



Guardians of the seabed: Nature-inclusive design of scour protection in offshore wind farms enhances benthic diversity

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ABSTRACT

In the past, a large part of the seabed of the southern North Sea was covered by hard substrates, including oyster beds, coarse peat banks, and glacial erratics. Human activities, particularly bottom trawl fisheries, led to the disappearance of most of these hard substrates, resulting in the loss of its associated diverse benthic life as well. However, the introduction of human-made structures such as offshore wind farms in the North Sea, offers a chance to provide habitat of similar functionality as the former hard substrates. The offshore wind farm infrastructure generally contains layers of rock material deployed at the base of the wind turbine foundations and cable crossings, so-called scour protection, aiming to prevent seabed erosion. The scour protection offers a unique habitat for rock-dwelling benthic organisms in an otherwise mostly soft-bottom environment. By designing the scour protection to be more nature-inclusive, the biodiversity of benthic life can be increased. In this study we examined the effect of substrate material and grading of the scour protection on the epibenthic biodiversity *in situ*. This was done by deploying research cages containing crates ($n = 15$) with different types of substrates (concrete, granite, and marble) on the scour protection within an offshore wind farm in the Dutch North Sea. The study revealed a significant ($p < 0.05$) positive relation between available substrate surface (pebble size) and taxonomic richness. Furthermore, a biological trait assessment of living habits (Tube dwelling, Burrowing, Free living, Crevice dwelling, *Epi*/endobiotic, and Attached) revealed variations in habit modes across substrate types, with marble and concrete samples showing greatest divergence. Marble samples contained a higher prevalence of tube dwelling organisms, whereas concrete samples contained a relatively higher prevalence of free living, *epi*/endobiotic and crevice dwelling organisms. The findings support the value of nature-inclusive scour protection designs, emphasizing that both taxonomic and functional diversity can be enhanced by increasing the available surface area of the scour protection and incorporating a variety of substrate types. By adopting these nature-inclusive design components, the coexistence of renewable energy production and a diverse marine benthic community can be further optimized.

1. Introduction

Historically, the seabed of the southern North Sea was characterized by large areas with hard substrates including oyster beds, coarse peat banks, gravel beds, and boulder clay (Olsen, 1883). As an example, oyster beds covered roughly 6.2% of the total seabed area within the North Sea basin during the late 19th and early 20th centuries (Bennema et al., 2020). Hard substrates serve as critical habitat for a wide range of

marine organisms, by providing attachment surface for sessile organisms and offering shelter and feeding grounds for mobile species (Wahl, 2009). However, human activities such as bottom-trawl fisheries, over-exploitation of commercial reef-building species, and sand extraction, together with climate change, pollution, and diseases have resulted in the destruction and degradation of large parts of these hard substrate habitats (de Groot, 1984; Gross and Smyth, 1946; Koringa, 1952; Weinert et al., 2016). As a consequence, the abundance and presence of

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many species dependent on these habitats have been severely impacted in the North Sea (Bennema et al., 2020; de Vooys et al., 2004). Nowadays, most of the southern North Sea seabed is characterized by a sandy or silty bottom, which holds a lower epibenthic community diversity (Lengkeek et al., 2013a, 2013b; ter Hofstede et al., 2022). The introduction of human-made structures such as offshore wind farms in the North Sea however, offers habitat that may be similar to the former hard substrates.

Ambitious targets have been set to significantly increase the capacity of offshore wind farms in the North Sea, aiming to achieve a substantial share of renewable energy in the energy mix. By 2022, Europe had a cumulative offshore wind farm capacity of 30 GW from which a great portion was situated within the North Sea region (Costanzo and Brindley, 2023). As part of the European Union's goals for climate neutrality, the total offshore wind energy capacity in Europe should become 450 GW by 2050 (The European Green Deal, 2019), of which approximately 47% or 212 GW is expected to be concentrated in the North Sea (Akhtar et al., 2021; Freeman et al., 2019). Assuming the utilization of next generation offshore wind turbines nearing 15 MW (Barter et al., 2023), this expansion would equate to the installation of around 14,133 wind turbine foundations in the North Sea. Surrounding the base of monopiles and on top of the cable crossings typically rocks are deposited. These rocks form a scour protection that prevents the seabed from eroding (scouring) near the turbine foundation and thereby help maintain the stability (den Boon et al., 2004; Glarou et al., 2020). The conventional scour protection is made up of two different layers of rock: a bottom filter layer made of coarse gravel topped with an armour layer made of larger rocks (Glarou et al., 2020) (Fig. 1; left). The radius and overall scour thickness depend on structural factors (i.e. the dimensions of the monopile) and various environmental factors (i.e. water depth, seabed sediment type, and prevailing hydrodynamic conditions) (De Vos et al., 2012; Whitehouse et al., 2011). Typically, the extent of the scour protection area resembles the region of the scour pit that would develop in the case that the monopile would be unprotected (den Boon et al., 2004). Larger turbine foundations often require a more extensive scour

protection to mitigate the risk of scour pit formation (Glarou et al., 2020; Zaaier and Van der Tempel, 2004). At the start of 2021, the total amount of armour layer in wind farms located in the southern North Sea was estimated to be around 1.80 km² (ter Hofstede et al., 2023b), but with the afore mentioned plans to expand the offshore wind industry this area could increase substantially in the nearby future.

Similar to oil/gas platforms and shipwrecks, a scour protection in an offshore wind farm creates a complex hard substrate habitat that offers attachment surface, refuge, and foraging ground for various benthic organisms (e.g. ter Hofstede et al., 2022; Glarou et al., 2020; Guerin et al., 2007; Leewis et al., 2000). Since, similar to natural reefs, these structures provide hard substrate habitats, they are often called artificial reefs. A complex web of interactions may establish at the scour protection which benefits a wide range of species and can promote the local biodiversity (Raoux et al., 2017; ter Hofstede et al., 2022). Moreover, these structures can function as stepping stones, connecting different habitats and facilitating the dispersal of species across the North Sea (Adams et al., 2014; de Mesel et al., 2015). Overall, the scour protection provides suitable hard substrate for reef development, increases the local biodiversity, and promotes the connectivity of isolated populations. Consequently, it has the potential to help contribute to the restoration of former hard substrate regions, such as gravel beds and boulder clay, within the southern North Sea. In addition, the expansion of the offshore wind industry reduces physical disturbances of the seabed over extended areas in the North Sea, by restricting bottom disturbing activities such as trawl fisheries. This allows for the development of newly formed hard substrate habitats and the protection of the soft-bottom environments in between.

In line with the growing recognition to integrate nature conservation and biodiversity considerations into the construction plans of offshore wind farms, new tenders for offshore wind farms in the Dutch North Sea incorporate aspects of nature-inclusive construction, with a growing emphasis on nature enhancement efforts (Rijksoverheid, 2022). By improving the design of existing and new marine infrastructure, such as offshore wind farms, restoration goals can be achieved at a much larger scale (ter Hofstede et al., 2023a). Aligned with this perspective, this study focuses on enhancing the nature-inclusive characteristics of the scour protection in offshore wind farms to optimize the diversity of the epibenthic community (Fig. 1; right). This was done by examining the potential effect of alternating substrate material and substrate grading on the biodiversity at the scour protection. The study involved the placement of three substrate types (marble, granite, and concrete) in research cages on top and above the scour protection of the two monopiles in the Borssele Offshore Wind Farm Site Lot V (The Netherlands). This is one of the first *in situ* studies on the potential to make the scour protection in offshore wind farms more nature-inclusive and therefore our results contribute to the understanding on how to tailor the future design of the scour protection in offshore wind farms with regards to the epibenthic biodiversity.

