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Research article

Decommissioning of offshore wind farms and its impact on benthic ecology

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ABSTRACT

At the end of their operational life time offshore wind farms need to be decommissioned. How and to what extent the removal of the underwater structures impairs the ecosystem that developed during the operational phase of the wind farm is not known. So, decision makers face a knowledge gap, making the consideration of such ecological impacts challenging when planning decommissioning. This study evaluates how complete or partial decommissioning of foundation structure and scour protection layer impacts local epibenthic macrofauna biodiversity. We assessed three decommissioning alternatives (one for complete and two for partial removal) regarding their impact on epibenthic macrofauna species richness. The results imply that leaving the scour protection layer in situ will preserve a considerable number of species while cutting of the foundation structure above seabed will be beneficial for the fauna of such foundation structures where no scour protection is installed. These results should be taken with a grain of salt, as the current data base is rather limited. Data need to be improved substantially to allow for reliable statements and sound advice regarding the ecological impact of offshore wind farm decommissioning.

1. Introduction

Construction and operation of offshore wind farms (OWF) affect the marine ecosystem (Dannheim et al., 2020; Degraer et al., 2019; Zupan et al., 2023). In an area that is otherwise impaired by intense trawl fishery, OWF provide retreats for fish and new habitats for hard-substrate associated organisms (Coolen et al., 2020b; Fowler et al., 2019; Lacey and Hayes, 2020; Lefaible et al., 2019). Such benthic communities develop and change in structure and composition over the operational phase of an OWF and develop valuable miniature ecosystems (Dannheim et al., 2020; de Mesel et al., 2015; Degraer et al., 2019; Zupan et al., 2023). At the end of their operational life-time OWF, however, need to be decommissioned (removed). The dismantling of the underwater structure most likely impacts hard-substrate associated species and might even result in the complete elimination of their habitat, if foundation structures were removed entirely. Decisions on how to decommission OWF, hence, directly impact the maintenance of the associated benthic community.

According to Jackson and Miller (2009) an artificial reef 'is a submerged structure placed on the seabed deliberately, to mimic some characteristics of a natural reef'. Historically the predominant reef structures in Southern North Sea were oyster reefs, stones and rocks as well as moorlog (Olsen, 1883), which have been largely lost due to overharvesting and trawl fishery (Coolen, 2017). Even though OWF are not artificial reefs following the definition of Jackson and Miller (2009), they are well known for their artificial reef effect in the North Sea (Dannheim et al., 2020; de Mesel et al., 2015; Degraer et al., 2019). After installation the underwater structures are colonised by hard-substrate associated species (Dannheim et al., 2017). Time since construction, material, surface orientation, salinity, sea water temperature, food availability, wave action, water current speed or direction, turbidity, light and shadows as well as the proximity of other reefs providing a source of larvae may affect the taxonomic composition of this community (Coolen et al., 2020b, Baeye and Fettweis, 2015). The vertical dimension of the installations itself also affects these benthic communities in their structure and diversity. The foundation structures exhibit a clear zonation (splash zone, intertidal zone and deep subtidal zone) each hosting a different community (de Mesel et al., 2015). However,

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these community are not distributed evenly along the structures. Coolen et al. (2020b) and van der Stap et al. (2016) report non-linear relationships between water depth and species richness at oil and gas platforms. The structural design of the foundation has a considerable influence on the communities as well. When investigating benthic megafauna at the OWF *alpha ventus* and *Riffgat,* Krone et al. (2017) found that community composition differed at the three different foundation types (monopiles, tripods and jackets), and Coolen et al. (2020b) showed that species composition is influenced by substrate types, too. Particularly the scour protection layer seems to be a valuable habitat for hard-substrate dwelling species (Coolen et al. 2019, 2020a; Fowler et al., 2019).

OWF consist of multiple wind turbines that sit on foundation structures. There are different foundation types; across Europe, monopiles made up more than 80% of the foundations in 2020, the remainder was mainly jackets and gravity-base foundations (Ramírez et al., 2021). Monopiles and gravity-base foundations are often surrounded by a scour protection layer often using rock armour consisting of gravel, quarry run stone, limestone or granitic blasted rock (Esteban et al., 2019; Whitehouse et al., 2011). The wind turbines are connected by inter-array cables that are usually merged on an offshore sub-station. Up to date, only six OWF were decommissioned (Herzig, 2021). These OWF were all small in wind turbine size and number and located near-shore in shallow waters. Hence, currently we lack experience in large scale OWF decommissioning and its effects on the marine environment (Birchenough and Degraer, 2020; Fowler et al., 2019). Decision-makers of OWF decommissioning thus have no reliable knowledge base for their decisions. This paper addresses this knowledge gap by presenting a case-study of the impact of different decommissioning alternatives on the associated epibenthic macrofauna biodiversity based on the available data sampled at OWF throughout Europe.

Eckardt et al. (2022) predict an increase of OWF decommissioning from 2025 onwards, with a large increase in the 2030's. Hence, decommissioning of the already installed OWF, but also proactive decommissioning planning for newly installed OWF, will become a pressing issue in OWF management in the near future. In 2020 the majority of offshore wind turbines installed in Europe had a capacity of 8–8.4 MW and 9.5 MW, respectively (Ramírez et al., 2021). Those OWF that face decommissioning soon, however, consist of about 80 turbines of an older generation each with a nominal power of 3–4 MW (Eckardt et al., 2022). So far, there is no standardized procedure for the decommissioning of OWF across Europe. Even though there is an agreement, that the turbines need to be removed and the foundation structures are cut at or below seabed, there is no clear consensus whether inter-array cables and the scour protection is to be removed (Britton, 2013; Drew, 2011; Eckardt et al., 2022; Stephenson, 2013).

This paper focuses on how the scope of OWF decommissioning affects the epibenthic macrofauna biodiversity. If OWF are decommissioned completely, the 'added' hard-substrate associated benthic biodiversity will be lost completely (Smyth et al., 2015), while partial decommissioning may maintain the increased overall benthic biodiversity (Coolen et al., 2020a; Fowler et al., 2019). This study aims to investigate how different scopes of decommissioning (i.e., complete removal, leaving scour protection layer in situ and/or cutting the foundation structure above seabed) impact epibenthic macrofauna biodiversity. In accordance with Coolen et al. (2020b) and van der Stap et al. (2016) we expect a non-linear relationship between water depth and species richness. As the scour protection layer is much more complex than straight steel monopiles we hypothesized to find a larger biodiversity there. Even though Coolen et al. (2020b) were not able show this effect for oil and gas platforms, we still make this assumption here. As the species composition differed between the steel structures and the rocky surroundings (Coolen et al., 2020b), we are interested in the species overlap and the uniqueness of species at the scour protection layer and foundation structure.

2. Material and methods

2.1. Data base

Our study used the BISAR (Biodiversity Information System of benthic species at ARtificial structures) dataset on OWF associated epibenthic macrofauna communities (*fide* (Dannheim et al)). We accessed these data through the Alfred-Wegener-Institute AWI Biodiversity information system 'CRITTERBASE' (Teschke et al., 2022). Data were selected based on the following criteria: (1) from offshore wind farms (OWF) and the research platform *FINO 1*, as its foundation structure equivalates to those of offshore wind turbines; (2) from foundation or scour protection layer; and/or (3) within sampling depth range from foundation up to 5 m above seabed. Five projects (*BelWind, C-Power, FINO 1, Princess Amalia* and *Horns Rev 1*) with 15 locations in four European countries suited the criteria (Table 1, Fig. 1). Foundation types include monopiles, gravity-base foundations and a jacket. Maximum sampling depth at the foundations ranged from 8 to 30 m and at the scour protection layer from 10 to 30 m. On the foundation scrape samples were collected. The scour protection layer was sampled by collecting or scraping. For locations PA1, PA20, PA45 and PA60 information on sampled area was missing. This information was provided by (Faasse, 2021) (Table 2).

