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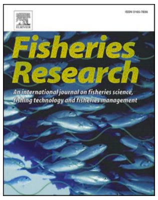

Short communication

Offshore wind farm foundations as artificial reefs: The devil is in the detail

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ABSTRACT

Climate change and global biodiversity loss call for clean energy production systems with minimised ecological impacts. Offshore wind energy production will become one of the main uses of global marine spaces within next decades. Offshore wind turbine foundations can function as artificial reefs but it is unknown if these capabilities apply to different foundation types. We collected field data on Atlantic cod (*Gadus morhua*), a species under pressure in the southern North Sea, around three foundation types to assess these capabilities. Catch rates showed that monopile foundations with rock protection on the seabed were able to attract significantly more fish than monopile foundations with sandbag protection and jacket foundations. Fish densities varied on small scales meaning that reef effects were spatially restricted. This implies that offshore wind energy production can be used as tool to combine climate change mitigation with local biodiversity conservation but that a consideration of the wind farm design is required.

1. Introduction

Offshore wind energy plays a key role in reducing global greenhouse gas emissions on the path towards a carbon-neutral energy production. Over the past decade global annual offshore wind energy capacities increased tenfold and reached 48 Gigawatt (GW) by the end of 2021 with China as the largest single-nation producer followed by Europe (World Forum Offshore Wind e.V, 2022). Nevertheless, leading industrial nations plan to further expand their offshore wind capacities to counteract rising greenhouse gas emissions within the next decades. In 2021, the Biden-Harris administration announced to increase the US' offshore wind power capacities to 30 GW by 2030 (The White House, 2021), which represents an almost 1000-fold increase compared to today. The EU plans to produce 150 GW of offshore wind energy by 2050, which means that approximately 10 % of the North Sea area will be covered with offshore wind farms (OWFs) in 2050 (Stelzenmüller et al., 2022). Without doubts, OWFs will become one of the main users of marine spaces within the next decades, which fuels concerns over spatial conflicts with other human activities and the ecological impact of these man-made structures on marine ecosystems.

OWFs are assemblages of individual wind turbines with varying foundation types. The shape of these foundation types mainly depends on water depth, sea bed substrate, tides and local current strength (Hammar et al., 2010; Matutano et al., 2013). Monopile foundations are most common in Europe and are comprised by a single steel tube driven into the seabed (see for example icons in Fig. 1). While Jacket foundations have a lattice framework, which is anchored at several points in the seabed, monopiles are often surrounded by scour protection made of for example rocks or sandbags. These hard-substrate structures introduced with OWFs can increase local habitat heterogeneity, because OWFs are usually built in soft-sediment areas (Degraer et al., 2020; Langhamer, 2012; Vandendriessche et al., 2015). Monopiles with rock protection can attract fish, which enhances local species diversity and density (Bergström et al., 2013; Buyse et al., 2022; Gimpel et al., 2023; Methratta and Dardick, 2019; Reubens et al., 2013). This suggests that offshore wind turbines function as artificial reefs, indicating that they might offer synergetic opportunities for climate change mitigation and species conservation by offering newly established suitable habitats for species under pressure (Thatcher et al., 2023). However, the scientific focus on investigations of monopiles with rock protection means that it is still uncertain if other, frequently used foundation types also act as artificial reefs (Degraer et al., 2020). Observational evidence on this

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question could inform decision making process on how to design such installations in order to enhance the ecological benefits of OWFs and combat the impacts of climate change.

OWFs have been built in the German part of the southern North Sea since 2012 making the region to one of the few global places with decade-long established OWFs. In our study we focused on Atlantic cod (*Gadus morhua*), a demersal species, which is known to aggregate around wind turbines with rock protection in summer and autumn (Degraer et al., 2020; Gimpel et al., 2023; Reubens et al., 2013). Cod was an important fishery resource in the southern North Sea, where it is threatened from overfishing and habitat loss through rising temperatures now (ICES, 2021; Núñez-Riboni et al., 2019). It is known to aggregate around wind turbines with rock scour protection in summer and autumn (Degraer et al., 2020; Reubens et al., 2013).