2. Methodology

2.1. Experimental design

On the scour protection of two monopiles (M01 and M02) in the Borssele Offshore Wind Farm Site Lot V, located around 20 km off the coast of the Netherlands, four research cages were deployed (Fig. 2). Each cage, with dimensions of 1370 × 1024 mm (length x width), held closed crates made of plastic. These crates were filled with either adult flat oysters, oyster spat on shell material, or substrate pieces of pebble-sized (22.2–263.7 cm²) concrete, granite or marble (Fig. 3). The crates themselves measured 39 × 29.5 × 21.5 cm (length x width x height) and contained diamond-shaped holes measuring 4 × 2.5 cm on all sides. The cages were positioned at an average depth of 30.4 ± 1.5 (standard error [se]) m. For the purpose of this research, only the pebble-sized substrates were subject to analysis. Each of the crates held approximately

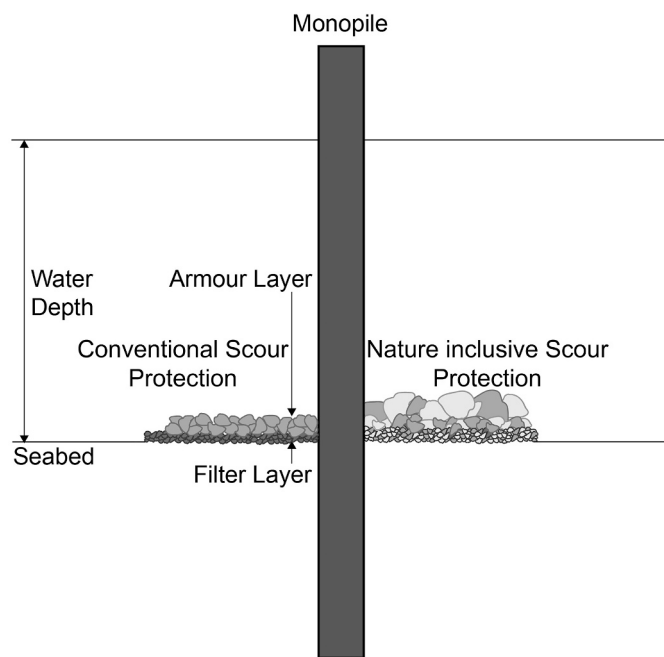


Fig. 1. The illustration shows a conventional scour protection on the left side of the monopile, whereas on the right side, a more nature-inclusive scour protection design is presented. This design incorporates a combination of substrate types and sizes. This study investigates the effect of substrate material and gradation of pebble sized stones in the nature-inclusive scour protection design on the epibenthic biodiversity. Figure is not drawn to scale.

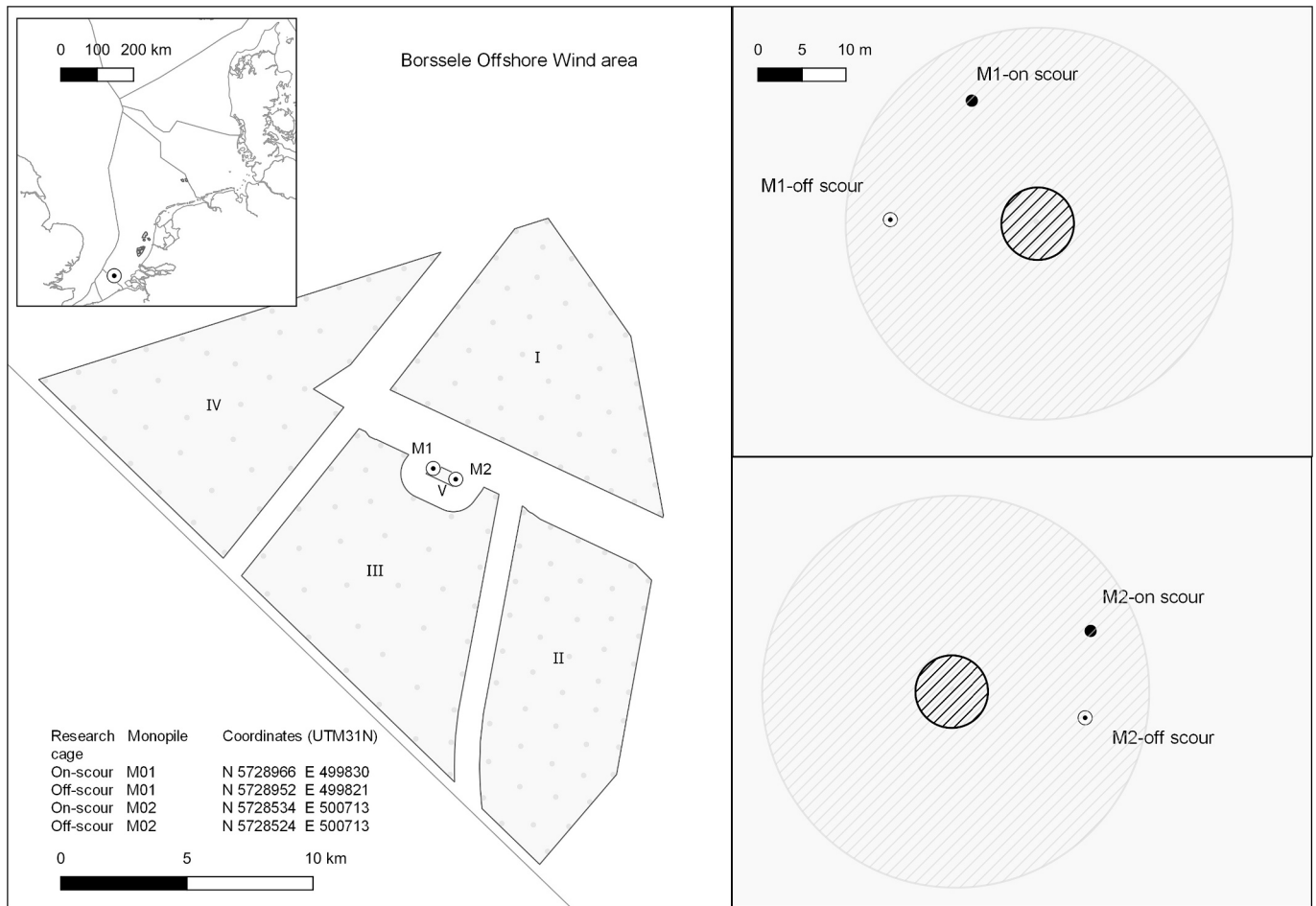


Fig. 2. Schematic representation of the research cage placements at the Borssele Offshore Wind Farm Site Lot V in the Dutch North Sea. The two monopiles have a diameter of 7.4 m. The scour protection around the base of both monopiles varies in shape. Granite stones, with a density of $2.65 \cdot 10^3 \text{ kg m}^{-3}$, are used in the scour protection. The filter layer spans approximately 16 m (laterally from the monopile) and comprises stones ranging from 45 to 180 mm in dimension, while the armour layer spans approximately 8 m (laterally from the monopile) and consists of stones weighing between 5 and 40 kg (translating to a median stone diameter of approximately 20 cm). The seabed within the Borssele Offshore Wind Farm is classified as Atlantic offshore circalittoral sand following the EUNIS habitat description (EMODnet, 2024).

