



# Benthic epifauna communities profit from the spatial combination of offshore wind farms and marine protected area in the south-eastern North Sea

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## Abstract

The Amrum Bank, a sandbank in the German Exclusive Economic Zone (EEZ) of the North Sea, accommodates a diverse marine ecosystem and is located northeast of the offshore wind farm (OWF) “Amrum Bank West.” In our study, we investigate epibenthic biodiversity by beam trawl and ring dredge catches at incremental distances to the wind farm. Using the same methodology, we compare biodiversity at the Natura 2000 marine protected area (MPA) “Sylt Outer Reef–Eastern German Bight,” where fishery has been excluded since March 2023, with surrounding locations that are still affected by fisheries. Both OWFs and MPAs prohibit fishing, but they have different primary objectives, with MPAs protecting biodiversity and OWFs generating renewable energy. The wind farm, where no fishing has been allowed since its operation began in 2015, may have been influencing epifaunal communities for several years. Our results indicate that the total number of individuals, the catch volume, and the Shannon–Wiener biodiversity index ( $H_s$ ) increased with increasing distance from the OWF. The correlation between  $H_s$  and distance to the OWF as well as catch volume in correlation with the distance was statistically significant ( $p=0.003$  and  $p=0.004$ ). Furthermore, species composition varied between protected and non-protected stations. Multidimensional scaling revealed a higher similarity in species composition within the MPA compared to non-protected areas, which exhibited greater variability. When comparing stations closest to and farthest from the OWF, 16 species showed differences in abundance of at least 10 individuals, with 9 of these species being found exclusively or in higher numbers at the stations farthest from the OWF. Linear mixed-effects models confirmed that both distance to the wind farm and protection status had statistically significant effects on the abundance of several species, with a general trend of increasing abundance and biodiversity with increasing distance. However, no stations were sampled within the OWF itself because access was restricted by regulations, which limits the scope of our conclusions. This study provides important insights into the ecological dynamics of the Amrum Bank and emphasizes the need to give greater weight to anthropogenic factors in marine conservation and management strategies. The conclusions of this study apply specifically to the unique conditions of the Amrum Bank: soft sediment habitats, a degraded seafloor recovering from industrial fishing, and bottom-fixed turbines. We conclude that OWFs could be accompanied (or surrounded) by MPAs in order to provide areas in which epifaunal biodiversity can thrive without disturbance, which ultimately increases ecosystem health and resilience. However, it is also important to note that other studies have shown that OWFs can negatively affect MPAs, depending on local ecological conditions, and this warrants further investigation.

**Keywords** Fishery management · No-fishing zone · Gradient · Community composition · Ecosystem disturbance · Renewable energy

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## Introduction

The south-eastern North Sea is a complex and dynamic area characterized by diverse geomorphological features (Beermann et al. 2023). The sandbanks provide a habitat for a specific epibenthic fauna that is adapted to the unstable and mobile sandy substrates, including a wide range of organisms adapted to the variable environmental conditions of this region (Ellis et al. 2011). In more recent years, the marine realm is not only interesting as a resource for aquatic food anymore. Already after the Kyoto protocol on global climate change (United Nations 1998), many countries were starting to change their energy mix towards a bigger share of renewable energies like solar, water, and wind power (Gusatu et al. 2021). The development of offshore wind farms (OWFs) (Coolen et al. 2022; Krone et al. 2013) is especially emerging because in offshore areas, wind resources are more abundant, stronger, and more consistent in terms of their availability compared to land-based wind resources (Perveen et al. 2014). Along with the rapid increase of OWFs, an urgent call to study the potential impacts of OWFs and their benefits on marine biodiversity arose (Inger et al. 2009). Evidence suggests that OWFs are associated with increased abundance of fish and sessile assemblages (Andersson and Öhmann 2010), as the enrichment of the macrofauna community around the foundations can serve as an additional food source for higher trophic levels (Schückel et al. 2011). Rumes et al. (2013) demonstrated that autumn benthic biomass can increase up to 4000-fold compared to the biomass originally present in the sediments, caused by a combination of new hard substrate and the exclusion of fisheries. The reef structures formed by the foundations pose a major anthropogenic influence on the marine fauna (De Mesel et al. 2015). OWFs recently may have the most dominant influences on benthic communities and marine ecosystems besides climate change (Gillson et al. 2022) and trawl fishery (Mazor et al. 2020; Callaway et al. 2002), which still have to be disentangled (Bundy et al. 2021; Simeoni et al. 2023). Benthic epifauna, a fundamental and very important component of marine fauna and marine ecosystems (Jennings et al. 2001) is also influenced by OWFs, as the artificial reef structures can serve as a habitat for a variety of epifaunal species like crabs (*Liocarcinus* spec.) or starfishes (*Asterias rubens*) (ter Hofstede et al. 2022). However, during the construction phase, disturbance of the habitat can also have a negative impact on benthic communities, at least temporarily (Vandendriessche et al. 2014). Furthermore, the no-take zones associated with OWFs can have a significant positive effect by providing a refuge for marine organisms, reducing fishing pressure, and allowing benthic communities to recover and thrive (Punt et al.

2009; Wilhelmsson and Langhamer 2014). Initial studies of combined marine protected areas (MPAs) and OWFs show an increase in commercially exploited crustaceans and other benthic taxa, but there is still a need for studies to investigate the specific effects (Ashley et al. 2014). In particular, benthic epifauna, which provides food and habitat for many other marine species and increases heterogeneity, plays a crucial role in the ecological health of a marine ecosystem (Chen et al. 2021).

Distance-based sampling offers several advantages as it eliminates the need for control stations and investigates a spatial gradient (Methratta 2021). It was already shown that diversity and biomass of species, such as crustaceans and echinoderms, increase in the vicinity of OWF (Rumes et al. 2013). Based on this, we hypothesize that epifaunal biodiversity, the number of species, and the number of individuals per species increase the closer we sample to the OWF, as no fishing is permitted there. The distance to the fishing exclusion zone increases the greater the distance to the OFW, i.e., the further away you get from the OWF, the closer you get to the zone in which fishing takes place. This study was carried out to check whether the chosen path of combining an OWF with an MPA at the Amrum Bank is a good example of how to combine marine protection and benefits.

