The International Journal of Life Cycle Assessment
https://doi.org/10.1007/s11367-025-02504-0

ORIGINAL PAPER

Benefits and impacts of offshore wind farms on benthic marine biodiversity in a life cycle assessment context

Liv Stranddorf[1,2,3] · Francesca Verones[4] · Stig Irving Olsen[1,3]

Received: 12 November 2024 / Accepted: 10 June 2025

Abstract

Purpose The global capacity of offshore wind energy is rapidly expanding, with the North Sea leading this growth. However, this region also hosts some of the world's oldest offshore wind farms, requiring decommissioning in the coming years. Apart from their benefits for energy generation, constructing and decommissioning offshore wind farms physically affect the marine ecosystem. This study aims to develop characterization factors to quantify impacts on marine benthic biodiversity, assessing changes in species richness and accounting for both positive and negative effects.

Method The study utilizes data on species richness at 17 artificial offshore structures and reference seabed sites in the North Sea. Polynomial models are developed to express the species richness on the structure as a function of structure age. The study considers two construction scenarios and three decommissioning scenarios and compares species richness on the artificial structure to the reference seabed. Additionally, it investigates species composition changes in different taxonomic groups and alien species. The richness models are used to develop characterization factors for biodiversity impacts, expressed as the time-integrated potentially disappeared fraction of species.

Results and discussion The developed characterization factors quantify potential loss or gain of species across taxonomic groups, enhancing the representation of biodiversity in life cycle assessment. While species richness on offshore structures generally increases over time, the net biodiversity impacts depend on the seabed type on which the structure is constructed. The characterization factors indicate that for sandy seabed, species richness on the structure exceeds that of the reference seabed after ~13 years. However, over a 25-year lifetime, construction on sandy seabed generally results in a net species loss due to declining species richness after the peak at a 13-year lifetime. Construction on hard seabed supports a net gain of species. Furthermore, characterization factors indicate that partial decommissioning will preserve 80–99% of the species richness on turbine structures. The net effect on ecosystem functioning is yet unclear, depending on, e.g., recolonization opportunities, reference state, and interaction with other marine activities.

Conclusion The developed characterization factors quantify both positive and negative biodiversity impacts from habitat changes associated with offshore wind farm construction and decommissioning in the North Sea, thus providing a basis for understanding and managing the ecological consequences of offshore wind farm projects. The findings indicate that the construction and decommissioning activities will cause changes in the total species richness and the richness of alien species and shifts in richness between taxonomic groups.

Keywords North Sea · Life cycle impact assessment · Characterization factors · Ecosystem quality · Biodiversity · Marine ecosystems · Species richness · Offshore wind energy

1 Introduction

The global capacity of offshore wind energy is rapidly expanding, supporting the sustainable transition of the energy system (WilLiams & Zhao 2023). The North Sea is a front-runner in this expansion, and today, it holds about two-thirds of the global offshore wind capacity (IEA 2019). Wind farms in the North Sea are, therefore, the focal point of this study. Countries bordering the North Sea have pledged to multiply the capacity of wind farms in the North Sea by eight times the levels of 2023 before 2050 (Henley 2023). Alongside the continuous expansion, the North Sea holds some of the world's oldest Offshore Wind Farms (OWFs), which will need decommissioning

Communicated by Ian Vázquez-Rowe.

Extended author information available on the last page of the article

in the coming years and decades (Lacal-Arántegui et al., 2019). Studies have shown that the presence, construction, and decommissioning of OWFs can have both positive and negative impacts on marine biodiversity, depending on the conservation priorities and species composition (Dannheim et al. 2020; De Mesel et al. 2015; Degraer et al. 2020; Spielmann et al. 2023; Wilson & ElLiott 2009). Research suggests that the North Sea was, prior to industrialization, extensively covered with rock reefs, coarse peat banks, and oyster beds, providing essential hard substrate habitats (Hofstede et al. 2022; Olsen 1883; Thurstan et al. 2023). However, many of these habitats have been largely destroyed due to human activities, including trawling, oyster dredging, and the extraction of marine boulders (Bennema et al. 2020; Lengkeek & Bouma 2010; Støttrup et al. 2017). OWFs and other artificial marine structures have been identified to provide hard substrate habitats similar to those of natural occurrence, and studies indicate that they can be beneficial for the North Sea environment (Degraer et al. 2020; Smyth et al. 2015). However, whether OWF structures can be considered positive or negative for the marine environment will depend on the habitat that was there before construction and how the structures are decommissioned (Hernández C. et al., 2021; van der Molen et al. 2014; Wilson and ElLiott 2009). The construction of OWFs can take place in different substrate and habitat types, e.g., in a sandy seabed or rocky seabed. The decommissioning can follow different scenarios varying from complete removal to leaving larger parts of the structure in the sea, and each of these scenarios will impact the marine ecosystem and biodiversity differently (Hall et al. 2020; Smyth et al. 2015; Spielmann et al. 2023). To make informed decisions regarding the construction and decommissioning impacts of OWFs, quantifying and assessing the associated impacts on marine biodiversity is necessary.

Life Cycle Assessment (LCA) is a suitable tool for quantifying the environmental impacts of products and processes and can support decision-making by highlighting impact hotspots, reduction potentials, and risks of shifting the burdens between different environmental impact categories (e.g., reducing the climate impacts but increasing the impacts on biodiversity) (de Baan et al. 2013; Hauschild et al. 2018). LCA consists of four phases, including the goal and scope definition, life cycle inventory (collection of data on resource uses and emissions), Life Cycle Impact Assessment (LCIA), and interpretation. In LCIA, the environmental impacts of the considered system are quantified using Characterization Factors (CFs). Today, impacts on biodiversity from some of the main anthropogenic pressures, such as land use change (Kuipers et al. 2021), climate change (de Visser et al. 2023; Li et al. 2022), and pollution (Oginah et al. 2023), can be quantified using LCIA at the damage level. However, CFs for quantifying the impacts of marine habitat changes associated with OWF construction and decommissioning are currently not existing but highly needed, considering the extensive expansion of OWFs in the North Sea (Stranddorf et al. 2024). Woods and Verones (2019) developed CFs for marine ecosystem damage from anthropogenic seabed disturbance, covering activities like offshore mining and trawl fishing, but the method is not applicable to the marine habitat changes associated with OWF construction and decommissioning. Li et al. (2023) developed CFs for the impacts of seabed occupation and the absence of trawling on benthic organisms due to the existence of OWFs and showed that the existence of artificial reefs provided by OWFs could lead to a doubling of species richness. However, they did not cover the impacts of habitat changes associated with construction and decommissioning. Spielmann et al. (2023) investigated the impacts of OWF decommissioning on benthic biodiversity, and their results imply that leaving parts of the OWF structure in place when decommissioning will conserve a considerable amount of species richness. However, they did not develop CFs based on their findings.

In this study, we develop the first CFs to assess the impacts of habitat change on marine benthic biodiversity associated with the construction and decommissioning of OWFs in the North Sea. The benthic species are representative of the marine life potentially affected by habitat changes associated with OWFs as the structures directly affect the seabed communities and provide hard substrates for marine growth, which affects the demersal and pelagic species via food chains (Desprez 2000; Heery et al. 2017). The impacts are expressed as a Potentially Disappeared Fraction of species integrated over time (PDF.year), which is a common unit for biodiversity impacts in LCA (Finkbeiner 2011; Hanafiah et al. 2013; Huijbregts et al. 2016; Woods et al. 2016) and the recommended unit of the Global Guidance on Environmental Life Cycle Impact Assessment Indicators (GLAM) (UNEP 2019). PDF is a convenient metric as it can be quantified across taxonomic groups and environmental compartments (Verones et al. 2022). LCA traditionally only covers negative impacts, but as man-made structures like OWFs may act as artificial reefs, providing habitat for multiple species, there is a need to enable the quantification of potential benefits for marine biodiversity (Dannheim et al. 2020; Degraer et al. 2020). To allow for quantification and assessment of both the benefits for and impacts on marine benthic biodiversity, our CFs cover increases and decreases in species richness. The impacts are calculated in relation to reference sites with sandy seabed or hard sediments (stone reef) and over the lifetime of offshore structures. The impacts highly depend on the baseline used in the assessment method, and it is, therefore, relevant to state that samples representing the reference sites were collected in 2008–2015 and are thereby representative of the seabed after the heavy industrialization of the North Sea. Additionally, we present a method to convert the relative impacts to absolute impacts (species.year) to make the impacts compatible with impacts of other systems.

To allow for more detail, the CFs are developed for eight different taxonomic groups and alien species, enabling assessment of the species composition on the offshore structure, compared to the reference sandy or hard substrate seabed. Alien species (as opposed to native species) are species that have spread or moved beyond the limits of their native geographic range into an area in which they do not naturally occur (Blackburn et al. 2014). Alien species are not necessarily harmful to the ecosystem in which they are located, but if they become dominant compared to naturally occurring species, they can have a harmful effect on the ecosystem and are then classified as invasive alien species (Pysek et al. 2020). To identify if an alien species is invasive, information on their influence on local ecosystems is needed, but this was not possible to obtain in this study. However, prevention of alien species introduction has been found to be the most effective way of minimizing the risk of invasion (Borgelt et al. 2024; Early et al. 2016; Leung et al. 2002). The occurrence of alien species is, therefore, included as an indicator of invasion risk.