2. Methods and material

2.1. Study site and data collection

We investigated abundance of Atlantic cod in proximity to wind turbine foundations to draw conclusions about the capabilities of three foundation types to attract demersal, locally endangered, predatory fish (Appendix A1). For this purpose, we chose an offshore wind energy cluster in the south-eastern part of the North Sea, which consists of three established OWFs and one OWF (“Kaskasi”) under construction (Fig. 1). The cluster is located in the German exclusive economic zone close to the island of Helgoland (Fig. 1) with the OWFs being in operation since 2015 (with the exception of Kaskasi). The northernmost OWF “Amrumbank West” consists of monopiles with scour protection made of sandbags, the southernmost OWF “Meerwind Süd/Ost” consists of monopiles with scour protection made of rocks and the OWF “Nordsee Ost” is built with jacket foundations. One turbine in the windfarm “Nordsee Ost” is a monopile with rock protection (see larger green dot at the very south-western end of the wind farm in Fig. 1). Commercial fishing is currently forbidden in the wind farm area and in a buffer zone of 500 m around the OWF (Gimpel et al., 2013). The study area is characterized by almost homogenously distributed fine sand and muddy sand sediment types (Fig. 1) and an average bottom depth of 23 m without steep slopes (Stelzenmüller et al., 2021).

We collected data on cod abundance using hook, lines and hand rods, which can be referred to as “angling”, because the use of other commonly used tools to investigate fish abundance is prohibited in German OWFs. Angling has been regularly used to assess fish abundance in OWFs (Methratta and Dardick, 2019; Reubens et al., 2013) and is a representative tool to assess local fish densities (Haggarty and King, 2006). Cod abundance was investigated in June 2019 and in June 2022. Angling was carried out from wind farm crew transfer vessels during daytime. We fished close to the turbines using metal lures of 200 g weight and a method called “jigging”. Angling was carried out with the same two experienced anglers at all stations to avoid bias due to potentially different angling skills. Both anglers fished at the same time and for the same time period at each station, while a third staff member recorded meta data. The duration of angling was recorded to calculate standardised catch rates as number of cod caught per angler and hour (Haggarty and King, 2006; Reubens et al., 2013). In total, 37 turbines were sampled, whereby each turbine was only sampled once (Fig. 1,