Our findings provide nuanced insights into the co-location of MPAs and OWFs. While enhanced benthic biodiversity near the wind farm indicates potential local conservation benefits, these outcomes are specific to the soft-bottom habitats of the North Sea. Thus, although co-locating MPAs and OWFs may offer advantages in similar settings, caution is warranted before generalizing these results to other habitat types or regions. This study should be viewed as a valuable case study that informs the broader discussion on co-location strategies for marine conservation, and further research is necessary to elucidate the underlying mechanisms and evaluate the applicability of these findings in different environmental contexts.

## Material and methods

### Sampling area

The Amrum Bank is an important geographic formation in the North Sea that extends about 48 km north of the island of Helgoland and 28 km west of the island of Amrum. This sandbank is part of the German exclusive economic zone (EEZ) (Sander et al. 2022) and is protected as part of the Natura 2000 site Sylt Outer Reef–Eastern German Bight. Its sandy and partly stony seabed (Rachor and Nehmer 2003) provides habitat for several key species like *A. rubens* (Linnaeus, 1758), *Liocarcinus holsatus* (Fabricius, 1798),

*Crangon crangon* (Linnaeus, 1758), and *Pagurus bernhardus* (Linnaeus, 1758) (Darr et al. 2012). In addition, the Amrum Bank has also become economically important because the offshore wind farm (OWF) “Amrum Bank West” has been built near this sand bank to generate renewable energy from wind and help to reduce CO<sub>2</sub> emissions from the energy sector (Gollub et al. 2014).

The stations (Fig. 1) were selected for comparative purposes both inside and outside the MPA Amrum Bank and at increasing distances from the OWF Amrum Bank West (80 turbines). This OWF is located near other wind farms to the south, including “Kaskasi” (38 turbines), “Nordsee Ost” (48 turbines), and “Meerwind Ost/Süd” (80 turbines), collectively covering approximately 190 km<sup>2</sup> (see <https://map.4coffshore.com/offshorewind/>). Sampling stations were distributed over an area of approximately 100 km<sup>2</sup> northeast of the OWF Amrum Bank West. A total of 25 stations were sampled during five expeditions over 2 years (2022–2023). Of these, 17 stations were located within the MPA at varying

distances to the OWF, while 8 stations outside the MPA, up to 12 sea miles from the OWF, were sampled for comparison. Sampling was conducted between May and October, with stations sampled in spring, summer, and fall in 2023 to reduce seasonal effects. All expeditions were carried out aboard the Research Vessel “Senckenberg” (see expedition dates and station coordinates in Table A1).

## Sampling methods

A ring dredge (ring diameter 1 m, mesh size 1 cm<sup>2</sup>) was used to qualitatively record in- and epifauna per station. The ring dredge is a net that is attached to a steel, ring-shaped frame. This ensures that the net penetrated the seafloor for up to 50 cm while being dragged in one direction at minimal speed for approximately 3 min. The catch was then photographically documented on board and subsequently sorted on board and recorded in a presence/absence matrix. A beam trawl (cod-end mesh size 1 cm<sup>2</sup>) was then towed