2 Methodology

2.1 Habitat change scenarios

Our study considers the habitat changes occurring in relation to OWF construction and decommissioning (Fig. 1). The study does not consider the activity of construction or decommissioning itself (i.e., disturbance of machinery, etc.), but merely the habitat before and after construction or decommissioning. We included two scenarios for habitat changes occurring as a consequence of construction: (I-C) The OWF is constructed on a sandy seabed, and (II-C) the OWF is constructed on hard substrates. The North Sea is today dominated by sandy seabed and only about 10% is covered by harder substrates like gravel and rocks (Coolen et al. 2018; European Commission 2024). Scenario I-C is, therefore, expected to be the most common scenario for construction. Furthermore, we consider three

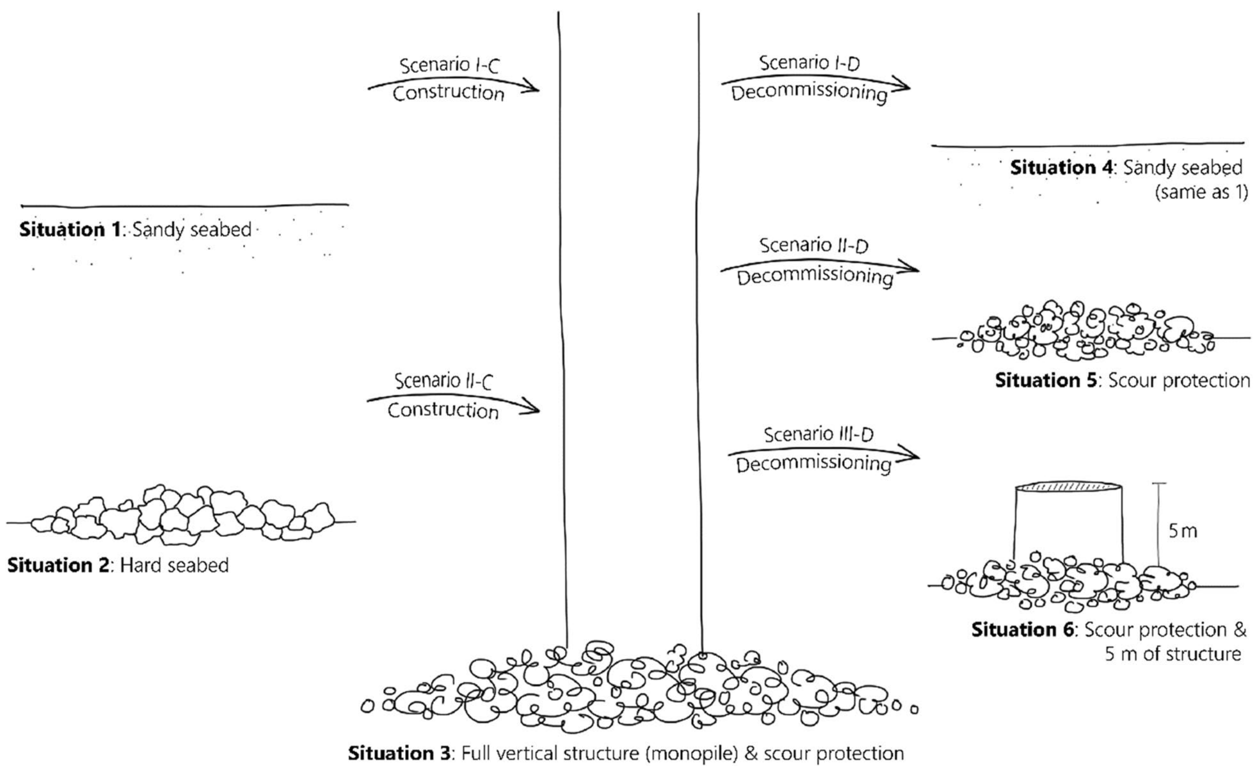

Fig. 1 Construction and decommissioning scenarios. Exemplified for a monopile structure, but the principle can be adapted to other foundation types. The foundation structure includes a vertical part (in this example the monopile), oftentimes constructed of steel. Additionally, it includes scour protection of materials like stones or concrete boulders. The construction scenarios of this study consider construction on a sandy seabed (I-C) or a hard substrate seabed (II-C). The decommissioning scenarios include removing everything, leaving a sandy seabed (I-D), leaving the scour protection (II-D), or leaving the scour protection and 5 m of the vertical structure (III-D)

scenarios for decommissioning, including variations in how much of the wind turbine foundations and the scour protection is removed. Scour protection refers to materials like rocks or concrete placed around the turbine foundation to prevent seabed erosion and maintain the foundation's integrity against currents and waves (Whitehouse et al. 2011). The scenarios for the habitat changes occurring in relation to decommissioning scenarios are as described by Spielmann et al. (2023): (I-D) The scour protection is removed, and the foundations are cut 1 m below the seabed, leaving no artificial hard substrates above the seafloor. This alternative reflects the general decommissioning requirements, e.g., in Germany (Spielmann et al. 2023). (II-D) The scour protection is left in situ, and the structure is cut 1 m below the seabed. This scenario reflects decommissioning considerations as implemented in the UK (Britton 2013; Drew 2011). (III-D) The scour protection is left in situ, and the foundations are cut 5 m above the seabed. Scenario III-D has not been practiced in the North Sea and is merely included as an academic exercise to investigate the potential effects of leaving parts of the foundation and the scour protection in place. The scenarios described for construction and decommissioning pertain solely to the turbine structures. To assess the impacts of habitat changes throughout the entire lifetime of an OWF, a construction scenario (I-C or II-C) can be combined with a decommissioning scenario (I-D, II-D, or III-D). The seabed habitat between the turbines within the OWF will either remain unchanged or be transformed from hard substrates to sandy seabed. The richness of sandy and hard seabed within the wind farm is considered comparable to the richness of the reference sites.

This study does not consider different removal technologies but merely investigates the impacts of changing habitat substrates. Furthermore, the study does not consider other partial decommissioning alternatives like "topping" (the upper section of the structure is removed and deployed on the seabed), "toppling" (laying down the structure on the seafloor), or "tow-and-place" (the entire structure is removed and deployed on the seabed somewhere else) (Claisse et al. 2015; Fowler et al. 2018), as these are deemed unlikely for the North Sea under the current policies (OSPAR Commission 1998; Spielmann et al. 2023).

2.2 Data collection and processing

This study used the "Biodiversity Information System of benthic species at ARtificial structures" (BISAR) dataset (Dannheim et al. 2025). BISAR contains data on benthic macrofauna collected in environmental impact studies, scientific projects, and species inventories conducted in the North Sea between 2003 and 2019. The dataset includes data collected from 17 artificial offshore structures, including seven OWFs, nine oil and gas platforms, and one research platform, including a total of 3864 samples and 890 species. The offshore structures were mainly located on sandy substrates (11 structures), some on coarse substrates (5 structures), and one oil/gas platform on muddy sand. Specifications on the habitat types surrounding the structures can be found in the Supplementary Information 1 (SI1). Furthermore, BISAR contains samples from two sandy seabed sites (sandy seabed reference) and one geogenic reef (hard substrate reference). As the database is a compilation of several individual datasets, aspects such as the sampling approaches (applied devices and methods), time of sampling (age of structure age, season, number of samples), and data gathering and storage are not identical for all samples in BISAR. Samples were collected on the offshore structure foundations by scraping off the organisms attached to the structure within a frame of 0.04 to 0.0625 m^2, varying between structure sites. Scour protection and the geogenic reef were sampled by scraping or collecting stones. The sandy seabed was sampled using Van Veen grabs or a box corer, which captures a seabed sample by penetrating the sediment and collecting the natural stratification. The samples were conserved in ethanol or borax-buffered formalin and brought to a laboratory, where all specimens were identified to the lowest possible taxonomic level, often to species level.

The response variable in the focus of this study is species richness, which is used as an indicator of biodiversity. For each sample, species richness was calculated as the number of unique instances of AphiaIDs across all taxonomic levels in the sample. The AphiaID is a unique identifier assigned to each taxon in the World Register of Marine Species (WoRMS) (HoRton et al. 2021) and helps track marine species names and ensure consistency in species data management (Vandepitte et al. 2015). BISAR includes information on location, installation date of the structure, foundation type (gravity, monopile, jacket, or tripod), sampling date, sampling technique, sampling depth, area sampled, species identified (AphiaID), and number of individuals identified. These parameters will hereinafter be referred to as "potential explanatory variables." In this study, additional "potential explanatory variables" were added: distance to the seabed was calculated based on water depth and sampling depth, and distance from the coast was calculated based on the location, using the "dist2coast" package for R (Kaiser 2022); structure age was calculated based on the installation date and sampling date. The additional variables were added based on Spielmann et al. (2023), who indicate their relevance for the species richness. All data processing was carried out using the software R version 4.3.2.

The samples from OWFs were taken at structure ages between 1 and 11 years, at oil and gas platforms between

2 and 43 years, and at the research platform between 1 and 4 years. To cover both construction and decommissioning, the database should span over the longest structure lifetime possible. As the structures of OWFs are similar to oil and gas platforms regarding structural design, the habitats provided by OWF structures are largely comparable to those offered by oil and gas platforms (Lemasson et al. 2022; Stranddorf et al. 2024). Therefore, data from all structure types were pooled. We used data from 1 to 25 years, as data from older structures were very scarce, reducing the total sample size from 3,864 to 3,555. The correlation between species richness and each potential explanatory variable was explored through visual investigations (scatter plots with fitted curves and boxplots) and correlation assessments (SI1) to identify which parameters influence species richness. We also investigated if the composition of species in different taxonomic groups changed with the sampling depth and the structure type. Structure age was identified as the only parameter strongly correlating with the richness on the structure.

2.3 Taxonomic groups and alien species

The taxa identified in the BISAR database were grouped based on their phylum. However, to have a large enough database for further development of species richness models, only phyla with 15 or more species were considered in this study. An overview of the number of species identified within all phylum groups can be found in SI1. In total, eight taxonomic groups (based on phylum) had a sufficient size (Table 1). Furthermore, this study investigates the change in the presence of alien species, as the occurrence of alien species is used as an indicator of invasion risk. We did this by comparing the BISAR species to the list of alien species in the North Sea from the MarINvaders Toolkit (Lonka et al. 2021; Verones et al. 2023). The list was extracted from MarINvaders on the 1 st of October 2024. The MarINvaders Toolkit integrates data on marine (alien) species from four existing databases: Ocean Biodiversity Information System (OBIS 2025), The World Register of Marine Species (WoRMS) (HoRton et al. 2021), Global Invasive Species Database (GISD 2025), and NatCon (Molnar et al. 2008). The OBIS database is used to identify if there is an occurrence of the respective species in the selected ecoregion (in this study, the North Sea), and each species is then searched for in the latter three databases to potentially identify as alien. In total, 41 alien species appeared in the BISAR database (see list in SI1).