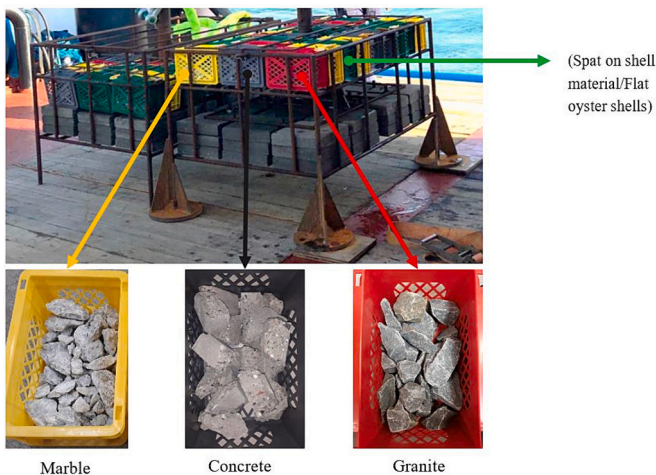


Fig. 3. On board picture of the cage types, left on-scour and right off-scour design, containing the crates filled with different substrates (marble, concrete and granite).

Table 1

Properties of stone substrates contained within the crates. The sorting coefficient was determined following the methodology by Trask (1932); the square root of the ratio of the first and third quartile diameters of the stones.

Stone type	Density (t m^{-3})	Median size (cm)	Sorting coefficient
Concrete	2.2	5.7	1.3
Granite	2.8	6.7	1.3
Marble	2.7	4.6	1.2

3.5 kg of material sourced from a specific substrate type (Table 1). Using a stratified random design, five replicates (crates) per substrate type were randomly positioned in each cage to avoid location effects within the cages (See supplementary material A. for the arrangement of the crates within the cages).

Two different cage designs were employed in this study (Fig. 3). The first design featured thin legs that enabled them to sink into the scour protection layer, allowing the crates to be placed directly on top of the scour protection. This design will be referred to as the “on-scour cage” hereafter. Conversely, the second cage type had supporting feet beneath its legs, preventing the cages from sinking into the scour protection. As a result they remained suspended approximately 40 cm above the scour protection. This design is referred to as the “off-scour cage”. In the on-scour cages, the crates were directly positioned atop the weights

(tiles) at the base of the cage (Fig. 3; left). In contrast, the off-scour cages featured a gap between the crates and the weights, resulting in the substrates within the crates in these cages being situated higher above the scour protection (Fig. 3; right). This arrangement simulated the effect of a thicker armour layer within the scour protection.

Both cage designs were employed in duplicate, totalling four cages with two different cage designs at the scour protection of each monopile. Following the installation on the 11th and 12th of October (2020), the placement and alignment of the cages atop the scour protection were examined and verified through the use of remotely operated vehicle (ROV) video footage and images (See supplementary material B.). Throughout the experiment, the cages experienced primarily tide-driven flow in two directions, as modelled for Site Lot I of the Borssele Offshore Wind Farm (the nearest site with available data): NNE and SSW. The modelled annual maximum depth-averaged current speed was 1.2 m s^{-1} and 1.1 m s^{-1} , respectively (Riezebos et al., 2015). The seawater temperature, as modelled for the Borssele Offshore Wind Farm, fluctuates annually between 3 and 20 °C (Smaal et al., 2017a, 2017b). After being submerged for approximately nine months, the cages were retrieved on the 10th of July (2021).

2.2. Species identification & quantification of stone size

After the cages were retrieved on board, the biodiversity within the crates was assessed. Approximately one third of the contents of each crate, encompassing stones and epifauna (both attached and mobile fauna), was collected and fixed in separate 2 L plastic containers with 6% formaldehyde. These collections were considered as samples for further analysis. When anemones were detected in a sample, the initial step involved adding MgCl_2 to relax these organisms prior to fixation. This was done to limit contraction of the animals.

Fifteen samples (five samples per substrate type divided over on-scour/off-scour cages) were randomly selected and used for taxonomic identification in the laboratory. Mobile fauna from the samples was collected using a 500 μm mesh size sieve. Tap water was used to wash off the formaldehyde. For each identified species from the mobile fauna, the number of individuals were determined. For sessile organisms, taxa were identified and the covered stone area by the fauna was estimated to the nearest cm^2 . All taxa were identified to the lowest taxonomic rank possible, while scoring very small individuals (often juveniles) to higher ranks, using the World register of marine species (WoRMS Editorial Board, 2022) as a reference of taxonomic nomenclature. When necessary a binocular stereo microscope was used during the identification procedure. Following identification, individuals from each non-colonial species in every sample, possessing a wet weight exceeding 0.01 g, underwent ash-free dry weighing (6 h at 500 °C after drying).

The surface area of each stone (available habitat for epifauna) was determined by covering each stone in aluminium foil with no overlaps. The foil was then weighed and converted to a surface area using the weight/surface ratio of the foil.

2.3. Data analysis

The data analysis was carried out at the sample level, as individual stones within a sample were not considered independent due to possible interactions of stones within a crate. Therefore, all sessile and mobile fauna identified within a given sample were merged. Subsequently, a functional trait and univariate analyses were performed using RStudio version 2023.03.0 + 386 (RStudio, 2023) and R version 4.2.3 (R Core Team, 2023).

2.3.1. Functional trait analysis

The on-scour and off-scour treatments were expected to influence the living habit (modes of living) characteristics of the fauna present. Consequently, a living habit functional trait assessment was conducted. By employing a fuzzy-coding approach, following the trait definitions

outlined in Degen and Faulwetter (2019), each unique taxon found within the samples was categorized based on one or more of the six living habit trait characteristics: Tube dwelling, Burrowing, Free living, Crevice dwelling, Epi/endobiotic, and Attached. This fuzzy-coding method allows taxa to express varying degrees of association with different trait categories, eliminating the need to assign a taxon to a single category. The majority of taxa identified in the samples were already present in the database of Clare et al. (2022). However, for the missing taxa, data was collected from a diverse array of sources, primarily drawing from published journal papers, books, and websites affiliated with various scientific institutions, in order to derive trait scores. These trait scores were assigned on a scale ranging from 0 to 3, with 0 signifying no association with a particular trait category and 3 indicating a strong association (Clare et al., 2022). If organisms could not be identified at the genus level but only at a higher taxonomic rank, and other organisms from the same taxonomic group which were identified at the genus level, were present in the samples, the trait scores were determined based on the proportional occurrence of those genus-level identified organisms. Subsequently, community weighted means for all living habit traits within each sample were calculated.