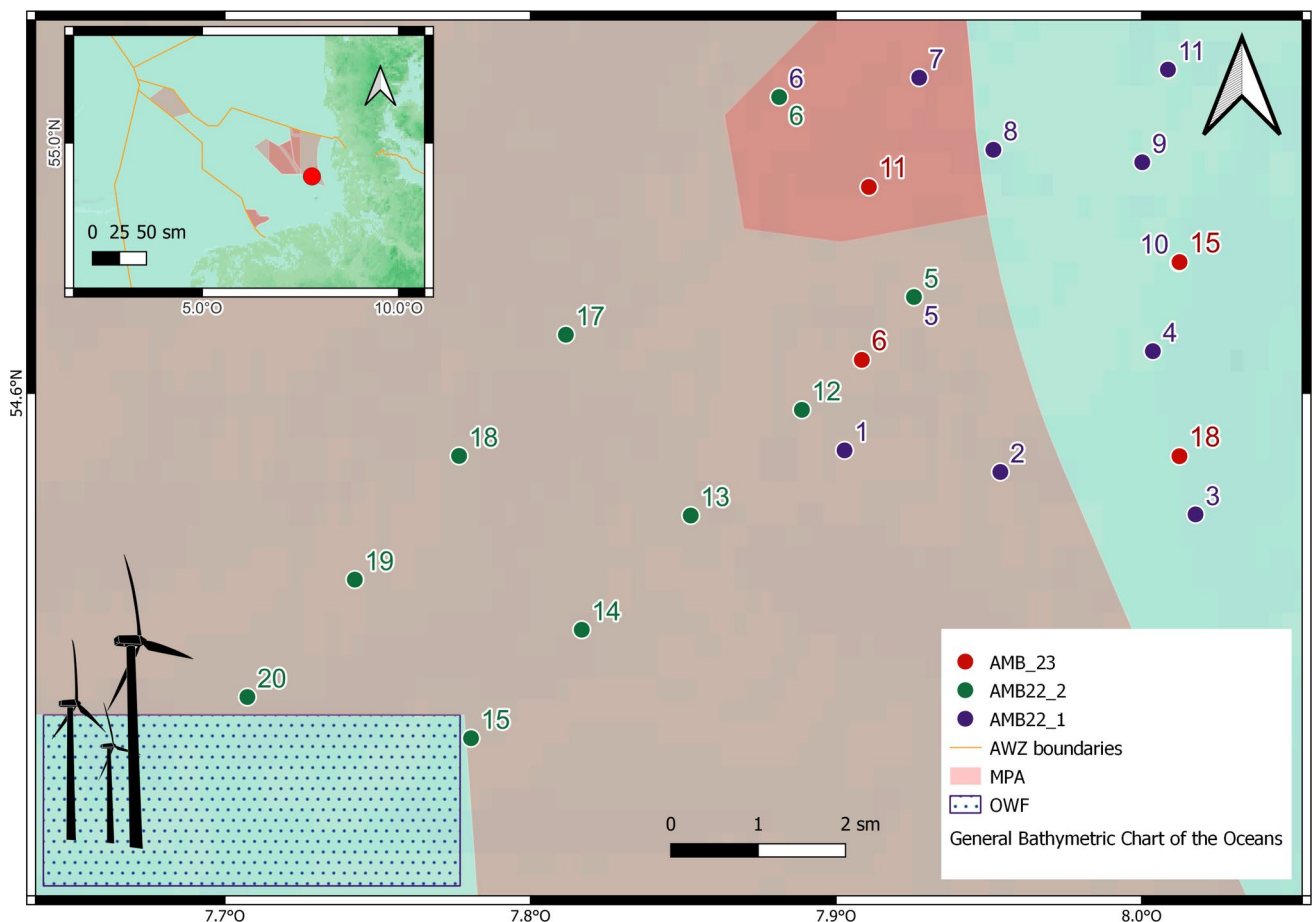


**Fig. 1** Map of the sampled area at Amrum Bank with MPA (marine protected area, red area). Green dots=AMB22\_2, blue dots=AMB22\_1, and red dots=AMB23. The blue dotted rectangle shows the area of the offshore wind farm Amrum Bank West. The

small map shows the German exclusive economic zone of the North Sea and the position of the sampled area within it (red dot in small map)

for a distance of one nautical mile (~ 1.85 km) in one direction at a speed of two knots (~ 3.7 km/h) over the seafloor to record epifauna and demersal fishes. This catch was also documented photographically, then sieved, and the coarse fraction was separated from the fine fraction (first sieve 1 cm<sup>2</sup>, second sieve 1 mm<sup>2</sup>). At three stations in October 2023 (stations 6, 15, and 18), the beam trawl was towed for a shorter distance of only 0.2 nautical miles (~ 370 m) due to logistical constraints. To ensure consistency in the dataset, the catch data from these shorter tows were extrapolated to match the standard towing distance of one nautical mile. This extrapolation was done by multiplying the observed counts by a factor of five, assuming a linear relationship between towing distance and catch volume. All captured animals were determined to species level, and the numbers of specimens were individually counted as quickly as possible (Table A2). The catch volume was determined using a measuring bucket by determining the number of liters of the haul. After that procedure, the animals were released back into their habitat to try to allow survival. Species or parts from the fine fractions as well as species that could not be fully determined or were of special interest were fixed in EtOH 96% or in a 5% formaldehyde-sea water solution and were brought ashore and into the laboratory. Species from the coarse fraction which were determined at the lab were added to the quantitative list, except colonial forms. In order to record water parameters, a CTD was lowered to the seafloor, and temperature and salinity of the water column were recorded.

## Statistical analyses

All statistical analyses were conducted using R (version 4.3.1) and the packages dplyr (version 2.4.0), tidyr (version 1.3.0), PMCMRplus (version 1.9.9), stats (version 4.3.1), MASS (version 7.3–60.0.1) nlme (version 3.1–163), emmeans (version 1.10.1), broom.mixed (version 0.2.9.5), and tidyverse (version 2.0.0). For the evaluation, the stations were divided into the groups “protected by MPA” and “not protected” according to their position. When the two groups protected and not protected were compared with each other, averaged values calculated for the number of respective stations were used. All analyses concerning only the occurrence of species without individuals were carried out using data generated from both the ring dredge and the beam trawl. All analyses in which numbers of individuals were included were carried out using only the data from the beam trawl. For reasons of better comparability, an average value of the individual abundances of the three expeditions from 2023 was calculated and used for the statistical analysis. This means that all three seasons are represented in the data, and the seasonal effect is reduced by averaging the values of the data of 2023. A Shapiro–Wilk test

showed that the species data from the 25 stations were not normally distributed ( $p < 0.001$ ). We then decided to use a Kruskal–Wallis test, as a non-parametric alternative to the one-way analysis of variance (ANOVA). The test showed significant differences between the groups protected and not-protected ( $p < 0.001$ ). For a post-hoc analysis, the Nemenyi test was chosen, which also showed significant differences between both groups ( $p < 0.001$ ). Biodiversity was assessed using the Shannon–Wiener index (Hs), which accounts for both species richness and evenness and is commonly applied in ecological studies of benthic macrofauna. This metric was selected for its ability to provide a balanced view of community composition while being robust to sample size and moderate heterogeneity. While we acknowledge that biodiversity is a multidimensional concept, including aspects such as functional, phylogenetic, and beta diversity, we focused on Hs as a general and interpretable indicator of alpha diversity across spatial gradients. The choice of a single diversity index was made to ensure comparability with previous studies and to maintain clarity in evaluating broad community patterns. Nonetheless, we recognize the limitations of relying on a single metric, as highlighted by Chase and Knight (2013) and Chao et al. (2014). A correlation analysis was carried out to find a relationship between proximity to the OWF, the number of individuals, the catch volume, and Hs, which is commonly used (Spellerberg and Fedor 2003). The significance of the three correlations was checked using a Pearson’s statistical test. A statistical analysis was also carried out at the species level to determine the possible relationship between proximity and distance to the OWF. A Spearman rank analysis was carried out and confirmed by a significance test according to Zar to see which species are positively or negatively influenced by proximity to the OWF. A multidimensional scaling in an MDS plot according to Bray–Curtis should reveal differences in the communities at each station and between the protected and unprotected stations. For a detailed comparison of species abundances, we selected four stations closest to the offshore wind farm and located within the MPA (Sylt Outer Reef–Eastern German Bight; stations 14, 15, 19, and 20 from expedition AMB22\_1) as well as four stations farthest from the OWF and outside the MPA (stations 8–11 from expedition AMB22\_1). The abundance of each species was summed across the respective four stations in each area. Species with a minimum difference of 10 individuals between the summed abundances of these two groups were identified for comparison.

