$ (kg·$24h^{-1}$)	June	12.54	-0.01	19	0.26	0.23	6.84	**0.02**
Cpue $_{\geq 130\ mm}$ (kg·$24h^{-1}$)	June	12.75	-0.01	19	0.25	0.21	6.35	**0.02**
Cpue $_{< 130\ mm}$ (kg·$24h^{-1}$)	June	1.11	0.00	19	0.11	0.07	2.44	0.13

Figure legends

Figure 1: Top panel: Median grain size distribution in the southern North Sea together with the location and status of offshore wind farms within the German EEZ and adjacent coastal waters (4COffshore.com, last update 2018). Note that the grain size distribution is shown in the Wentworth scale where the grain diameter (d) is calculated as $\log_2(d)$. The greater the values the smaller the actual grain diameter (e.g. sand < 4 > silt) (www.coastmap.hzg.de). The OWF areas are located at depth ranging from 10 to 50 m; mid panel: water depth (m) and OWFs being in operation, under construction or licensed; bottom panel: Location of turbines (grey dots) within the offshore wind farm Meerwind Süd/Ost and sampling stations (black dots).

Figure 2: Results of the non-linear regression of total catch of brown crab standardised by 24 h soaking time as biomass (top left), numbers (top right), biomass of females (second from top left), biomass of males (second from top right), minimum (second from bottom left) and maximum (second from top right) carapace width (mm) sampled at a station, and biomass of brown crab with a carapace with < 130 mm (bottom left) and ≥ 130 mm (bottom right) as a function of distance to the nearest wind turbine (m; maximum distance ≤ 1500 m); the dashed line indicates the 500 m buffer zone around the sampled offshore wind farm and the shaded area designates the 95 % confidence level.

Figure 3: Time series of total annual fishing effort (h) per distance to nearest offshore wind farm class (< 5 km, 5-10 km, 10-20 km, 20-30 km, > 30 km) and depth range (m).

Figure 4: Time series of annual mean distance (km) of the total fishing effort (black dots) allocated to the respective OWF. The vertical lines indicate the fishing restrictions due to the presence of the OWF since 2012 (top) and 2015 (bottom) and the horizontal line indicates that at distances > 10 km fisheries benefits due to the spill-over of brown crab is not very likely (see Figure 6).

Figure 5: Four archetypes of potential fishing patterns of passive gear fisheries targeting brown crab in the vicinity of an offshore wind farm (OWF). The vertical grey line indicates the beginning of fishing restrictions due to the construction of an OWF. The distance of 5 km to the OWF indicates the potential area (dark green) where a spill-over of brown crabs might results in increased catches. The

grey dashed line indicates a fishing patterns at distances > 10 km which cannot be related to potential fisheries benefits of OWF (grey zone).The black line reflects an attraction of fishing effort by an OWF after its implementation; the grey line represents recurrent fishing activities after displacement, indicating rather a suitable habitat than a potential spill-over mechanism; the black dashed line designates attracted fishing effort due to expected fisheries benefits (spill-over); the grey dashed lines represent fishing activities which cannot be related to the presence of an OWF.

Figure 6: Illustration of relative catches and apparent consumption of brown crab in UK, Ireland, Spain and France and trade between these, “others” and to China in tonnes live weight equivalent.

Figure 7: Simulated daily break-even catches for different price scenarios for brown crab.