2.4 Species richness models

To enable the development of CFs expressing the impacts on species from the changes in habitat substrates associated with construction and decommissioning, models expressing the change in species present on the structure and in the seabed are needed. For the development of species richness models, the data was divided into five datasets, reflecting different habitat situations as represented in Fig. 1: Situations 1 and 4, samples from sandy seabed outside of the wind farms (669 samples); Situation 2, samples from the geogenic reef (11 samples); Situation 3, samples from the full artificial structure, meaning the vertical structure and scour protection (1,667 samples); Situation 5, samples from the scour protection and the bottom five meters of the structure (736); and Situation 6, samples from the scour protection (587 samples). For each dataset, richness models were formulated for the total species richness, alien species, and for each taxonomic group separately. Situations 1 and 2 represent baselines where artificial structures are not present and are also used to represent the seabed between the turbines within the OWF. The data used to represent Situations 1 and 4 are the same, as it is assumed that if all OWF components are removed, the area will be (re)turned to a sandy seabed uninfluenced by artificial structures. It should be noted that the sample size of the dataset representing Situation 2 is considerably smaller than the other datasets, and its statistical power is considered low (power = 0.52, compared to Situation 1). The sampling procedures are different for sampling sandy and hard bottom seabed, and hard bottom sampling is generally considered more technically difficult, which may influence the data grounds for this habitat type (Coolen et al. 2022; MichaeLis et al. 2019). The results of the scenario considering construction on a hard substrate seabed should, therefore, be

Table 1 Taxonomic groups considered in this study, grouped based on phylum. The number of species identified in the dataset (n) per taxonomic group is indicated in brackets

Phylum	Species groups
Porifera ($n = 15$)	Sponges
Cnidaria ($n = 89$)	Sea anemones, corals, sea firs, and jellyfish
Annelida ($n = 226$)	Segmented worms
Mollusca ($n = 172$)	Snails, slugs, mussels, oysters, cockles, clams, and squid
Arthropoda ($n = 243$)	Crustaceans and sea spiders
Bryozoa ($n = 52$)	Sea mats, horn wreck, and lace corals
Echinodermata ($n = 30$)	Starfish, brittle stars, sea urchins, and sea cucumbers
Chordata ($n = 15$)	Sea squirts, fish, lancelets, and mammals

interpreted bearing this in mind. The statistical power of all datasets can be found in SI1.

The richness of species group g in Situation 1 or 2 (sandy or hard seabed) and within the seabed of the OWF ($R_{sb,x,g}$) is defined as the mean richness across all samples from seabed type x, and where n is the number of samples from the considered seabed type (Eq. 1). The richness of species group g on the full artificial structure (Situation 3), including the vertical structure and scour protection ($R_{\mathrm{full,g}}(t)$) is formulated as a second-degree polynomial model fitted to the richness of each species group g in year t (Eq. 2). $\beta_{0,\mathrm{full,g}}$, $\beta_{1,\mathrm{full,g}}$, and $\beta_{2,\mathrm{full,g}}$ are the model parameters that define the polynomial relationship. The richness of species group g in the new habitat following the decommissioning a structure with age t ($R_{\mathrm{decom,g}}(t)$) is formulated differently depending to the chosen decommissioning scenario (Eq. 3). In the case of partial removal (Situation 5 or 6), it is formulated as a second-degree polynomial model fitted to the richness of each species group g in year t for the given partial removal scenario p (leaving scour protection or leaving scour and 5 m of the foundation). $\beta_{0,\mathrm{p,g}}$, $\beta_{1,\mathrm{p,g}}$, and $\beta_{2,\mathrm{p,g}}$ are the model parameters that define the polynomial relationship. In case of complete removal (Situation 4), it is equal to the richness on a sandy seabed type, $R_{\mathrm{sb,sandy,g}}$ (Eq. 1). The unit of richness is *species/turbine* or *species/OWF seabed*, depending on whether the assessment covers the habitat changes related to the turbine structures or the seabed in between the structures.

$$R_{\mathrm{sb,x,g}} = \frac{\sum_{i=1}^{n} R_{i,\mathrm{x,g}}}{n} \left[\frac{\mathrm{species}}{\mathrm{turbine}} \mathrm{or} \frac{\mathrm{species}}{\mathrm{OWF\ seabed}} \right] \tag{1}$$

$$R_{\mathrm{full,g}}(t) = \beta_{0,\mathrm{full,g}} + \beta_{1,\mathrm{full,g}} \bullet t + \beta_{2,\mathrm{full,g}} \bullet t^2, t \in [1:25] \left[\frac{\mathrm{species}}{\mathrm{turbine}} \right] \tag{2}$$

$$R_{decomm,\mathrm{g}}(t) = \begin{cases} \beta_{0,p,\mathrm{g}} + \beta_{1,p,\mathrm{g}} \bullet t + \beta_{2,p,\mathrm{g}} \bullet t^2, t \in [1:25] \\ R_{sb,sandy,g'} \quad (for\ complete\ removal) \end{cases} \left[\frac{\mathrm{species}}{\mathrm{turbine}} \right] \tag{3}$$

The richness models for scour protection and for scour protection + 5 m of the foundation ($R_{\mathrm{decom,t,g}}$) were constrained never to exceed the richness of the full structure. Additionally, the richness is constrained to never go below 0. The constraints were modeled using constrained optimization in the software R, utilizing the constrOptim function. The constraints apply to the total richness, the richness of aliens, and the richness within each taxonomic group.

2.5 Development of characterization factors (CFs)

The Potentially Disappeared Fraction of species (PDF) within species group g due to habitat changes related to the turbine (*tb*) structures is expressed for the construction (Eq. 4), decommissioning (Eq. 5), and the whole lifetime (Eq. 6) for a turbine structure with a lifetime of t years. For construction impacts, the reference state of richness is the richness on the seabed that was there before construction ($R_{\mathrm{sb,x,g}}$). For decommissioning, the reference state of richness is the richness on the full structure at the time of decommissioning ($R_{\mathrm{full,g}}(t_1)$). The new state in relation to construction is the richness on the full structure ($R_{\mathrm{full,g}}(t)$). The new state in relation to decommissioning ($R_{\mathrm{decom,g}}(t)$) is the richness of either the scour protection and the bottom 5 m of the water column structure, the scour protection alone, or the sandy seabed. The lifetime impacts are calculated as the sum of the impacts from the construction and the impacts from decommissioning using the richness in the seabed prior to construction as the reference state. The impacts of habitat changes occurring within the seabed of the OWF ($PDF_{\mathrm{OWFsb,s,g}}(t)$) are expressed for each species group g in Eq. 7. Here, s represents the considered life cycle stage(s) (construction, decommissioning, or lifetime), the terms *pre* and *post* refer to the seabed before and after the considered life cycle stage, and t is the considered time. For impacts of habitat changes in the seabed related to construction and lifetime, t_0–t_1 refers to the lifespan of the structure. For impacts of habitat changes related to decommissioning and lifetime, t_1–t_2 pertains to the time considered after the structure has been decommissioned.

$$PDF_{\mathrm{tb},construction,\mathrm{g}}(t) = \int_{t_0}^{t_1} \frac{R_{sb,x,\mathrm{g}} - R_{full,\mathrm{g}}(t)}{R_{sb,x,\mathrm{g}}} dt \left[\frac{\mathrm{PDF.year}}{\mathrm{turbine}} \right] \tag{4}$$

$$PDF_{\mathrm{tb,decommissioning,g}}(t) = \int_{t_1}^{t_2} \frac{R_{\mathrm{full,g}}(t_1) - R_{\mathrm{decom,g}}(t)}{R_{\mathrm{full,g}}(t_1)} dt \left[\frac{\mathrm{PDF.year}}{\mathrm{turbine}} \right] \tag{5}$$

$$PDF_{\mathrm{tb},lifetime,\mathrm{g}}(t) = \int_{t_0}^{t_1} \frac{R_{sb,x,\mathrm{g}} - R_{full,t,\mathrm{g}}(t)}{R_{sb,x,\mathrm{g}}} dt + \int_{t_1}^{t_2} \frac{R_{sb,x,\mathrm{g}} - R_{\mathrm{decom},t,\mathrm{g}}(t)}{R_{\mathrm{sb,x,g}}} dt \left[\frac{\mathrm{PDF.year}}{\mathrm{turbine}} \right] \tag{6}$$

$$PDF_{OWFsb,s,\mathrm{g}}(t) = \frac{R_{sb,pre,g} - R_{sb,post,g}}{R_{sb,pre,g}} dt \left[\frac{\mathrm{PDF.year}}{OWF\ seabed} \right] \tag{7}$$

The proposed factors express the local Potentially Disappeared Fraction of species (PDF) at the new state compared to the original state, integrated over the considered timeframe (PDF.year). The integration over time expresses that the species may locally disappear within the considered timeframe but may return when the structure no longer occupies the area. The modeling of the factors for PDF is conceptually illustrated in Fig. 2, where t_0 expresses the time of construction, t_1 is the time of decommissioning, and t_2 is the considered time after decommissioning. In the period after construction and until decommissioning, the species richness may increase or decrease, depending on the taxonomic group. After decommissioning, the level of richness is assumed to be stable, as data and studies proving other developments in richness are lacking.

Since every turbine foundation within an OWF is commonly constructed in the same way, the richness is expected to be the same on all foundations in the OWF. Importantly, the sum of the impacts from construction and decommissioning will not equal the lifetime impacts, as they do not apply the same reference state to represent the original state of richness (the denominator). Therefore, Eqs. 4 and 5 can only be used to zoom in on a specific lifecycle stage, whereas Eq. 6 can be used to assess the biodiversity impacts from the local habitat changes associated with the entire structure lifecycle.

Based on the factors for PDF, we developed Characterization Factors (CFs) expressing the PDF for the entire OWF, considering both the impacts from habitat changes associated with the turbine structures ($PDF_{\text{tb,s,g}}(t)$) and the seabed within the OWF ($PDF_{\text{OWFsb,s,g}}(t)$) (Eq. 8). s represents the considered life cycle stage(s) (construction, decommissioning, or lifetime) and g is the considered species group. n_{tb} is the number of turbines within the assessed OWF, A_{tb} is the area of the footprint of one turbine, including foundation and scour protection, A_{sb} is the area of the seabed within the OWF, and A_{OWF} is the area of the whole OWF, including turbine and seabed.

$$CF_{\text{OWF,s,g}}(t) = \frac{PDF_{\text{tb,s,g}}(t) \bullet n_{\text{tb}} \bullet A_{\text{tb}} + PDF_{\text{OWFsb,s,g}}(t) \bullet A_{\text{sb}}}{A_{\text{OWF}}} \left[\frac{\text{PDF.year}}{\text{OWF}}\right] \quad (8)$$

The relative impacts ($CF_{\text{OWF,s,g}}(t)$ expressed in $\frac{\text{PDF.year}}{OWF}$) can be converted to absolute impacts ($\frac{\text{species.year}}{OWF}$), which will make the impacts compatible with the metric used in, e.g., the LCIA method ReCiPe (Huijbregts et al. 2016). The absolute impacts on species richness within each species group g associated with the life cycle stage(s) s (construction, decommissioning, or lifetime) can be calculated using Eq. 9. R_{orig} is the original state of richness, i.e., $R_{\text{sb,pre,g}}$ for habitat changes associated with construction and lifetime, and $R_{\text{full,t,g}}$ for habitat changes related to decommissioning.