To address the limitations of separate statistical tests for distance and protection status—namely, inflated type I error rates and the assumption of independence between variables—we applied linear mixed-effects models (LMMs). Specifically, we modeled distance to the OWF and protection status as fixed effects and included station identity as

a random effect to account for spatial autocorrelation and repeated measures.

The data were first transformed into long format to allow for species-wise modeling. Species that occurred at fewer than five stations were excluded from the analysis to reduce zero inflation and convergence issues. Each species was modeled individually, with abundance as the response variable. The broom.mixed and emmeans packages were used to extract model estimates,  $p$  values, and confidence intervals for fixed effects. Model assumptions were evaluated via residual diagnostics, and model fit was compared using the Akaike Information Criterion (AIC).

This approach enables a comprehensive and statistically robust assessment of the influence of proximity to OWFs and protection status on benthic species distributions, overcoming the limitations of previous univariate tests.

## Results

### Biodiversity

A total of 93 species were captured using the beam trawl and ring dredge (online supplementary). These

consisted of the phyla Annelida (11 species), Arthropoda (17 species), Bryozoa (4 species), Chordata (28 species), Cnidaria (5 species), Ctenophora (1 species), Echinodermata (6 species), and Mollusca (21 species). Thirty-two of the species found were only detected in the beam trawl, while 27 of the species were only detected in the ring dredge. All remaining 34 species were found in both nets. The three species with the highest number of individuals at the stations within the marine protected area (MPA) were, in descending order, the crab *C. crangon* and the starfishes *Ophiura ophiura* and *A. rubens*. At the stations not located in the MPA, the most frequently found species in descending order of number of individuals are the starfish *O. ophiura* and the crabs *C. crangon* and *L. holsatus*.

The mean Hs of all stations within the protected area was 1.76, and the mean Hs of the stations that were not protected was lower (1.34) (Fig. 2). Only one station, which was located in the non-protected reference area, had a Shannon–Wiener index of 2.1, which is above the average of the stations located in the protected area. All other non-protected stations were below the average Hs of the protected stations, and none of the protected stations had Hs below the average of the unprotected stations.

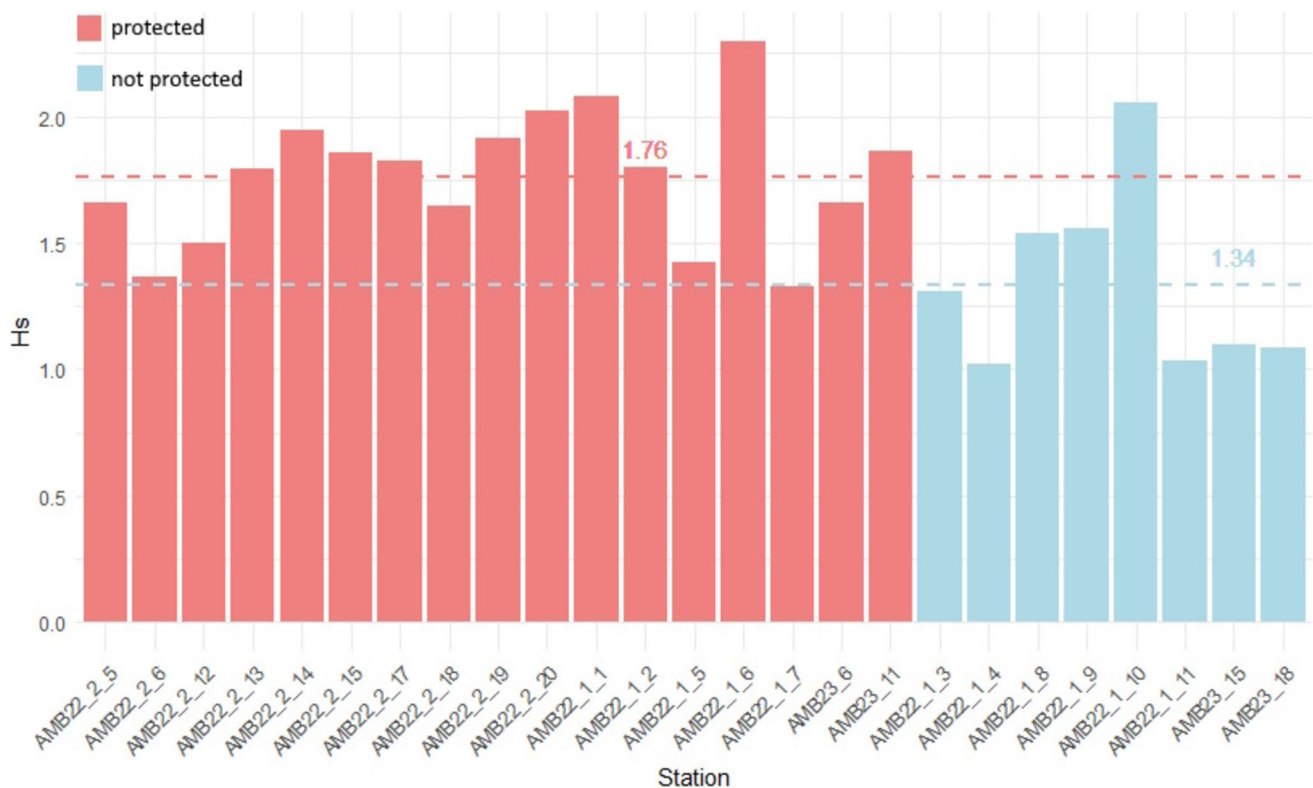


**Fig. 2** Shannon-biodiversity indices (Hs) of sampled stations, red bars are the stations within the MPA, blue bars are not protected. Dotted lines mark the mean Hs of each group