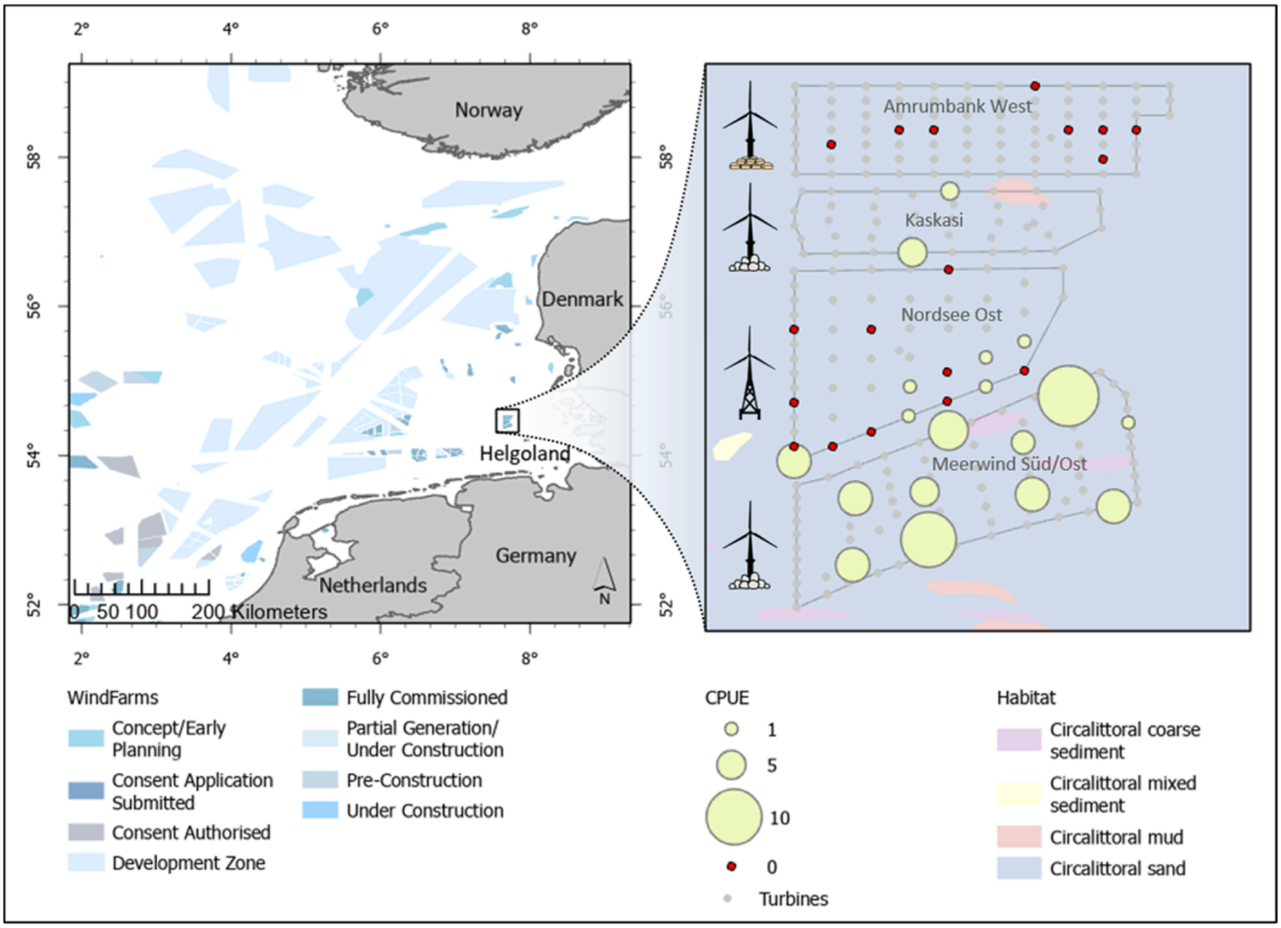

Fig. 1. Overview of offshore wind farm designated and already constructed areas in the North Sea with a focus on our study site close to the island of Helgoland. Focus shows distribution of sampling stations and foundation types chosen for our study. Dots show catch rates of cod around sampled stations.

Appendix A1). Turbines were chosen randomly and as ship time allowed. However to detect potential gradients in cod abundance between foundation types the southernmost line of turbines in the OWF "Nordsee Ost" received special attention. During first period of sampling, in June 2019, catch rates were usually highest at the beginning of each station and when catch rates around one turbine declined the site was left and a new one approached. We noticed that catch rates often decreased after about 20 min of angling. For this reason we limited sampling duration to 20 min per wind turbine in 2022. The number of stations around turbines with sandbag protection was considerably lower, because the hooks got frequently entangled in the fabric of the sandbags. Hence fishing was repeatedly interrupted, but a fishing time of 20 min ensured. In 2019 we measured bottom temperature data around monopiles with rock protection indicating a homogeneous distribution of around 14 C° (Stelzenmüller et al., 2021). On scales of few kilometres or even only hundreds of meters this is not surprising considering that the study region is not a frontal zone but shows gradual and not abrupt spatial changes in its physical properties (Núñez-Riboni and Akimova, 2015).

2.2. Statistical analysis

We modelled catch rates as a function of foundation type, year and station depth to investigate the relationship of catch rates and potential explanatory variables. The analysis was done in R (R: Development Core Team, 2022) using the package "MASS" (Venables and Ripley, 2002) and a generalized linear model (GLM) with negative binomial distribution and log link. Foundation type and year were used as factors. The explanatory variable "year" was included to investigate a year effect, potentially caused by for example different environmental regimes affecting cod abundance in the southern North Sea between the two sampling years. The model was defined as:

$$C_i = \exp\left(\beta_{0i} + \beta_{1i} F_i + \beta_{2i} Y_i + \beta_{3i} D_i\right) + \varepsilon_{i,}$$

where C is the dependent variable catch rate, F the foundation type, Y the year and D the depth at each station for each sample i. The error term ε was assumed to be negative-binomial-distributed. The model was checked for over dispersion (Crawley, 2005).

3. Results

Catch rates of cod were considerably higher around monopiles with rock protection than around monopiles with sandbag protection or around Jacket foundations (Fig. 1, Fig. 2, Table 1). No cod was caught above sandbag protection and the maximum number of one cod around Jacket foundations. This pattern was confirmed by the results of the generalized linear model (Table 1), where rock foundation was the only significant predictor ($p < 0.001$). Even two turbines in the wind farm "Kaskasi", where the installation of rock protection was finalized only four weeks prior to sampling, showed with values of 3 and 5.5 higher catch rates than any Jacket station or around monopiles with sandbags (Fig. 2).