$$CF_{\text{species,OWF,s,g}}(t) = R_{\text{orig}} \bullet CF_{\text{OWF,s,g}}(t) \left[\frac{\text{species.year}}{\text{OWF}}\right] \quad (9)$$

3 Results

3.1 Species richness models

From the correlation assessments (Sect. 2.2. and SI1), we found that the total species richness on the vertical structure and on the scour protection is only clearly correlated with the structure's age. Furthermore, we did not find a relationship between the composition of species in different taxonomic groups and the sampling depth and structure type. Therefore, we consider the species composition to spread evenly along the structure depth and to be equal on different structure types. As we did not find a relation between the

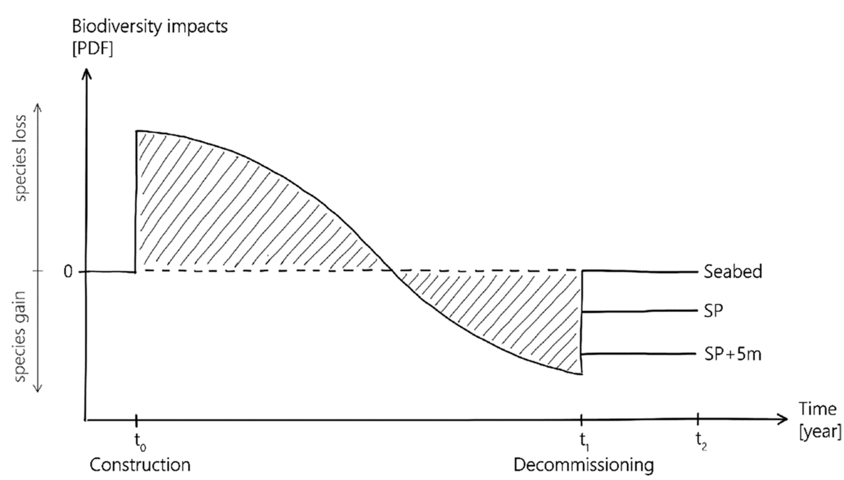

Fig. 2 Conceptual illustration of the PDF modeling. *Y*-axis: the Potentially Disappeared Fraction of species (PDF), and *x*-axis: time in years. t_0 is the time immediately following the completion of construction, t_1 is the time of decommissioning, and t_2 is the considered time after decommissioning. A positive PDF means a loss of species, and a negative PDF means an increase of species

area sampled and the number of species present, we consider the richness to be independent of the sampling area. Therefore, the richness models for the different taxonomic groups were expressed as a function of the structure's age.

Species richness models were formulated independently for each species group (total richness, alien species, and the eight taxonomic groups). Thus, the models for taxonomic groups should primarily be used to indicate the richness development within the specific taxonomic group over the structural age and how the richness of different taxonomic groups relates to each other. Summarizing the richness across all taxonomic groups will not necessarily equal the total richness, and thus, the total richness should be calculated using the model for total richness.

3.1.1 Species richness on the structure

The species richness present on the full structure can be expressed using Eq. 2, and the model parameters $\beta_{0,\text{full},g}$, $\beta_{1,\text{full},g}$, and $\beta_{2,\text{full},g}$ are presented in Table 2 under the header "Full structure." The species richness on the scour protection and on scour protection + 5 m can be expressed using Eq. 3. The model parameters $\beta_{0,p,g}$, $\beta_{1,p,g}$, and $\beta_{2,p,g}$ (p = scour protection or p = scour and 5 m of the foundation) are presented in Table 2 under the headers "Scour protection" and "Scour protection + 5 m." The rows of the table present the model parameters for each species group, g.

Model statistics can be found in SI1. β_0 parameters express the intercept, meaning the richness when the structure age t = 0. For Annelida, the intercept is < 0, which was accounted for in the CF development by setting all values below 0 to 0. β_1 parameters represent the linear coefficient, determining the direction and steepness of the slope at t = 0. β_2 parameters express the quadratic coefficient, indicating if the relationship is U-shaped (β_2>0) or inverted U-shaped (β_2<0).

Table 3 Average richness at the two considered seabed types (sandy or hard), output from Eq. 1. The brackets indicate 95% confidence intervals

Species group (g)	Sandy seabed	Hard seabed
Total richness	30.0 [27.5–32.6]	16.1 [6.42–25.8]
Porifera	0	0.0909 [−0.112–0.293]
Cnidaria	2.15 [1.68–2.61]	4.36 [2.50–6.22]
Annelida	22.3 [19.2–25.4]	1.82 [0.262–3.37]
Mollusca	6.81 [5.75–7.88]	1.27[−0.348–2.89]
Arthropoda	6.63 [6.04–7.21]	4.73 [1.20–8.26]
Bryozoa	0.274 [0.195–0.353]	1.91 [1.15–2.67]
Echinodermata	2.51 [2.13–2.88]	0.273 [−0.162–0.707]
Chordata	0.0213 [0.00562–0.0371]	0.818 [0.231–1.41]
Aliens	0.210 [0.162–0.259]	2.45 [1.44–3.47]

3.1.2 Richness on seabed types

The species richness ($R_{\text{sb},x,g}$) of species group g in seabed type x (sandy or hard) was calculated as the mean across all samples using Eq. 1. The results are listed in Table 3, and the 95% confidence intervals are given in brackets. The seabed richness represents the richness in the reference state of marine habitats in the North Sea, where artificial structures are not present. Additionally, it represents the seabed within the OWF where no turbine structures are placed. The mean richness is about twice as high in the sandy seabed compared to the hard seabed, which is mainly due to a high presence of species in the taxonomic group *Annelida*. The sandy seabed also has a higher richness of *Mollusca*, *Arthropoda*, and *Echinodermata*. *Cnidaria*, *Arthropoda*, and *Bryozoa* dominate the hard seabed, and the presence of alien species is about 12.5 times higher in the hard seabed compared to the sandy seabed.

Table 2 Model parameters for the polynomial models for richness on the structural sections

Species group (g)	Full structure			Scour protection			Scour protection + 5 m		
	β_0	β_1	β_2	β_0	β_1	β_2	β_0	β_1	β_2
Total richness	7.9×10^{0}	2.1×10^{0}	-3.4×10^{-2}	5.6×10^{0}	2.4×10^{0}	-4.0×10^{-2}	5.3×10^{0}	2.4×10^{0}	-4.1×10^{-2}
Porifera	2.0×10^{-1}	2.8×10^{-2}	-1.3×10^{-3}	1.3×10^{-1}	-8.3×10^{-3}	3.0×10^{-4}	2.0×10^{-1}	-1.7×10^{-2}	5.5×10^{-4}
Cnidaria	1.2×10^{0}	3.9×10^{-1}	-1.0×10^{-2}	6.4×10^{-1}	4.5×10^{-1}	-1.2×10^{-2}	6.0×10^{-1}	4.5×10^{-1}	-1.2×10^{-2}
Annelida	-7.0×10^{-1}	1.1×10^{0}	-3.2×10^{-2}	-2.0×10^{0}	1.2×10^{0}	-3.2×10^{-2}	-2.0×10^{0}	1.2×10^{0}	-3.2×10^{-2}
Mollusca	1.4×10^{0}	3.8×10^{-1}	-9.0×10^{-3}	1.3×10^{0}	3.4×10^{-1}	-8.1×10^{-3}	1.1×10^{0}	3.1×10^{-1}	-7.3×10^{-3}
Arthropoda	3.2×10^{0}	6.5×10^{-1}	-7.8×10^{-3}	1.7×10^{0}	7.2×10^{-1}	-7.8×10^{-3}	1.6×10^{0}	7.2×10^{-1}	-8.0×10^{-3}
Bryozoa	1.0×10^{0}	1.0×10^{-1}	-5.5×10^{-4}	1.0×10^{0}	1.1×10^{-1}	-6.8×10^{-4}	1.0×10^{0}	1.1×10^{-1}	-8.3×10^{-4}
Echinodermata	7.9×10^{-1}	1.1×10^{-1}	-2.7×10^{-3}	6.3×10^{-1}	8.9×10^{-2}	-1.4×10^{-3}	6.3×10^{-1}	8.9×10^{-2}	-1.4×10^{-3}
Chordata	2.6×10^{-1}	1.6×10^{-2}	-5.6×10^{-4}	1.4×10^{-1}	-1.7×10^{-2}	1.1×10^{-3}	1.3×10^{-1}	-1.3×10^{-2}	7.9×10^{-4}
Aliens	2.5×10^{0}	2.6×10^{-1}	-9.5×10^{-3}	2.2×10^{0}	2.9×10^{-1}	-1.0×10^{-2}	2.1×10^{0}	2.8×10^{-1}	-1.0×10^{-2}

3.2 Characterization factors

We developed CFs for the relative impacts (PDF.year/OWF) on the total species richness, the richness of alien species, and the richness within each taxonomic group (Table 1) from habitat changes associated with construction, decommissioning, and the lifetime of an OWF with a lifetime of 1–25 years (Eq. 8). Additionally, we presented a method to convert the relative impacts to absolute impacts (species.year/OWF) (Eq. 9). In Sect. 3.2.1., we present an example of relative impacts (PDF.year) for an OWF with a lifetime of 25 years, as this is expected to be the standard lifetime for OWFs. For the decommissioning and lifetime impacts, we consider 1 year after the decommissioning (t_2 in Eqs. 5 and 6). The relative and absolute CFs for each species group at each lifetime can be found in SI2, together with CFs of the decommissioning and lifetime impacts considering a longer period (25 years) after decommissioning. SI2 also presents an interactive tool where impacts are provided based on wind farm specific information (age of decommissioning, number of turbines, and area of the turbines and the whole OWF).

For some taxonomic groups, it was not possible to calculate CFs. This applies to the taxonomic group *Porifera* in scenarios where the pre-construction state was sandy seabed (sandy seabed reference), as no *Porifera* are present in samples from the sandy seabed, and thus $R_{\mathrm{sd,sandy,g}}$ in Eqs. 4 and 6 will be 0. In PDF modeling, only species groups that are present in the reference site are considered in the impact modeling (Kuipers et al. 2025). It also applies to the lifetime impacts of all taxonomic groups going from sandy seabed (pre-construction) to sandy seabed (post-decommissioning), as the model assumes that the state after decommissioning will be the exact same as before construction.

The CFs are given in the unit PDF.year or species.year per OWF. Thus, positive numbers indicate a potential decrease in species, while negative numbers indicate a potential increase in species during the considered period. The composition of species present in the reference seabed may be very different from the species composition on the structural parts, resulting in very large increases/decreases within some taxonomic groups. Furthermore, our CFs express the impacts integrated over time, while many other CFs express the impacts per year.