2.3.2. Univariate analysis

Biodiversity within each of the fifteen samples was assessed by quantifying species richness ($S \text{ sample}^{-1}$, only including taxa at species level) and taxonomic richness ($T \text{ sample}^{-1}$, including all taxa). Taxonomic richness was determined by a hierarchical approach, beginning with the consolidation of higher taxonomic data to the lowest level whenever feasible. For instance, in cases where some organisms could not be confidently identified to genus level, for example only to family level, but others within the same family were identified at the genus level, a family-level assignment was elevated to the genus level based on the proportion of occurrences of different genera within that family. If no data was available to facilitate this conversion from family to genus level within the same taxonomic family, the organism retained its classification at the family level in the dataset.

To model the taxonomic richness as a function of covariates, a Poisson generalized linear model (GLM) with log link function was used. Substrate surface (continuous), substrate type (categorical with three levels; granite, marble, and concrete), and cage type (categorical with two levels; on-scour and off-scour cage) were selected as potential covariates explaining patterns and trends in taxonomic richness. Following the protocol by Zuur et al. (2010), the data was first explored to assess presence of outliers, zero-inflation, collinearity of covariates, relationships between taxonomic richness and covariates, and possible interaction terms. Subsequently, a stepwise model selection procedure was performed. Starting from a model including all covariates Eq. (1), the variable with the lowest explanatory value based on the Akaike Information Criterion (AIC) was stepwise removed using the drop1 function. Eventually, the model that best explained the pattern in taxonomic richness was selected as the best model fit. Model assumptions were verified by assessing dispersion, homogeneity, independence, and influential observations following the protocol by Zuur and Ieno (2016).

$$\text{Taxonomic richness}_i \sim \text{Poisson}(\mu_i)$$

$$E(\text{Taxonomic richness}_i) = \mu_i$$

$$\text{var}(\text{Taxonomic richness}_i) = \mu_i$$

$$\ln(\mu_i) = \text{Intercept}_i + \text{SubstrateSurface}_i + \text{SubstrateType}_i + \text{CageType}_i$$

3. Results

3.1. Community

Upon retrieval, the cages were still in their original position and orientation at the exact same location of installation as was validated through ROV inspection. Epifauna covered the entirety of the research



Fig. 4. Picture taken on board after the retrieval of an on-scour cage after it had been submerged for approximately 9 months.

cages, including the retrieval mechanism, the weighting tiles, and the exterior of the plastic crates (Fig. 4). The external surface of the research cages for example, showed large numbers of starfish (*Asterias rubens*) and velvet swimming crabs (*Necora puber*) (Fig. 5). A similar assemblage was found on the surrounding scour protection roughly concluded from inspection of ROV footage. In the vicinity of these research cages, several large fish species were found, including multiple pouts (*Trisopterus luscus*) and a cod (*Gadus morhua*) concealed beneath a research cage at monopile M02.

A total of 17,072 individuals (cm^2 for colonial species) belonging to 131 different taxa (of which 71 species) were observed in the fifteen samples. Of the individuals, 88% ($n = 15,079$) were identified to the species level (Table 2) and 2% ($n = 279$) to the genus level, leaving 10% ($n = 1715$) identified to higher levels. Arthropods (13 species) and Annelids (34 species) were the most abundant species groups, with 12,260 and 3053 individuals respectively. Nemertea and Platyhelminthes were only identified to phylum level and consisted of 155 and 33 individuals respectively. Other phyla observed included Mollusca (8 species), Bryozoa (7 species), Cnidaria (4 species), Echinodermata (3 species), and Chordata (2 species). Overall, a mean sample taxonomic richness of 49 ± 1.78 (se) taxa and a mean sample species richness of 30 ± 1.16 (se) species was recorded. All substrate types showed a similar phylum distribution pattern (Fig. 6, see supplementary material C. for cage type). However, the Arthropoda, Bryozoa and Cnidaria were most abundant at marble samples, and Mollusca were least abundant at concrete samples. For instance, the Arthropoda *Jassa herdmani* and *Monocorophium acherusicum* were more prevalent in the marble samples, similarly for the Bryozoa *Conopeum reticulatum* and *Electra pilosa*, and the Cnidarian *Tubularia indivisa*. Some other findings

are the absence of the Annelid *Heteromastus filiformis* in granite samples, the at least double abundance of the Arthropods *Monocorophium acherusicum* and *Verruca stroemia* in the marble samples compared to the other substrate types, and the presence of the Echinodermata *Amphipholis squamata* only in marble samples. Additionally, reef building species often considered important policy-relevant species in the North Sea such as *Sabellaria spinulosa* (recorded in all substrate samples), *Janice conchilega* (recorded in granite and marble samples), and *Mytilus edulis* (recorded only in marble samples) were identified in this study.

3.2. Functional diversity

The functional traits indicate that the distribution characteristics related to living habit show consistent patterns across the different substrate types and cage types, whereas the actual proportions do differ across substrate types (Fig. 7). Tube dwelling species, in particular, dominate all treatments, followed by free living species. Burrowing species and those inhabiting crevices/holes or living under stones are the least abundant in all treatments. When examining the proportions of the trait groups, no clear distinctions emerge between the two cage types. On the other hand, between the substrate types there are some differences visible. The free living group exhibits greater proportions in marble and granite samples when compared to concrete. The dominance of the tube-dwelling trait is marked by the presence of *Monocorophium* and *Jassa*, which are particularly abundant in marble samples, followed by granite samples. Conversely, *Stenothoe* stands out as significantly more abundant in concrete samples, contributing to a higher representation of the free living, *epi/endobiotic*, and crevice dwellings groups within the concrete samples.

3.3. Univariate analysis

In the full model Eq. (1), no clear relation between substrate type and cage type with taxonomic richness was found ($p > 0.05$). Therefore, these variables were removed during the model selection procedure. In the resulting final model with substrate surface only as explanatory variable, a significant effect of sample surface area on taxonomic diversity was found ($p < 0.05$, McFadden's pseudo- $R^2 = 0.34$) (Fig. 8; Table 3). This means that a larger substrate surface area leads to an increased taxonomic richness.

4. Discussion

Knowledge on the development of marine growth at the scour protection is essential for improving the design of the conventional scour protection towards a more nature-inclusive design. While earlier research primarily centred on the broader potential for enhancing ecological functionality within offshore wind farms, including initiatives like the co-development of flat oyster (*Ostrea edulis*) reefs in existing and planned wind farms and incorporating nature-inclusive add-ons such as



Fig. 5. Screenshots, captured from ROV videos just before retrieval, showing research cages covered with marine life.

Table 2

Mean abundance (n per sample or “*” denotes measurement in cm² for colonial species) species list with standard error per substrate type. Nemertea and Platyhelminthes are not included in this list, since they were only identified at phylum level.