The data of the different projects were combined into a single data set and pre-processed to achieve a consistent taxonomic representation on the lowest taxonomic level in the following way: (i) Multiple entries of the same species (AphiaID) within the same sample were pooled (ii) Simultaneous entries of different taxa (e.g., species *Urticina felina* and genus *Urticina*) were merged on the lowest taxon. (iii) In case of simultaneous entries of higher taxonomic levels and of several lower taxonomic levels, the numbers referring to the higher levels were distributed proportionally among the lower levels (Coolen et al. 2020a, 2020b). We identified 330 taxa in total, of which 219 were defined on species level, 51 on genus level and 30 on family level.

The distance from seabed was calculated as the difference between water depth and sampling depth. Water depth of the OWF *BelWind*, *C-Power*, *Princess Amalia* and *Horns Rev 1* was assumed to be equivalent to the maximal sampling depth at the scour protection layer. At *Fino 1* water depth is 30 m (Forschungs- und Entwicklungszentrum Fachhochschule Kiel GmbH, 2022). Community age was calculated in months from installation date to sampling date. For this, Julian counts for these dates were calculated with the Julian function of the R package date (Therneau et al., 2022). In order to control for seasonal effects, Julian dates starting with 1 on January 1st using the format function were calculated.

Taxonomic richness (hereafter referred to a species richness) as number of unique lowest taxa per sample were calculated with help of the rarefy function of the R package vegan (Oksanen et al., 2022). The function calculates 'the expected species richness in random subsamples of size *sample* from the community'. In order to account for different sampled areas, *sample* was set to be a scaled abundance (Ab_{sc}), i.e., the product of the ratio of the sampled area (SA) per sample to the smallest sampled area and the observed abundance (Ab_{obs}) of the sample.

$$Ab_{sc} = \frac{\min(SA)}{SA} * Ab_{obs}$$

2.2. Decommissioning alternatives

Our study examines three decommissioning alternatives: (I) The scour protection layers are removed (if installed) and foundations are cut 1 m below seabed. This alternative reflects the general maximal decommissioning requirements, e.g., in Germany. (II) The scour protection layers are left in situ (if installed) and foundations are cut 1 m below seabed. This alternative reflects decommissioning considerations as for example in the UK (Britton, 2013; Drew, 2011; Stephenson, 2013)

Table 1
Characteristics of the OWF projects selected for analysis.

Project	Country	Location	Water depth	Year commissioned	Years sampled	Sample type	Foundation type
BelWind	Belgium	BW2	30 m	2009	2010–2014	Foundation	Monopile
						Scour protection	–
		BW8	30 m	2009	2013, 2015, 2017, 2018	Foundation	Monopile
						Scour protection	–
C-Power	Belgium	CP5	30 m	2008	2009–2015, 2019	Foundation	Gravity-base
						Scour protection	–
		CP6	30 m	2008	2010, 2012, 2013, 2016, 2018	Foundation	Gravity-base
						Scour protection	–
Fino 1	Germany	FINO	30 m	2003	2005–2007	Foundation	Jacket
Princess Amalia	Netherlands	PA1	23 m	2007	2011, 2013	Foundation	Monopile
						Scour protection	–
		PA20	21 m	2006	2011, 2013	Foundation	Monopile
						Scour protection	–
		PA45	24.5 m	2007	2011, 2013	Foundation	Monopile
						Scour protection	–
		PA60	23.5 m	2007	2011, 2013	Foundation	Monopile
						Scour protection	–
Horns Rev 1	Denmark	HR33	10 m	2002	2003–2005	Scour protection	–
		HR55	10 m	2002	2003–2005	Scour protection	–
						Foundation	Monopile
		HR58	10 m	2002	2003–2005	Scour protection	–
						Foundation	Monopile
		HR91	10 m	2002	2003–2005	Scour protection	–
		HR92	10 m	2002	2003–2005	Scour protection	–
		HR95	10 m	2002	2003–2005	Scour protection	–
						Foundation	Monopile

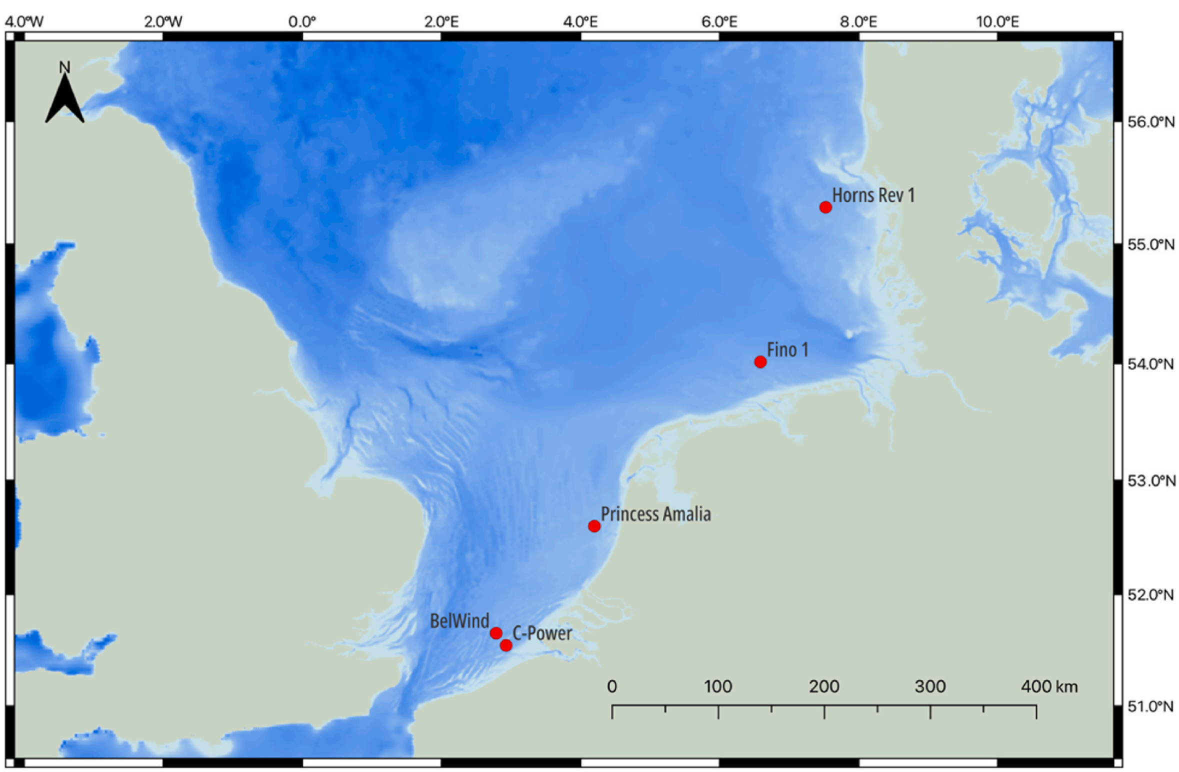

Fig. 1. Locations of the analysed offshore wind farms and research platform (red dots) in the North Sea.

and enables analysis of impacts on the epibenthic macrofauna biodiversity by maintaining some of the hard-substrate structures. (III) The scour protection layers are left in situ (if installed) and foundations are cut at 5 m above seabed, allowing to analyse the effect of maintaining hard-substrate structures above sea bed level. For all decommissioning alternatives it is assumed that foundation structures are cut with abrasive water jet cutting from the inside and inter-array cables are removed.