3.2.1 Relative impacts for and OWF with a lifetime of 25 years

To apply the developed CFs, inventory information regarding the OWF age at the time of decommissioning (t), number of turbines (n_{tb}), footprint area per turbine structure (A_{tb}), and the total area of the OWF (A_{OWF}) needs to be provided. In this example, we present the relative impacts (PDF.year) for an OWF with the following inventory: $t = 25$ years, $n_{\mathrm{tb}} = 80$ turbines, $A_{\mathrm{tb}} = 707\ \mathrm{m}^2$ (diameter of circular footprint: 30 m), and $A_{\mathrm{OWF}} = 20\ \mathrm{km}^2$. The seabed between the turbines within the OWF is considered to be maintained as the seabed type on the site prior to construction. For interpretation of the results, it is important to note that the impacts from habitat changes related to construction and decommissioning apply different reference states (richness in seabed before construction and richness on the full structure at decommissioning age, respectively) and are, therefore, not directly additive. To assess the impacts of habitat changes throughout the entire lifetime of the OWF, the lifetime impacts should be considered, as this applies the same reference richness for both construction and decommissioning impacts (the richness in seabed prior to construction).

The relative impacts for the OWF assessed in this example (Table 4 and Fig. 3) indicate that the habitat change associated with construction will cause a relative net loss in the total number of species if the initial seabed is sandy. This is especially due to *Annelida* species, which are highly present in the sandy seabed (on average 22 *Annelida* species) and only to a small extent on the structure (varying from 0 to 9 species during the structure lifetime). The habitat changes from constructing the OWF on a sandy seabed will also cause a net loss of *Mollusca* and *Echinodermata* species. The fraction of *Cnidaria*, *Arthropoda*, *Bryozoa*, and *Chordata* species will increase as a result of construction on a sandy seabed. Especially the fraction of *Bryozoa* and *Chordata* will increase largely as their presence in the sandy seabed is low (an average of 0.27 and 0.021 species, respectively) compared to their presence on the structure (*Bryozoa* 1.2–3.3, and *Chordata* 0.3–0.4 during the structure lifetime). If the initial seabed is hard, the construction will cause an increase in the total number of species present over the 25 years of operation. The fraction of species in six out of eight taxonomic groups will increase (*Porifera*, *Annelida*, *Mollusca*, *Arthropoda*, *Bryozoa*, and *Echinodermata*) while only two groups will decrease (*Cnidaria* and *Chordata*).

All decommissioning scenarios result in a net loss in the total number of species, but the impacts of decommissioning are generally small compared to the impacts of construction. This is largely because the decommissioning impacts in this example are only integrated over 1 year, while the construction impacts are integrated over a timeframe of 25 years. The impacts from partial removal are very small, thus leaving either the scour protection or the scour protection + 5 m of the foundation will maintain roughly the same richness as on the full structure. If the structure is completely removed, the loss in the total number of species will be larger, but increases are also observed for *Annelida*, *Mollusca*, and *Echinodermata*. As the impacts from habitat changes associated with decommissioning are small compared to the impacts from habitat changes related to construction, the lifetime impacts are close to the same as the construction impacts.

Table 4 Relative impacts for an OWF with a lifetime of 25 years (t), 80 turbines (n_{tb}), 707 m^2 turbine footprint (A_{tb}), and OWF area of 20 km^2 (A_{OWF}). The impacts are given in the unit PDF.year/OWF. PDF indicates a Potentially Disappeared Fraction of species; thus, positive numbers indicate a potential decrease in the number of species, while negative numbers indicate a potential increase in the number of species. NA indicates that CFs were not possible to calculate. Abbreviations: *Sandy*, sandy seabed; *Hard*, hard seabed; Full, full structure; *SP*, scour protection

Species group (g)	Construction		Decommissioning 1 yr after decommissioning			Lifetime 1 yr after decommissioning				
	Sandy to full	Hard to full	Full to SP + 5m	Full to SP	Full to sandy	Sandy to SP + 5m	Sandy to SP	Hard to SP + 5m	Hard to SP	Hard to sandy
Total richness	6.2×10^{-3}	-5.0×10^{-2}	1.0×10^{-5}	2.2×10^{-5}	7.0×10^{-4}	5.3×10^{-3}	1.4×10^{-3}	-5.4×10^{-2}	-5.4×10^{-2}	-5.2×10^{-2}
Porifera	NA	-1.4×10^{-1}	6.2×10^{-12}	8.7×10^{-12}	2.8×10^{-3}	NA	NA	-1.5×10^{-1}	-1.5×10^{-1}	-1.5×10^{-1}
Cnidaria	-6.1×10^{-2}	6.0×10^{-3}	2.5×10^{-5}	3.3×10^{-5}	1.5×10^{-3}	-6.4×10^{-2}	-6.4×10^{-2}	5.8×10^{-3}	5.9×10^{-3}	7.4×10^{-3}
Annelida	5.0×10^{-2}	-1.8×10^{-1}	2.6×10^{-12}	2.6×10^{-12}	-6.1×10^{-3}	5.2×10^{-2}	5.2×10^{-2}	-1.9×10^{-1}	-1.9×10^{-1}	-2.1×10^{-1}
Mollusca	2.7×10^{-2}	-1.6×10^{-1}	2.8×10^{-4}	5.4×10^{-4}	-8.9×10^{-4}	2.8×10^{-2}	2.8×10^{-2}	-1.7×10^{-1}	-1.7×10^{-1}	-1.8×10^{-1}
Arthropoda	-3.3×10^{-2}	-7.5×10^{-2}	1.5×10^{-13}	2.6×10^{-8}	1.6×10^{-3}	-3.7×10^{-2}	-3.7×10^{-2}	-8.1×10^{-2}	-8.1×10^{-2}	-7.6×10^{-2}
Bryozoa	-5.0×10^{-1}	-1.1×10^{-2}	2.3×10^{-5}	5.2×10^{-5}	2.6×10^{-3}	-5.3×10^{-1}	-5.3×10^{-1}	-1.3×10^{-2}	-1.3×10^{-2}	-9.0×10^{-2}
Echinodermata	2.4×10^{-2}	-3.6×10^{-1}	1.1×10^{-10}	3.8×10^{-10}	-7.7×10^{-4}	2.5×10^{-2}	2.5×10^{-2}	-3.8×10^{-1}	-3.8×10^{-1}	-3.8×10^{-1}
Chordata	-1.1×10^{0}	4.1×10^{-2}	4.7×10^{-13}	3.2×10^{-12}	2.6×10^{-3}	-1.1×10^{0}	-1.1×10^{0}	4.3×10^{-2}	4.3×10^{-2}	1.1×10^{-2}
Aliens	-1.2×10^{0}	-3.6×10^{-2}	2.6×10^{-5}	2.6×10^{-5}	2.6×10^{-3}	-1.2×10^{0}	-1.2×10^{0}	-3.6×10^{-2}	-3.6×10^{-2}	-3.3×10^{-2}

In LCA, an increase in species is generally considered positive. However, as opposed to the other species, an increase in alien species cannot be considered positive as they may pose a risk to the native species and the ecosystem's functionality. The alien species should, therefore, be considered separately (Fig. 4). The construction of the OWF structures on a sandy seabed is associated with a potential increase in PDF over the considered 25 years of lifetime of − 1.2 PDF.year/OWF. This is the largest relative impact among all species groups and all construction and decommissioning scenarios. As the presence of alien species on the reference hard seabed is higher than on the sandy seabed, the relative impacts of constructing on a hard seabed are much smaller (−0.036 PDF.year). As for the other species groups, the impacts from decommissioning are very small compared to the impacts from construction ($2.6 \times 10^{-5} - 2.6 \times 10^{-3}$ PDF.year), and the two partial removal scenarios show that they will maintain roughly the same richness of alien species as on the full structure.

4 Discussion

4.1 CF application

To our knowledge, this study is the first to develop CFs for the benthic biodiversity impacts of the marine habitat changes associated with OWF construction and decommissioning in the North Sea. The developed CFs enable quantifying impacts and benefits on biodiversity expressed as potential loss or gain of species integrated over time. The developed CFs contribute to a better understanding of biodiversity impacts and a better representation of biodiversity in LCA. We applied the unit PDF.year, which is the applied and recommended unit of other LCIA frameworks, e.g., LC-IMPACT (Verones et al. 2020) and GLAM (UNEP 2019). We also enabled the impacts to be expressed in the unit species.year, which is the applied unit of the LCIA method ReCiPe 2016 (Huijbregts et al. 2016). Our CFs are therefore applicable in LCA and can be compared to other CFs expressing impacts on biodiversity as PDF.year or species.year.

The CFs are intended for application in research as well as in the offshore wind industry, e.g., by OWF developers, to support decisions around the construction and decommissioning of OWFs in the North Sea. We, therefore, aim to make the needed Life Cycle Inventory (LCI) easily accessible to users. The LCI needed for application includes wind farm specific information including the OWF age at the time of decommissioning (1–25 years), number of turbines, footprint area per turbine structure, and the total area of the OWF. Additionally, the needed LCI includes the substrate type prior to construction (sandy or hard) and the expected decommissioning strategy (complete removal, leaving scour protection,

