



# Decadal trends in macrobenthic communities in offshore wind farms: Disentangling turbine and climate effects

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## ABSTRACT

We present results of a study covering 13 years of data (2008–2020), investigating for the first time the combined impacts of offshore windfarm (OWF) turbine-related and climate-related variables on soft-sediment macrobenthic communities in the Southern North Sea, focusing on two Belgian OWFs, Belwind and C-Power. We hypothesized that both turbine presence alongside climate change would affect macrobenthos in the long-term. Our analysis revealed that climate variables, particularly sea surface temperature (SST) influenced macrobenthos abundance, species richness and diversity. Species richness was additionally affected by the North Atlantic Oscillation (NAO). While most community indices increased with rising SST, diversity declined with higher temperatures. Our analysis supported that the already known short-term (max. 3 years) turbine-related impacts are consistent through time (13 years). Sediments near turbines and in deeper waters were richer in organic matter, characterized by finer sand, and supported more enriched soft-sediment communities compared to locations further away. A transition from the originally prevailing *Nephtys cirrosa* community towards a more diverse macrobenthic community was observed near the turbines. Our study emphasizes the need for long-term studies and the importance of distinguishing turbine presence from climate change effects when assessing the impacts of OWFs on marine ecosystems.

## 1. Introduction

Offshore wind energy (OWE) is an important renewable energy source in the global effort to decarbonize and mitigate greenhouse gas emissions (International Energy Agency, 2019), aligning with the United Nations Sustainable Development Goal (SDG) 7 to ensure access to “affordable, reliable, sustainable and clean energy by 2030” (United Nations Department of Economic and Social Affairs, 2023). A significant expansion of offshore wind capacity is therefore expected in the coming decades, with an estimated addition of over 380 gigawatts (GW) across 32 countries (Wind Energy Council, 2023) to a current total installed capacity of 64.3 GW. In Europe, offshore wind installations surpassed 30 GW by the end of 2022, constituting 47 % of the global total (Wind Energy Council, 2023). Annual growth projections for Europe are optimistic, with additional installations of up to 99 GW by 2030 (Wind Europe, 2017).

These commitments have led to the allocation of numerous zones for

offshore wind development across European waters, such as in the Belgian part of the North Sea (BPNS), where nine offshore wind farms (OWFs) are operational on a surface area of 238 km<sup>2</sup>, and an additional zone of 285 km<sup>2</sup> was designated in the Belgian Marine Spatial Plan (Degraer et al., 2022; Verhalle, 2020; Rumes and Brabant, 2021).

The development and operational phases of OWFs are known to impact benthic ecosystems (Dannheim et al., 2020; Degraer et al., 2020). However, in sandy sediments, the effects of OWF construction are relatively short-lived, as a rapid recovery (2 to 4 years) of soft-sediment macrobenthic communities is noticed post-construction (Coates et al., 2015; van Dalfsen et al., 2000). The operational period, which generally lasts 20 to 25 years following the construction of OWFs, is characterized by impacts of the presence of hard-substrate foundations and their colonising fauna in an often naturally sandy environment, which (Dannheim et al., 2020; Hiscock et al., 2002) leads to changes in the hydrodynamics of the area (Christiansen et al., 2022; Daewel et al., 2022) and in the seabed relief (Hiscock et al., 2002), as well as an

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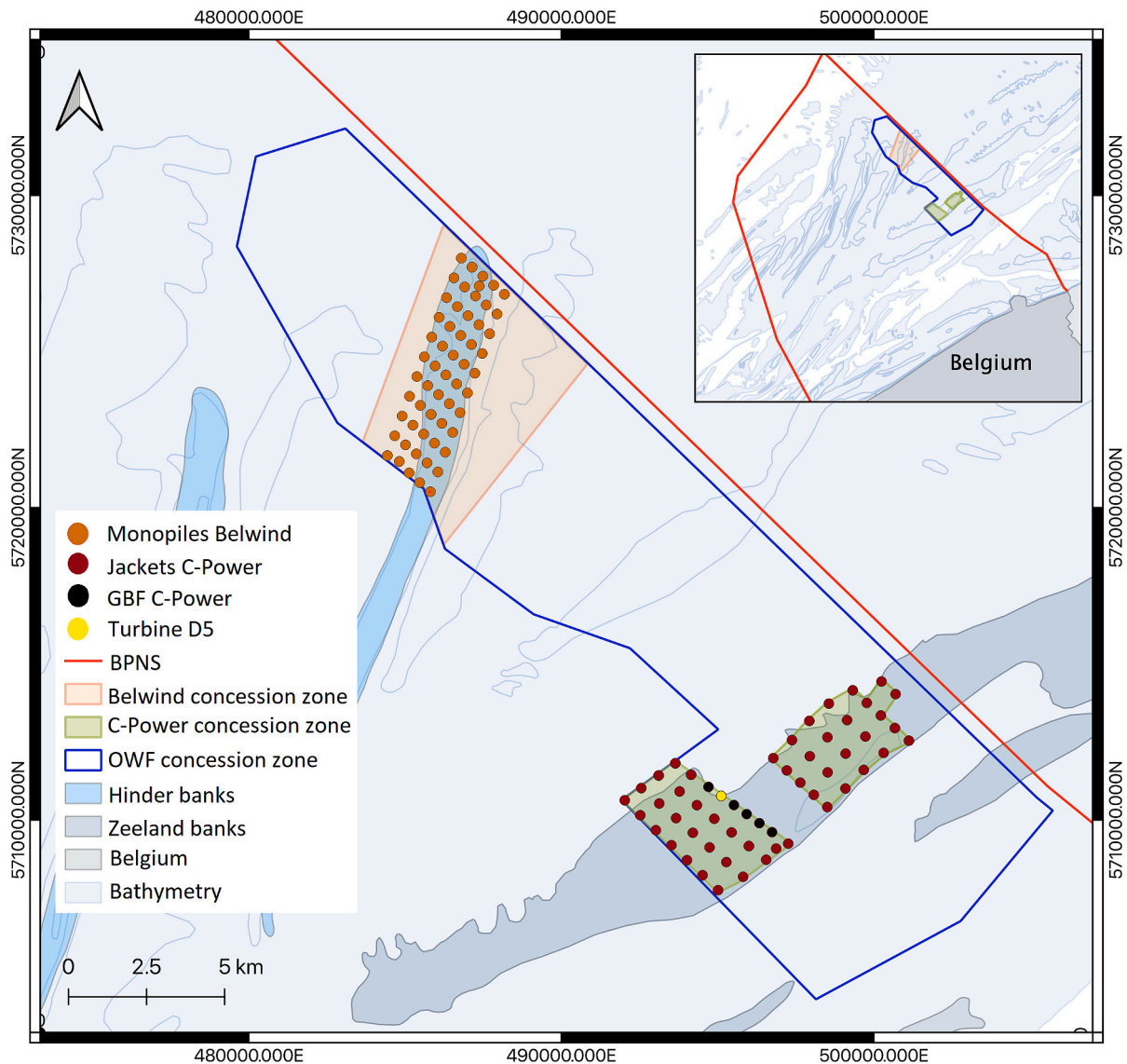


Fig. 1. Study region. Wind turbines are designated in orange (Monopiles, Belwind), red (Jacket foundations, C-Power), black (Gravity base foundations, C-Power) and yellow (Turbine D5, where targeted monitoring took place). The boundary of the Belgian OWF concession zone is delineated by a blue polygon. Projection: EPSG:32631 – WGS84 / UTM ZONE 31 N. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

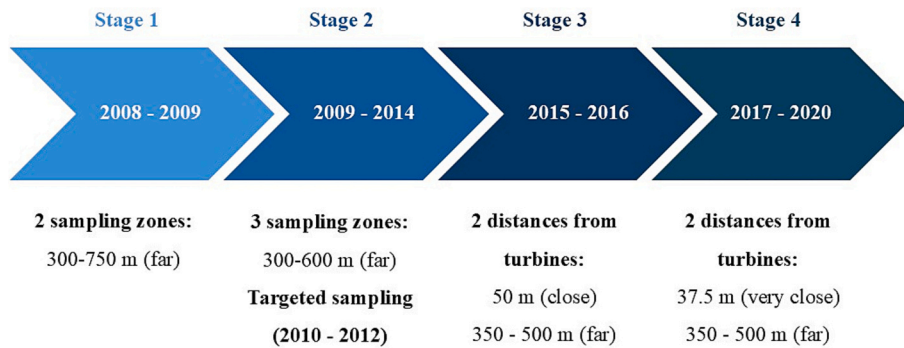
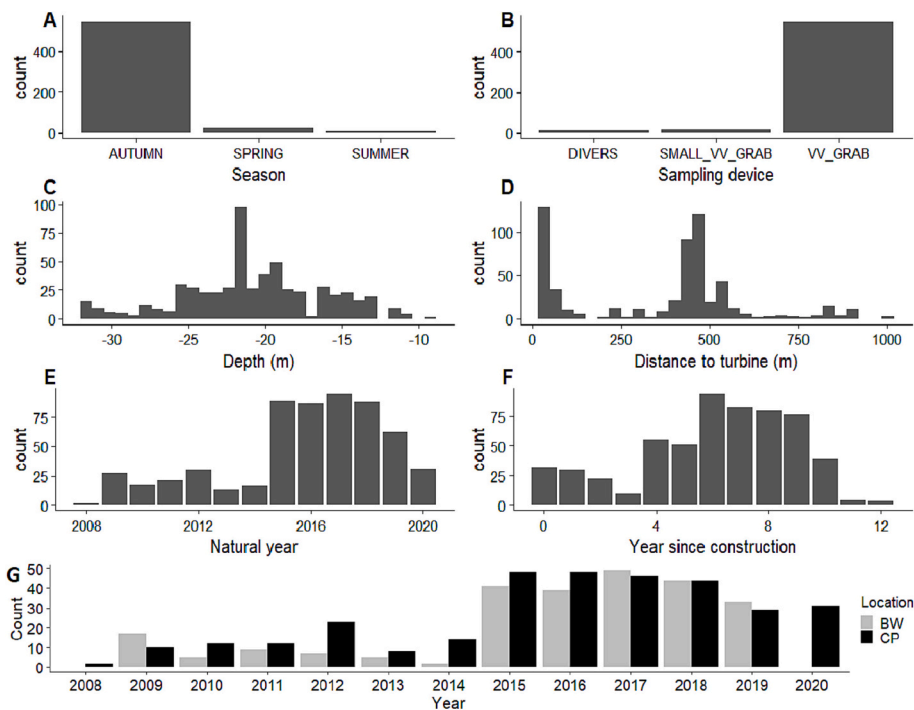