Figure 1

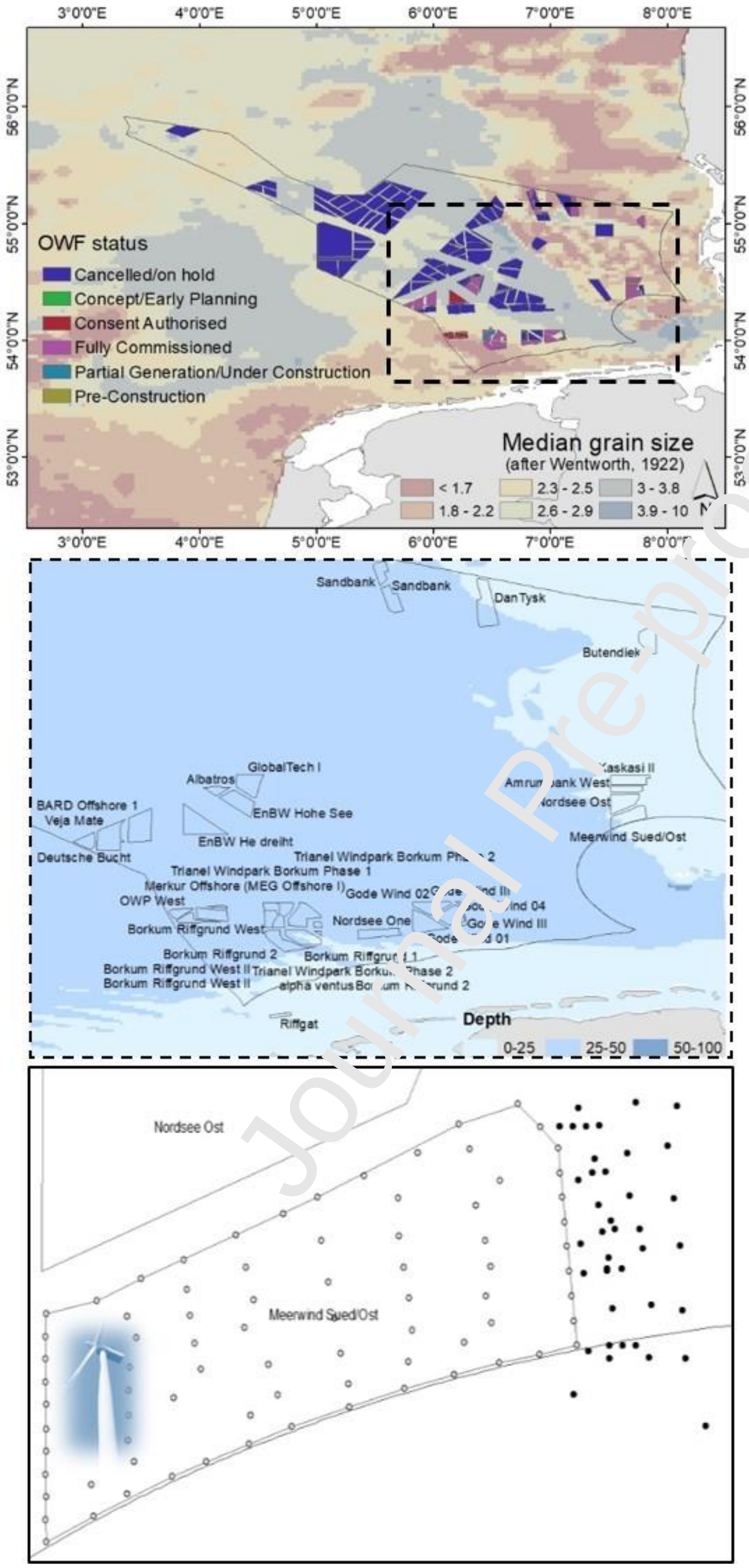

3°0'0"E
4°0'0"E
5°0'0"E
6°0'0"E
7°0'0"E
8°0'0"E
56°0'0"N
55°0'0"N
54°0'0"N
53°0'0"N
OWF status
Cancelled/on hold
Concept/Early Planning
Consent Authorised
Fully Commissioned
Partial Generation/Under Construction
Pre-Construction
Median grain size
(after Wentworth, 1922)
< 1.7
1.8 - 2.2
2.3 - 2.5
2.6 - 2.9
3 - 3.8
3.9 - 10
N
Sandbank
Sandbank
Dan Tysk
Butendiek
GlobalTech I
Albatros
BARD Offshore 1
Veja Mate
EnBW Hohe See
EnBW He dreiht
Deutsche Bucht
Trianel Windpark Borkum Phase 1
Merkur Offshore (MEG Offshore I)
Gode Wind 02
OWP West
Nordsee One
Borkum Riffgrund West
Borkum Riffgrund 2
Borkum Riffgrund West II
Borkum Riffgrund West II
alpha ventus
Riffgat
Meerwind Sued/Ost
Depth
0-25
25-50
50-100
Nordsee Ost
Meerwind Sued/Ost