Species	Phylum	Class	Order	Family	Genus	Concrete	Granite	Marble
<i>Glycera lapidum</i>	Annelida	Polychaeta	Phyllodocida	Glyceridae	<i>Glycera</i>	2	4	0
<i>Psamathe fusca</i>	Annelida	Polychaeta	Phyllodocida	Hesionidae	<i>Psamathe</i>	20.2 ± 2.4	13.8 ± 4.4	21.4 ± 4.7
<i>Syllidia armata</i>	Annelida	Polychaeta	Phyllodocida	Hesionidae	<i>Syllidia</i>	1	2	0
<i>Eunereis longissima</i>	Annelida	Polychaeta	Phyllodocida	Nereididae	<i>Eunereis</i>	5.7 ± 0.3	7 ± 2.3	11 ± 2.9
<i>Eteone flava</i>	Annelida	Polychaeta	Phyllodocida	Phyllodocidae	<i>Eteone</i>	3.5 ± 0.6	4.1 ± 1.7	3.4 ± 1.0
<i>Eulalia ornata</i>	Annelida	Polychaeta	Phyllodocida	Phyllodocidae	<i>Eulalia</i>	1	0	1
<i>Eulalia viridis</i>	Annelida	Polychaeta	Phyllodocida	Phyllodocidae	<i>Eulalia</i>	1	1	0
<i>Eumida sanguinea</i>	Annelida	Polychaeta	Phyllodocida	Phyllodocidae	<i>Eumida</i>	1	2 ± 0.0	1
<i>Phyllodoce maculata</i>	Annelida	Polychaeta	Phyllodocida	Phyllodocidae	<i>Phyllodoce</i>	1.2	0	2 ± 1.0
<i>Phyllodoce mucosa</i>	Annelida	Polychaeta	Phyllodocida	Phyllodocidae	<i>Phyllodoce</i>	16.9 ± 10.2	18.3 ± 5.8	20.8 ± 5.1
<i>Gattyana cirrhosa</i>	Annelida	Polychaeta	Phyllodocida	Polynoidae	<i>Gattyana</i>	2.9 ± 0.9	7.4 ± 4.1	8.1 ± 6.6
<i>Harmothoe clavigera</i>	Annelida	Polychaeta	Phyllodocida	Polynoidae	<i>Harmothoe</i>	0	0	1.9
<i>Harmothoe extenuata</i>	Annelida	Polychaeta	Phyllodocida	Polynoidae	<i>Harmothoe</i>	12.7 ± 7.9	3.5 ± 2.5	4.7 ± 1.6
<i>Lepidonotus squamatus</i>	Annelida	Polychaeta	Phyllodocida	Polynoidae	<i>Lepidonotus</i>	23.6 ± 6.9	18.6 ± 3.4	37.7 ± 17.0
<i>Pholoe baltica</i>	Annelida	Polychaeta	Phyllodocida	Sigalionidae	<i>Pholoe</i>	10.4 ± 3.3	8.6 ± 2.9	11.4 ± 2.3
<i>Pholoe inornata</i>	Annelida	Polychaeta	Phyllodocida	Sigalionidae	<i>Pholoe</i>	0	0	1
<i>Procerastea halleziana</i>	Annelida	Polychaeta	Phyllodocida	Syllidae	<i>Procerastea</i>	1	1	0
<i>Syllis armillaris</i>	Annelida	Polychaeta	Phyllodocida	Syllidae	<i>Syllis</i>	2	0	1
<i>Spirobranchus lamarcki</i>	Annelida	Polychaeta	Sabellida	Serpulidae	<i>Spirobranchus</i>	10.9 ± 3.1	4.3 ± 1.1	9.1 ± 1.7
<i>Spirobranchus triquetus</i>	Annelida	Polychaeta	Sabellida	Serpulidae	<i>Spirobranchus</i>	17.3 ± 4.9	8.4 ± 4.2	12.0 ± 3.0
<i>Aonides paucibranchiata</i>	Annelida	Polychaeta	Spionida	Spionidae	<i>Aonides</i>	2.5 ± 1.5	0	0
<i>Dipolydora caulleryi</i>	Annelida	Polychaeta	Spionida	Spionidae	<i>Dipolydora</i>	1	0	1
<i>Dipolydora coeca</i>	Annelida	Polychaeta	Spionida	Spionidae	<i>Dipolydora</i>	0	1	0
<i>Malacoceros jirkovi</i>	Annelida	Polychaeta	Spionida	Spionidae	<i>Malacoceros</i>	3	2.5	0
<i>Spio martinensis</i>	Annelida	Polychaeta	Spionida	Spionidae	<i>Spio</i>	0	0	1
<i>Chaetozone zetlandica</i>	Annelida	Polychaeta	Terebellida	Cirratulidae	<i>Chaetozone</i>	2	0	1.5 ± 0.5
<i>Lagis koreni</i>	Annelida	Polychaeta	Terebellida	Pectinariidae	<i>Lagis</i>	2 ± 1.0	3.2 ± 0.4	3.7 ± 2.2
<i>Lanice conchilega</i>	Annelida	Polychaeta	Terebellida	Terebellidae	<i>Lanice</i>	0	1	1.3
<i>Neoamphitrite figulus</i>	Annelida	Polychaeta	Terebellida	Terebellidae	<i>Neoamphitrite</i>	1	0	0
<i>Heteromastus filiformis</i>	Annelida	Polychaeta		Capitellidae	<i>Heteromastus</i>	24	0	34
<i>Mediomastus fragilis</i>	Annelida	Polychaeta		Capitellidae	<i>Mediomastus</i>	21.0 ± 9.3	34.6 ± 21.9	44.4 ± 16.1
<i>Notomastus latericeus</i>	Annelida	Polychaeta		Capitellidae	<i>Notomastus</i>	1.5 ± 0.5	8.5 ± 5.5	4.6 ± 1.1
<i>Sabellaria spinulosa</i>	Annelida	Polychaeta		Sabellariidae	<i>Sabellaria</i>	21.6 ± 1.4	25.6 ± 6.3	38.3 ± 11.4
<i>Aora gracilis</i>	Arthropoda	Malacostraca	Amphipoda	Aoridae	<i>Aora</i>	0	36	0
<i>Gitana sarsi</i>	Arthropoda	Malacostraca	Amphipoda	Amphilochidae	<i>Gitana</i>	4 ± 1	1.7 ± 0.7	1
<i>Jassa herdmani</i>	Arthropoda	Malacostraca	Amphipoda	Ischyroceridae	<i>Jassa</i>	153.7 ± 39.2	270.3 ± 76.2	308.4 ± 106.4
<i>Monocorophium acherusicum</i>	Arthropoda	Malacostraca	Amphipoda	Corophiidae	<i>Monocorophium</i>	232.5 ± 29.8	268.5 ± 58.0	635.4 ± 253.1
<i>Phtisica marina</i>	Arthropoda	Malacostraca	Amphipoda	Caprellidae	<i>Phtisica</i>	28 ± 113.4	30.6 ± 9.2	9.2 ± 1.9
<i>Stenothoe monoculoides</i>	Arthropoda	Malacostraca	Amphipoda	Stenothoidae	<i>Stenothoe</i>	1.4 ± 0.3	2.8 ± 1.0	3.4 ± 1.2
<i>Stenothoe valida</i>	Arthropoda	Malacostraca	Amphipoda	Stenothoidae	<i>Stenothoe</i>	58.0 ± 22.1	43.8 ± 9.7	32.4 ± 10.1
<i>Pilumnus hirtellus</i>	Arthropoda	Malacostraca	Decapoda	Pilumnidae	<i>Pilumnus</i>	1.3 ± 0.3	2	1
<i>Pisidia longicornis</i>	Arthropoda	Malacostraca	Decapoda	Porcellanidae	<i>Pisidia</i>	64.6 ± 12.6	45.6 ± 9.2	51 ± 16.5
<i>Pseudocuma (Pseudocuma) simile</i>	Arthropoda	Malacostraca	Cumacea	Pseudocumatidae	<i>Pseudocuma</i>	1	0	0
<i>Balanus crenatus</i>	Arthropoda	Thecostraca	Balanomorpha	Balanidae	<i>Balanus</i>	10.5 ± 4.1	22.3 ± 11.6	16.7 ± 7.9
<i>Perforatus perforatus</i>	Arthropoda	Thecostraca	Balanomorpha	Balanidae	<i>Perforatus</i>	0	0	1.7
<i>Verruca stroemia</i>	Arthropoda	Thecostraca	Verrucomorpha	Verrucidae	<i>Verruca</i>	15.2 ± 4.4	24.8 ± 6.6	50.8 ± 40.3
<i>Conopeum reticulum</i> *	Bryozoa	Gymnolaemata	Cheilostomatida	Electridae	<i>Conopeum</i>	4.8 ± 1.5	5.6 ± 1.2	9 ± 2.7
<i>Electra pilosa</i> *	Bryozoa	Gymnolaemata	Cheilostomatida	Electridae	<i>Electra</i>	6.8 ± 1.6	13 ± 1.0	23.4 ± 9.4
<i>Callopora dumerilii</i> *	Bryozoa	Gymnolaemata	Cheilostomatida	Calloporidae	<i>Callopora</i>	1 ± 0.0	1	1.7 ± 0.3
<i>Alcyonidium diaphanum</i> *	Bryozoa	Gymnolaemata	Ctenostomatida	Alcyonidiidae	<i>Alcyonidium</i>	0	1	1
<i>Alcyonidium parasiticum</i> *	Bryozoa	Gymnolaemata	Ctenostomatida	Alcyonidiidae	<i>Alcyonidium</i>	0	0	1
<i>Arachnidium fibrosum</i> *	Bryozoa	Gymnolaemata	Ctenostomatida	Arachnidiidae	<i>Arachnidium</i>	1	1	1 ± 0.0
<i>Vesicularia spinosa</i> *	Bryozoa	Gymnolaemata	Ctenostomatida	Vesiculariidae	<i>Vesicularia</i>	0	0	1.5 ± 0.5
<i>Ciona intestinalis</i>	Chordata	Ascidacea	Phlebobranchia	Cionidae	<i>Ciona</i>	1 ± 0.0	0	1 ± 0.0
<i>Diplosoma listerianum</i> *	Chordata	Ascidacea	Aplousobranchia	Didemniidae	<i>Diplosoma</i>	7 ± 2.0	7.2 ± 1.5	9.4 ± 4.6
<i>Tubularia indivisa</i> *	Cnidaria	Hydrozoa	Anthoathecata	Tubulariidae	<i>Tubularia</i>	2	0	5
<i>Clytia hemisphaerica</i> *	Cnidaria	Hydrozoa	Leptothecata	Campanulariidae	<i>Clytia</i>	1 ± 0.0	1	1
<i>Obelia bidentata</i> *	Cnidaria	Hydrozoa	Leptothecata	Campanulariidae	<i>Obelia</i>	0	1	0
<i>Alcyonium digitatum</i> *	Cnidaria	Anthozoa	Malacalcyonacea	Alcyoniidae	<i>Alcyonium</i>	5 ± 0.4	5.2 ± 0.5	7 ± 2.5
<i>Asterias rubens</i>	Echinodermata	Asterozoa	Forcipulatida	Asteriidae	<i>Asterias</i>	0	2.5 ± 0.5	8
<i>Psammechinus miliaris</i>	Echinodermata	Echinozoa	Camarodonta	Parechinidae	<i>Psammechinus</i>	2	1	1
<i>Amphipholis squamata</i>	Echinodermata	Ophiurozoa	Ophiuroidea	Amphipholidae	<i>Amphipholis</i>	0	0	6
<i>Abra alba</i> *	Mollusca	Bivalvia	Cardiida	Semellidae	<i>Abra</i>	2	4 ± 0.0	4.4 ± 2.1
<i>Hiatella arctica</i>	Mollusca	Bivalvia	Adapedonta	Hiatellidae	<i>Hiatella</i>	0	1	0
<i>Musculus discors</i>	Mollusca	Bivalvia	Mytilida	Mytilidae	<i>Musculus</i>	0	0	1
<i>Mytilus edulis</i>	Mollusca	Bivalvia	Mytilida	Mytilidae	<i>Mytilus</i>	0	0	5.2
<i>Heteranomia squamula</i>	Mollusca	Bivalvia	Pectinida	Anomiidae	<i>Heteranomia</i>	0	0	1
<i>Mimachlamys varia</i>	Mollusca	Bivalvia	Pectinida	Pectinidae	<i>Mimachlamys</i>	1	0	0
<i>Crepidula fornicata</i>	Mollusca	Gastropoda	Littorinimorpha	Calyptaeidae	<i>Crepidula</i>	0	0	1.7 ± 0.3
<i>Pusillina inconspicua</i>	Mollusca	Gastropoda	Littorinimorpha	Rissoidae	<i>Pusillina</i>	2	2	1 ± 0.0