Fig. 2. Sampling Design Overview. Sampling procedures in C-Power and Belwind OWFs changed over four periods: 2008–2009, 2009–2014, 2015–2016, and 2017–onwards. Stage 1 applies only to C-Power, as Belwind was not yet built. From 2010 to 2012 targeted sampling was carried out. For this, additional samples were taken by divers along four gradients at seven distances (1 m to 200 m) from turbine D5 in C-Power.



**Fig. 3.** Variable occurrences across the dataset. Count is the number of samples. A; Season. B; Sampling device. C; Water depth. D; Distance to the nearest turbine. E; Natural year the sample was taken. F; Year since construction of the OWF. G; Number of samples per year divided by location.

**Table 1**

Univariate GAM models. L indicates included in the model as a linear term, S indicates included as a smoother and F as a factor. \* indicates that there is an interaction with Location for that term. S stands for species richness, N for abundance and H for Shannon-Wiener diversity. Nb stands for negative binomial distribution and G for Gaussian distribution. Log stands for Log-link function and Iden for Identity function. R stands for random factor.

Family	Link	Fine sediment fraction	TOM	Water Depth	Distance to turbine	Year since construction	SST max	SST min	NAO	Location	Season
S	Nb	Log	S	L	L	S*	–	L	S	–	R
N	Nb	Log	S	L	S	L	–	S	–	–	R
H	G	Iden	S	S	L	S*	S	–	–	F	R

**Table 2**

ManyGLM model and predictor variables selected. Nb stands for negative binomial. Log stands for Log-link function. ✓ indicates that the variable is included in the model, – indicates excluded. R indicates random factor.

Family	Link	Fine sediment	TOM	Water depth	Distance turbine	Year since construction	SST max	SST min	NAO	Location	Season
Nb	Log	✓	✓	✓	✓	✓	–	✓	–	✓	R

enrichment in finer sand near turbines (Coates et al., 2014; Lefaible et al., 2023). Sediments with a higher fine sediment fraction, within 200 m of a wind turbine, also had a decreased permeability, affecting nutrient cycles in the sediment (Toussaint et al., 2021). These new hard substrate structures (turbines and scour protection layers) provide opportunities for fouling organisms to establish themselves (Degraer et al., 2020; Hutchison et al., 2020; Lindeboom et al., 2011), attracting epibenthos and fish (Buyse et al., 2022; Reubens et al., 2014; ter Hofstede et al., 2022). The fouling fauna usually consists of filter-feeding organisms, that filter large amounts of water (Voet et al., 2023), enhancing the flow of faecal pellets (Mavraki et al., 2022) to the seafloor near the turbine (Baeye and Fettweis, 2015). These faecal pellets can then serve as new food sources for soft-sediment macrobenthos (Mavraki et al., 2022), resulting in a higher organic matter (OM) content in sediments near turbines (Coates et al., 2014). This enrichment in OM will increase macrobenthic abundance and diversity (Coates et al., 2011; Maar et al., 2009), leading to shifts in macrobenthic community structure (Hiscock et al., 2002). However, these effects have hitherto only been demonstrated for periods up to seven years after OWF construction (Coolen

et al., 2022). Additionally, their impact is dependent upon the distance of the OWF from the coast, turbine types (Lefaible et al., 2023), and environmental parameters such as water depth (Coolen et al., 2022; Lefaible et al., 2023).

At the same time, Sea Surface Temperatures (SSTs) are altered due to climate change which can significantly impact marine ecosystems (Hoegh-Guldberg and Bruno, 2010), leading to changes in physico-chemical properties and biological responses such as altered species physiology, distribution, growth and community structure (Brierley and Kingsford, 2009; Dippner et al., 2014; IPCC, 2014; Kröncke et al., 2013; Voet et al., 2022). Macrobenthic species have a limited mobility, and as a result, they can effectively integrate local changes over time making them valuable tools for monitoring environmental shifts associated with climate change (Birchenough et al., 2015). Between 1991 and 2022, SST increased by 0.3 °C per decade in the North Sea, along with an increase in the frequency and intensity of marine heat waves (European Environment Agency, 2023). According to climate projections, SST in European basins is expected to further increase by 2–6 °C by 2100 under the high emissions scenario (European Environment Agency, 2023). In

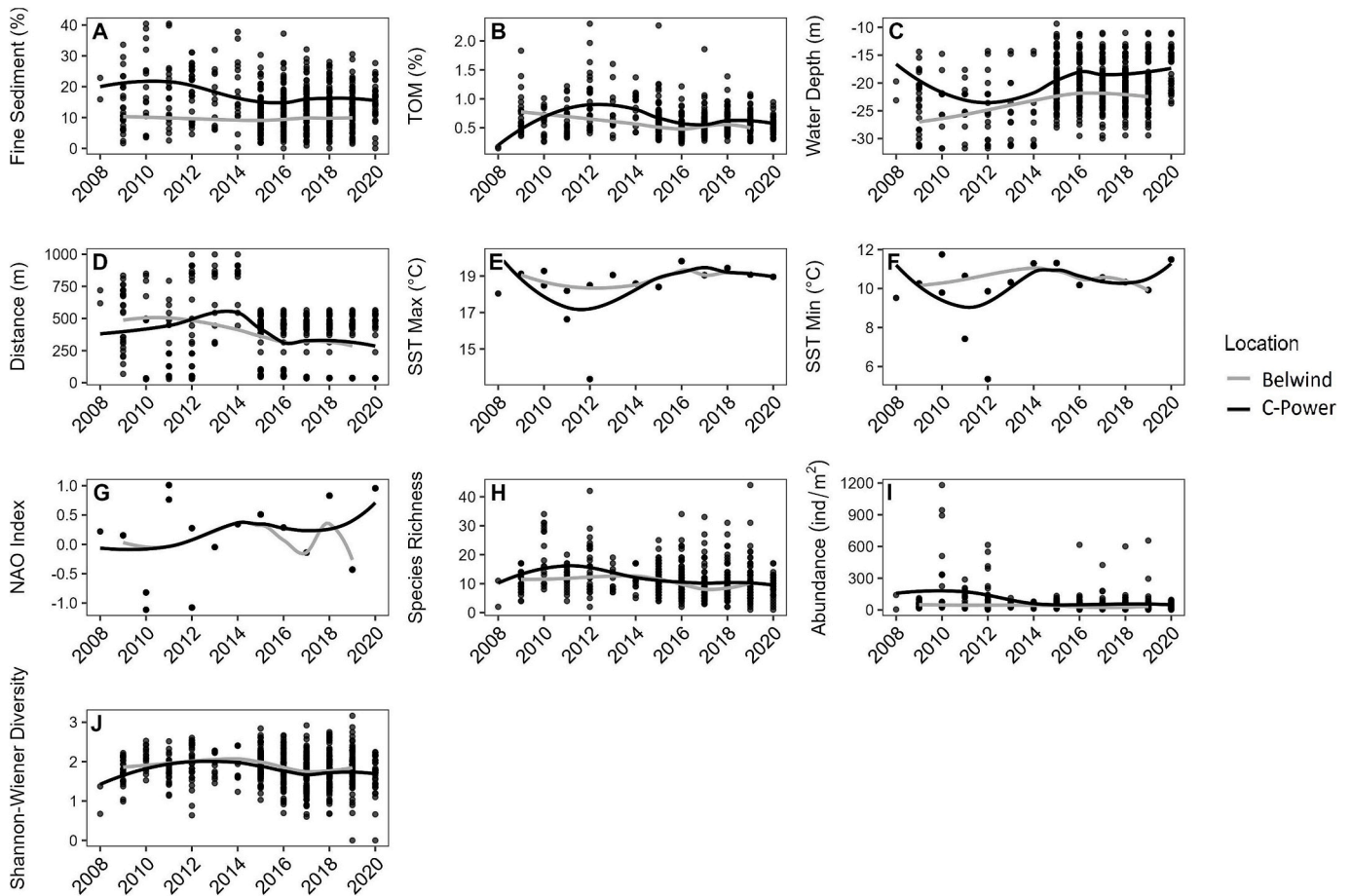


Fig. 4. Decadal trends of the response and predictor variables selected in this study divided by location. In the Y axis the variable is displayed and in the X axis the year of the study.