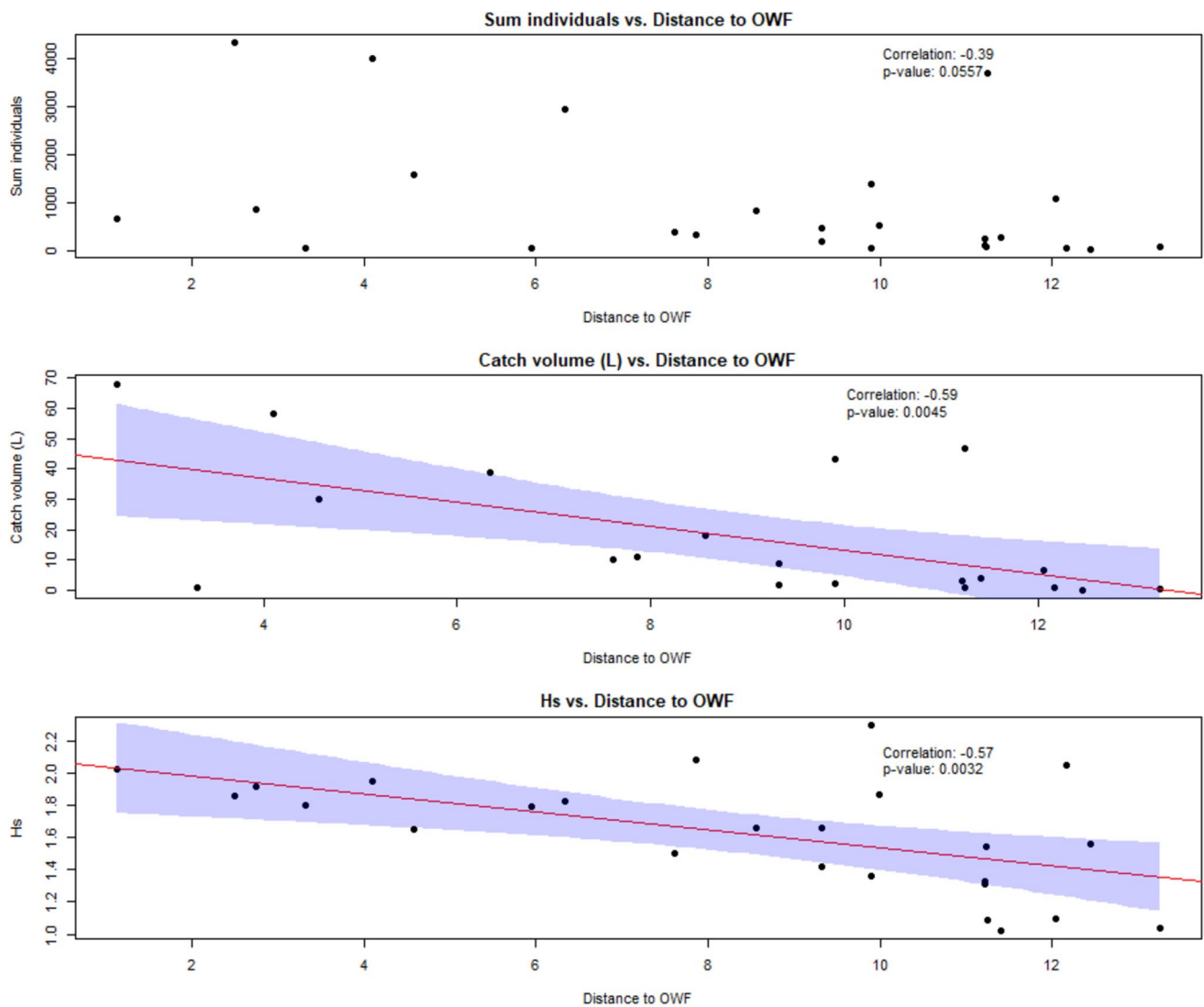


**Fig. 3** Correlations with the distance to the OWF. Once with the sum of individuals (top), once with the catch volume (middle), and once with the Shannon–Wiener index (bottom). The correlation coefficient

and the significance value  $p$  according to Pearson are shown at the top right. The red line shows the linear regression in each case with confidence intervals in blue

### Correlations with offshore wind farm distance

The sum of individuals per station as well as the catch volume and the Shannon–Wiener index (Hs) correlated negatively with an increasing distance to the OWF (Fig. 3). The correlation with biodiversity index Hs and the catch volume shows a significant factor according to Pearson ( $p=0.0045$  for catch volume and  $p=0.0032$  for Hs).

A Spearman rank analysis indicated that the individual abundances of 14 specific species were significantly negatively correlated with increasing distance from the wind farm, as confirmed by a significance test according to Zar (Table 1). The three species with the highest abundances

in closest proximity to the OWF are the starfish *Astropecten irregularis* (Pennant, 1777) and the fish species *Agonus cataphractus* (Linnaeus, 1758) and *Callionymus lyra* (Linnaeus, 1758).