Other partial decommissioning alternatives such as 'topping', where parts or the complete structures are placed on the seabed as suggested by Fowler et al. (2019), are deemed unlikely for the North Sea under the current policy regime and considering future expansion targets.

2.3. Analyses

The data set consists of the following variables. Species richness is the response variable. Categorical variables are the location (with 15

Table 2
Information on benthic sampling locations and area within each OWF project.

Project	Location	Sample type	Sampled area per sample	Reference
BelWind	BW2 and BW8	Foundation	0.0625 m^2	Kerkhof et al., (2022)
		Scour protection	0.0435 and 0.082 m^2	Kerkhof et al., (2022)
C-Power	CP5 and CP6	Foundation	0.0625 m^2	Kerkhof et al., (2022)
		Scour protection	0.0232 and 0.192 m^2	Kerkhof et al., (2022)
Fino 1	FINO	Foundation	0.04 m^2	Schröder et al., (2008)
Princess Amalia	PA1, PA20, PA45 and PA60	Foundation	0.056 m^2	Coolen et al., (2020a)
		Scour protection	0.21 m^2	(Faasse, 2021)
Horns Rev 1	HR33, HR55, HR58, HR91, HR92 and HR95	Foundation and scour protection	0.04 m^2	Leonhard and Frederiksen (2006); Leonhard and Pedersen (2004)

levels, one for each foundation), sample type (with the two levels foundation and scour protection layer) and foundation type (with the three levels monopile, jacket and gravity-base foundation). Continuous variables are distance from seabed in meters, seasonality as day of the year and community age in months. Data exploration was conducted according to the protocol of Zuur et al. (2010). Species richness across all data points was assumed to follow a Poisson distribution. Cleveland's dotcharts (Cleveland, 1985) were used to check for outliers in the continuous variables. Boxplots were created to inspect the relation of the categorical variables and the response variable. A Pearson's Chi-squared test (Patefield, 1981) was conducted to test for dependency between sample type and foundation. To visually inspect continuous variables and to test for correlation, *ggscatter* of the *ggpubr* package (Kassambara, 2020) with method *kendall* for calculating correlation coefficients was used. For the entire data set considering all locations, the continuous variables (seasonality, distance from seabed and community age) are only weakly correlated with each other (seasonality and distance from seabed: correlation coefficient = 0.086, p-value <0.05, community age and distance from seabed: correlation coefficient = 0.059, p-value <0.05, seasonality and community age: correlation coefficient = 0.21, p-value <0.05).

We conducted the following analyses: (1) comparison of species richness at the scour protection layer and the entire location of different foundation types, (2) analysis of impact of distance from seabed on species richness and (3) investigation of impact of decommissioning alternatives on epibenthic macrofauna biodiversity (Table 3).

(1) Kruskal-Wallis rank sum tests were conducted to test for differences in species richness between gravity-base foundations and monopiles at the scour protection layer and the entire foundation structure. The 14 locations with scour protection layer were used to calculate species richness at the scour protection layer. All locations were used to calculate the species richness of the entire location, i.e., scour protection layer and foundation structure.
(2) In order to account for non-linear relationships, generalised additive mixed models (GAMM) were created using the mgcv package (Wood, 2011) to analyse effects of distance from seabed on species richness. For this analysis, only data sampled at the foundation structures was considered. Decommissioning alternative III assumes that foundation structures are cut at 5 m above seabed, hence, only such locations were considered at which samples were collected on the foundation up to 5 m above seabed. Location CP5 fulfils these criteria, but it was excluded as only a single sample was collected at the foundation structure up to 5 m above seabed and it was the only location with a gravity-base foundation. Hence, the number of samples was too low for running a GAMM. FINO, the only location with a jacket, on the other hand, was included in the analysis, as 64 samples were collected at the foundation structure up to 5 m above seabed. In total, five locations, one jacket (FINO) and four monopiles (PA20, HR55, HR58 and HR95) were suitable for further analysis (Table 3). As species richness was significantly higher at the jacket (Kruskal-Wallis rank test, Chi-squared = 94.4, df = 1, p-value <0.0001), GAMM were created for the two foundation types separately. The continuous variables (seasonality, distance from seabed and community age) of the data sets were visually inspected and tested for correlation following the same procedure as outlined above. The continuous variables of both data sets are only weakly correlated with each other (for monopiles: seasonality and distance from seabed: correlation coefficient = 0.048, p-value = 0.25, community age and distance from seabed: correlation coefficient = −0.11, p-value = 0.0076, seasonality and

Table 3
Number of samples (n) per location from the scour protection layer and from the entire foundation at different distances from seabed. 'x' indicates that the location was used in the analysis: (1) comparison of species richness at the scour protection layer and the entire location of different foundation types, (2) analysis of impact of distance from seabed on species richness and (3) investigation of impact of decommissioning alternatives on epibenthic macrofauna biodiversity.

Project	Location	Scour protection layer		n on foundation per distance from seabed													Used in analysis		
		n	Depth in m	0 m	1 m	2 m	3.8 m	4 m	4.7 m	4.9 m	5 m	>5–10 m	>10–15 m	>15–20 m	>20–25 m	>25 m	(1)	(2)	(3)
BelWind	BW2	6	30	–	–	–	–	–	–	–	–	–	29	–	–	–	x	–	–
	BW8	3	30	–	–	–	–	–	–	–	–	–	23	–	–	–	x	–	–
C-Power	CP5	20	30	–	–	–	–	–	–	–	1	4	65	3	3	1	x	–	x
	CP6	6	30	–	–	–	–	–	–	–	–	3	16	–	5	–	x	–	–
Fino	FINO	–	–	29	1	–	–	4	–	–	30	32	10	39	37	36	–	x	x
Princess Amalia	PA1	3	23	–	–	–	–	–	–	–	–	4	4	4	7	–	x	–	–
	PA20	3	21	–	–	–	–	4	–	–	–	–	4	8	4	–	x	x	x
	PA45	4	24.5	–	–	–	–	–	–	–	–	4	4	4	8	–	x	–	–
	PA60	3	23.5	–	–	–	–	–	–	–	–	4	4	4	8	–	x	–	–
Horns Rev	HR33	72	10	–	–	–	–	–	–	–	–	–	–	–	–	–	x	–	–
	HR55	96	10	–	–	12	12	12	–	–	–	66	–	–	–	–	x	x	x
	HR58	97	10	–	–	12	–	12	–	12	–	56	–	–	–	–	x	x	x
	HR91	72	10	–	–	–	–	–	–	–	–	–	–	–	–	–	x	–	–
	HR92	71	10	–	–	–	–	–	–	–	–	–	–	–	–	–	x	–	–
	HR95	96	10	–	–	14	–	10	12	–	–	60	–	–	–	–	x	x	x

community age: correlation coefficient = 0.076, p-value = 0.081, for the jacket seasonality and distance from seabed: correlation coefficient = −0.028, p-value = 0.58, community age and distance from seabed: correlation coefficient = −0.056, p-value = 0.26, seasonality and community age: correlation coefficient = 0.35, p-value <0.0001). A Poisson distribution with log link was used for the GAMM. Location (*i*) was considered as random effect in the GAMM of the monopiles to account for spatial pseudo-replication. To account for seasonal effects, sampling dates as Julian dates of the year were included. Community age in months was also included in the model. Distance from seabed, community age and seasonality were considered as smoothing terms (*f*()). The variables were included in different combinations (Table 5). The formula for the model considering all variables is:

$$\ln(\text{species richness}_{ij}) = \alpha + f(\text{distance from seabed}_{ij}) + f(\text{community age}_{ij}) + f(\text{seasonality}_{ij}) + \text{location}_j + \varepsilon_{ij}$$

The residuals ε_i of the best fitting models were assumed to approach normal distribution with mean of 0 and variance of σ.