Figure 2

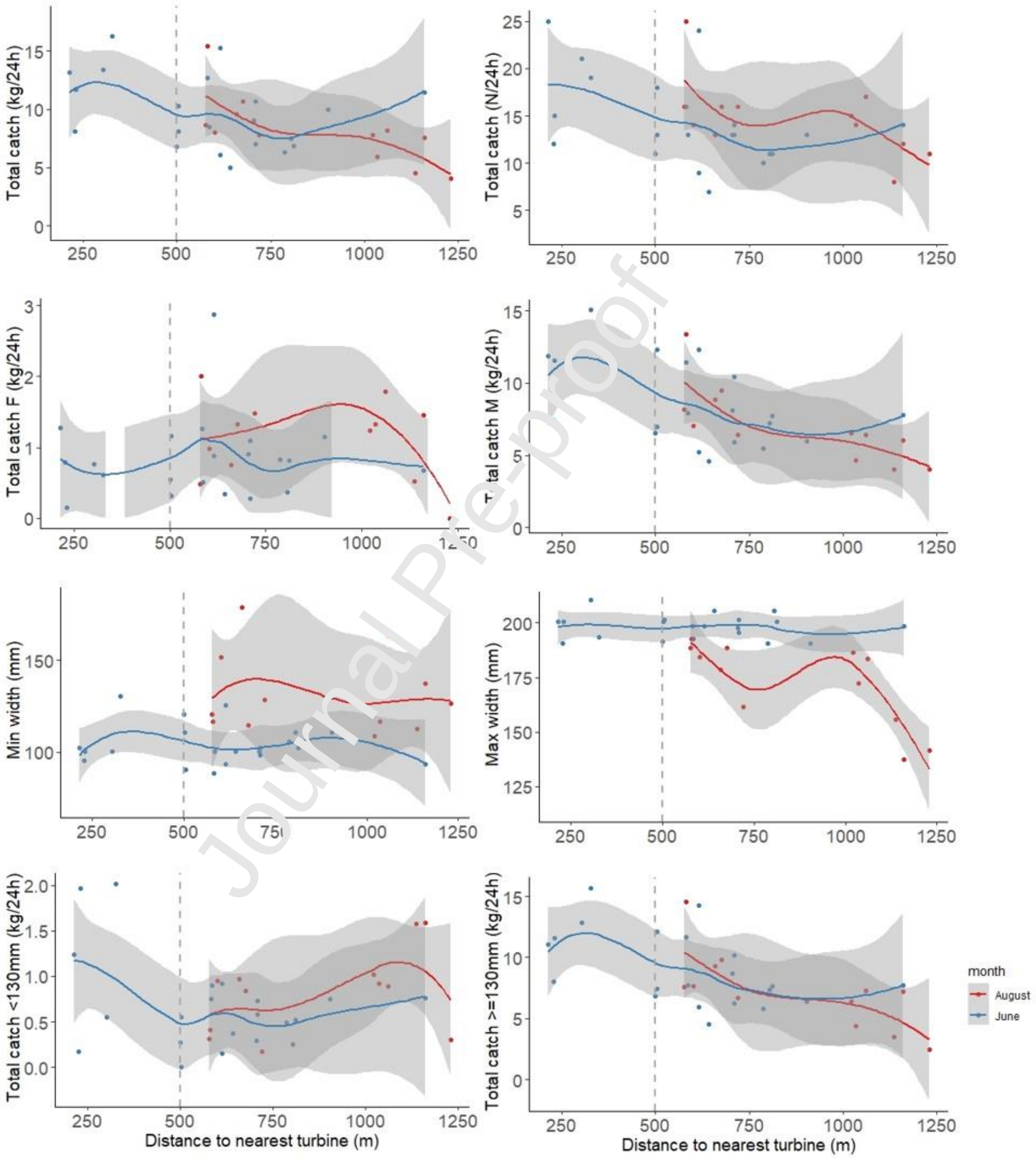

Total catch (kg/24h)
Total catch (N/24h)
Total catch F (kg/24h)
Total catch M (kg/24h)
Min width (mm)
Max width (mm)
Total catch <130mm (kg/24h)
Total catch >=130mm (kg/24h)
250
500
750
1000
1250
Distance to nearest turbine (m)
month
August
June

Figure 3

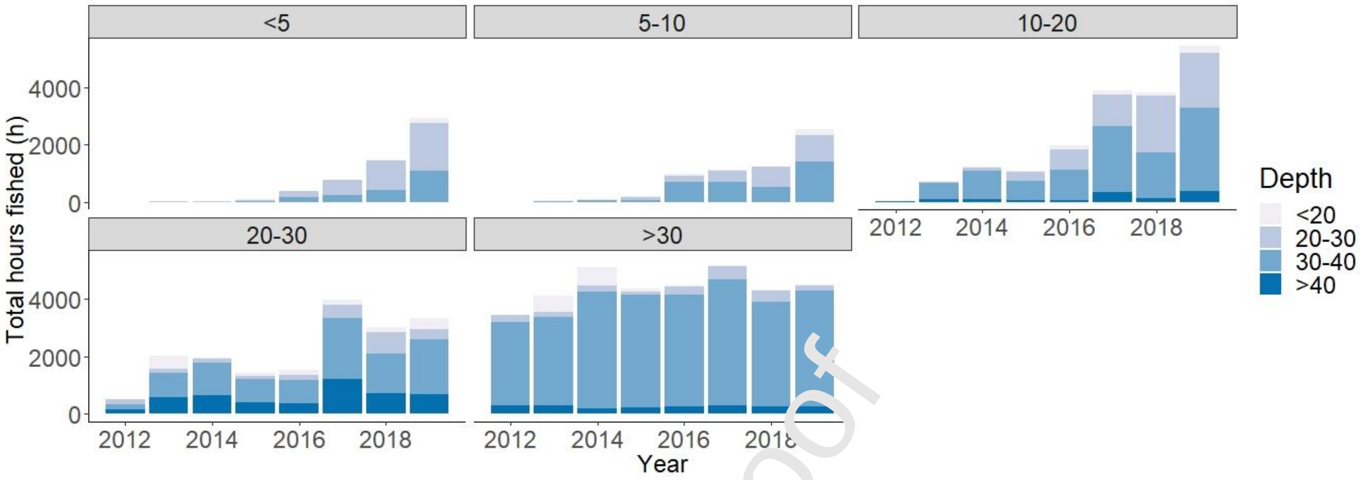

<5
5-10
10-20
20-30
>30
Total hours fished (h)
0
2000
4000
2012
2014
2016
2018
Year
Depth
<20
20-30
30-40
>40