4. Discussion

The exploitation of co-benefits of management measures such as the production of CO_2 free energy and marine conservation is seen as key for the urgently needed transformative change of governance systems to deliver on international biodiversity, climate change and sustainable development policies (Pascual et al., 2022; Smith et al., 2019). Hence, our results add to the scarce empirical evidence on the relation between the design and construction details of offshore wind turbines and their capacity to function as artificial reefs and therefore contributing to conservation benefits. The here presented increased catch rates above rock protection were in line with results from a previous study, where values ranged from ~ 2 – 14 individuals per hour and angler during summer months (Reubens et al., 2013). We found striking differences in cod densities on scales of only few hundreds of meters, especially between wind farms built of different foundation types (Fig. 1). These results indicate that cod selectively occupies offshore wind turbine foundations. OWFs have previously been hypothesized to lead to so-called "spillover" effects, which could benefit local fishery resources (Berkel et al., 2020; Stelzenmüller et al., 2022, 2021). This led to a discussion if OWFs should be opened for commercial fishing or rather serve as marine protected areas (Berkel et al., 2020; Langhamer, 2012). More robust conclusions on the potential of OWFs to support large-scale recoveries of fish populations will require more work on the reproductive success of fish spawning in and around OWFs. However, our results indicate aggregation effects of monopiles with rock protection are locally restricted, which questions the suitability of OWFs to support large-scale recoveries of threatened fish populations. A recent study in the same area indicated that cod uses the OWF as feeding ground in the summer and migrates to the wider southern North Sea for spawning in winter (Gimpel et al., 2023). Further behavioural studies using for example tagging experiments could improve our understanding on migrations and seasonal movement patterns around OWFs.

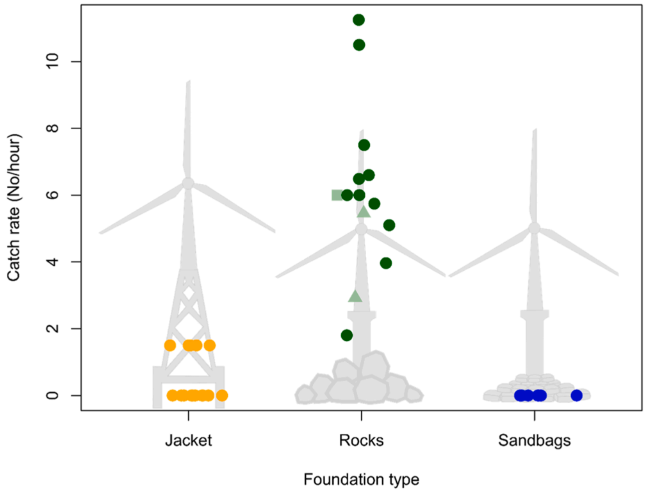

Fig. 2. Catch rates of Atlantic cod around wind turbines with different foundation and protection types in the southern North Sea. Jacket and sandbag foundation samples were taken in 2022, rock foundation samples mainly in 2019. The transparent green rectangle shows catch rates around the only established rock foundation station sampled in 2022 and transparent triangles show catch rates around two newly established rock foundations in the wind farm "Kaskasi" (see Fig. 2) in 2022.

Table 1
Test results of a generalized linear model testing the effect of foundation type, year and bottom depth on catch rates of cod around offshore wind turbines. Foundation type and year were used as factors.

	Coefficient estimate	Standard error	z-value	Pr (>|z|)
(Intercept)	0.13	1.88	0.069	0.945
Rock foundation	2.24	0.46	4.878	<0.001
Sandbag foundation	-19.68	5486.78	-0.004	0.997
Bottom depth	-0.02	0.07	-0.285	0.776
Year 2022	-0.32	0.30	-1.080	0.280

Future work is further required to understand how offshore wind installations affect pelagic fish species, such as European sea bass (*Dicentrarchus labrax*) or saithe (*Pollachius virens*) and how artificial reef effects from OWFs could enhance local reproduction and recruitment. Interestingly, black sea bass (*Centropristis striata*), a reef-associated, demersal species, showed increased densities around the Jacket foundations of Block Island Wind Farm, the first offshore wind farm in North America located at the East coast of the US (Carey et al., 2020). Block Island Wind Farm is however located close to natural, rocky reefs and might therefore be difficult for comparison with an offshore wind farm in the sandy southern North Sea.