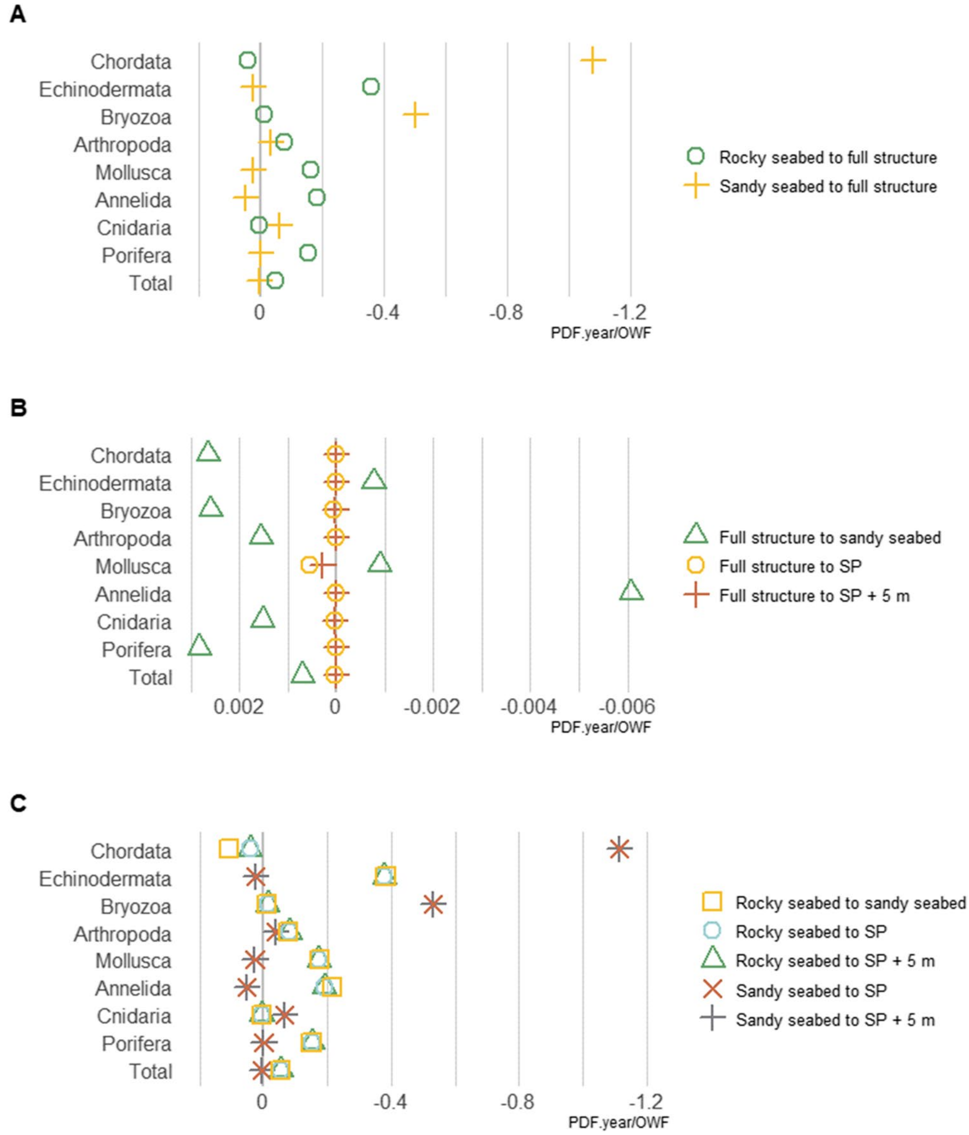

Fig. 3 Relative impacts for an OWF with a lifetime of 25 years (t), 80 turbines (n_{tb}), 707 m^2 turbine footprint (A_{tb}), and OWF area of 20 km^2 (A_{OWF}). The impacts are given in the unit PDF.year/OWF. Impacts are shown for the total richness and eight taxonomic groups from different scenarios for habitat change associated with **A** construction, **B** decommissioning, and **C** the whole lifetime of the OWF. The impacts for decommissioning and lifetime are calculated considering 1 year after decommissioning. Be aware that the scale of the x-axis differs for each of the three graphs. Unit: PDF•year per OWF. Abbreviations: SP, scour protection; PDF, Potentially Disappeared Fraction of species

or leaving scour protection + 5 m of foundation). It is essential to highlight that the CFs for construction and decommissioning should only be applied to zoom in on the impacts of each habitat change scenario. To assess the impacts of habitat changes from both construction and decommissioning, the CFs for lifetime impacts should be applied.

4.2 CF interpretation

Our richness models show that the richness in the sandy seabed is notably higher than in the hard seabed, primarily due to a high presence of species in the phylum *Annelida*. Within *Annelida*, species belonging to the taxonomic class *Polychaeta* are particularly abundant in sandy and muddy seabed types (Ager 2005; Ballerstedt 2005; MoRtimer-Jones 2007). While the hard seabed and the artificial structures host species within all eight considered phyla, the sandy seabed does not host species from the phylum *Porifera. Porifera* can grow on both hard and sandy substrates, but at locations with much turbidity, they need a hard substrate to attach to (NOAA 2024). The hard seabed is especially dominated by *Arthropoda* species, namely those belonging to the taxonomic order *Amphipoda*, which are often found on hard substrates, including both natural and artificial reefs (Sedano et al. 2020). *Amphipoda* are also highly present on the turbine structure, where the richness is very mixed between different phyla.

Similarly to Spielmann et al. (2023), our results imply that the total species richness on the man-made structure increases over time, eventually surpassing the level of richness in both the sandy and hard seabeds. When only considering the total richness of species present in the habitat, the habitat formed by OWF structures after 25 years of lifetime (total richness = 40 species) is more comparable to the

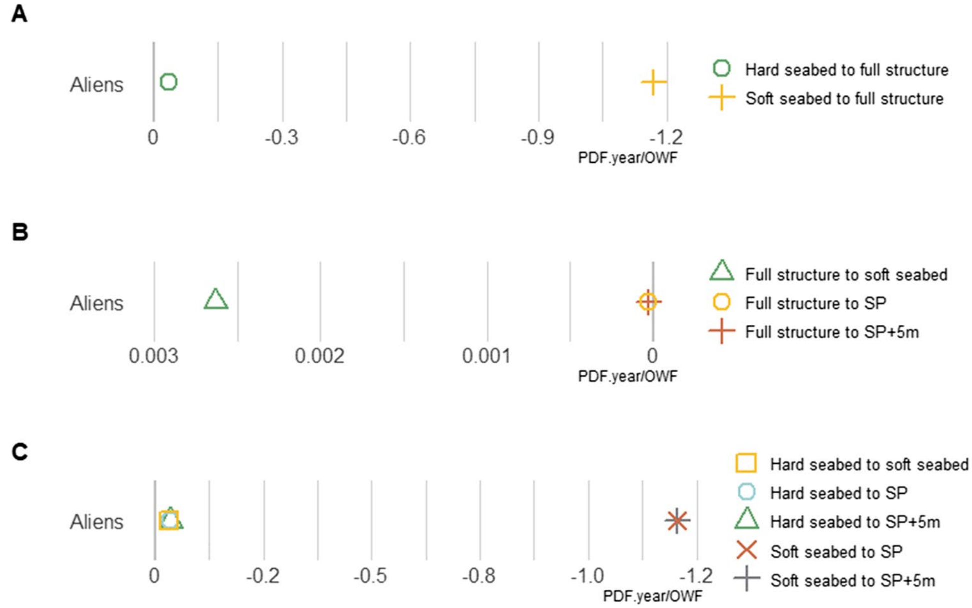

Fig. 4 Relative impacts on alien species for an OWF with a lifetime of 25 years (t), 80 turbines (n_{tb}), 707 m^2 turbine footprint (A_{tb}), and OWF area of 20 km^2 (A_{OWF}). The impacts are given in the unit PDF.year/OWF. The impacts are shown for habitat changes associated with **A** construction, **B** decommissioning, and **C** the whole lifetime of the OWF. The CFs for decommissioning and lifetime are calculated considering 1 year after decommissioning. Be aware that the scale of the x-axis differs for each of the three graphs. Unit: PDF•year per OWF. Abbreviations: SP, scour protection; PDF, potentially disappeared fraction of species

sandy seabed (total richness = 30 species) than to the hard substrate seabed (total richness = 16 species). However, considering the composition of species, the habitat formed by OWF structures after 25 years of lifetime is more comparable to a hard seabed than a sandy seabed. Additionally, the results imply that leaving the scour protection in situ when decommissioning will preserve 80–99% of the species that are present on the structure itself. However, the significance of the decommissioning impacts and the overall impacts of the habitat changes associated with OWFs should be interpreted in relation to the time-integrated impacts throughout the lifetime of the OWF.

To provide a comprehensive assessment of habitat changes associated with OWFs, our modeling framework includes both the turbine structures and the seabed within the OWF area. The seabed between turbines is assumed to remain largely undisturbed, with species richness modeled as equivalent to reference sites outside the OWF. This assumption is necessary due to the limited availability of long-term data on species richness development within the OWF seabed. The CFs are calculated based on the proportional contribution of these habitat components, considering the number of turbines (n_{tb}), the footprint area per turbine (A_{tb}), and the total OWF area (A_{OWF}). The relative impact is, therefore, strongly influenced by the density of turbines within the wind farm (n_{tb}/A_{OWF}), where a larger total OWF area relative to the number of turbines results in lower overall impacts. This framework allows for the interpretation of the impacts considering the broader habitat conditions within the OWF, as opposed to only considering the localized habitat changes around turbine structures. The time-integrated impacts on the total species richness from construction on a sandy seabed increase until year 13, after which the impacts start decreasing (see SI1 and SI2). This pattern is driven by the fact that the richness on the full turbine structure exceeds the richness of the sandy seabed after year 13. For constructions on the hard seabed, the time-integrated impacts start decreasing after year 4, when the richness on the structure exceeds the richness on the hard seabed. From year 10, the impacts of the construction on hard seabed started to be negative, meaning a total increase in species richness during the considered period. The lifetime impacts for constructions on sandy seabeds, calculated for 1 year after decommissioning, decrease after year 12 but never reach a total gain of species during a lifetime of 25 years. For a structure constructed on a hard seabed, the lifetime impacts will reach a total gain of species already after a lifetime of 9 years. If considering 25 years after decommissioning (see results of this in SI2), a total gain of species will be reached for the structure in sandy seabed, if the structure stands for at least 19 years after decommissioning, and for the structure in hard seabed, if it stands for at least 6 years after decommissioning.

As the impacts from decommissioning apply another baseline (the full structure) than the construction and lifetime impacts do (the seabed), the impacts from decommissioning cannot be directly compared to the impacts of construction and lifetime but merely be used in an isolated assessment of the decommissioning phase. The richness is assumed to be steady after decommissioning, meaning that the impacts from decommissioning will be the same every year. The time-integrated impacts of decommissioning will, therefore, develop linearly over time. This assumption has been made due to the lack of data following decommissioning, and we highly recommend future decommissioning projects to gather appropriate data on the ecological development after decommissioning.

4.3 Conservation priorities

Whether the newly established habitat can be considered positive or negative depends on what is regarded as the desired state. For many offshore structure projects, the legal requirements are that the site should be returned to its original state, i.e., the state prior to construction, when decommissioning (Schläppy et al. 2021; Watson et al. 2023). As large parts of the North Sea are covered by sandy seabed (Coolen 2017), the sandy seabed may often be interpreted as the desired state. However, studies indicate that larger areas of the North Sea have previously been covered by rock reefs (Coolen 2017; Houziaux et al. 2011; Olsen 1883) and oyster reefs (Houziaux et al. 2011; Thurstan et al. 2023), providing hard substrate habitats. But due to anthropogenic activities such as trawling (de Groot 1984; Lengkeek and Bouma 2010), oyster dredging (Bennema et al. 2020; Berghahn and Ruth 2005; Watson et al. 2006), and extraction of marine boulders as raw materials for construction on land (Kristensen et al. 2017; Støttrup et al. 2017), the hard substrate habitats have been disturbed and largely destroyed. On the grounds of this, it can be argued that compared to its natural state, the North Sea lacks hard substrates today (Coolen 2017) and that it is desired to increase the presence of hard substrates in the North Sea. The desired state should, however, be dependent on the location and should be determined prior to the construction of an OWF.