Figure 4

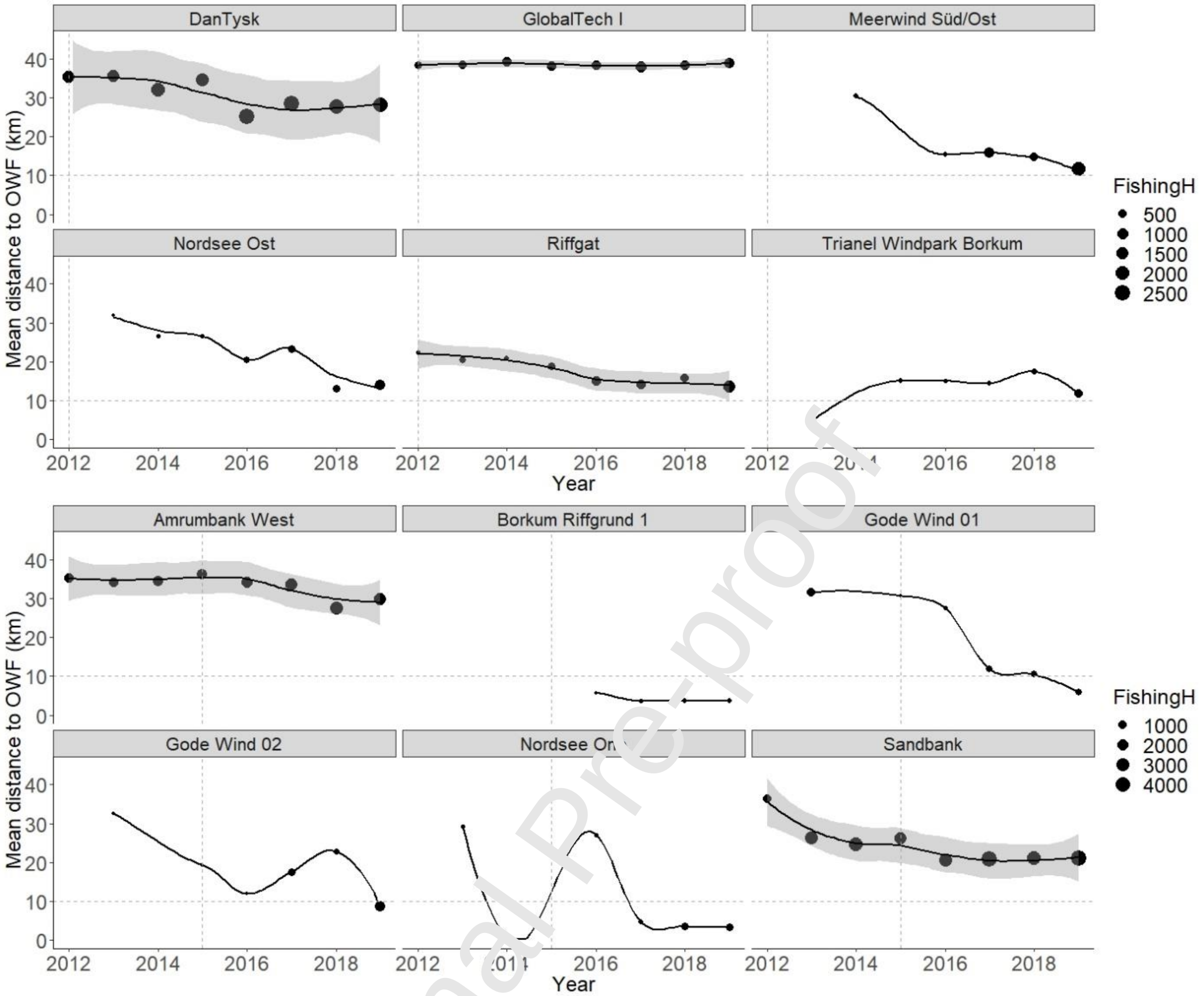

DanTysk
GlobalTech I
Meerwind Süd/Ost
Nordsee Ost
Riffgat
Trianel Windpark Borkum
Mean distance to OWF (km)
0
10
20
30
40
2012
2014
2016
2018
Year
FishingH
500
1000
1500
2000
2500
Amrumbank West
Borkum Riffgrund 1
Gode Wind 01
Gode Wind 02
Nordsee One
Sandbank
FishingH
1000
2000
3000
4000