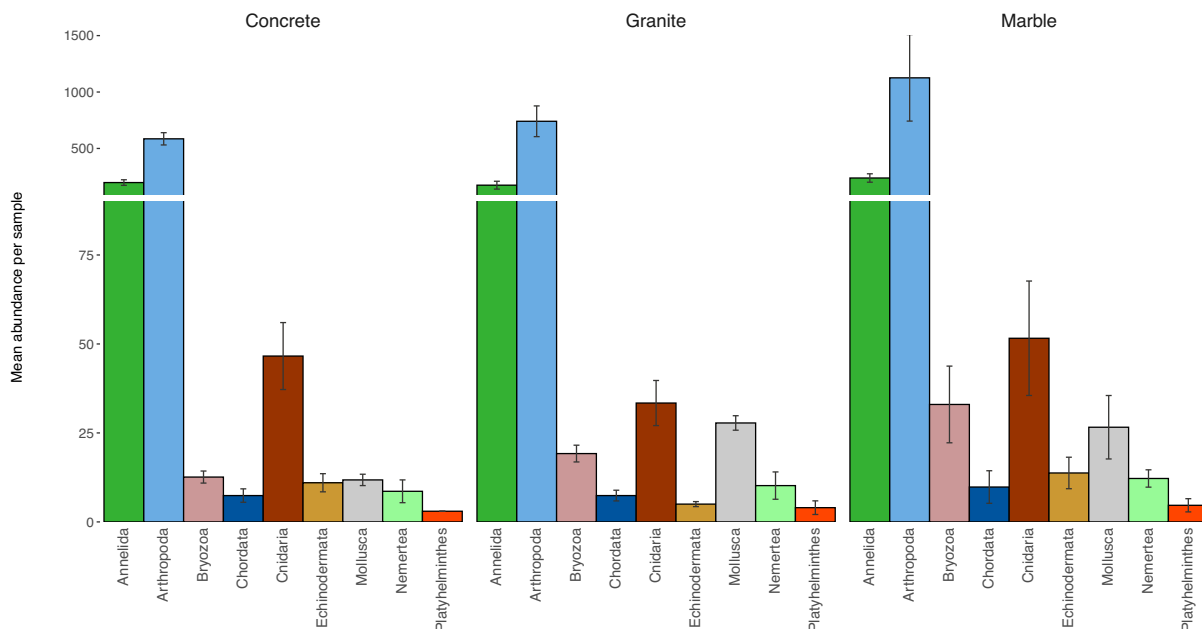


Fig. 6. Bar plots showing mean sample phylum abundance with standard errors per substrate type. Plots were made using the ggbreak package from Xu et al. (2021).