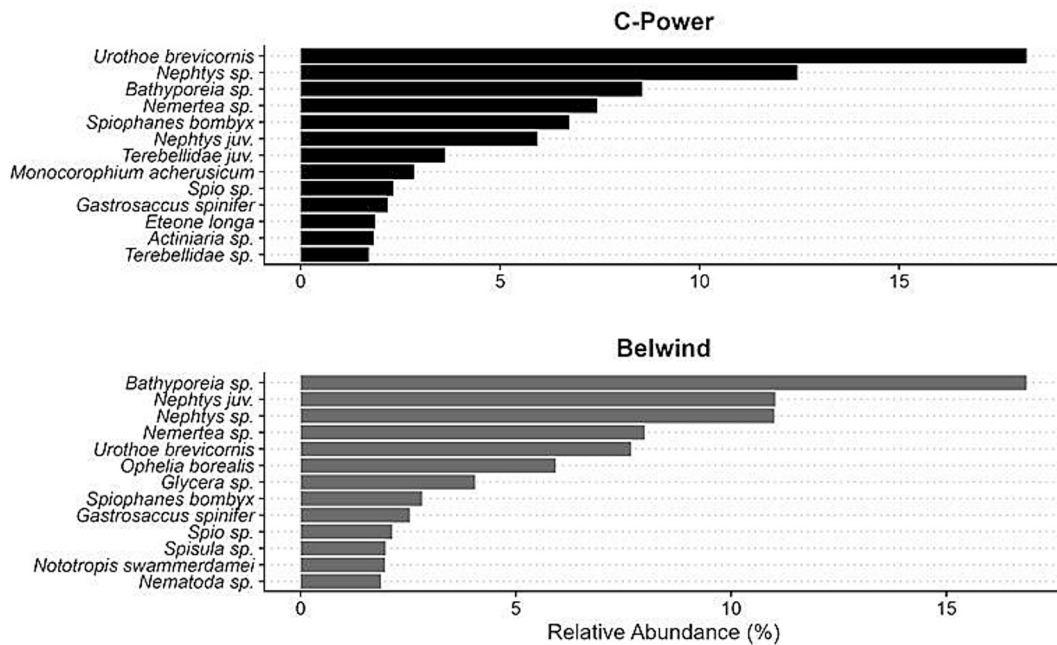
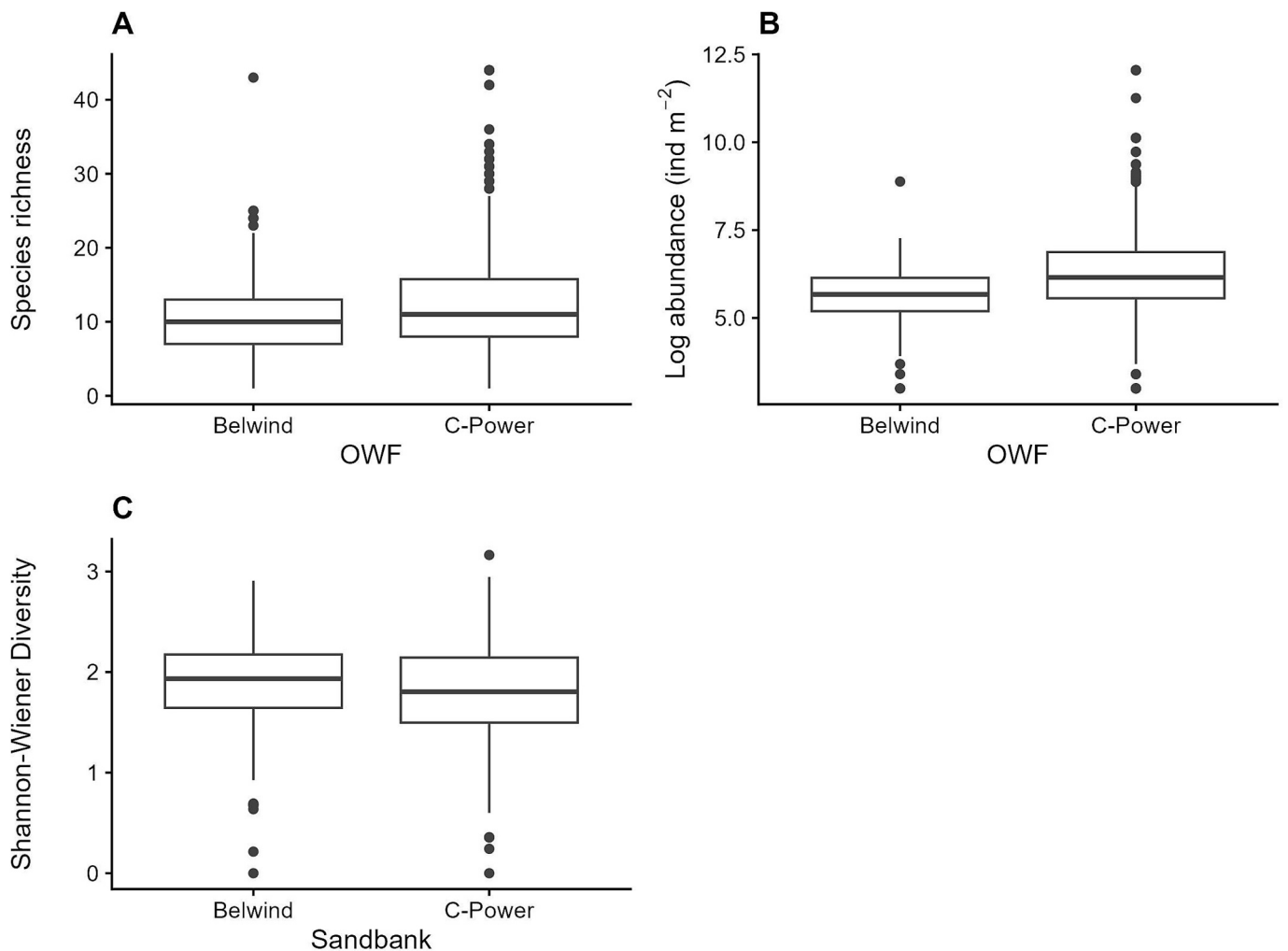


Fig. 5. Relative abundance of species throughout the years. The Y-axis lists the species that contributed more than 2 % of the abundance throughout the 13-year period. X-axis shows relative abundance of the selected species.



**Fig. 6.** Boxplots of the three community indices per OWF. A. Species richness, B. Log transformed abundance, C. Shannon-Wiener Diversity index. In the boxplot, the line inside the box shows the median of the data. The edges of the box represent the lower quartile and upper quartile, respectively. The lower hinge denotes the smallest data value greater than the first quartile, while the upper hinge indicates the largest data value less than the third quartile. The whiskers extend from the quartiles to show the range of variability outside these percentiles. Data points falling beyond the whiskers are considered exceptionally high or low but are not classified as outliers (refer to section 2.4.1 for further details).

the shallow southern North Sea, benthic environments are specially vulnerable to climate change, as they tend to warm more rapidly due to their shallow waters and closeness to the shoreline (García-Soto and Pingree, 2012; Harris et al., 2014). This can cause a northward shift in species distributions (Weinert et al., 2016). Along with SST, the North Atlantic Oscillation (NAO) also contributes to variability in marine ecosystems (McLean et al., 2018). The NAO affects the hydroclimatic state of the North Sea (Wieking and Kröncke, 2001), where negative NAO values reflect extreme cold winters, leading to mortality in macrobenthos (Dippner and Kröncke, 2003; Kröncke et al., 2013).

Generally, studies on the effects of OWFs on macrobenthos have relied on data gathered over limited duration, i.e.  $\leq 3$  years (Coates et al., 2014; Coates et al., 2015; Hutchison et al., 2020; Lefaible et al., 2023; Lu et al., 2019), with one exception of a study spanning seven years (Coolen et al., 2022). To our knowledge, no studies on the effect of longer-term presence ( $> 10$  years) of OWF turbines on macrobenthos exist. Nevertheless, extended research is essential to capture how soft-sediment macrobenthic communities develop after years of OWF presence in marine environments. On a larger timescale, it is important to consider that macrobenthic communities are influenced not only by the presence of turbines but also by the effects of climate change. Therefore, it is important to account for climate change when assessing the long-term impacts of OWFs on soft-sediment infauna.