### Comparison of protected and non-protected stations

The MDS analysis (multidimensional scaling) visualizes the differences between different stations based on their epifaunal composition (Fig. 4). The dots in the graph represent different stations, which are distinguished by their location in space and by the respective cruise code and protection status



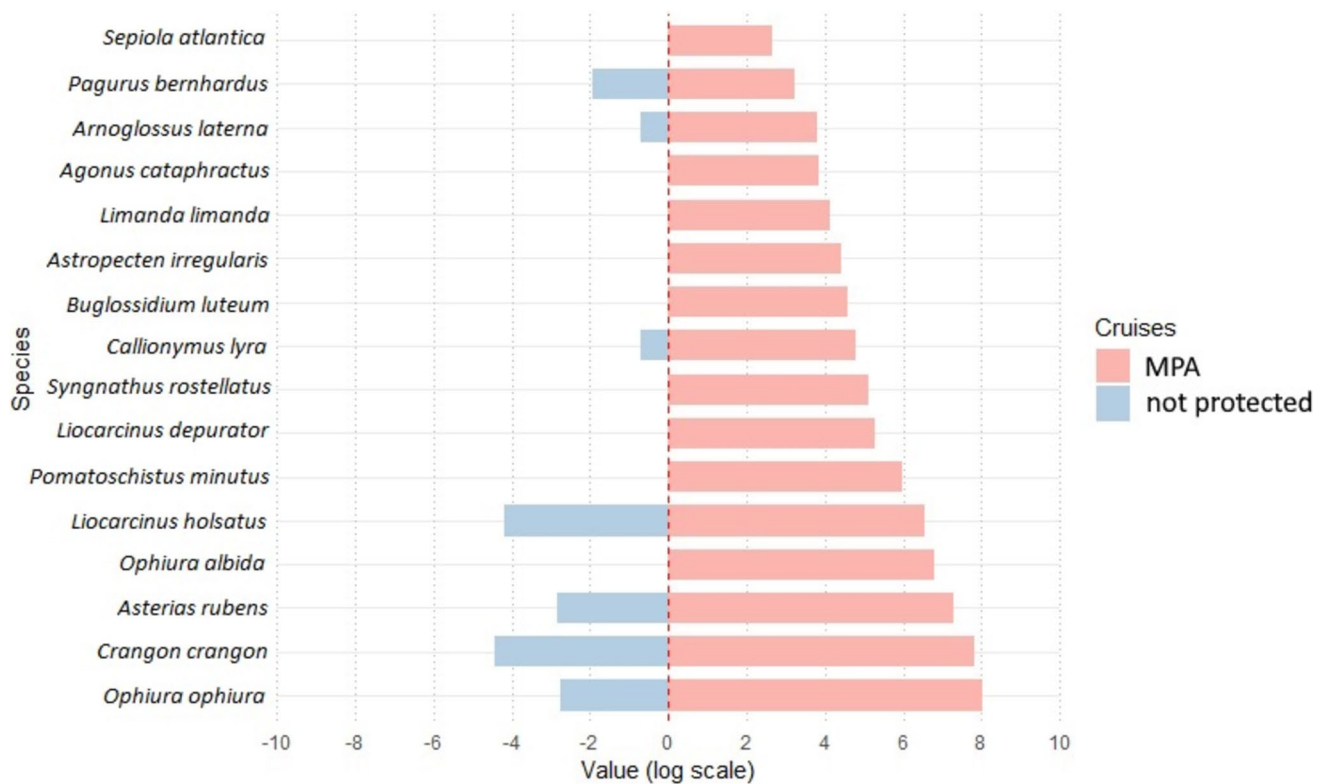


**Fig. 5** Logarithmic representation of the sum of individuals per species of the four outermost stations 8–11 of expedition AMB22\_1 (red bars) and the four nearest stations to the OWF 14, 15, 19, and 20 of

expedition AMB22\_2 (blue bars). Only species with a minimum difference of 10 individuals between the sum of the respective four stations are listed

rather than distance, suggesting that protected areas have a more pronounced impact on their abundance or distribution patterns than proximity to wind farms. Notably, species such as *Agonus cataphractus*, *Anthozoa* indet., *A. rubens*, *A. irregularis*, *Callionymus lyra*, *Callionymus maculatus*, *C. crangon*, *Hyperoplus lanceolatus*, *Limanda limanda*, *Liocarcinus depurator*, *L. holsatus*, *Macropodia rostrata*, *Myoxocephalus scorpius*, and *Buglossidium luteum* exhibit significant positive associations with protection status. This indicates that these species tend to have higher abundances or improved ecological conditions within protected zones. Several species showed significant negative relationships between abundance and distance, suggesting a decrease in their presence farther from the wind farm. For example, *A. cataphractus* displayed a highly significant negative estimate for distance (estimate =  $-822$ ,  $p < 0.001$ ), indicating that abundance declines with increasing distance. Similarly, *Anthozoa* indet. (estimate =  $-61.9$ ,  $p < 0.001$ ), *A. rubens* (estimate =  $-31,400$ ,  $p < 0.001$ ), and *A. irregularis* (estimate =  $-1720$ ,  $p < 0.001$ ) also exhibited significant negative distance effects. Other species with significant negative distance estimates included *C. lyra* ( $-2130$ ,  $p < 0.001$ ), *L. holsatus* ( $-22,200$ ,  $p < 0.001$ ), and *M. scorpius* ( $-66.5$ ,  $p < 0.001$ ). Conversely, some species showed positive but

non-significant estimates for distance, such as *Alcyonium digitatum* (estimate =  $17.6$ ,  $p = 0.14$ ), *Allotheuthis subulata* (estimate =  $70.3$ ,  $p = 0.55$ ), and *Bryozoa* indet. (estimate =  $25.3$ ,  $p = 0.40$ ), indicating no clear pattern in relation to distance.

## Discussion

### Biodiversity

The epibenthic community was studied in relation to the proximity to an offshore wind farm (OWF) and the surrounding marine protected area (MPA) at the Amrum Bank. *Crangon crangon*, *O. ophiura*, and *A. rubens* were the most frequently found species at the stations within the MPA, typical species for the morphology of this area (Neumann et al. 2008). The sediment structure of the Amrum Bank consists mainly of fine sand and medium to coarse sand Brockmeyer and Theobald (2016). This means that differences in the sediment should have little to no influence on the occurrence of different species in this study. These depths of the individual stations range from 8.39 to 22.68-m depth (Table A1). The greatest differences