The number of basis functions of the smooth terms were adjusted to enable 'potential variation in the smoother' (Pedersen et al., 2019). For seasonality they were set to 3, due to an assumed bell-shaped pattern throughout the year, with low values in winter that increase during spring, reaching top-values in summer and a decrease in fall (Coolen et al., 2022). Due to small k-index values, for the smoothing terms community age and distance from seabed, k was set to the largest value possible (community age: for monopiles k = 8 and for jacket k = 11, sampling depth: for monopiles k = 20 and for jacket k = 9). This corresponds to the maximum number of unique community ages and depths, respectively, sampled. AIC (Akaike's Information Criterion) values were calculated to identify the best fitting model (Akaike, 1973).

(3) In order to investigate the impact of the decommissioning alternatives on the epibenthic macrofauna biodiversity, the underwater construction of the wind turbines was subdivided into the following sections: A: scour protection layer, B: scour protection layer and foundation structure up to 5 m above seabed and C: foundation structure beyond 5 m above seabed. Only locations were considered that were sampled at 0–5 m above seabed and at the scour protection layer. The location FINO has a jacket foundation without scour protection but was also included in the analysis. In order to assess the impact of decommissioning alternatives on the epibenthic macrofauna biodiversity, (i) the percentage of species maintained per section and (ii) species overlap as well as uniqueness of species per section were analysed and (iii) decommissioning alternatives were compared. Species overlap as well as unique species per section was investigated by creating Venn diagrams for each location using the *eulerr* package (Larsson, 2020). The percentage of species maintained was calculated as the proportion of species (and lowest taxon, respectively) per section, i.e., the scour protection layer and/or the foundation structure up to 5 m above seabed, in relation to the total number of species per location, i.e., the scour protection layer and the entire foundation structure. To test for the influence of the decommissioning alternatives on the percentage of species maintained, a Dunn's test was performed (R Core Team, 2019).

3. Results

For a general overview, species richness as number of species per sample for the scour protection layer and the entire location, i.e., the scour protection layer and the foundation structure, are presented in Table 4 and Fig. 2. A list of taxa identified per location is provided as supplementary material.

3.1. Comparison of species richness at the scour protection layer and the entire location of different foundation types (1)

Species richness per sample varies among the different foundation types, but does not differ between the entire location (foundation structure and scour protection layer) and scour protection layer only (Fig. 3). Species richness is significantly higher at gravity-base foundations than at monopiles, both for the entire location (Chi-squared = 231.43, df = 1, p-value <0.001) and at the scour protection layer only (Chi-squared = 71.07), df = 1, p-value <0.001). On gravity-base foundations species richness does not differ significantly (Chi-squared = 2.196, df = 1, p-value = 0.139) between scour protection layer (mean ± SD: 12.6 ± 2.4, median: 12.5, IQR: 2.3, n: 26) and the entire location (mean ± SD: 11.5 ± 2.7, median: 11.9, IQR: 3.6, n: 127). At monopiles species richness is significantly (Chi-squared = 10.402, df = 1, p-value = 0.0013) lower at the scour protection layer (mean ± SD: 5.6 ± 1.9, median: 5.6, IQR: 2.4, n: 526) than at the entire location (mean ± SD: 6.2 ± 2.5, median: 5.9, IQR: 2.7, n: 946).

3.2. Analysis of impact of distance from seabed on species richness (2)

Generalised additive mixed models (GAMM) were conducted to investigate the relationship between species richness and distance from seabed for monopiles and the jacket (Table 5). Based on the Akaike information criterion (AIC), the model (Model = GAMM_J_4, AIC = 83.25) considering all three smoothing terms (distance from seabed, seasonality and community age) fits the jacket data best. For monopiles, the

Table 4
Total number of species, species richness as rarefied number of species per sample (mean ± standard deviation (SD)) at the scour protection layer and for the entire location (foundation and scour protection layer).

Project	Location	Foundation type	Scour protection layer			Entire location		
			Total	Mean	SD	Total	Mean	SD
BelWind	BW2	monopile	54	9.9	4.0	99	8.8	4.2
	BW8	monopile	39	11.9	1.6	92	8.7	3.3
C-Power	CP5	gravity-base foundation	87	12.4	2.5	141	11.5	2.8
	CP6	gravity-base foundation	48	13.2	1.9	82	11.4	2.7
Fino 1	FINO	jacket	–	–	–	115	7.9	2.3
Princess Amalia	PA1	monopile	39	10.4	1.7	83	10.7	4.1
	PA20	monopile	23	5.3	0.6	73	8.8	3.3
	PA45	monopile	45	10.0	3.7	84	9.2	2.7
	PA60	monopile	35	7.9	0.8	79	10.5	3.1
Horns Rev 1	HR33	monopile	48	5.3	1.9	48	5.3	1.9
	HR55	monopile	47	5.7	1.7	54	5.6	1.7
	HR58	monopile	55	5.7	1.9	61	5.6	1.9
	HR91	monopile	35	4.8	1.2	35	4.8	1.2
	HR92	monopile	42	5.4	1.6	42	5.4	1.6
	HR95	monopile	49	5.6	1.4	65	5.8	1.5

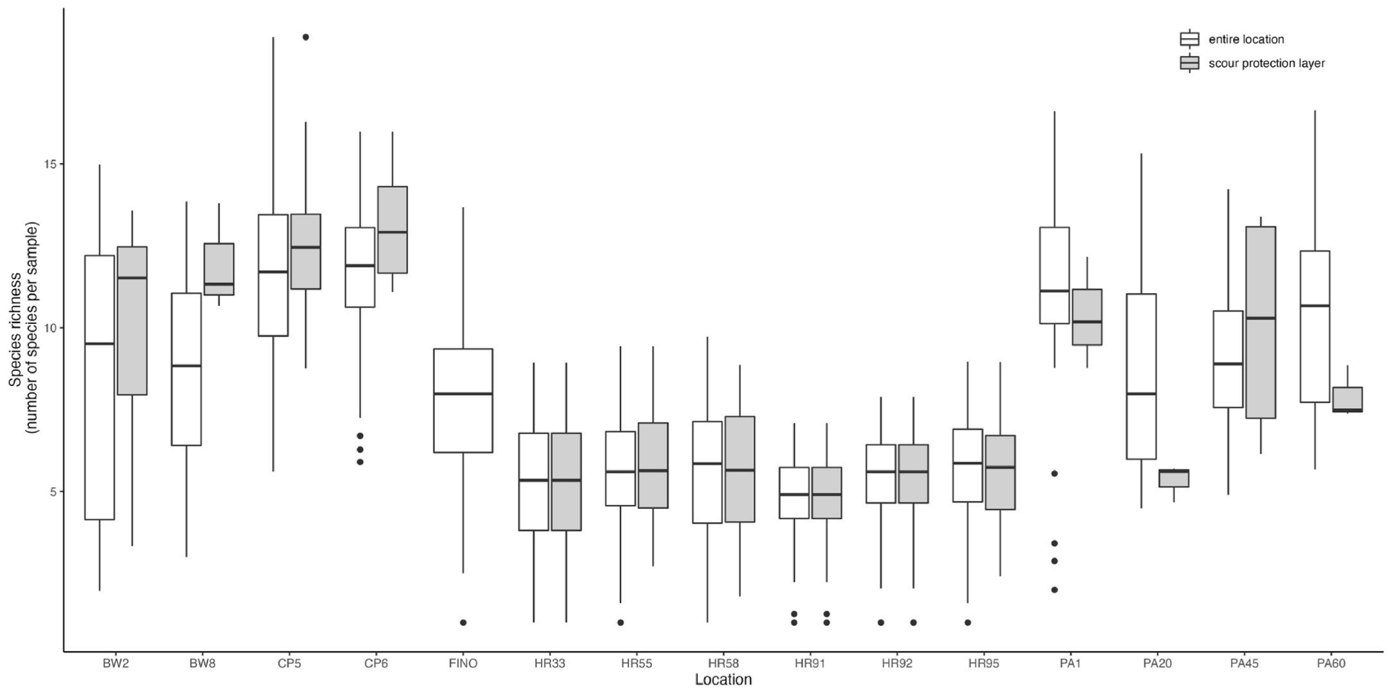

Fig. 2. Species richness as rarefied number of species per sample at the scour protection and the entire location (foundation structure and scour protection layer).