This study explores how macrobenthic communities have evolved over the years (2008–2020) since the construction of two OWFs in the BPNS, C-Power and Belwind. Univariate and multivariate modelling approaches were used to investigate how the taxonomic composition and diversity of macrobenthos communities responded to a set of abiotic variables and climate indices.

## 2. Material and methods

### 2.1. Study area

Sampling was conducted in two OWFs, C-Power and Belwind, located at 27 km and 46 km off the Belgian Coast, respectively (MUMM, 2024). Both OWF are located on sandbanks, the Thornton Bank and the Bligh Bank respectively. The current regime of those areas is characterized by semi-diurnal tidal currents oriented along a northeast-southwest axis (Baeye and Fettweis, 2015). Wind speeds increase with distance from the coast, and the dominant wind direction is west-southwest (Baeye and Fettweis, 2015).

The construction of C-Power began in 2008 on the Thornton Bank, part of the Zeeland Banks system (Vlaeminck et al., 1989). The wind farm became partially operational in 2009 with 6 gravity-based foundations (GBF). By 2013, the facility was fully operational, featuring a

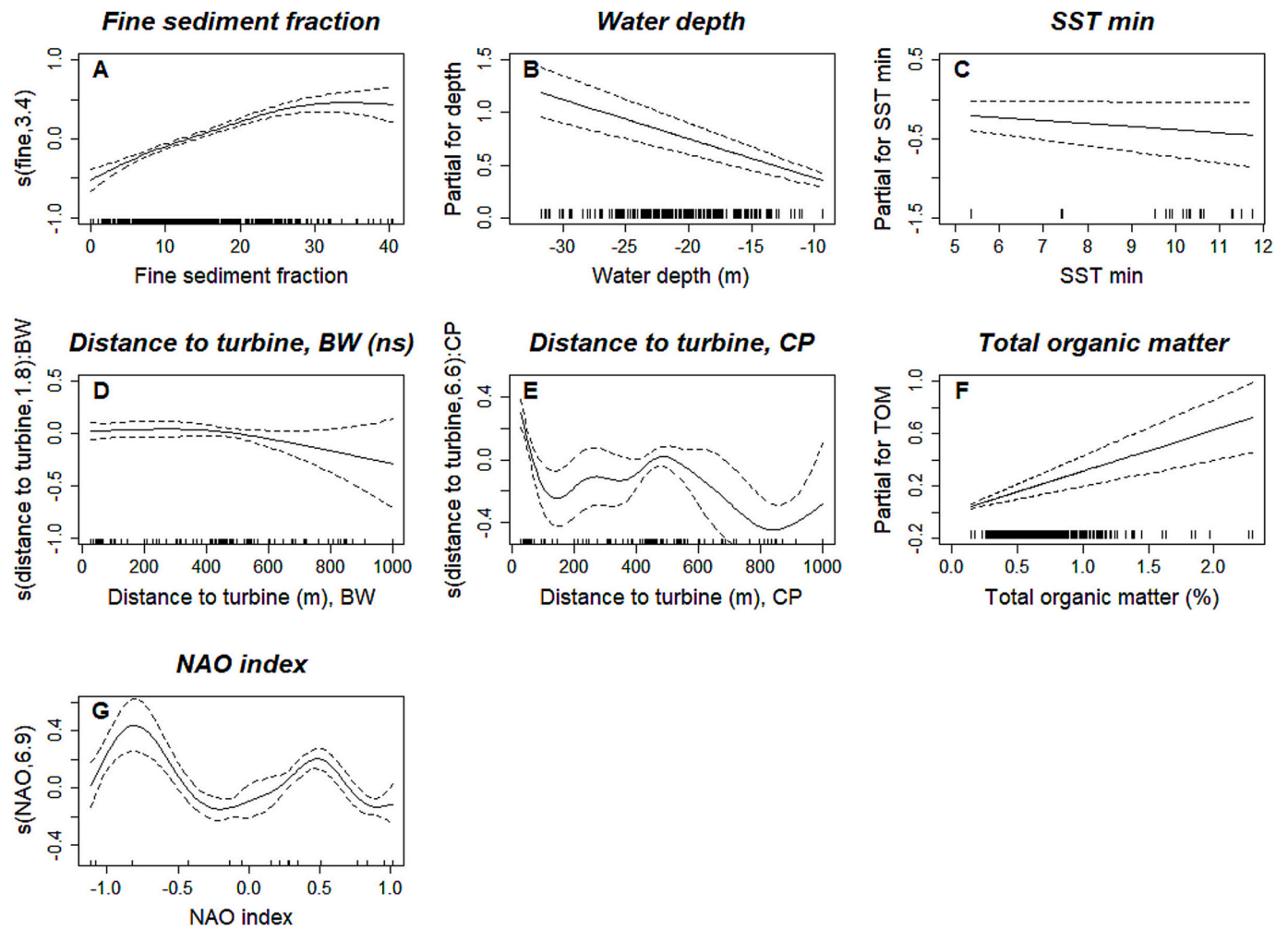


Fig. 7. Species richness model output. The ordinate axis displays the smoothers for each predictor variable, with the number of basis functions ( $k$ ) indicated in parentheses. Dashed lines represent standard errors (SE). “ns” indicates predictors that are not statistically significant.

total of 54 wind turbines, including 48 with jacket foundations, spaced 500 to 700 m apart and positioned at water depths spanning 18 to 24 m (Coates et al., 2014; C-Power, 2024; MUMM, 2024). The C-Power OWF is influenced by coastal waters, characterized by higher turbidity and lower salinity (Lacroix et al., 2004).

Belwind, located on the Bligh Bank, part of the Hinder Banks system (Vlaeminck et al., 1989), was constructed between 2009 and 2010 and has been operational since 2011 (MUMM, 2024). This OWF comprises 55 monopile turbines, spaced 500 to 650 m apart and situated at a depth range of 15 to 40 m (Fig. 1). The Belwind OWF is only influenced by clear waters from the English Channel, resulting in conditions of low turbidity and high salinity (Vlaeminck et al., 1989).

## 2.2. Sample design, collection and treatment

### 2.2.1. Biotic data

Macrobenthic samples were collected annually from 2008 to 2020 at the Thornton Bank (C-Power OWF) and Bligh Bank (Belwind OWF) sites. Sampling was carried out in the Spring, Summer, and Autumn at various distances from the turbines. In both wind farms sampling procedures underwent changes over the years as there were four periods with different ship-based sampling strategies (2008 / 2009–2014 / 2015–2016 / 2017–2020) (Fig. 2) (see suppl. Material 1).

Soft-sediment communities were sampled using different techniques depending on proximity to the turbine. At distances greater than 15 m from the turbine and in reference areas, Van Veen (VV) grabs were used,

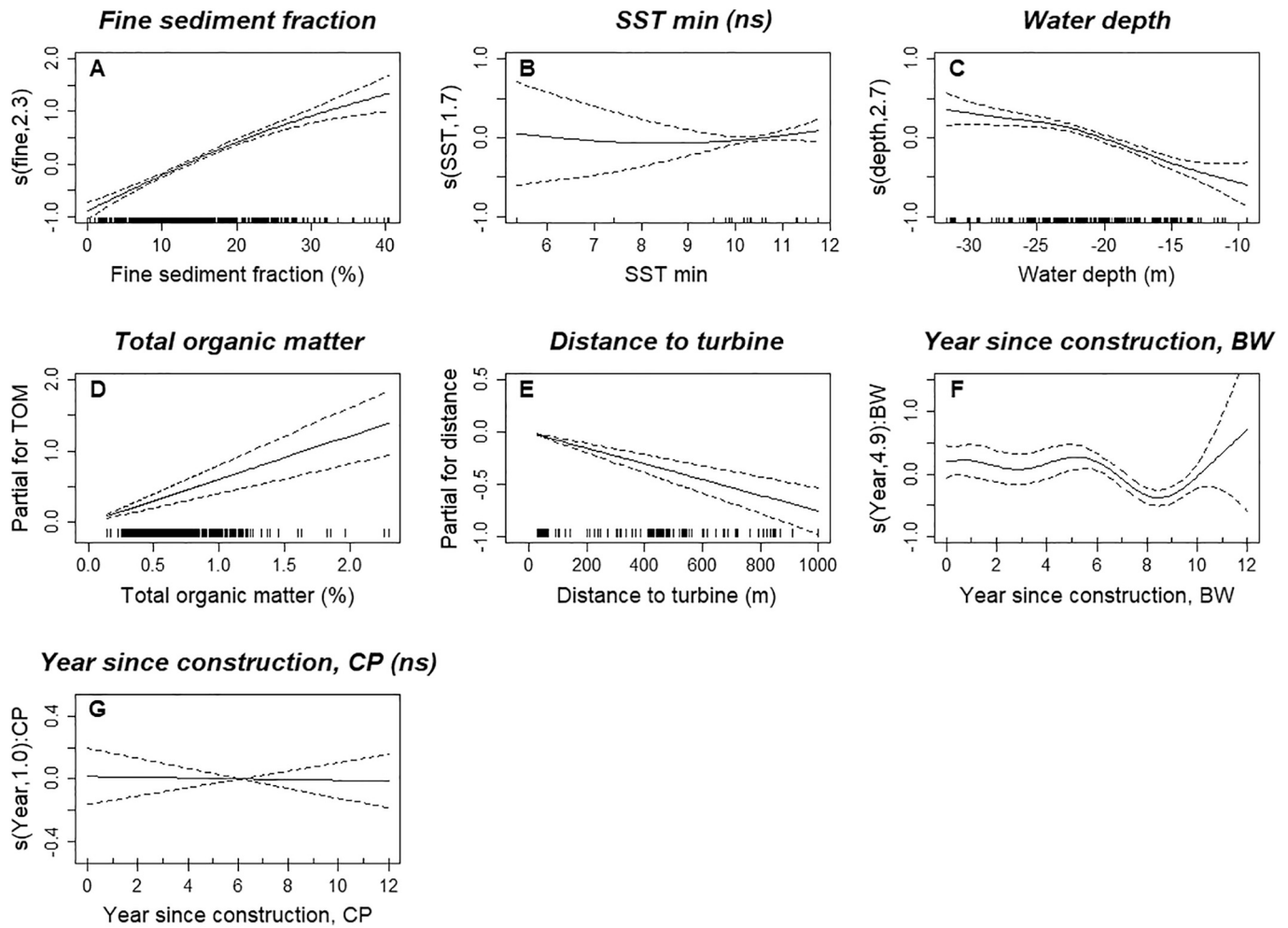
with a surface area ranging from 0.0247 to 0.1 m<sup>2</sup>. In contrast, samples taken within 15 m from the turbine were collected by scientific divers using an airlift system equipped with 1 mm mesh bags, covering an area of 0.1 m<sup>2</sup>. Before 2015, samples at each location were collected in triplicate. From 2015 onwards, a single replicate was taken. Samples were sieved using a 1 mm mesh and preserved in a 4 % formaldehyde-seawater solution. In the laboratory, 1 % Rose Bengal was used to stain the samples, after which they were sieved over 1 mm sieve. Organisms were identified when possible, to the lowest taxonomic level, usually species, counted and preserved in a formaldehyde solution (4 %).