Figure 5

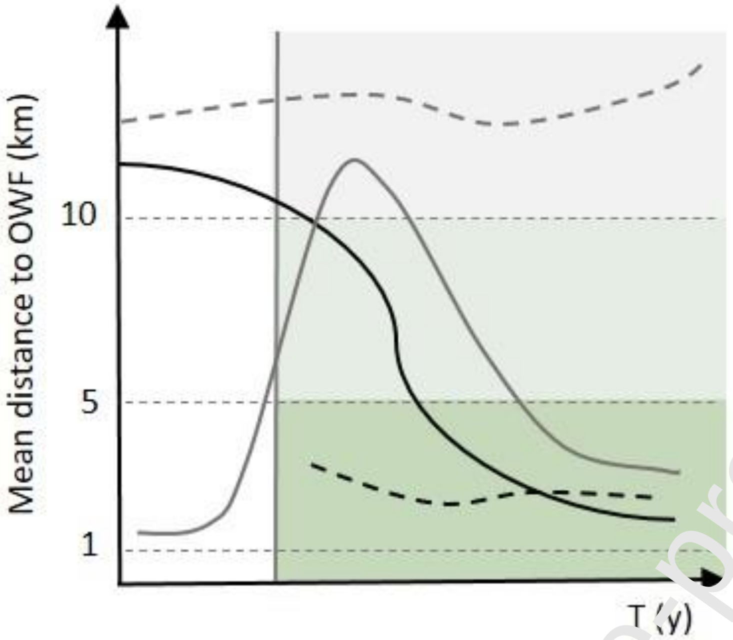


Figure 6

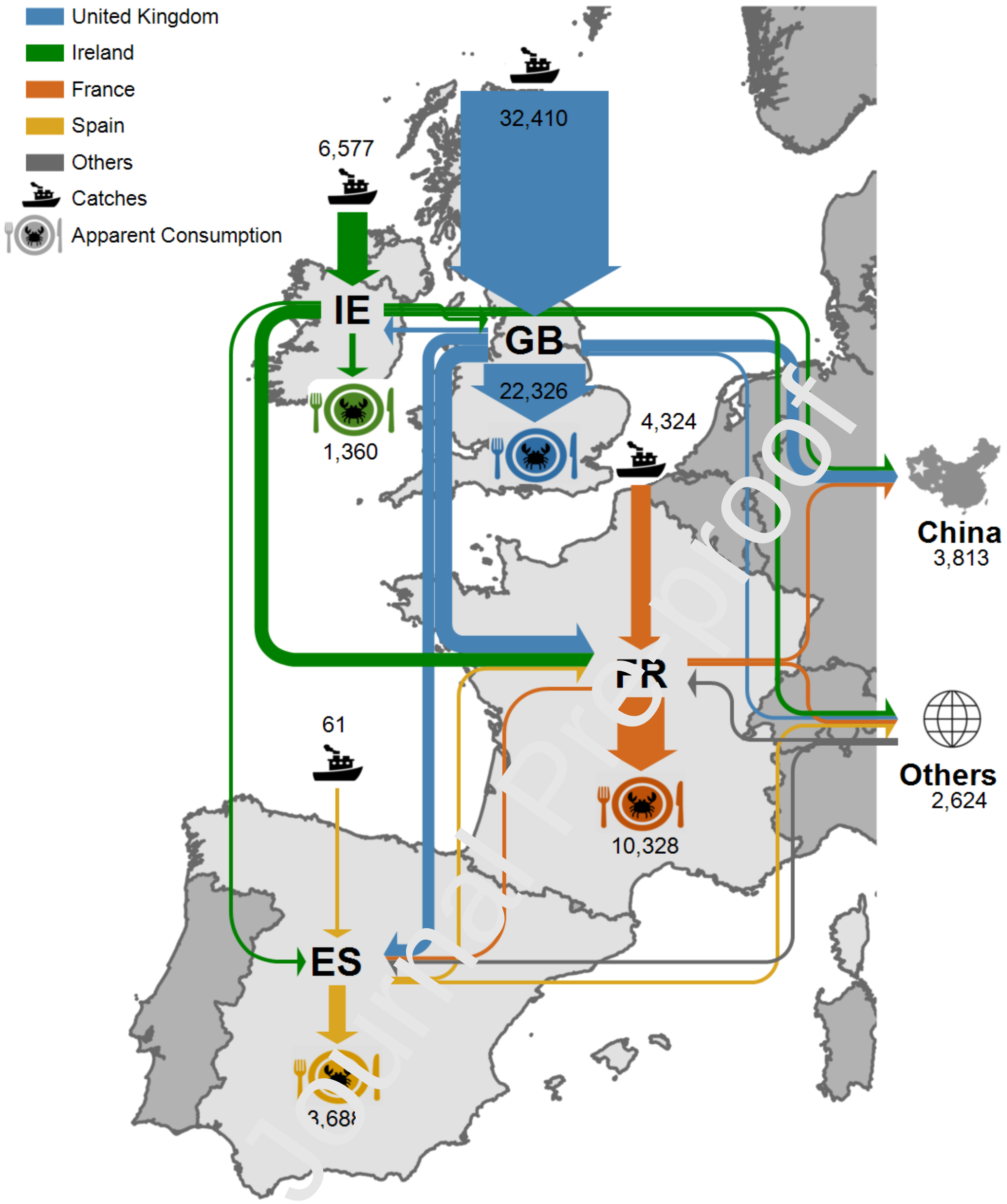
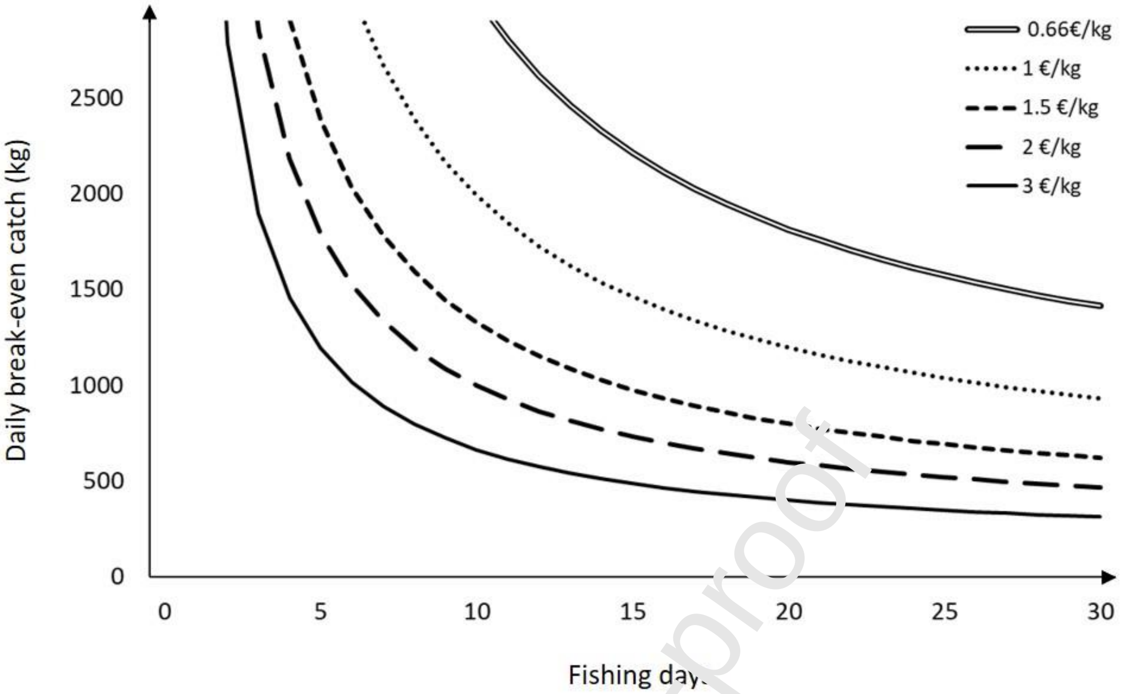