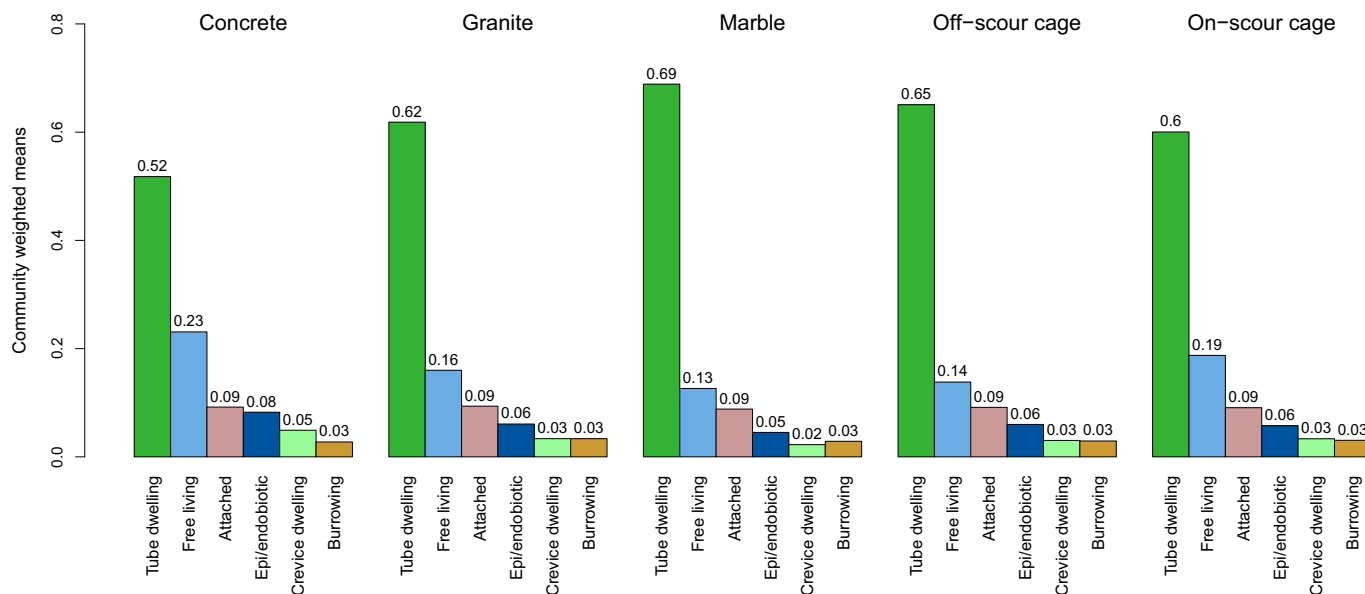


Fig. 7. Community weighted means of living habit traits based on substrate and cage type.

fish hotels, reef cubes/balls, etc. (e.g. Hermans et al., 2020; Smaal et al., 2017a, 2017b), the present work aims to generate specific insights towards promoting biodiversity within the scour protection. Although, various suggestions have already been proposed to optimize the design of the scour protection (e.g. Lengkeek et al., 2017; ter Hofstede et al., 2023b), to our knowledge this is one of the first *in situ* studies to provide results on how alternating substrate material and substrate gradation in the scour protection influences the diversity of the epibenthic community.

Although the sample size was limited due to budgetary and time restrictions, we showed that the proportions of living habit traits change with different substrate types, suggesting that variation in substrate type in the scour protection may increase functional diversity. We further showed a positive relation between available surface area and taxonomic richness, indicating that increasing the surface area of the scour

protection may lead to a higher biodiversity.

4.1. Comparison with other offshore wind farms and hard substrates

A multitude of species were documented during the sample analyses in the laboratory, as well as through the examination of ROV video footage. It is likely that there are more mobile species inhabiting the area, but they may have gone unnoticed in the ROV footage due to reduced visibility caused by the high turbidity and limited light conditions, or possible avoidance of the area due to the presence of the ROV. A total of 71 species were identified in the samples analysed during this study (Table 2). This surpasses the findings from a previous study in the Borssele Offshore Wind Farm at the scour protection in Lot III and IV, where in total 65 species were recorded using ROV video inspection (De Rijke Noordzee). Moreover, the species richness observed in our study

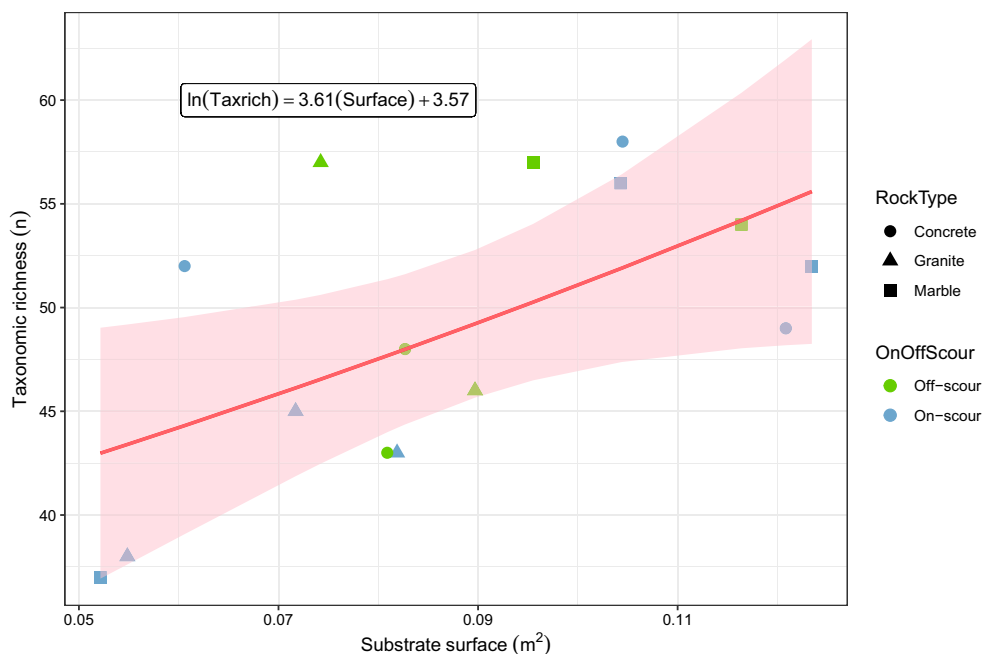


Fig. 8. Fitted model relation (red line, ribbon: 95% confidence interval) between substrate surface and taxonomic richness. Substrate type is indicated with different symbols and cage type with different colours, however, both variables are not part of the model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3

GLM model output with substrate surface as explanatory variable and taxonomic richness as response variable.