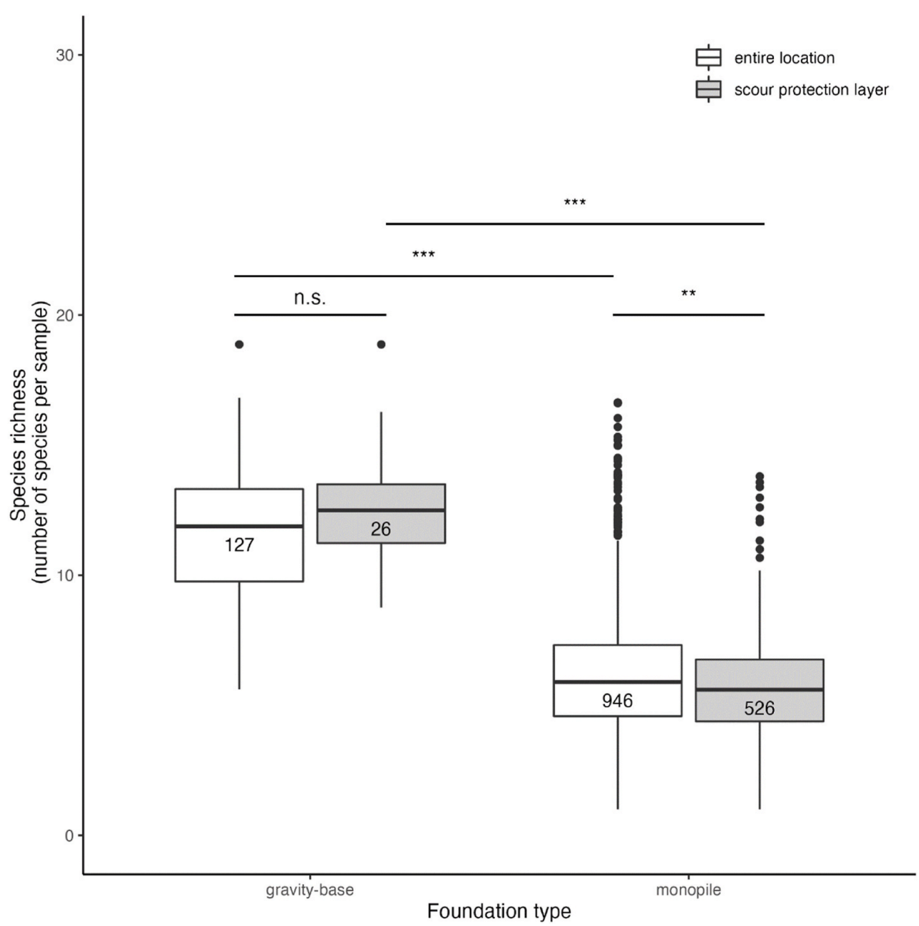

Fig. 3. Species richness at the entire location (foundation and scour protection layer) as well as at the scour protection layer only for gravity-base foundations and monopiles (numbers in the boxes indicate number of observations per group, horizontal lines above the whiskers indicate variables that are compared) with p-values $p < 0.001$: ***, $p < 0.01$: **, $p < 0.05$: *, $p > 0.1$: n.s (not significant).

Table 5
Residual degrees of freedom (Res.df) and Akaike information criterion (AIC) of general additive mixed models (GAMM) considering distance from seabed, seasonality, community age and/or foundation type (x = term is considered, - = term is not considered).

Foundation type	Model	Smoothing terms			Res.df	AIC
		Distance from seabed	Seasonality	Community age		
Monopile	GAMM_MP_1	X	–	–	304.04	199.86
	GAMM_MP_2	X	X	–	302.91	185.03
	GAMM_MP_3	X	–	X	298.95	195.37
	GAMM_MP_4	X	X	X	299.94	187.14
Jacket	GAMM_J_1	X	–	–	215.83	108.59
	GAMM_J_2	X	X	–	211.01	96.09
	GAMM_J_3	X	–	X	209.00	87.61
	GAMM_J_4	X	X	X	210.69	83.25

model with the best AIC values (model = GAMM_MP_2, AIC = 185.03) was not applied, as residuals did not approach normal distribution. Instead, the model considering all smoothing terms that has only slightly higher AIC (model = GAMM_MP_4, AIC = 187.14) was selected. Therefore, models that consider distance from seabed, seasonality and community age for both foundation types are presented.

The summary of the model for the monopiles (GAMM_MP_4) shows that all three smoothing terms are non-linear and significant (Table 6; $p < 0.001$). Species richness is only slightly decreasing up to about 5 m above seabed (Fig. 4). Thereafter, there is a drop of species richness up to about 10 m above seabed where it evens out. The relationship of species richness and community age is quite constant up to an age of about 40 months. Thereafter, species richness increases with the age of the community, albeit with rising uncertainty.

The summary of the model for the jacket (GAMM_J_4) indicates that only the effects of community age and seasonality are non-linear and significant (Table 6; $p < 0.01$). The effect of distance from seabed is linear and mean species richness remains constant over the entire length of the foundation structure (Fig. 5). Species richness increases with community age up to an age of about 20 months, stays almost constant until an age of 45 month and decreases thereafter. The relationship between seasonality and species richness is only minorly non-linear and with a slightly increasing trend.

3.3. *Investigation of impact of decommissioning alternatives on epibenthic macrofauna biodiversity (3)*

3.3.1. *Percentage of species maintained per section (i)*

The number and percentage of species found per section and location in relation to the entire location are given in Table 7. On average (±SD) 69.16 ± 23.84% of the species are found on the scour protection layer (section A), ranging from 31.51% (23 of 73 species) at PA20 to 90.16% (55 of 61 species) at HR58. The mean percentage of species found on the scour protection layer and on the foundation structure up to 5 m above seabed (section B) was highest (78.24 ± 15.71%) compared to the other two sections (A and C). The percentage of species found on the foundation structure beyond 5 m above seabed (section C) is on average (74.70 ± 10.41%) lower than in section B but higher than in section A. PA20 is the only location where the percentage species per scour protection layer and foundation up to 5 m (section B) is clearly lower (56.16%) compared to section C (87.67%).

Table 6
Effective degrees of freedom (edf) and p-values of the smooth terms of the GAMM GAMM_MP_4 and GAMM_J_4.