4.4 Alien species

The presence of alien species can cause changes in native species extinction probabilities, genetic composition, behavior patterns, richness and abundance, phylogenetic and taxonomic diversity, and ecosystem productivity (Blackburn et al. 2014). Thus, a high presence of alien species may pose a risk to the natural ecosystem. To enable an indication of such risks, we covered alien species in a separate species group. However, alien species are not necessarily harmful species but merely species that do not naturally occur in the considered area (Blackburn et al. 2014). The presence of alien species is thereby not necessarily problematic, but if the alien species become dominant over the native taxa, they can be considered invasive and may pose a threat to the ecosystem (Bulleri & Airoldi 2005).

Our models show that the presence of alien species on the OWF structures is much larger than in the reference hard seabed (at year 25: 1.2 times) and especially in the sandy seabed (at year 25: 14 times larger). This is comparable to the findings of Degraer et al. (2020), who explain that the vertical habitats going from the seabed and above the water surface are largely new to the open sea and offer a niche for alien species to extend their distribution and/or strengthen their population. Adams et al. (2014) indicate that the creation of hard substrates in an environment dominated by sandy mobile substrates can favor hard substrate species by creating new dispersal pathways and thereby facilitate species migrations. This is called the "stepping stone effect" and can fundamentally impact the population structure and aid passage for alien and potentially invasive species (Adams et al. 2014). An observed example of the stepping stone effect is the spread of the barnacle *Balanus perforatus*, which has spread from the south of the North Sea to the northern part of the North Sea by the connection of man-made reefs (De Mesel et al. 2015; Glasby et al. 2006). Importantly, Dauvin (2024) investigated if there are grounds for claiming that there is a greater frequency of alien invasive species in OWFs than in other marine habitat types and concluded that the evidence of such an effect still needs to be documented.

4.5 Limitations of the developed CFs

Our CFs represent species richness, which is one of many measures of biodiversity impacts. Other relevant parameters include species abundance, area or volume of habitat, biomass, or reproductivity, species functionality, which all cover different aspects of biodiversity (Li et al. 2023; Smyth et al. 2015; Woods et al. 2016). Multiple parameters should be considered to get an exact picture of an ecosystem's biodiversity level (Finkbeiner 2011). However, in LCA, it is desired to have one indicator for ecosystem quality, i.e., biodiversity impacts, to increase comparability between different assessments. However, PDF.year and species.year only cover the species richness and generally assume that an increase in richness is positive, while a decrease in richness is negative. We argue that whether an impact can be considered positive or negative is highly dependent on the composition of species and the desired habitat.

The CFs developed in this study only cover benthic species. However, studies indicate that the established artificial habitats also attract mobile species, e.g., finfish species (Bergström et al. 2013; Carey et al. 2020; Reubens et al. 2014), which use the structures as a shelter and the benthic species as a food source. Our CFs do not allow for quantification of such associated effects, but they should be considered when applying our CFs. Additionally, the offshore structures may affect the ecosystem in the surrounding areas, especially if other hard substrates are present nearby (Degraer et al. 2020; Wilhelmsson & Malm 2008). This is also not considered in our CFs.

In our study, we defined taxonomic groups based on phylum, which groups organisms based on their fundamental characteristics (Samal et al. 2019). Another approach to grouping could be based on the function the species provide to the habitat or the ecosystem. The characteristics and functions of a species may be needed, desired, or unwanted, depending on the desired state. *Sabellaria spinulosa* or *Lanice conchilega* (*Annelida*) are species with reef-building functions, as they create biogenic reefs themselves by building tubes from sand or shell fragments (Ager 2008; Jackson & Hiscock 2008). The blue mussel (*Mytilus edulis*) also possesses a reef-building function, as its shells fall off the structure and create a habitat for other organisms (Krone et al. 2013). Species in the same phylum group have similar fundamental characteristics but may hold different ecosystem functions. Similarly, species with similar functions may belong to different phyla. Grouping based on functions may thereby be beneficial to investigate the ecosystem as a whole but would require assessing each species separately, which is complex and timely.

The biodiversity impacts estimated using our CFs refer to the local potential net loss of species due to the offshore construction- and decommissioning-induced changes to marine habitats. It is important to underline that the impacts are local, as the species may still be globally present even though the species have disappeared at a local scale (Verones et al. 2022). However, if species are lost locally, the risk of global extinction may increase. Kuipers et al. (2019) and Verones et al. (2022) developed global extinction probabilities (GEP), a scaling approach to indicate the extent to which regional species loss in a respective area may contribute to global species extinction. However, among the taxonomic groups we considered in our study, only *Enchinodermata* and *Bryozoa* are partially covered by the existing GEPs. Expansion of the GEPs requires information on the range area of the considered species and the IUCN threat level of the species (Verones et al. 2022).

4.6 Uncertainties and data needs

The samples representing the reference seabed (sandy and hard) were collected in 2008–2015 and are thereby representative of the seabed after the heavy industrialization of the North Sea (Bennema et al. 2020; Lengkeek & Bouma 2010; Støttrup et al. 2017; Thurstan et al. 2023). They can therefore not be claimed to represent a natural state of the North Sea. Furthermore, the database for the seabed types is not very strong, as BISAR currently only includes data from 2 sandy sediment sites and 1 geogenic reef (hard seabed). The seabed within the OWF is assumed to remain unchanged compared to its pre-construction state, i.e., the reference seabed. Additionally, species richness within the OWF seabed is assumed to remain constant throughout the OWF's operational lifetime. These assumptions are necessary due to the lack of available data on seabed conditions within OWFs. However, it is likely that the richness of the different taxonomic groups is influenced by the presence of surrounding structures, though the specific nature of these effects remains uncertain. To enhance the model in this regard, systematic seabed sampling within OWFs is required and should be conducted throughout their operational lifespan. Furthermore, the species richness is assumed to be uniform across all turbines. However, variations may arise due to factors such as differences in hydrodynamic conditions affecting recolonization, varying degrees of protection among turbines, or differences in seabed characteristics and depths. The data used is expected to bring some uncertainties to the study results. Firstly, the samples were collected over a period of 16 years by different researchers using different approaches, which is expected to have brought some inconsistency to the database. Secondly, the pooling of samples from different structures and foundation types to cover both construction and decommissioning for structures with ages of 1–25 years is expected to bring uncertainty to the results. The structural design and materials used for offshore structures like OWFs and oil and gas platforms are similar and thus comparable in terms of marine biodiversity impacts (Lemasson et al. 2022). Additionally, we did not find any correlation between structure type or foundation type and species richness. However, some essential differences between the two structure types may influence the species richness. For example, oil and gas platforms are typically constructed in deeper waters and further offshore and often discharge contaminants during their operational lifetime, which may affect the species richness on the structure (Ekins et al. 2006). Additionally, oil and gas platforms are rarely arranged close to each other in farms, like wind turbines are, but have a larger footprint on the seafloor per unit. Thirdly, the samples from offshore structures only cover the organisms attached to the structure and the scour protection. They do not cover samples from the sand underneath the scour protection, which is expected to contain some species similar to the sandy seabed. We, therefore, expect that the species richness at an offshore structure would be higher if the species in the sand underneath the scour protection were also sampled.

Our approach to identifying alien species included comparing the species present in the BISAR database to the IUCN list of alien species in the North Sea included in the MarINvaders Toolkit (Lonka et al. 2021; Verones et al. 2023). The MarINvaders Toolkit is continuously updated according to updates in IUCN, and the impacts on aliens may vary depending on when the list was extracted. Our assessment is based on a list extracted in September 2024. We also investigated impacts on threatened species, using the same approach as for aliens. However, as only one threatened species (*Homarus Gammarus*) occurred in the BISAR database, the threatened species were excluded from this study.

To validate the results of this study, we suggest focused investigations and data collection from offshore structures. The data collection procedures should be standardized in terms of sampling methods and data processing to ensure comparability between studies. Furthermore, for each structure and foundation type, the data should be collected continuously over time and over different parameters like depth, distance from the seabed, sampled area, and seasonality to enable a deeper investigation of the parameters' influence on species richness. To expand the coverage of the CFs geographically, structures in other areas should be investigated, e.g., the Baltic Sea or the Formosa Strait, as they are some of the large development areas for OWFs (4C Offshore 2023).

5 Conclusion

This study presents CFs for evaluating the impacts on marine benthic biodiversity from habitat changes associated with the construction, decommissioning, and whole lifetime of OWFs in the North Sea. The developed CFs enable the quantification of both positive and negative impacts on marine benthic biodiversity, thus providing a basis for understanding and managing the ecological consequences of OWF projects. To allow for more detail, the CFs are developed for eight different taxonomic groups, as well as alien species. The study covers two scenarios for construction, i.e., constructing on a sandy seabed or a rocky seabed, and three scenarios for decommissioning, i.e., removing the entire structure, leaving the scour protection, or leaving the scour protection and the bottom 5 m of the turbine foundation. The findings suggest that the construction and decommissioning activities may lead to changes in the total species richness and the richness of alien species and shifts in richness between different taxonomic groups. Furthermore, the results indicate that the species richness on the OWF structure could exceed the richness on a sandy or rocky seabed if the structure has a lifetime of 13 years or more. However, considering the impacts integrated over the structure's lifetime (expected to be 25 years in most cases), the study suggests that the construction on sandy seabeds generally results in a net loss of species, while the construction on hard seabeds appears to result in a net gain of species. The CFs for decommissioning indicate that leaving the scour protection could maintain most of the total species richness. Whether the changes in species richness associated with habitat transformations can be regarded as positive or negative depends on the desired habitat, as the total species richness, presence of alien species, and the composition of species within different taxonomic groups vary with the habitat type. We, therefore, highlight the importance of defining the desired habitat at the considered location, considering the taxonomic composition, and considering the total species richness. Future research should focus on expanding the CFs to cover more geographic regions and taxonomic groups and on collecting data continuously over time and different parameters like depth, distance from the seabed, sampled area, and seasonality to enable a deeper investigation of the parameters' influence on species richness.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11367-025-02504-0.