### 2.2.2. Environmental data

Grain size distribution and organic matter content were determined by subsampling each grab sample with a 3.6 cm diameter core. During targeted sampling, cores ( $\varnothing$  2.7 cm) were taken by divers and the first five cm were analyzed for median grain size (MGS) and OM content. All sediment samples underwent drying for 48 h at 60 °C, and grain size distribution was assessed using laser diffraction on a Malvern Mastersizer which allow for the quantification of MGS and the percentage of fine sediment (% <250  $\mu$ m) for each sample. Total organic matter (TOM) content was derived from Eq.1:

$$TOM (\%) = \left( \frac{\text{Dry Weight} - \text{Ash Free Dry Weight}}{\text{Dry Weight}} \right) \times 100 \quad (1)$$

where: Dry Weight refers to the sediment dried for 40 h at 60 °C, and



**Fig. 8.** Macrobenthic abundance model output. The ordinate axis displays the smoothers for each predictor variable, with the number of basis functions ( $k$ ) indicated in parentheses. Dashed lines represent standard errors (SE). “ns” indicates predictors that are not statistically significant.

Ash-Free Dry Weight refers to the sediment dried for 2 h at 500 °C.

Year since the wind farm construction was determined by deducting the turbine’s construction year from the sampling year. Water depths at the sampling locations were extracted from a 20-m resolution bathymetry layer using QGIS (QGIS Development Team, 2020). Additionally, distance from the sampling points to the closest turbine was calculated. Only data from the year when the minimum sample distance to a turbine stayed constant was included, since the distance to the closest turbine changed over time as additional turbines were built. Samples taken before turbine construction or more than 1 km away were excluded from the analysis. Thus, the data were analyzed using a gradient design. The study also incorporated SST and NAO. SST data were taken from the EU Copernicus Marine Environment Monitoring Service. Seasonally averaged daily SST measurements were used, with extreme events identified by their maximum and minimum values. NAO data was obtained from the NOAA Climate Prediction Centre and the NOAA Physical Sciences Laboratory, respectively. Monthly NAO values were also averaged by season (see supplementary material 3).

### 2.3. Data quality control

Different numbers of replicates were collected over the years; thus, for consistency, only the first replicate from each location was used in this study. Samples with fine-sand fractions exceeding 80 % and/or TOM contents greater than 2 % were excluded ( $n = 9$ ), as these values were considered unrealistic for the sandy sediments in the study region.

Macrobenthic data was taxonomically matched with the World Register of Marine Species (WoRMS Editorial Board, 2024) and lumped to the lowest possible taxonomic level (see suppl. Material 2). Some specimens that were identified to higher taxa (e.g. Phylum, Class or Order) were removed from the dataset (see suppl. Material 2) as they would influence the biodiversity pattern (<1 % of the abundance). The lumping system operated as follows: organisms with a relative abundance below 5 % were excluded, while those above this threshold were subject to lumping (see suppl. Material 2 for more information regarding the lumping procedure). The final dataset comprised a total of 578 samples of which 56 % and 44 % originated from the C-Power and Belwind OWFs, respectively (Fig. 3).

### 2.4. Data analysis

#### 2.4.1. Univariate analysis

Three measures of diversity were calculated: species richness ( $S$ , number of species in each sample), abundance ( $N$ , number of organisms in each sample), and Shannon-Wiener diversity index ( $H$ ). Data exploration was conducted to check for outliers, collinearity between variables, and interactions between the predictor variables and location, following the recommendations of Ieno and Zuur (2015) (see suppl. Material 4). Due to strong collinearity between fine-sand % and MGS ( $r = 0.8$ ), the last was excluded from the analysis, as fine sediment fraction and macrobenthic communities have a robust association (Lefaible et al., 2023). Additionally, average SST showed a high correlation with

**Table 3**

Selected GAM models. ‘:’ indicates interaction between both variables. Location (CP: C-Power; BW: Belwind) is modelled as a factor and Season are modelled as a random factor.

Species richness	edf	p-value
Fine sediment fraction	3.43	<2e-16
Water depth	1.00	<2e-16
SST minimum	1.00	0.02
Distance to turbine:BW	1.82	0.19
Distance to turbine:CP	6.64	<2e-16
TOM	1.00	7.7e-08
NAO	6.99	1.9e-06
Variance explained: 57.1 %		
R <sup>2</sup> = 0.559		

Abundance	edf	p-value
Fine sediment fraction	2.31	< 2e-16
SST minimum	1.67	0.33
Water depth	2.66	< 2e-16
TOM	1.00	8.26e-10
Distance turbine	1.00	9.73e-12
Year since construction:BW	4.99	2.22e-06
Year since construction:CP	1.00	0.93
Variance explained: 71.2 %		
R <sup>2</sup> = 0.39		

Shannon-Wiener diversity	edf	p-value
Fine sediment fraction	4.12	<2e-16
Water depth	1.00	1.3e-06
SST maximum	7.91	9.2e-07
Distance to turbine:BW	2.11	0.11
Distance to turbine:CP	6.10	0.003
TOM	3.83	0.006
OWF	–	0.15
Variance explained: 30.5 %		
R <sup>2</sup> = 0.272		

both SSTmin and SSTmax values ( $r = 0.7$ ), leading to its exclusion from the analysis. Remaining variables did not show a variance inflation factors (VIF) higher than 3 (see suppl. Material 4). All analysis were performed using R version 4.3.1 (R core Team, R. D. C., 2009).

Generalized Additive Models (GAMs) were developed for the three response variables (S, N, H) using the R package “mgcv” (Wood, 2017). Sample surface area was included as an offset in the models to account for differences between the VV grab and scientific diver samples (0.1 m<sup>2</sup>) and the smaller VV grab (0.0247 m<sup>2</sup>). A forward selection approach was used to build the models, with the simplest model including one variable and gradually adding more. The optimal model for each response variable was selected by choosing the one with the lowest Akaike Information Criterion (AIC). If effective degrees of freedom (edf) = 1, the variable was treated as a linear term, whereas deviations from 1 indicated the use of a smoother function (s) (see Table 1). Sampling effort was not evenly distributed over the sampling seasons and was hence considered a random factor. After model selection, residuals were plotted against each variable and visually inspected to verify the assumption of homogeneity of variance (see suppl. Material 5).

#### 2.4.2. Multivariate analysis

The relationship between macrobenthic community composition and environmental variables was investigated using many generalized linear models (manyGLMs) with the R package “mvabund” (Wang et al., 2012). The same predictor variables used in the GAMs were applied here. Multivariate models were built using manyGLMs, which fits a generalized linear model for each species in the dataset and uses resampling-based hypothesis testing to evaluate the significance of explanatory variables (Wang et al., 2012). Model selection followed a forward

selection approach based on the AIC sum criterion, adding predictor variables step by step and selecting the model with the lowest AIC sum value. The final model included fine sediment fraction, years since turbine construction, location, distance to turbine, water depth, TOM, and SST max as variables (Table 2). No interactions were included, as they complicate the ecological interpretation of the model. After model selection, residuals versus fitted values were visually inspected to confirm the assumptions of linear models. Once the model was selected, residuals vs fitted values were visually checked for linear model assumptions (see suppl. Material 6).