United Kingdom
Ireland
France
Spain
Others
Catches
Apparent Consumption
32,410
6,577
IE
GB
22,326
1,360
4,324
China
3,813
FR
61
Others
2,624
10,328
ES
3,68

Figure 7


0.66€/kg
1 €/kg
1.5 €/kg
2 €/kg
3 €/kg
Daily break-even catch (kg)
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
Fishing days

Appendix A

Table A.1: Summary statistics of the standardised total brown crab catches as biomass (kg) and numbers (Cpue; females = F; males = M; Carapace width < 130 mm; Carapace width ≥ 130 mm) from 41 sampling stations comprising the arithmetic mean (mean), standard deviation (sd), minimum value (min), maximum value (max), and range of values (max-min).

Measure	**mean**	**sd**	**min**	**max**	**range**
Soaking time (min)	1961	653	1406	2865	1459
Cupe (kg·24h^{-1})	8.9	3.0	4.0	16.3	12.3
Cupe (N·24h^{-1})	14.5	4.2	7.0	25.0	18.0
Distance to nearest turbine (m)	918	539	213	2650	2437
Depth (m)	23.0	0.8	22.0	24.8	2.8
Surface temperature (C°)	17.1	1.7	14.0	19.0	5.0
Bottom temperature (C°)	16.4	2.0	14.2	18.8	4.6
Cupe $_{F}$ (kg·24h^{-1})	0.9	0.6	0.0	2.9	2.9
Cupe $_{M}$ (kg·24h^{-1})	7.9	2.8	3.9	15.1	11.1
Cupe $_{\geq 130\ mm}$ (kg·24h^{-1})	8.1	3.0	2.5	15.7	13.2
Cupe $_{< 130\ mm}$ (kg·24h^{-1})	0.8	0.5	0.0	2.0	2.0

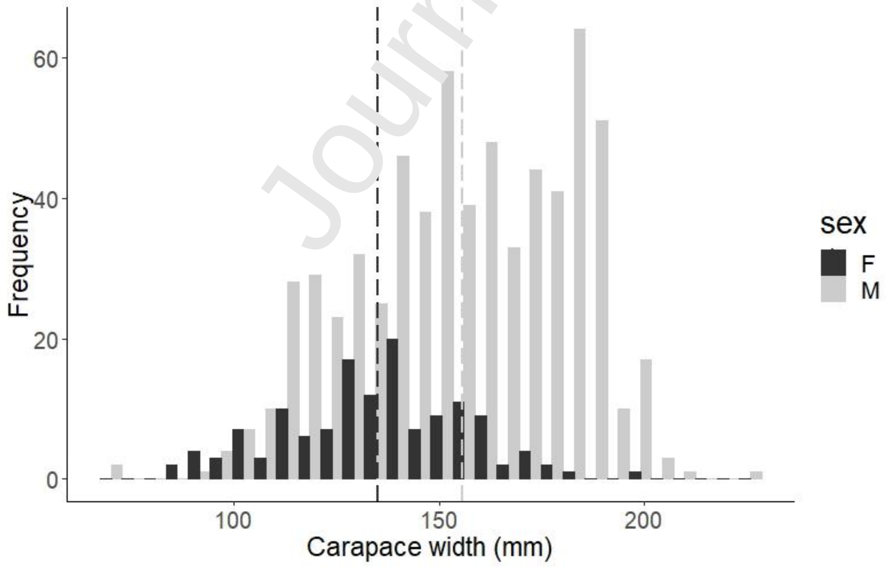


Figure A.1: Frequency distribution of the carapace width (mm) of the sampled female (F, black) and male (M, grey) brown crabs, dashed lines indicate the respective mean width (F = 135 mm, M =156 mm).