Although the results of our model indicate that turbine foundation type is the primary driver of differences in catch rates, it remains uncertain, which factors affect small-scale variability in catch rates around monopiles with rock protection (Table 1, Fig. 2). These differences could have, for example, emerged because of daily or hourly differences in hunting activity of fish, which would mean that catch rates did not accurately reflect fish densities. Another factor affecting the variability might be related due to differences in attraction potential between individual monopiles with rock protection. However, according to Haggarty and King (2006), angling does reflect differences in fish densities at study sites within circular plots of a radius of 10 m, which is a comparable size to our sites. Differences in attraction potential between monopiles, which would likely lead to differences in fish densities, might be related to competition or food availability, which would affect habitat suitability around individual turbines. Reubens et al. (2013) also detected differences in catch rates between turbines and explained these with differences in densities as well as fish behaviour affecting for example aggregation and habitat selection. Behavioural investigations and direct observations of fish distribution around turbines could provide more detail in this context. A more method-critical aspect could relate to the effect of varying levels of concentration during fishing. Catching a fish requires a high level of focus because the angler has to respond quickly to an attack in order to safely hook the fish. A decline in concentration due to long working hours might be responsible for fish losses and minor differences in catch rates. However, using a standardized sampling approach with the same anglers we attempted to minimise this potential bias.

We present results of a study based on a relatively small number of samples, which will need to be re-evaluated in the future. Nevertheless, it delivers urgently needed observational evidence on how such co-benefits could be implemented cost-effectively where appropriate, but emphasizes that wind farm design needs to be carefully considered at the planning stage. Our results imply that the design of OWFs can likely be adapted to needs and requirements for local species protection making future OWFs potentially to the “tip of the scale” for the implementation of area based management measures to enhance the protection of marine biodiversity.

CRediT authorship contribution statement

Haslob Holger: Conceptualization, Data curation, Investigation, Writing – original draft, Writing – review & editing. **Werner Karl Michael:** Conceptualization, Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Gimpel Antje:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Writing – original draft, Writing – review & editing. **Reichel Anna F.:** Visualization, Writing – original draft, Writing – review & editing. **Stelzenmüller Vanessa:** Conceptualization, Investigation, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

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.

Data availability

Original data are in the appendix.

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Appendix A. : Raw data used for this publication

Station	Year	Foundation	Depth	Catch rate (fish/hour)
1	2022	Jacket	23.4	0
2	2022	Jacket	23.4	0
3	2022	Jacket	23.4	1.5
4	2022	Jacket	23.8	0
5	2022	Jacket	24.2	1.5
6	2022	Jacket	24.7	0
7	2022	Jacket	24.8	1.5
8	2022	Jacket	23.6	1.5
9	2022	Jacket	23.8	0
10	2022	Jacket	23.9	1.5
11	2022	Sandbags	22.5	0
12	2022	Sandbags	21.8	0
13	2022	Sandbags	20.8	0
14	2022	Sandbags	20.1	0
15	2022	Sandbags	19.8	0
16	2022	Jacket	23	0
17	2022	Jacket	23.9	0
18	2022	Jacket	25.8	0
19	2022	Sandbags	18.8	0
20	2022	Sandbags	19.9	0
21	2022	Sandbags	21.2	0
22	2022	Rocks (Nordsee Ost)	23.8	6
23	2022	Jacket	24.6	0
24	2022	Rocks (Kaskasi)	21.4	2.927

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(*continued*)

Station	Year	Foundation	Depth	Catch rate (fish/hour)
25	2022	Rocks (Kaskasi)	23.1	5.455
26	2022	Jacket	22.5	0
27	2019	Rocks	22	1.8
28	2019	Rocks	26	6.48648649
29	2019	Rocks	23	5.74468085
30	2019	Rocks	24	3.96226415
31	2019	Rocks	26	5.1
32	2019	Rocks	NA	6
33	2019	Rocks	26	6
34	2019	Rocks	23	10.5
35	2019	Rocks	23	7.5
36	2019	Rocks	22	6.6
37	2019	Rocks	22	11.25

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