*Anova.manyglm* function was applied with 999 bootstrap iterations, and the *p.uni* argument set to “adjusted,” to identify which environmental variables had a significant effect on individual species ( $p$ -value < 0.05). The coefficients of species showing significant responses to each environmental variable were then visualized. Positive coefficient values indicated a positive association between the species and the environmental variable, while negative values reflected a negative association.

### 3. Results

#### 3.1. Decadal trends of key variables

Throughout the study period, the fine sediment fraction and TOM content fluctuated, with an increase observed between 2010 and 2013 in C-Power, followed by a stabilization in Belwind, both parameters exhibited a stable trend (Fig. 4.A.B). Sampling depth showed a slight increase from 2015 onwards in both OWFs due to the construction of new turbines at greater water depths (Fig. 4.C). The distance to the turbine decreased with time due to the increasing turbine construction and changes in sampling design (Fig. 4.D). SST maximum and minimum, along with the NAO index, demonstrated oscillating trends throughout the years (Fig. 4.E.F.G). The three response variables, species richness, abundance, and Shannon-Wiener diversity, remained relatively stable across the study period in both OWFs (Fig. 4.H.I.J).

The dataset comprised 23,960 individuals of 160 countable taxa. C-Power harbored 158 taxa whereas Belwind had 145,106 of which being found at both wind farms. C-Power had 52 unique taxa, while Belwind had 39. The burrowing amphipod *Urothoe brevicornis* (14.8 %) was the most abundant species across the whole dataset, followed by the errant polychaeta *Nephtys* sp. (12 %), the amphipod *Bathyporeia* sp. (11.2 %) and the ribbon worms *Nemertea* sp. (7.6 %) (Fig. 5).

#### 3.2. Univariate response

Throughout the study period species richness (S) ranged between 1 and 44 in C-Power and between 2 and 25 in Belwind (Fig. 6.A). The selected model explained 57 % of the variation and showed that the dominant predictor for species richness was fine sediment fraction. In addition, S was significantly and linearly related to TOM, water depth and SST min (Table 2, Fig. 7. B., C., F.): it increased with water depth and with higher fractions of TOM, whereas it showed a slight decrease with increasing SST. Significant non-linear relationships were detected between S and fine sediment fraction and NAO: S increased with increasing fine-sand fraction, levelling off at fine sand fraction ~30 % (Fig. 7.A), whereas there was a bimodal relation between S and NAO (Fig. 7.G). Distance to turbine did not affect richness significantly in Belwind, whereas a significant non-linear effect was found in C-Power with an increase from 1000 to 200 m and a stable state from 200 until closer distances (Fig. 7.D.E).

Macrobenthos abundances in C-Power ranged from 20 to 24,898 ind m<sup>-2</sup> and from 20 to 1330 ind m<sup>-2</sup> in Belwind (Fig. 6.B). The most explanatory predictor for abundance (N) was fine sediment fraction and the selected model explained more than 70 % of the variation (Table 2). N increased significantly and linearly with TOM (Fig. 8.D) and with decreasing distances from the nearest turbine in both wind farms (Fig. 8. E). Fluctuations in N over the years differed between OWFs: abundance

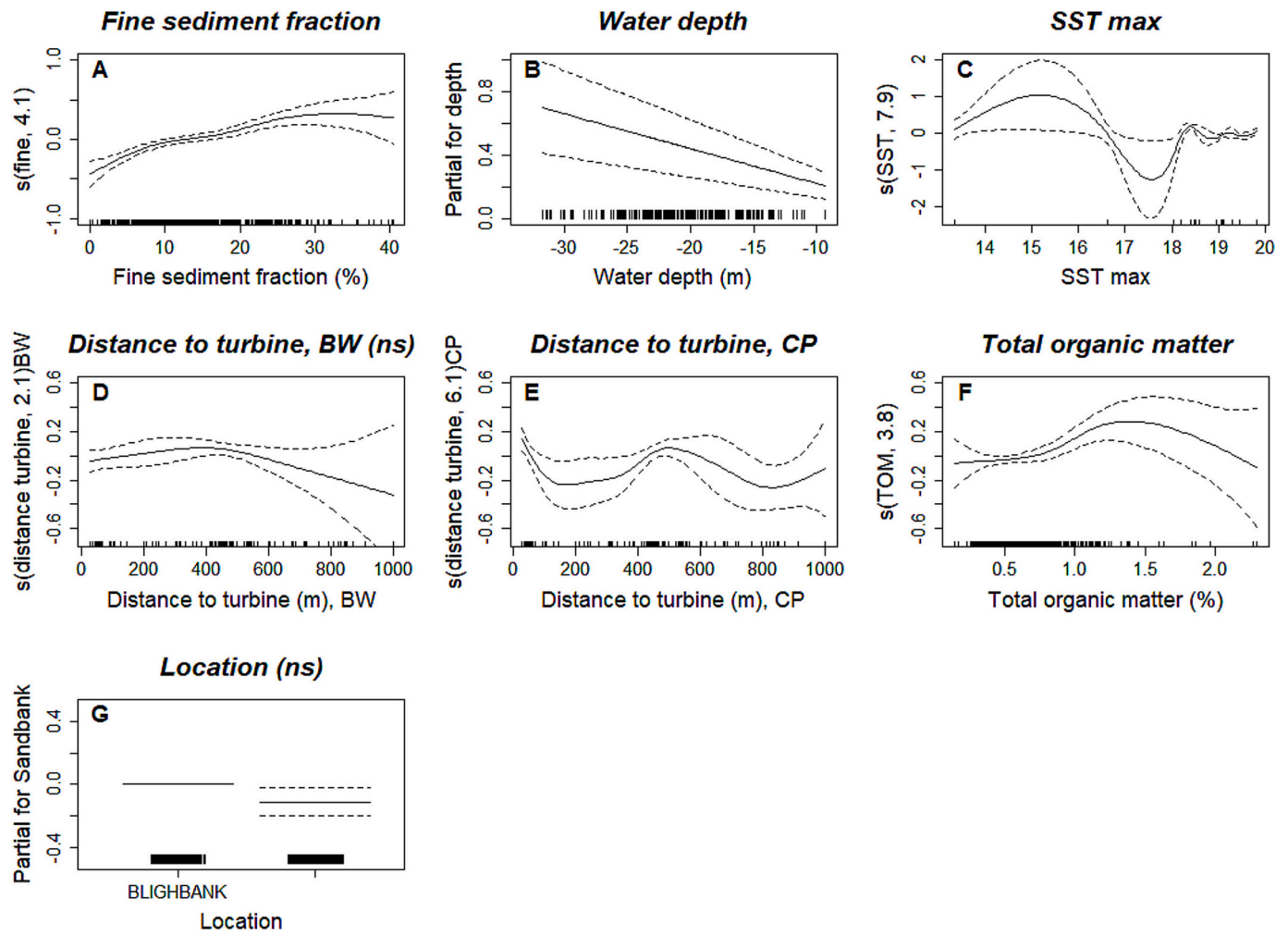


Fig. 9. Shannon-Wiener Diversity model output. The ordinate axis displays the smoothers for each predictor variable, with the number of basis functions (k) indicated in parentheses. Dashed lines represent standard errors (SE). “ns” indicates predictors that are not statistically significant.

**Table 4**  
Results of multivariate generalized linear model. Signif. codes: \* =  $p < 0.1$ , \*\* =  $p < 0.01$ , \*\*\* =  $p < 0.001$ .

Parameter	Residual DF	DF diff	Deviance	p-value	Significant species
Fine sediment	557	1	2248.9	0.001 ***	47
Year since construction	556	1	1182.4	0.006 **	10
Distance to turbine	555	1	807.2	0.030 *	0
Location	554	1	718.0	0.033 *	0
Water depth	553	1	674.4	0.032 *	0
TOM	552	1	582.6	0.032*	0
SST max	551	1	575.2	0.034 *	0