Smooth term	GAMM_MP_4		GAMM_J_4	
	edf	p-value	edf	p-value
Distance from seabed	4.122	<0.001	1.000	n.s.
Community Age	2.303	<0.001	3.765	<0.001
Seasonality	1.638	<0.001	1.767	<0.01

3.3.2. *Species overlap and uniqueness of species per section (ii)*

The number of species identified on the scour protection only, ranged from 6 species at PA20 (n = 3) to 25 species at CP5 (n = 20) (Table 3 and Fig. 6). At CP5 and PA20 large amounts of species were exclusively found on the foundation structures beyond 5 m above seabed (CP5: 51 species, n = 76; PA20: 32 species, n = 16). This share was smaller at HR55 (5 species, n = 66), HR58 (2 species, n = 56) and H95 (10 species, n = 60). The Venn diagrams (Fig. 6) indicate a strong overlap in species composition between foundation structure and scour protection layer with some species exclusively present in either section at the locations HR55, HR58 and HR95. Species overlap between sections was smallest at location CP5 and the location had the highest number of unique species occurring only at the scour protection layer as well as at the foundation beyond 5 m above seabed. At PA20 the overlap of species on scour protection layer and foundation is the smallest and there are no unique species at foundation up to 5 m above seabed. At FINO, the jacket, no scour protection layer was installed. Here, foundation species inventories below and beyond 5 m overlap distinctly and the number of species unique to the individual sections are distributed evenly.

3.3.3. *Comparison of decommissioning alternatives (iii)*

Decommissioning alternatives II (69.16 ± 23.84% species richness maintained) and III (78.24 ± 15.71% species richness maintained) do not differ significantly from each other, but both differ significantly from decommissioning alternative I (0%) (Dunn's test comparison of decommissioning alternatives: I vs. II: p-value = 0.020, I vs. III: p-value = 0.004, II vs. III: p-value = 0.624) (Table 8).

4. Discussion

Our study indicates that decommissioning strategies differ in their ecological impact, i.e., the way they cause loss or maintenance of epibenthic macrofauna biodiversity. Complete decommissioning has the most negative effect, obviously, as all hard bottom fauna will be lost. Partial decommissioning preserves more than two thirds of the hard bottom fauna (Table 8). Leaving the scour protection layer in place is the deciding measure, while keeping parts of the foundation structure adds little further biodiversity.

In the following we will (i) take a critical view on the limitations of our data and methods, (ii) discuss our findings in greater detail, (iii) explore further aspects of the ecological relevance of OWF decommissioning and (iv) evaluate possible recommendations for decommissioning management.

4.1. *Limitations of data and methods*

An underlying challenge of this analysis is the poor data basis with regard to the number of suitable samples. Undoubtedly the BISAR dataset available through CRITTERBASE represents the best data collection on European OWF fouling communities in terms of data volume, data quality and data harmonisation currently available.

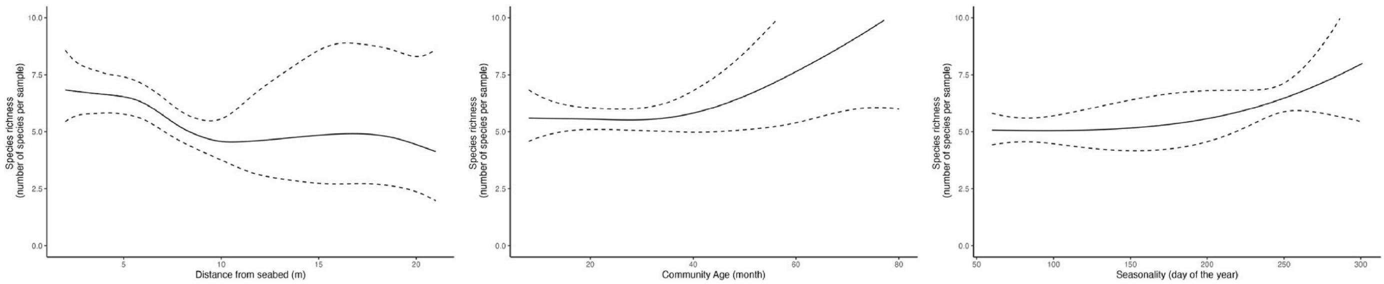

Fig. 4. Relationship between species richness (number of species per sample) and distance from seabed (m), community age (month) and seasonality (day of the year) for monopiles (solid lines) and 95% confidence intervals (dashed lines) (estimates derived from model GAMM_MP_4).

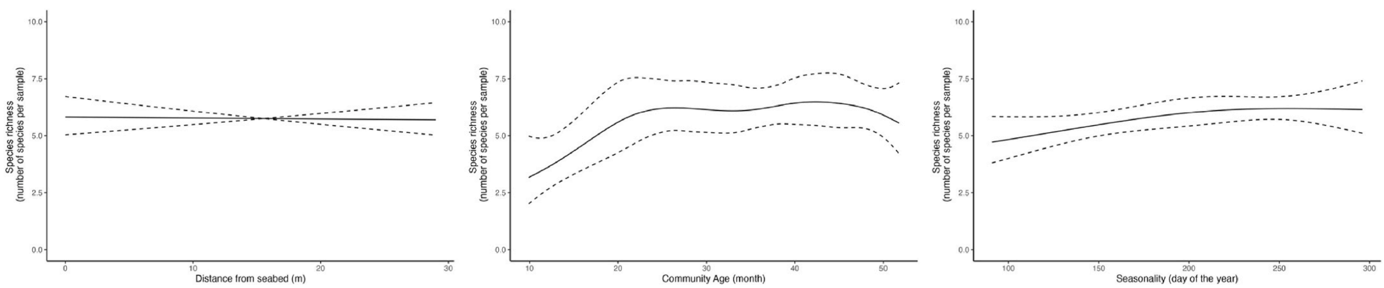

Fig. 5. Relationship between species richness (number of species per sample) and distance from seabed (m), community age (month) and seasonality (day of the year) for the jacket (solid lines) and 95% confidence intervals (dashed lines) (estimates derived from model GAMM_J_4).

Table 7
Number (n) and percentage (%) of species per section in relation to the entire location for each location and mean values and standard deviation (SD) per section.

Location	Entire location		A: Scour protection layer		B: Scour protection layer and foundation up to 5 m above seabed		C: Foundation beyond 5 m above seabed	
	n	%	n	%	n	%	n	%
CP5	141	100.00	87	61.70	90	63.83	115	81.56
FINO	115	100.00	–	–	89	77.39	89	77.39
PA20	73	100.00	23	31.51	41	56.16	64	87.67
HR55	54	100.00	47	87.04	49	90.74	38	70.37
HR58	61	100.00	55	90.16	59	96.72	35	57.38
HR95	65	100.00	49	75.38	55	84.62	48	73.85
Mean ± SD:		100.00 ± 0.00		69.16 ± 23.84		78.24 ± 15.71		74.70 ± 10.41

Nevertheless, it does not meet all requirements to provide fully reliable answers to the question under concern. One of the reasons for this is the distinct methodical heterogeneity of national ecological OWF monitoring programmes. They vary e.g., in sample type (foundation and scour protection), sampling area, depth and duration (Bundesamt für Seeschifffahrt und Hydrographie, 2013; Degraer et al., 2013; Coolen et al., 2020b).

Furthermore, OWF vary structurally, e.g., regarding the design of foundation types as well as their environmental setting, such as water depth, currents, distance to shore. In order to account for the influence of all these variables on, e.g., species richness, a very large number of samples is required. For this analysis data of only a single jacket, two gravity-base foundations in a single OWF and 12 monopiles in three OWF were suitable. The water depth at the monopiles spans a wide range, from 10 to 30 m (and will become more variable as future OWF projects move further offshore). Last but not least, sampling designs differed considerably; at two locations the foundation was only sampled at a water depth of 10 to 15 m and at three locations samples were only collected on the scour protection layer. The insufficient and inconsistent monitoring programmes impairs the validity of our analysis to some extent, and thus, any advice on decommissioning derived from this study should be taken with a grain of salt.