Appendix B

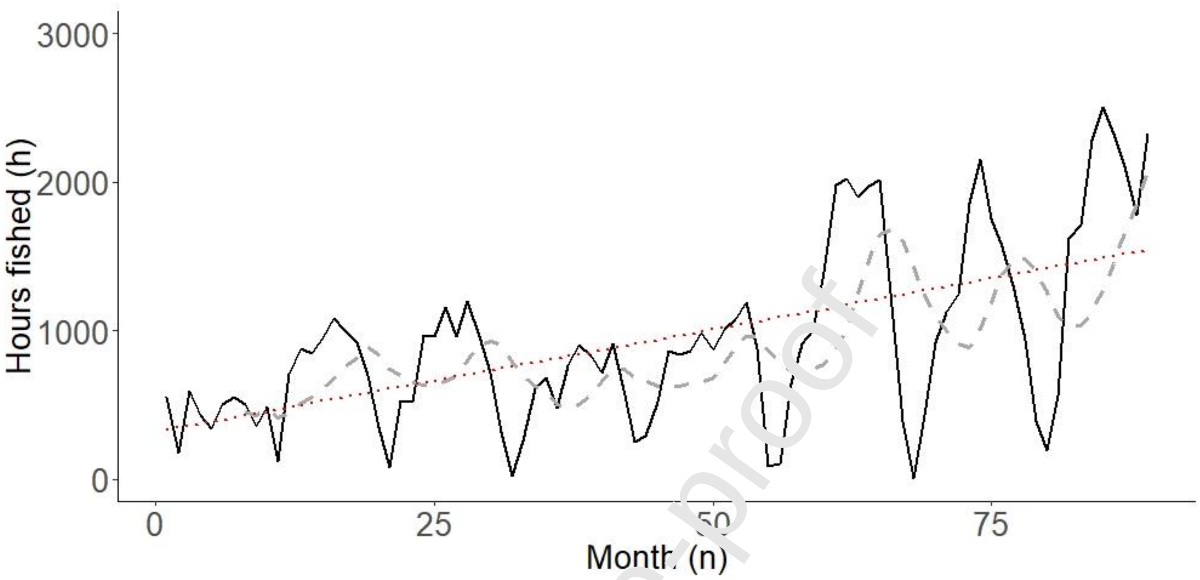
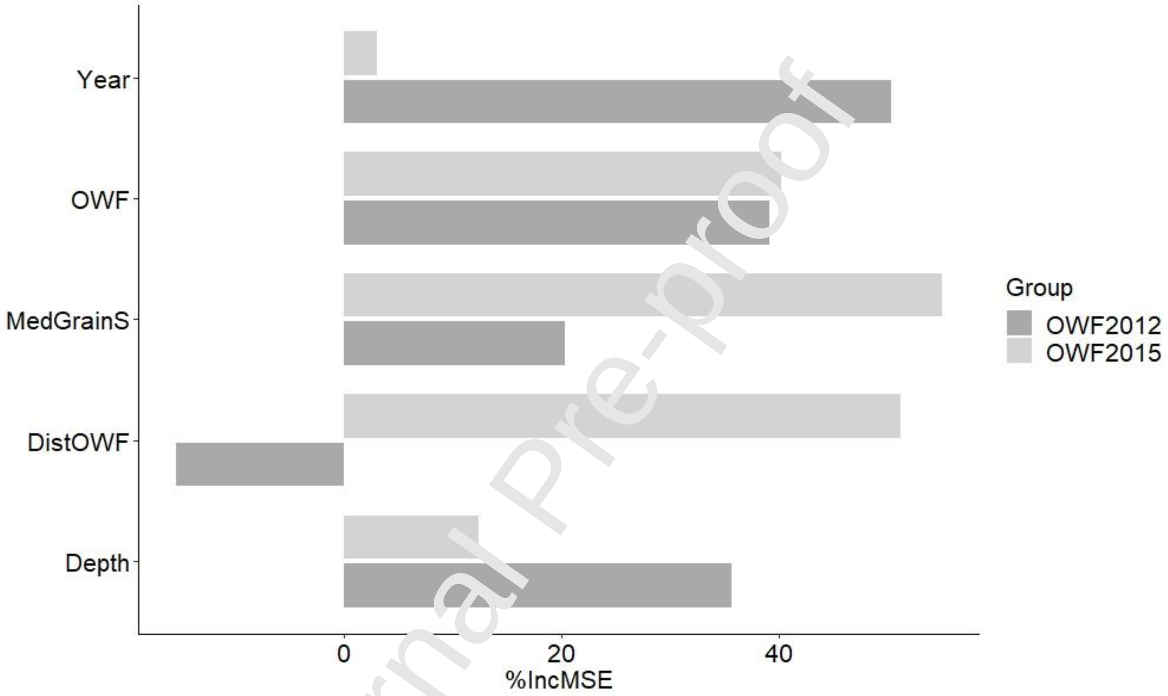


Figure B.1: Within the German North Sea the temporal pattern of the total hours fished with pots (h) showed an increase of fishing effort during the summer month of each year (black solid line). Detrending the data with a moving average of 8 years (grey dashed line) confirmed the fitted linear increase of fishing effort over time (red line).

Appendix C

Figure C.1: Calculated rank importance as increased mean square error (%; IncMSE) of the explanatory variables determining the allocation of the total annual fishing effort (h) around OWFs being in operation since 2012 (dark grey bar) and 2015 (light grey bar), respectively.



Appendix D

Table D.1: Mean cost and effort data for German beam trawlers (18 - 24 m) targeting brown shrimp extracted from (STECF, 2019b), estimated costs for beam trawlers deploying traps. We assumed a reduction of 50 % in fuel consumption and energy costs and repair and maintenance costs. When targeting brown crab with traps, towing resistance does not apply, and the auxiliary engine is not in use. Wear and tear of equipment is considerably lower compared to beam trawling. Other costs remain unchanged. All variable costs except for crew costs were estimated per GT-fishing day. Crew costs were estimated as share of the revenue.