in depth can be found at expedition AMB22\_2, where the MDS plot (Fig. 4) showed a higher diversity. Station 18 had a very high number of individuals of *O. ophiura* in the first two expeditions of the AMB23 trips, which decreased to nearly zero in the last expedition (online supplementary). This could be the reason why station 18 shows outliers in the MDS analysis in the first two expeditions. *Ophiura ophiura* is considered an opportunist that can quickly fill or leave niches, which explains the different numbers of individuals (Neumann et al. 2009). As other abiotic parameters also prevail with increasing depth, this may only play a little role in the occurrence of different species (Rees et al. 1999). The most common species found in both areas are not entirely the same. *Asterias rubens*, which is otherwise very common in the North Sea Hahn et al. 2022, Hahn et al. submitted, expected (2024), is no longer one of the three most frequently found species at the not-protected stations and has been replaced by *L. holsatus* (Fabricius, 1798). This leads to the assumption that species are affected and benefit differently from fishing exclusion zones associated with the wind farm and trawling activity (van der Reijden 2021). The common swimming crab *L. holsatus* is very mobile and can benefit nutritionally from sediment stirred up by trawlers or rotten carcasses (Groenewold and Fonds 2000). This may explain why *L. holsatus* tends to occur in areas further away from the OWF, where the fishing exclusion zone no longer applies and fishing activity is higher. The stations that are protected by MPA show a higher mean Shannon–Wiener biodiversity index than the stations that are not protected. However, as no stations were sampled directly within the OWF area, caution is needed in attributing these findings solely to OWF influence. Moreover, the distinction between the goals of the OWF and the MPA must be emphasized: MPAs are primarily established to conserve biodiversity, as per IUCN guidelines, while OWFs primarily aim to produce renewable energy. Despite the shared no-fishing feature, these differences could lead to distinct ecological impacts and management implications. Comparing benthic communities directly between MPA sites and OWF sites could provide further insights into these differences. The formation of artificial reefs can lead to an improvement of a habitat (Langhamer et al. 2016), especially when it comes to very uniform areas (Mavraki et al. 2020a, b) such as the sandy Amrum Bank. In general, it has previously been established that a greater abundance of species can be found in the vicinity of a wind farm, especially near the pylons (Lefaible et al. 2023). Changes in the habitat and the altered occurrence of various epifaunal species naturally also lead to shifts in food webs and energy flows, but studies assume that these changes have no influence on the resilience of an ecosystem close to the OWF but rather make it more stable (Raoux et al. 2019). Nonetheless, our

findings indicate that, while the co-location of MPAs and OWFs may enhance local benthic biodiversity through combined effects of fishing exclusion and artificial reef formation, such benefits are highly specific to the soft-bottom habitat of this study area. Our LME analysis supports this interpretation by showing that species richness and abundance significantly increase closer to the OWF, suggesting favorable and more stable habitat conditions near wind turbines.

### Correlations with offshore wind farm distance

The observed negative correlation between the number of individuals, catch volume, and biodiversity (Shannon–Wiener index) with increasing distance from the OWF highlights the potential influence of the fishing exclusion zone and habitat conditions near the wind farm (Fig. 3). These findings suggest that proximity to the OWF may create favorable conditions for epibenthic communities, potentially due to reduced fishing pressure and other localized factors. This is also confirmed by the extended statistical analysis with mixed-effects modeling, as it also confirms that some species decrease significantly with increasing distance to the OWF. It is important to note that this enhanced biodiversity gradient is likely influenced by the unique environmental characteristics of the study area, and such patterns may not be directly transferable to other habitats. On the contrary, of course, this means that the factors mentioned increase in the vicinity of a wind farm, which goes hand in hand with the studies mentioned so far. The formation of artificial reef structures primarily promotes epifaunal diversity, but after an acclimatization phase, a variety of species communities (Pineda-Metz et al. 2023). It is also interesting to note that no species seems to statistically benefit from a greater distance to the wind farm, but on the contrary, 14 species occur in higher numbers of individuals the closer one gets to the OWF. The three species *A. irregularis* (Pennant, 1777), *A. cataphractus* (Linnaeus, 1758), and *C. lyra* (Linnaeus, 1758) show the highest statistical significance, i.e., are most likely to be found in high numbers of individuals, the closer you get to the wind farm. This goes hand in hand with existing findings that OWFs also favor the occurrence of larger and mobile species (Mavraki et al. 2020a, b). Even though flatfish are more likely to be found in sandy areas, the alternation of sandy areas between the pylons of the OWF offers more protection and favors the occurrence of flatfish (Buyse et al. 2022), reinforced by the effect of the lack of fishing. Gradient-based studies have also confirmed precisely this phenomenon, that biodiversity markers such as species density or diversity decrease with increasing distance from the wind farm (Methratta 2021). These results underscore that, while the combined influence of OWFs and fishing exclusion

can benefit local benthic communities, caution is warranted when generalizing these findings to other ecological contexts, but the combination of the OWF with the protected area appears to have a positive effect on epibenthic diversity, as previous studies have already assumed (Ashley et al. 2014; Dunckley and Solandt, 2022).

### Comparison of protected and non-protected stations

The two areas, divided into those protected by MPA and not protected, showed statistically significant differences in their data. Commercially used species such as *B. luteum* (Risso, 1810) or *L. limanda* (Linnaeus, 1758) benefit from the no-fishing zone and occur in higher numbers in the MPA than outside it. The MDS analysis shows a clearer grouping of the protected stations, which indicates a more homogeneous faunistic composition in these areas. The non-protected stations, on the other hand, are more variably distributed, possibly indicating a stronger influence of external factors such as human activities. In order to better understand the specific effects of MPAs compared to OWFs, it would be beneficial to directly compare the benthic communities at sites associated with OWFs and at sites associated with MPAs. Although both areas benefit from the exclusion of fishing, the primary objectives of biodiversity conservation in MPAs and renewable energy production in OWFs may result in different ecological impacts. A comparison of the species from four stations in the immediate vicinity of the OWF and four stations further away, outside the MPA, also shows that all species occur in significantly higher numbers of individuals in the vicinity of the OWF. Here too, fish species such as *Arnoglossus laterna* (Walbaum, 1792), *L. limanda*, or *B. luteum* are mainly found in the protected areas. In general, other studies confirm that the species richness of demersal fishes and thus also of commercially exploited species such as flatfish is considerably higher in the vicinity of wind turbines, which is consistent with our results (Wilhelmsson et al. 2006; Stenberg et al. 2015). However, other species such as the crustaceans *L. holsatus* and *L. depurator* (Linnaeus, 1758), various starfish, and even mussels such as *Sepioloa atlantica* (d'Orbigny, 1842) also occurred in significantly higher numbers of individuals in the vicinity of the OWF. Even though species like *Liocarcinus* can benefit from trawling activity, as mentioned above, they seem to prefer the protected areas. The lack of sediment disturbance and the artificial reefs forming around the wind turbines (Krone et al. 2013; Glarou et al. 2020) can explain the increased occurrence of starfish species and mussels. The LME results further strengthen this interpretation by confirming statistically significant higher abundance and species richness of some species in stations classified as protected compared