4.2. Impact of decommissioning on epibenthic macrofauna biodiversity

Various authors found an overall increase in species richness by offshore installations in an otherwise soft-sediment environment (Coolen et al., 2020b; Fowler et al., 2019; Lacey and Hayes, 2020; Lefaible et al., 2019). This can be deduced to the artificial reef effect (Dannheim et al., 2020) as these structures provide habitat, food and shelter (Fowler et al., 2019). If all OWF structures were removed completely, this habitat and all species associated would be lost. This is well known from decommissioning of offshore oil and gas installations e.g., van Elden et al. (2022).

Our results show clearly that leaving the scour protection layer in situ will preserve the majority of hard-substrate associated species (69.16 ± 23.84%, Table 8). The scour protection layer of the monopiles can host very high percentages of all species (up to 90.16%, Table 7) and a large proportion of species that is also present in other sections (Fig. 6). Generally, leaving the scour protection layer in situ would preserve many species unique to that section as well as a large proportion of epibenthic macrofauna biodiversity of the entire location (scour protection layer and the foundation structure). A study on the comparison of decommissioning alternatives for the gravity-based structure of a Dutch gas platform revealed that about 26% of the species would be lost, if the concrete gravity-base foundation and the steel structures were removed completely and the rock dump was left in situ or scattered (Coolen et al., 2020a). Furthermore, the increase in the number of hard bottom dwellers, e.g., of edible crab (*Cancer pagurus*), points to a biomass increase associated with the scour protection layer, see Krone et al. (2017) and Coolen et al. (2019). One location in our analysis, i.e., PA20, had a distinctively lower percentage of species at the scour protection layer than all other locations (only 31.5% compared to at least 61.7%, Table 7). This might be related to deeper waters (24.5 m), as

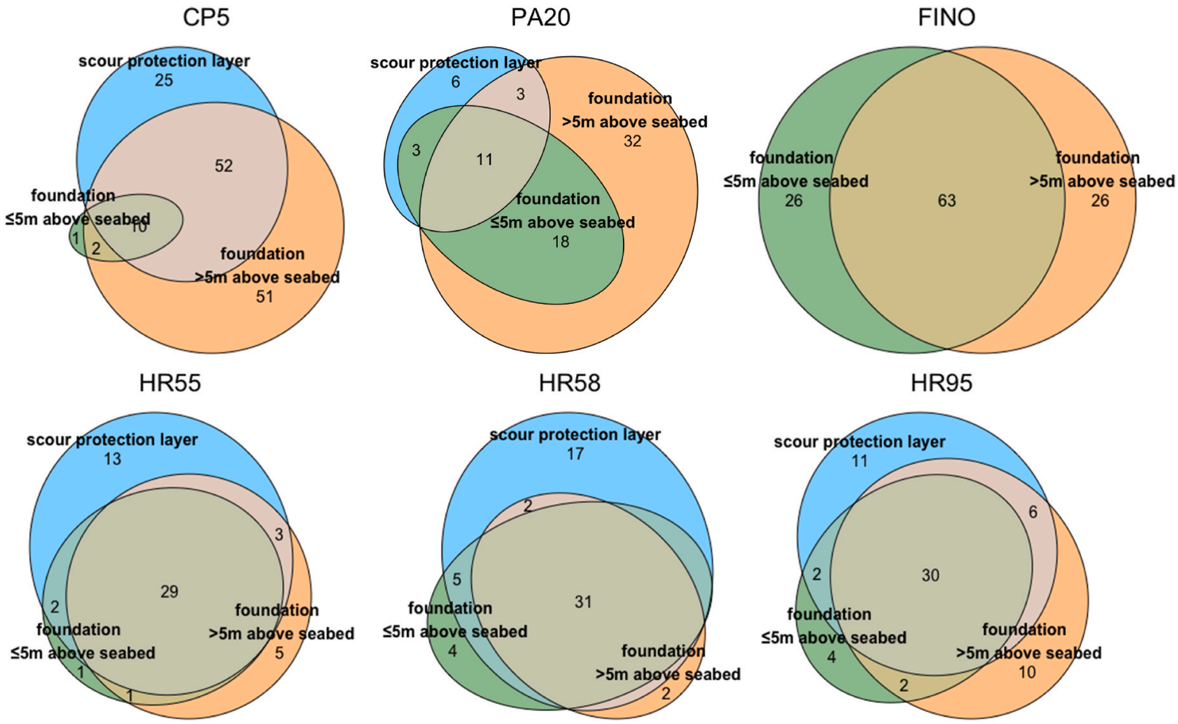

Fig. 6. Venn diagrams for overlap of species between scour protection layer (blue) and foundation structure up to 5 m (green) and beyond 5 m above seabed (orange) for the locations CP5, PA20, FINO, HR55, HR58 and HR95. (Numbers represent the number of species per section and overlap, respectively).

Table 8
Percentage (%, mean ± standard deviation (SD)) of species maintained per decommissioning alternative.

Decommissioning alternative	Scour protection layer	Foundation structure	Percentage of species richness maintained (%) (Mean ± SD)
I	Removed	Cut 1 m below seabed	00.00
II	Left in situ	Cut 1 m below seabed	69.16 ± 23.84
III	Left in situ (if installed)	Cut 5 m above seabed	78.24 ± 15.71

species composition of upper and lower parts of the foundation differ distinctly (Coolen et al. 2020b, 2022).

The relationship of species richness to distance from seabed differed between the different foundation types: at the jacket structures, species richness was constant along the entire vertical structure (Fig. 5), while at monopiles it changed in a non-linear way (Fig. 4), similarly to oil and gas platforms (Coolen et al., 2020b). Marine fouling assemblages on oil and gas platforms in the North Sea showed an increase in species richness down to a water depth of about 15 to 20 m and a decrease beyond this depth (van der Stap et al., 2016). The intermediate disturbance hypothesis (Connell, 1978) may explain these observations, as high biodiversity at intermediate depth is maintained by intermediate disturbances (Coolen et al., 2020b; van der Stap et al., 2016). Fortune and Paterson (2020) argue that this depth effect can also be explained by the competition of dominant species. Our results, however, are not in line with Coolen et al. (2020b), Fortune and Paterson (2020) and van der Stap et al. (2016), as species richness at the monopiles was highest close to the seabed. This might imply that cutting the foundation structures above seabed would considerably contribute to maintaining benthic species richness. Our analysis, however, reveals that this is only true for locations without scour protection layer, i.e., when cutting the jacket up to 5 m above seabed would maintain 77% of the species, thereof 26 unique species and 63 species found also beyond 5 m above seabed (Table 7, Fig. 6). Cutting the monopile and gravity-base foundation structures up to 5 m above seabed will increase the percentage of species that would be maintained only slightly (about 2–9%, without location PA20) compared to leaving the scour protection layer in situ only. Further, there are only a few species present exclusively on the lowest 5 m of the foundation (2 to 6 species per location without PA20, Fig. 6). Accordingly, cutting foundations above seabed when scour protection is present, does not contribute considerably to preserving species richness. This coincides with removal options for oil and gas platforms where less species were present on the steel legs of the structure than on surrounding rock dumps (Coolen et al., 2020a). The community composition was found to also differ between the different foundation types (Krone et al., 2017). Krone et al. (2017) reported differences in fish and crab species inventory on jacket and tripod foundations compared to monopiles, but attributed this not to the different structural design of the foundation, but rather to the scour protection layer present at the monopile only.