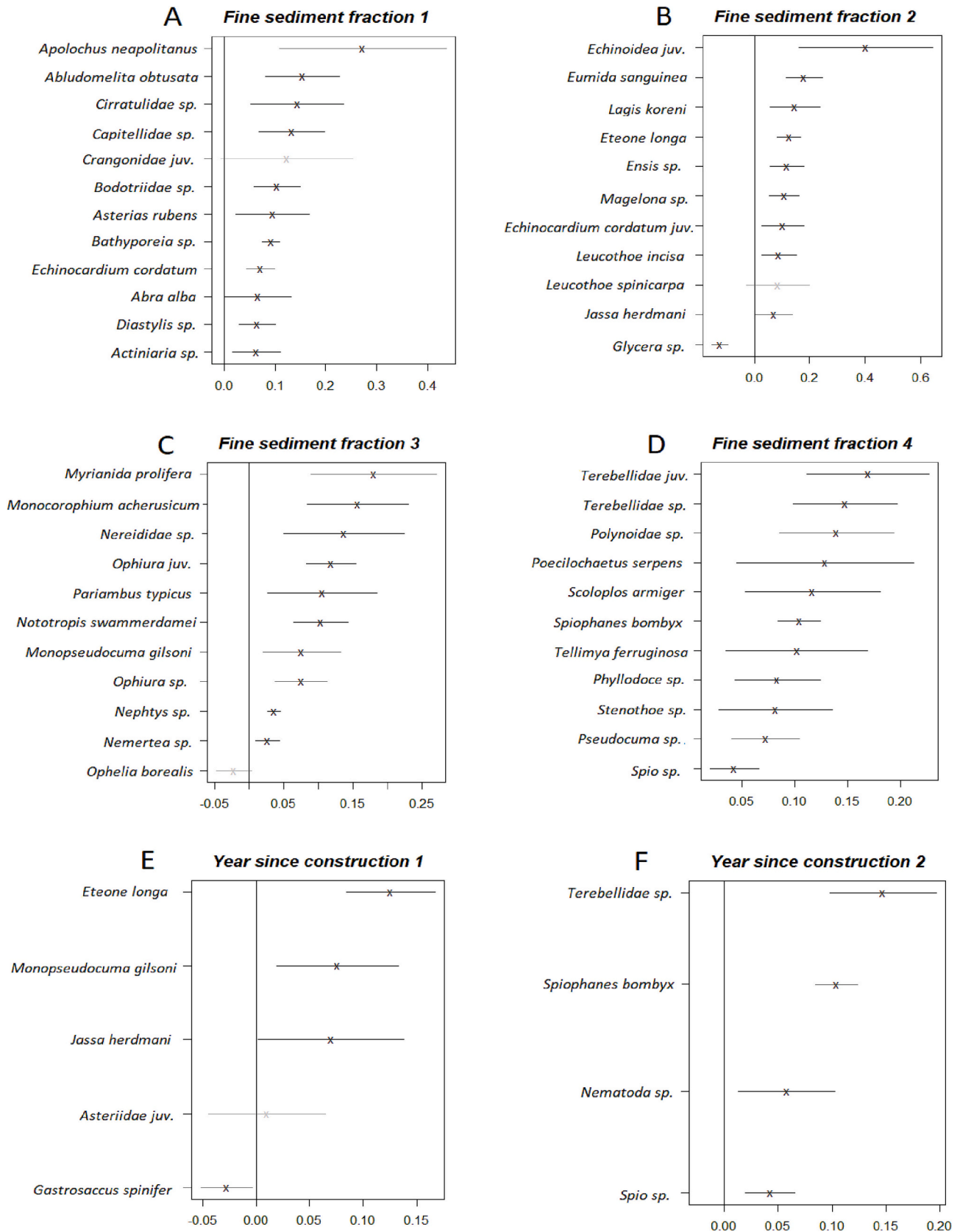
fluctuated significantly across the years in Belwind, while no significant change was observed at C-Power (Fig. 8.F, G). There were significant non-linear trends between N and water depth and fine sediment fraction: N was higher in deep waters and at higher values of fine sediment (Fig. 8.A, C). Macrobenthic abundance was significantly higher during Summer compared to Spring and Autumn (Fig. 8.H). SST min did not have a significant effect on N (Fig. 8.B).

Diversity ranged from 0 to 3.16 in C-Power and from 0 to 2.84 in Belwind (Fig. 6.C). The H model explained up to a 30 % of the variance, the main predictor again being fine sediment fraction (Table 3). H

increased significantly and linearly with water depth (Fig. 9.B). There were non-linear relationships between H and the other predictor variables. H increased with higher fine sediment fraction and TOM values but plateaued when fine sediment reached 30 % or declined when TOM exceeded 1.5 % (Fig. 9.F). The effect of distance to turbine on diversity was OWF specific. In C-Power there was a significant increase of diversity closer to the turbine whilst distance to turbine did not have a significant effect in Belwind (Fig. 9. D, E). H showed a notable relationship with SST max, peaking at temperatures between 14 and 16 °C and declining around 17–18 °C (Fig. 9.C). Location did not significantly affect diversity, however, was lower in C-Power compared to Belwind (Fig. 9.G).

### 3.3. Multivariate response

The multivariate generalized linear model indicated that all predictor variables, except SST min, significantly affected macrobenthic community composition ( $p$ -value  $< 0.05$ ) (Table 4). Additionally, both fine sediment fraction and years since construction significantly influenced individual species. Fine sediment fraction had the most substantial impact, with 46 species showing a significant preference for finer sediments, while two species, *Glycera* sp. and *Ophelia borealis*, preferred coarser sediments (Fig. 10.A-D). Year since construction significantly affected ten species: *Gastrosaccus spinifer* was more abundant in the initial years following construction (Fig. 10.E), whereas *Asteriidae* juv., *Eteone longa*, *Jassa herdmani*, *Monopseudocuma gilsoni*, *Nematoda* sp., *Spio*



**Fig. 10.** Coefficient plots from the many GLM model. Each cross represents a coefficient estimate, with the horizontal line indicating the 95 % confidence interval for that estimate. Coefficients with confidence intervals that do not cross zero are deemed statistically significant and are colored in black. Positive coefficients reflect a positive relationship (an increase in the predictor variable results in an increase in the outcome variable), while negative coefficients indicate a negative association (an increase in the predictor variable leads to a decrease in the outcome variable). For better visualization, the significant species are displayed in separate graphs. The Y-axis lists the significant species for each variable, while the X-axes, which vary across graphs, represent the coefficient estimate values.

sp., *Spiophanes bombyx*, and *Terebellidae* sp. were more prevalent in the later years (Fig. 10.F).

#### 4. Discussion

This study is the first to combine turbine-related and climate-related drivers of variability in macrobenthos community composition and diversity in mobile sediments inside operational OWFs, and does so with a dataset spanning a hitherto unsurpassed duration. Our results demonstrate that local factors remain the main drivers of change in macrobenthic communities, but also highlight the importance of considering climate variables. Additionally, our analysis also revealed a combination of site and turbine-specific impacts. Understanding and disentangling the effects of turbine presence, of climate change and of local factors when studying long-term trends is critical for effective management of OWFs in the context of ongoing environmental change and expected OWF expansion.

##### 4.1. Influence of the turbines

OWFs in the BPNS are usually situated in areas characterized by medium to coarse sediment and low OM content (De Maerschalck et al., 2006). Such sediments support soft-sediment macrobenthic communities with low abundance and diversity, such as the *Nephtys cirrosa* community (Breine et al., 2018), which were indeed present in these areas prior to OWF construction (De Maerschalck et al., 2006). However, the introduction of new hard substrates in this sandy habitat creates additional surfaces available to fouling organisms (Degraer et al., 2020; Hutchison et al., 2020; Lindeboom et al., 2011). The fouling fauna that colonizes the turbine, will enhance the deposition of faecal pellets and detritus rich in TOM to the sediment (Maar et al., 2009), adding food for sediment-inhabiting fauna (Maar et al., 2009; McKindsey et al., 2011; Ysebaert et al., 2009) and leading to sediment fining near turbine (Coates et al., 2014; Lefaible et al., 2023), resulting in a lower permeability which will facilitate OM retention. The presence of these submerged vertical structures also cause modifications of the local hydrodynamic regime (Christiansen et al., 2022; Daewel et al., 2022) and seabed topography (Hiscock et al., 2002). These effects combined promote the transition towards an “intermediate community” with higher abundances of typical offshore species and more fine-sediment associated species such as the one from the *Abra alba* community (Breine et al., 2018; Coates et al., 2014), which may further contribute to sediment fining and OM accumulation (Breine et al., 2018; Van Hoey et al., 2004). This could be due to the presence of tube-building polychaetes, such as *Lanice conchilega*, an autogenic and allogenic ecosystem engineer, which actively construct tubes from coarser particles, thereby increasing the finer sediment fractions of the seabed (Braeckman et al., 2014; Rabaut et al., 2007). It is likely that most of the *Terebellidae* species in the dataset were *Lanice conchilega* as juveniles of this species are quite hard to identify. This process enhances a positive feedback loop that facilitates further transition towards a community with more and more characteristics of the *Abra alba* communities. Depending on the type of foundation present, associated impacts to the ecosystem will be different (Lefaible et al., 2023). The two most common foundations found in Belwind and C-Power are monopiles and jackets respectively. Both these foundations will have a different impact on the hydrology (Rivier et al., 2016; Welzel et al., 2020), but also on the type of organisms that will colonize the structure. Jackets are known to be dominated by the blue Mussel *Mytilus edulis* down to 20 m depth (Hutchison et al., 2020), while the part colonized by mussels on monopile is restricted to the five first meter below the water (Coolen et al., 2022). This, coupled with the fact that monopiles require a scour protection layer around the structure, could result in less fouling impact in the OWF of Belwind (Lefaible et al., 2023), which consist exclusively of monopiles. Belwind seemed to harbour lower species richness and slightly lower diversity than C-Power close to the turbines, probably due to the limited fouling impact