to non-protected ones, even when accounting for random variation across expeditions and hauls. Our results confirm previous studies by demonstrating that biodiversity near and within OWFs significantly differs from that in areas further away (ter Hofstede et al. 2022). This suggests that wind farms create distinct ecological conditions that can influence species composition and abundance. This effect is not a local phenomenon but can also be observed in other seas (Wang et al. 2019). These findings reinforce the idea that integrating renewable energy infrastructure with marine conservation measures can yield significant local ecological benefits; however, such outcomes are context-specific. They also highlight the need for further integrated research comparing OWF and MPA sites across diverse environmental contexts to better inform marine spatial planning. The construction of OWFs has increased significantly in recent decades (Gusatu et al. 2020). Furthermore, large-scale expansions of offshore wind farms are planned for the future, as indicated by market analyses and projections of upcoming new OWF capacity for various European countries (Wind Europe 2024; Wilhelmsson et al. 2006). Studies such as this are important in order to protect marine ecosystems and to plan these as efficiently as possible with the combination of MPAs and fishery exclusion zones.

### Broader implications of MPA-OWF co-location

While our study provides evidence that the co-location of an offshore wind farm (OWF) and a marine protected area (MPA) in a soft-bottom habitat of the North Sea can enhance benthic epifaunal diversity, it is important to contextualize these findings within the broader literature. Our results indicate that the observed benefits—namely, increased biodiversity and higher abundances of key species—are strongly linked to the specific characteristics of our study area, including its history of intensive fishing and the nature of the soft-bottom substrate. Areas with different substrate types (e.g., rocky or gravel seabeds) or with alternative wind turbine configurations (such as floating structures) may respond differently to the combination of fishing exclusion and artificial reef effects. Moreover, previous studies (e.g., Lefaible et al. 2023; ter Hofstede et al. 2022) have similarly reported that local environmental conditions are critical in determining the ecological outcomes of co-locating MPAs and OWFs. In addition, it is important to consider that regulatory and management frameworks for MPAs and OWFs often differ, potentially influencing the success and ecological outcomes of co-location strategies. Therefore, while our data support the potential benefits of combining MPAs with OWFs in soft-bottom environments, we advocate for a cautious, case-by-case approach when applying these findings to other contexts. Our study suggests that, although a synergistic benefit is evident in this specific setting, the

broader applicability of such co-location strategies requires further investigation, particularly regarding potential trade-offs between renewable energy production and biodiversity conservation. Future research should explore various habitat types and turbine configurations to develop a more comprehensive understanding of the broader ecological implications of such co-location strategies (Ashley et al. 2014). In summary, our findings contribute valuable insights to the ongoing debate on MPA–OWF co-location, emphasizing that integrated spatial planning which considers both conservation and renewable energy objectives can yield localized benefits, but should not be assumed to serve as a one-size-fits-all solution.

## Conclusion

The construction of offshore wind farms (OWFs) is accompanied by the exclusion of fishing in the German EEZ. In addition to the effect of artificial reef formation, the exclusion of mobile, ground-touching fisheries appears to have a clearly positive effect on the majority of species and the overall epibenthic diversity in various aspects at the Amrum Bank. Although OWFs and MPAs both share the feature of no-fishing, they differ significantly in their primary goals: OWFs aim to generate renewable energy, while MPAs focus on biodiversity conservation as defined by the IUCN. As epifauna plays a crucial role in the health of marine ecosystems, our study shows that the combination of offshore wind farms and marine protected areas increases epibenthic diversity. Additionally, we found that individual epifauna species benefit greatly from these measures, highlighting the importance of creating MPAs in the North Sea to counteract anthropogenic impacts. However, it must be emphasized that no stations were sampled directly within the OWF area, which limits conclusions about the differences between the OWF and surrounding MPAs. According to our data, the way of combining OWF and MPA at the Amrum Bank is beneficial for the benthos and could also be considered for other marine areas in the future. Nevertheless, this conclusion applies specifically to our studied soft-bottom habitats in degraded areas recovering from intensive fishing and with bottom-fixed turbines. In other ecological contexts, such as rocky or gravel seabeds or with floating turbines, the effects could differ significantly.

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## Declarations

**Conflict of interest** The authors declare no competing interests.

**Ethical approval** All applicable international, national, and/or institutional guidelines for animal testing, animal care, and use of animals were followed by the authors.

**Sampling and field studies** All necessary permits for sampling and observational field studies have been obtained by the authors from the competent authorities and are mentioned in the Acknowledgements, if applicable. The study is compliant with CBD and Nagoya protocols.

**Data availability** All data supporting the findings of this study are available within the paper and its Supplementary information. Species data are provided in Supplementary Table A2.

**Author contribution** Conceptualization: SJH. Field studies: SJH, MS. Data curation: SJH. Formal analysis: SJH. Funding acquisition: AB. Project administration: AB. Supervision: AB, MS. Visualization: SJH. Writing—original draft: SJH. Writing—review and editing: MS, SJH, AB.

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