	Estimate	Std. error	z value	P-value
Intercept	3.573	0.152	23.440	<2e-16
Substrate surface	3.609	1.655	2.181	0.0292

was also higher compared to the diversity reported at scour protections in other offshore wind farms within the Dutch North Sea. For instance, in the Offshore Wind Farm Egmond aan Zee, researchers identified a total of 35 species from rock samples collected at the scour protection over a 4-year period (Bouma and Lengkeek, 2012). Similarly, in the Princess Amalia Wind Farm, 42 species were found on rock samples collected from the scour protection 6 years after construction (Vanagt and Faasse, 2014). The method of sampling (rocks placed in crates within cages versus collecting rocks from the scour protection itself) could perhaps explain the difference. Moreover, the difference in rock surface area for the samples could potentially also explain the offset in these results, as we show here that this is of significant influence on richness. Additionally, seasonal fluctuations might exert influence on the abundance and presence of particular species during the monitoring period (Van Moorsel, 2014). For example, samples collected from the scour protection in the Offshore Wind Farm Egmond aan Zee were obtained in February and September, whereas samples from this investigation were collected in July. Furthermore, the duration of underwater exposure for human-introduced hard substrates also plays a role in shaping the development of the biofouling community (Zupan et al., 2023). In this study, the cages containing the samples were submerged for a period of 9 months, a relatively short timeframe compared to the other studies. This may result in different succession stages, potentially influencing the community composition and diversity (Zupan et al., 2023).

Compared to other hard substrates in the Dutch North Sea that are known to locally enhance the biodiversity, the samples analysed in this study showed a comparable level of species richness. For instance, the species richness observed at a concrete gas platform foundation was 65 species (Coolen et al., 2020), and the average species richness at 10

shipwrecks distributed over the Dutch North Sea was 57 species (Lengkeek et al., 2013a, 2013b). This shows that the construction of offshore wind farms holds the potential for creating artificial habitats that foster a similar diverse benthic community as other artificial reef structures, achieved through the implementation of a nature-inclusive scour protection design.

4.2. Effect of alternating substrates

The univariate analysis did not show a significant effect of substrate type and cage type on the taxonomic richness. This might be attributed to the relatively small sample size ($n = 15$ samples) which may lack sufficient statistical power to detect a difference. However, a significant positive correlation between substrate surface and the taxonomic richness was shown. This demonstrates that increasing the total available surface area in the scour protection improves the effectiveness of the scour protection in promoting biodiversity. A greater surface creates more space for species attachment which is known to enhance biodiversity (Bailey-Brock, 1989; Langhamer, 2012). Additionally, by increasing the quantity of stones used or by selecting stones of varying sizes a greater number of holes and crevices are created in the scour protection. These niches can serve as habitats for mobile species seeking refuge or foraging opportunities, which also stimulate the biodiversity (Lengkeek et al., 2017). The biological trait analyses for the functional trait living habit showed similar patterns between the different type of samples. However, proportional abundances varied among the substrate types, with concrete and marble samples differing the most. This observation suggests that the choice of different materials in the scour protection design could enhance functional diversity, as different substrate types may attract a diverse array of species.

4.3. Nature-inclusive design of the scour protection

Beyond the impact of stone type and available surface area on functional diversity and biodiversity, as investigated in this study, various other considerations can be integrated into the design of the scour protection to ecologically enhance marine infrastructure. In addition to the use of large rocks as usual, incorporating smaller rocks in

the armour layer of the scour protection introduces small-scale complexity with small cavities and narrow crevices, creating suitable habitats for smaller species and may play a role in supporting the early life stages of various organisms (Lengkeek et al., 2017). Combining larger and smaller rocks at different locations within the scour protection increases the overall habitat heterogeneity, which could accommodate a broader size range of rock-dwelling species and thereby promote the biodiversity within the scour protection (ter Hofstede et al., 2022). For example, incorporating an additional layer of rocks into the scour protection can offer habitat for a variety of species, including crabs, lobsters, and juvenile cod (Hermans et al., 2020). Additionally, modifying the shape of individual components and the overall shape of the scour protection to be more irregular, with extensions in all directions, generates additional surface area (Lengkeek et al., 2017; ter Hofstede et al., 2023a, 2023b), which we have shown is likely to influence the biodiversity.

Factors like surface texture/roughness, chemical composition, and fine-scale relief can also influence the attached epibenthic community (Beatriz et al., 2006; Hixon and Brostoff, 1985). The use of a calcareous substrate in the scour protection, such as marble and limestone, instead of conventional granite or occasionally concrete, may provide benefits, as it is known to stimulate the settlement of shellfish larvae (e.g. Colsoul et al., 2020; Potet et al., 2021; Soniat et al., 2005). Marble is therefore used as a nature-inclusive add-on in the scour protection in some offshore wind farms, for example in the Dutch offshore wind farm Hollandse Kust (noord & zuid) (Crosswind, 2023). Furthermore, when concrete is used in the scour protection, intentional roughening of its surface to mimic natural rock can promote the colonization of pioneering species (Moschella et al., 2005; Potet et al., 2021). Moreover, the toxicity of concrete can be lowered by employing environmentally friendly adhesives (Perkol-Finkel and Sella, 2014).

Another approach to encourage colonization is the active introduction of specific ecosystem engineering species to the scour protection area, facilitating the establishment of new populations. Some North Sea wind farms, for example, present opportunities for co-designing with oyster bed restoration efforts (Kamermaans et al., 2018). This strategy of active introduction can stimulate population recruitment in areas where natural recruitment is limited or beyond the current range of existing populations. Consequently, the scour protection can act as a stepping stone, connecting various habitats and facilitating species dispersal and movement throughout the North Sea.

5. Conclusion

In conclusion, our study revealed that habit traits vary with different substrate types, suggesting that variation in scour protection substrates could enhance the functional diversity of the epibenthic community. Moreover, we identified a positive correlation between available surface area and taxonomic richness, indicating that expanding the surface area of the scour protection may stimulate the biodiversity. We recommend further *in situ* research on a larger scale to explore the potential benefits of diversifying rock sizes and shapes, incorporating more calcareous rocks, enhancing surface roughness, and actively introducing specific species (such as the ecosystem engineering species *O. edulis*) to promote biodiversity within the scour protection. By adopting a nature-inclusive design for scour protection, the coexistence of renewable energy production and a diverse marine benthic fauna can be optimized.

CRedit authorship contribution statement

Enzo M. Kingma: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Remment ter Hofstede:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Edwin Kardinaal:** Methodology, Conceptualization. **Rebecca Bakker:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Oliver Bittner:** Investigation. **Babeth**

van der Weide: Investigation. **Joop W.P. Coolen:** Writing – review & editing, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve readability and the quality of English writing. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

Edwin Kardinaal reports financial support was provided by Van Oord. Joop W.P. Coolen reports financial support was provided by TKI Delta Technology. Joop W.P. Coolen reports financial support was provided by TKI Offshore Wind. If there are other authors, they 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

Data used for the analyses during this study can be found in the supplementary material.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.seares.2024.102502>.

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