4.3. Further aspects of the ecological relevance of OWF decommissioning

In the past, potential impacts on the marine environment were ignored when removing offshore structures. E.g., the Danish OWF *Vindeby* was dismantled completely, although the environmental impact assessment indicated that the removal of the structures could lead to a decline in the Atlantic cod (*Gadus morhua*) ((Nicolaisen et al., 2016) in Fowler et al., 2019). Just as for benthic species OWF provide shelter as well as feeding and nursing grounds for fish species as indicated by an increase in fish abundance (Stenberg et al., 2015; van Hal et al., 2017). Structures close to the seabed are of special importance to juvenile Atlantic cod, as they primarily forage on smaller crustaceans such as amphipods and small crabs which are found on the lower parts of the foundation and on the scour protection layer (Krone et al., 2017; Reubens et al., 2013). Other opportunistic feeders like the pelagic horse mackerel (*Trachurus trachurus*) were found to at least seasonally visit OWF to feed on energy-rich species like *Jassa herdmani* (Mavraki et al., 2021). Also, the fisheries exclusion effect, i.e., the closure for fisheries in and around the OWF, benefits fish communities and allows the seafloor and its communities to recover from intensive trawling (Birchenough and Degraer, 2020). Apparently, OWF alter the local food-web beyond the benthic community, but the implications for the food-web and eventually the OWF decommissioning are not well understood yet.

The impact of OWF structures on the surrounding soft-bottom community is currently not completely understood (Dannheim et al., 2020; Degraer et al., 2019; Hutchison et al., 2020; Lefaible et al., 2019). The area covered by OWF is very small, i.e., only about 1.7% of the total area of the North Sea in 2020, and thus such effects may be negligible on the ecosystem level (Ter Hofstede et al., 2023;2017; Fowler et al., 2019). However, many OWF were built over the past years and more will be installed in the future. How and to what extent soft-bottom communities are impacted by the increased number of OWF and would be affected by partial decommissioning demands further investigations.

Maintaining OWF structures might also have other large-scale impacts e.g., upholding connectivity by providing stepping stones for the dispersal of hard-substrate associated species (Degraer et al., 2020). The potential regional impact of OWF and of their removal, respectively, are neglected in decision-making processes for decommissioning quite often (Fowler et al., 2019). The relevance of the artificial structures for the connectivity of species and communities depends on the uniqueness of the habitat and on their location and distance in relation to other habitats and structures (Fowler et al., 2019). Structures that resemble suppliers, e.g., spawning sites, should not be removed, if the established network functions were to be maintained, as shown for pelagic dispersal and connectivity between hard substrates in the North Sea (van der Molen et al., 2018). The structures, however, might not only enhance connectivity of indigenous species. The vertical structure of OWF resembles an offshore habitat that is usually not present in the North Sea and, hence, may provide a habitat for non-indigenous species (Coolen, 2017; Dannheim et al., 2017; de Mesel et al., 2015). A considerable higher proportion of non-indigenous species were found in the intertidal parts of such structures than at the deeper parts (Coolen et al., 2020b; de Mesel et al., 2015). Consequently, a partial decommissioning in terms of leaving the scour protection in place and cutting foundation structures just a couple of meters above seabed would remove potential habitat for non-indigenous species and, thus, may be considered a defensive measure regarding the dispersal of non-indigenous species. To which extent prevailing OWF structures will affect the connectivity at regional or even larger scales, especially when considering the installation of new OWF, remains to be investigated.

We can see the scour protection layer as an additional valuable benthic habitat that might even host species of conservational interest (Fowler et al., 2019). E.g., a study on subsea pipelines found five such species on the pipes and a further 13 rare taxa in the neighbouring sediment (Lacey and Hayes, 2020). Compared to natural habitats and to decade-old human-introduced structures such as oil and gas platforms, most OWF are comparatively new habitats and the associated community is still relatively young. Coolen et al. (2022) hypothesized that an interplay of inhibition, due to a shortage of spatial resources and consumption of other larvae by early colonisers, and keystone species which increase habitat by facilitating secondary hard substrate, may result in an 'pseudo-equilibrium' at low water depth. Another study, however, was not able to support this theory and rather postulated that the communities are subject to constant change due to the ability to colonise already occupied spaces and the mortality of already present individuals (Zupan et al., 2023). It appears, thus, very challenging to predict how the benthic community will develop over the operational phase of the OWF and whether habitats valuable for species, also of commercial or conservational interest, will persist. Consequently, further research near the end of the operational life time is required to enable more reliable statements regarding the current ecological status of and possible ecological impacts of OWF decommissioning.

4.4. Recommendations for decommissioning management

Due to the patchy data basis currently available, our recommendations for OWF decommissioning regarding its ecological impact leave much to be desired in terms of clarity and reliability. Nonetheless, our results clearly suggest, that if the maintenance of epibenthic macrofauna biodiversity in the OWF area was an objective of decommissioning, then (i) the scour protection layer should be left in situ or (ii) foundation structures without scour protection should be cut above seabed.

However, in order to validate the results of this study and to acquire in-depth knowledge on the cause-effect relationships systematic and long-term surveys are required (Dannheim et al., 2020; Degraer et al., 2019; Fowler et al., 2019), we suggest targeted investigations of decommissioning impacts on:

- epifauna at the scour protection layer and the bottom of the foundation
- surrounding soft-bottom and fish communities
- species of commercial and conservational interest
- overall food-web and
- connectivity of communities

over the entire or at least towards the end of the operational life-time of the OWF turbines, in order to make well-founded recommendations for OWF decommissioning.

This study presents possible impacts of partial decommissioning on the epibenthic macrofauna biodiversity. However, if partial decommissioning is to be considered, other aspects need to be accounted for. (i) With increasing expansion targets for renewable energies (Bundesministerium für Wirtschaft und Klimaschutz, 2022), the subsequent use of the OWF area needs to be considered. Remaining scour protection layer would probably not be an obstacle, but whether foundation structures cut just above seabed would be a problem for new installations depends among others on the new park layout (Eckardt et al., 2022). New foundation structures could probably not be installed in the same locations as the old ones, even if they were removed completely (Eckardt et al., 2022). (ii) Also, partial decommissioning might impair the safety and efficiency of traffic, e.g., foundation structures cut above seabed might be an obstacle for shipping and fishery; how or to what extent, though, remains to be investigated in detail (Eckardt et al., 2022). (iii) Another relevant factor to be considered are the decommissioning costs. Decommissioning alternatives where the scour protection layer is left in situ, are associated with the lowest net costs per MW (Eckardt et al., 2022). However, costs that are potentially associated with continued monitoring of components left in place in offshore areas, are not considered in the calculations stated by Eckardt et al. (2022).

5. Conclusion

The current state of knowledge implies that partial decommissioning of offshore structures – leaving the scour protection layer in situ in particular - is beneficial for the conservation of local hard-bottom dwelling species and overall benthic biodiversity. However, in order to validate our findings and for a better assessment of the impacts of different alternatives of offshore wind farm decommissioning on the ecosystem more data is required. Currently, monitoring programmes vary considerably among European countries, resulting in an inconsistent data set. Especially programmes for investigations of the foundation structure near the seabed and the scour protection towards the end of the operational life are missing. For well-founded predictions of impacts of decommissioning on the whole system, targeted, systematic and long-term surveys of the benthic and fish communities within and around offshore wind farms are required.

CRediT authorship contribution statement

Vanessa Spielmann: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jennifer Dannheim:** Conceptualization, Data curation, Supervision, Validation, Writing – review & editing. **Thomas Brey:** Conceptualization, Supervision, Validation, Writing – review & editing. **Joop W.P. Coolen:** Conceptualization, Data curation, Supervision, Validation, 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

All data used will be publically available within the BISAR (Biodiversity Information System of benthic species at ARtificial structures) dataset by the AWI Biodiversity information system CRITTERBASE.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.119022.

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