	German beam trawler 18-24 m	**German beam trawler 18-24 m using traps**	**Assumption**
Energy costs / day (€)	280.6	140.3	-50%
Repair and maintenance costs / day (€)	329.4	164.7	-50%
Other variable costs / day (€)	24.4	24.4	Unchanged
Sum (energy, repair, other variable costs)/day	634.4	329.4	
Crew share on revenue	22%	22%	Unchanged

Table D.2: Break even scenarios for different combinations of days of fishing and crab prices.

Fishing days	**Variable costs (€)**	**Depreciation per day (€)**	**Break even revenue per day (€·d^{-1})**	**Break even catch (kg·d^{-1}) at 0.66€/kg**	**Break even catch (kg·d^{-1}) at 1 €/kg**	**Break even catch (kg·d^{-1}) at 1.5€/kg**	**Break even catch (kg·d^{-1}) at 2€/kg**	**Break even catch (kg·d^{-1}) at 3€/kg**
1	403	13000	16263	24641	16263	10842	8132	5421
5	2013	2600	3575	5417	3575	2383	1788	1192
10	4026	1300	1989	3014	1989	1326	995	663
15	6039	867	1460	2212	1460	973	730	487
20	8052	650	1196	1812	1196	797	598	399
25	10065	520	1037	1571	1037	691	519	346
30	12078	433	932	1412	932	621	466	311

CRediT author statement

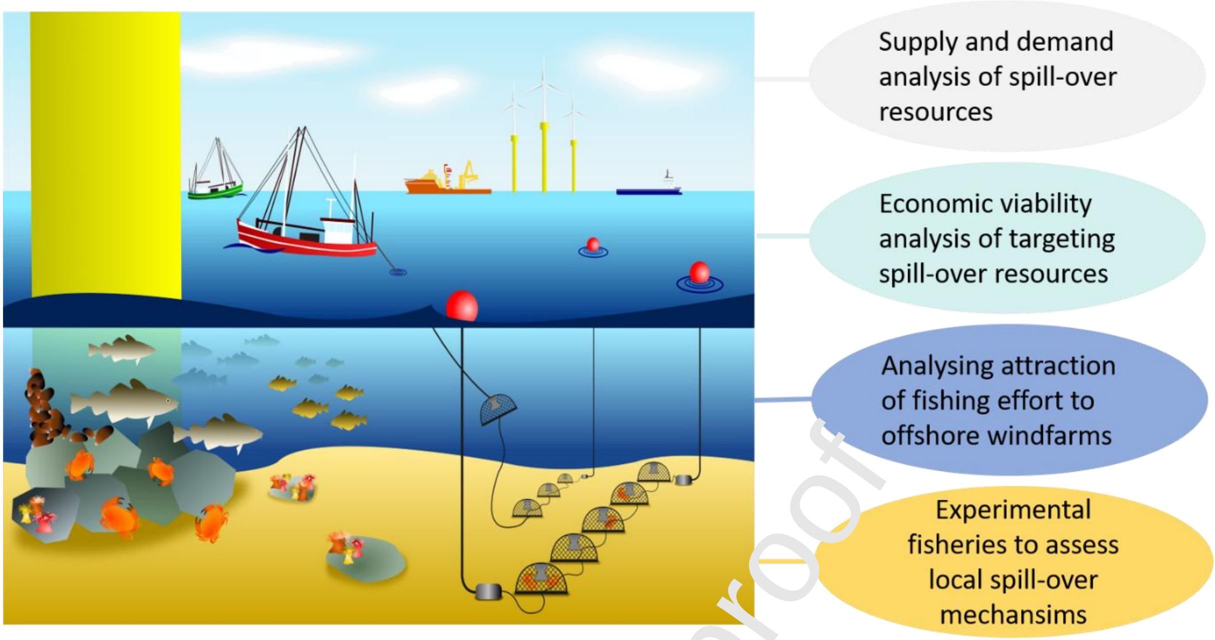
Vanessa Stelzenmüller: Conceptualization, Methodology, Resources, Formal analysis, Data curation, Funding acquisition, Writing - Original Draft; **Antje Gimpel**: Conceptualization, Methodology, Resources, Data curation, Project administration, Writing - review & editing; **Holger Haslob**: Conceptualization, Methodology, Resources, Data curation, Writing - review & editing; **Jonas Letschert**: Methodology, Resources, Formal analysis, Writing - review & editing; **Jörg Berkenhagen**: Methodology, Resources, Formal analysis, Writing - review & editing; **Simone Brüning**: Methodology, Resources, Formal analysis, Writing - review & editing

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Graphical abstract



Supply and demand analysis of spill-over resources

Economic viability analysis of targeting spill-over resources

Analysing attraction of fishing effort to offshore windfarms

Experimental fisheries to assess local spill-over mechansims

Highlights

- Co-locating offshore wind farms and fisheries challenges marine spatial planning
- We provide a socio-ecological assessment of co-location solutions
- Experimental fisheries revealed spill-over of brown crab from offshore wind farm
- Economic analyses showed a potential for economically viable pot fisheries
- Co-location solutions need to consider ecological and socio-economic trade offs