potential in Belwind. The increased abundance at closer distances in both OWF corroborated earlier observations in the vicinity of jacket foundations on the BPNS for established communities (> 7y after construction) (Lefaible et al., 2023). Our study confirms this trend for both monopile and jacket foundations and shows that this turbine effect on sediment fining, originally described for the early operational phase of gravity-based turbines (Coates et al., 2014), still holds in the long term and for different turbine types. We also identified species associated with changes at the community level in both OWFs. While species from the *N. cirrosa* community (e.g. *Urothoe brevicornis*) are still present, we also noted the emergence of species associated with the *Abra alba* community (e.g. *Terebellidae* sp.), indicating a transition towards an “intermediate” macrobenthic community, more diverse than the one originally present (Breine et al., 2018). Although not significant, we observed the emergence of *Terebellidae* sp. at distances further away from the turbines throughout the years, suggesting that the influence of turbine presence may still be expanding. While macrobenthic abundance and species richness increased with increasing TOM, corroborating previous studies (Coates et al., 2014; Lefaible et al., 2023). Shannon-Wiener diversity declined when TOM content exceeded 1.5 % (Fig. 9.F). A similar trend was observed for species richness in Lefaible et al. (2023), which analyzed part of the data in sediments around jackets at C-Power. This decrease in diversity may be attributed to the proliferation of opportunistic species in areas with high food availability (TOM), leading to increased dominance and a reduction in Shannon-Wiener diversity (Johansen et al., 2018; Keeley et al., 2013).

Our study also confirms the importance of water depth as a predictor of macrobenthic community structure and diversity in the shallow part of the North Sea (Armonies et al., 2014; Coolen et al., 2022; Lefaible et al., 2023). Response variables peaked at 30 m water depth, indicating optimal macrobenthic conditions at this depth. Deeper regions are less affected by wave action and sediment disruption, which supports the establishment of species and density rich communities (Cheng et al., 2021). In our study, finer sediments are usually found at greater water depths, typically corresponding to troughs and gullies between sandbanks (Van Lancker et al., 2012).

Unlike previous studies that have been mainly based on shorter time periods, i.e.  $\leq 3$  years (Coates et al., 2014; Coates et al., 2015; Hutchison et al., 2020; Lefaible et al., 2023; Lu et al., 2019), the present study includes long-term data spanning from the early operational phase. Our findings reveal that the patterns observed in short-term studies persist well beyond the time scope of those studies, with indications that these patterns continue to evolve, as evidenced by the increasing presence of *Terebellidae* even at greater distances. Specifically, species richness and Shannon-Wiener diversity are not influenced by years since construction. However diverse long-term patterns in macrobenthic abundances have been observed, with fluctuations over the years only found in the Belwind OWF in contrast to more stable macrobenthic abundance values for C-Power. Differences in environmental conditions, distance to the coast, and foundation types between Belwind and C-Power could explain the variations in abundance trends observed. Belwind is situated in a more dynamic environment with stronger currents (Legrand and Baetens, 2021), which intensifies sediment resuspension and reduces OM enrichment compared to C-Power (Lefaible et al., 2023). Furthermore, the distinct foundation types—monopiles at Belwind and gravity-based or jacket foundations at C-Power—may influence the degree and impact of artificial reef effects on benthic communities (Lefaible et al., 2023).

Additionally, a consistent decline in species richness and diversity is evident at further distances from turbines in both OWFs, in line with previous studies (Coates et al., 2014; Lefaible et al., 2023). Interestingly, and in contrast to Belwind, in our long-term study there is a slight increase in richness and diversity at further distances from the turbines (~500 m) in C-Power. Over the course of the time series, the observed fluctuations suggest a potential spillover effect, indicating that the influence of turbine-related factors, such as organic matter deposition (Maar et al., 2009) and changes in hydrodynamics (Christiansen et al.,

2022), may be extending beyond 500 m from individual turbines. This expansion implies a likely interaction between the factors “distance to turbine” and “years since construction,” suggesting that turbine-related impacts are not static but evolve over time. As turbines increase in number over the years, processes such as sediment deposition, changes in organic matter distribution, and hydrodynamic alterations may extend their reach. This supports the hypothesis of a cumulative effect, where the overlapping influence of multiple turbines amplifies the spatial extent and intensity of these impacts. Such cumulative effects highlight the importance of long-term monitoring to fully understand how the combined and evolving influence of turbines shapes the broader marine ecosystem.

#### 4.2. Influence of weather and climate

We showed that variations in SSTs affect macrobenthic communities. During our 13-year study period, SST increased by an average of 1.5 °C (see suppl. Material 3) with year-to-year fluctuations. SST affected all response variables. Additionally, species richness was affected by NAO. Almost all indices tended to increase with increasing SST, however, Shannon-Wiener diversity decreased when temperature reached higher values (17–18 °C). This can possibly be related to an increase in the abundance of opportunistic species, as suggested by the positive relationship between years since construction and the abundance of the polychaetes *Spiophanes bombyx* and *Spio* sp., the amphipod *Jassa herdmani*, the cumacean *Monopseudocuma gilsoni*, and nematodes. These species, characterized by being small, mobile, and short-lived, align with an r-strategy (Lavaleye, 1999), and are typically more tolerant to environmental changes, often at the expense of less tolerant taxa such as larger, sessile, and long-lived species (Levin et al., 2009). However, this observation should be interpreted with caution, and further research on the long-term response of these species to climate fluctuations are needed to validate this hypothesis. Our work corroborates past studies (Dippner and Kröncke, 2003; Kröncke et al., 2013), albeit with a longer time span than ours, in showing that changes in macrobenthic communities in the North Sea can be related to climate indices (NAO). In addition, our results highlight the importance of taking rising SST into consideration when trying to explain spatio-temporal variability in benthic communities. This underscores the need for long-term monitoring in OWFs to fully understand these impacts. Additionally, long-term studies on climate change impacts on benthos often struggle to distinguish these impacts from those of beam trawling (Ghodrati Shojaei et al., 2016; Meyer et al., 2018). Our study offers the opportunity to examine climate change impacts within a fisheries exclusion zone, albeit with OWF turbine effects as an important covariate. In addition to direct effects of rising temperatures on the physiology of the benthic species (Brierley and Kingsford, 2009), rising temperatures can also indirectly affect their distribution, e.g. through changes to primary production, leading to alterations in the abundance and phenology of phytoplankton availability (Desmit et al., 2020; Suikkanen et al., 2007). Enhanced primary production will increase the flux of OM to the sediments (Suikkanen et al., 2007). Parallely, rising temperatures will accelerate pelagic mineralization, reducing the amount of OM that reaches the seafloor (Timmermann et al., 2012; Wikner and Andersson, 2012), thereby affecting the food supply for macrobenthic organisms.

#### 5. Conclusion

Our comprehensive long-term analysis of data collected in Belwind and C-Power concession areas highlights the significant impact of both turbine- and climate-related variables on macrobenthic communities. While local factors such as fine sediment, TOM and water depth emerged as primary predictors of macrobenthic community descriptors, SST also played a crucial role over longer time scales. As such, our findings emphasize the importance of considering weather and climate variables in long-term studies of benthic communities. Nevertheless, the

dominance of turbine-related predictor variables suggests that they remain the key drivers of biological responses, as macrofaunal abundance and diversity exhibited clear relationships with TOM and fine sediment content, with ideal conditions for soft-sediment macrobenthic communities observed in deeper zones between sandbanks. The variations in response to distance from the turbine and years since construction underscored the site-specific nature of impacts, highlighting the need for long-term studies considering different turbine foundations and areas with different hydrodynamical regimes. Future research should include additional environmental parameters, such as primary production and implement a comprehensive seasonal sampling strategy. This will capture the complete temperature gradient, thereby deepening our understanding of the impacts of offshore wind farms on marine ecosystems.

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

During the preparation of this work the author(s) used CHAT GPT in order to improve grammar and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

#### CRediT authorship contribution statement

**C. Jammár:** Software, Investigation, Formal analysis, Data curation, Writing – review & editing, Writing – original draft. **A. Reynés-Carдона:** Software, Investigation, Formal analysis, Data curation, Writing – review & editing, Writing – original draft. **J. Vanaverbeke:** Validation, Supervision, Software, Data curation, Conceptualization, Writing – review & editing. **U. Braeckman:** Validation, Supervision, Project administration, Funding acquisition, Data curation, Conceptualization, Writing – review & editing. **Nene Lefaille:** Writing – review & editing. **Steven Degraer:** Writing – review & editing. **Tom Moens:** 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

Data used in this study is openly available at the Belgian Marine Data Center (BMDC) doi.org/10.24417/bmdc.be:dataset:2880.

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## Appendix A. Supplementary data

Supplementary materials contain figures about the sampling designs across the years (Suppl. Fig. 1), species lumping procedure (Suppl. Fig. 2), climate indices across the years (Suppl. Fig. 3), data exploration and visualization (Suppl. Fig. 4), univariate model validation (Suppl. Fig. 5), multivariate analysis model validation and significant species plots (Suppl. Fig. 6). The dataset used in this article is openly accessible at [<https://doi.org/10.1016/j.seares.2024.102557>].

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