Acknowledgements We thank all experts of the Working Group for Marine Benthal and Renewable Energy Developments (WGMBRED) of the Council for the Exploration of the Sea (ICES) for creating and providing the BISAR dataset on benthic communities related to European OWFs. We accessed these data through the Biodiversity information system "CRITTERBASE" of the Alfred Wegener Institute. Furthermore, we wish to acknowledge Philip Gjedde for providing updated data on alien species from the MarINvaders Toolkit, which enabled the quantification of changes in alien species presence. The manuscript was reviewed using Grammarly to enhance grammar and language clarity.

Funding Open access funding provided by Technical University of Denmark This study was enabled by funding from the Danish Innovation Fund (1044-00104B) and Biowins, a Vattenfall research support fund.

Data Availability Some supporting data is reported in the supplementary material, consisting of 2 files. Additional data can be made available on request.

Declarations

Competing interests The authors declare no competing interests.

References

4C Offshore (2023) Global offshore wind farm database and intelligence. Retrieved 6 July 2023 from https://www.4coffshore.com/windfarms/

Adams TP, Miller RG, Aleynik D, Burrows MT, Frederiksen M (2014) Offshore marine renewable energy devices as stepping stones across biogeographical boundaries. J Appl Ecol 51(2):330–338. https://doi.org/10.1111/1365-2664.12207

Ager O (2005) Spiophanes bombyx: a bristleworm. Plymouth: Marine Biological Association of the United Kingdom. Retrieved August 2 from https://www.marlin.ac.uk/species/detail/1705

Ager O (2008) Lanice conchilega sand mason. Plymouth: Marine Biological Association of the United Kingdom. https://www.marlin.ac.uk/species/detail/1642

Ballerstedt S (2005) Scoloplos armiger: armoured bristleworm. Plymouth: Marine Biological Association of the United Kingdom. Retrieved August 2 from https://www.marlin.ac.uk/species/detail/1721

Bennema FP, Engelhard GH, Lindeboom H, Norkko J (2020) Ostrea edulis beds in the central North Sea: delineation, ecology, and restoration. ICES J Mar Sci 77(7–8):2694–2705. https://doi.org/10.1093/icesjms/fsaa134

Berghahn R, Ruth M (2005) The disappearance of oysters from the Wadden Sea: a cautionary tale for no-take zones. Aquat Conserv 15(1):91–104. https://doi.org/10.1002/aqc.635

Bergström L, Sundqvist F, Bergström U (2013) Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community. Mar Ecol Prog Ser 485:199–210. https://doi.org/10.3354/meps10344

Blackburn TM, Essl F, Evans T, Hulme PE, Jeschke JM, Kühn I, Kumschick S, Marková Z, Mrugała A, Nentwig W, Pergl J, Pyšek P, Rabitsch W, Ricciardi A, Richardson DM, Sendek A, Vilà M, Wilson JRU, Winter M, Genovesi P, Bacher S (2014) A unified classification of alien species based on the magnitude of their environmental impacts. PLoS Biol 12(5). https://doi.org/10.1371/journal.pbio.1001850

Borgelt J, Dorber M, Geron C, Kuipers KJJ, Huijbregts MAJ, Verones F (2024) What is the impact of accidentally transporting terrestrial alien species? A new life cycle impact assessment model. Environ Sci Technol 58(7):3423–3436. https://doi.org/10.1021/acs.est.3c08500

Britton M (2013) Decommissioning programme for London array

Bulleri F, Airoldi L (2005) Artificial marine structures facilitate the spread of a non-indigenous green alga, Codium fragile ssp. tomentosoides, in the north Adriatic Sea. J Appl Ecol 42(6):1063–1072. https://doi.org/10.1111/j.1365-2664.2005.01096.x

Carey DA, Wilber DH, Read LB, Guarinello ML, Griffin M, Sabo S (2020) Effects of the Block Island Wind Farm on coastal resources: lessons learned. Ocanography 33(4):70–81. https://doi.org/10.5670/oceanog.2020.407

Claisse JT, Pondella DJ 2nd, Love M, Zahn LA, Williams CM, Bull AS (2015) Impacts from partial removal of decommissioned oil and gas platforms on fish biomass and production on the remaining platform structure and surrounding shell mounds. PLoS ONE 10(9):e0135812. https://doi.org/10.1371/journal.pone.0135812

OSPAR Commission (1998) OSPAR decision 98/3 on the disposal of disused offshore installations

Coolen JWP (2017) North sea reefs. Benthic biodiversity of artificial and rocky reefs in the southern North Sea. Wageningen University, Wageningen, NL

Coolen JWP, van der Weide B, Cuperus J, Blomberg M, Van Moorsel GWNM, Faasse MA, Bos OG, Degraer S, Lindeboom HJ (2018) Benthic biodiversity on old platforms, young wind farms, and rocky reefs. ICES J Mar Sci 77(3):1250–1265. https://doi.org/10.1093/icesjms/fsy092

Coolen JWP, Wijnhoven S, Bergsma J, Mavrak N (2022) Sampling hard substrates in Dutch offshore wind farms. Wageningen Marine Research

Dannheim J, Bergström L, Birchenough SNR, Brzana R, Boon AR, Coolen JWP, Dauvin J-C, De Mesel I, Derweduwen J, Gill AB, Hutchison ZL, Jackson AC, Janas U, Martin G, Raoux A, Reubens J, Rostin L, Vanaverbeke J, Wilding TA, Wilhelmsson D, Degraer S (2020) Benthic effects of offshore renewables: identification of knowledge gaps and urgently needed research. ICES J Mar Sci 77(3):1092–1108. https://doi.org/10.1093/icesjms/fsz018

Dannheim J, Kloss P, Vanaverbeke J, Mavraki N, Zupan M, Spielmann V, Degraer S, Birchenough SNR, Janas U, Sheehan E, Teschke K, Gill AB, Hutchison Z, Carey DA, Rasser M, Buyse J, van der Weide B, Bittner O, Causon P, Krone R, Faasse M, Wrede A, Coolen JWP (2025) Biodiversity Information of benthic Species at ARtificial structures - BISAR. Sci Data 12(1):604. https://doi.org/10.1038/s41597-025-04920-1

Dauvin JC (2024) Do offshore wind farms promote the expansion and proliferation of non-indigenous invertebrate species? Mar Pollut Bull 206:116802. https://doi.org/10.1016/j.marpolbul.2024.116802

de Groot SJ (1984) The impact of bottom trawling on benthic fauna of the North Sea. Ocean Manag 9(3–4):177–190. https://doi.org/10.1016/0302-184X(84)90002-7

de Baan L, Mutel CL, Curran M, Hellweg S, Koellner T (2013) Land use in life cycle assessment: global characterization factors based on regional and global potential species extinction. Environ Sci Technol 47(16):9281–9290. https://doi.org/10.1021/es400592q

de Visser S, Scherer L, Huijbregts M, Barbarossa V (2023) Characterization factors for the impact of climate change on freshwater fish species. Ecol Indic 150. https://doi.org/10.1016/j.ecolind.2023.110238

De Mesel I, Kerckhof F, Norro A, Rumes B, Degraer S (2015) Succession and seasonal dynamics of the epifauna community on offshore wind farm foundations and their role as stepping stones for non-indigenous species. Hydrobiologia 756(1):37–50. https://doi.org/10.1007/s10750-014-2157-1

Degraer S, Carey D, Coolen J, Hutchison Z, Kerckhof F, Rumes B, Vanaverbeke J (2020) Offshore wind farm artificial reefs affect ecosystem structure and functioning: a synthesis. Oceanography 33(4):48–57. https://doi.org/10.5670/oceanog.2020.405

Desprez M (2000) Physical and biological impact of marine aggregate extraction along the French coast of the Eastern English Channel: short- and long-term post-dredging restoration. ICES J Mar Sci 57(5):1428–1438. https://doi.org/10.1006/jmsc.2000.0926

Drew J (2011) Decommissioning strategy. GWYNT Y MÔR OFFSHORE WIND FARM LTD

Early R, Bradley BA, Dukes JS, Lawler JJ, Olden JD, Blumenthal DM, Gonzalez P, Grosholz ED, Ibanez I, Miller LP, Sorte CJ, Tatem AJ (2016) Global threats from invasive alien species in the twenty-first century and national response capacities. Nat Commun 7:12485. https://doi.org/10.1038/ncomms12485

Ekins P, Vanner R, Firebrace J (2006) Decommissioning of offshore oil and gas facilities: a comparative assessment of different scenarios. J Environ Manage 79(4):420–438. https://doi.org/10.1016/j.jenvman.2005.08.023

European Commission (2024) EMODnet: geology. European Commission. Retrieved September 23 from https://emodnet.ec.europa.eu/en/geology

Finkbeiner M (eds) (2011) Towards life cycle sustainability management. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-1899-9

Fowler AM, Jørgensen A-M, Svendsen JC, Macreadie PI, Jones DOB, Boon AR, Booth DJ, Brabant R, Callahan E, Claisse JT, Dahlgren TG, Degraer S, Dokken QR, Gill AB, Johns DG, Leewis RJ, Lindeboom HJ, Linden O, May R, Murk AJ, Ottersen G, Schroeder DM, Shastri SM, Teilmann J, Todd V, Hoey GV, Vanaverbeke J, Coolen JWP (2018) Environmental benefits of leaving offshore infrastructure in the ocean. Front Ecol Environ 16(10):571–578. https://doi.org/10.1002/fee.1827

GISD (2025) Global Invasive Species Database Version 2015.1. Invasive Species Specialist Group. www.iucngisd.org/gisd/

Glasby TM, Connell SD, Holloway MG, Hewitt CL (2006) Nonindigenous biota on artificial structures: could habitat creation facilitate biological invasions? Mar Biol 151(3):887–895. https://doi.org/10.1007/s00227-006-0552-5

Hall R, João E, Knapp CW (2020) Environmental impacts of decommissioning: onshore versus offshore wind farms. Environ Impact Assess Rev 83. https://doi.org/10.1016/j.eiar.2020.106404

Hanafiah MM, Leuven RS, Sommerwerk N, Tockner K, Huijbregts MA (2013) Including the introduction of exotic species in life

cycle impact assessment: the case of inland shipping. Environ Sci Technol 47(24):13934–13940. https://doi.org/10.1021/es403870z
Hauschild MZ, Rosenbaum RK, Olsen SI (2018) Life cycle assessment: theory and practice. Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3
Heery EC, Bishop MJ, Critchley LP, Bugnot AB, Airoldi L, Mayer-Pinto M, Sheehan EV, Coleman RA, Loke LHL, Johnston EL, Komyakova V, Morris RL, Strain EMA, Naylor LA, Dafforn KA (2017) Identifying the consequences of ocean sprawl for sedimentary habitats. J Exp Mar Bio Ecol 492:31–48. https://doi.org/10.1016/j.jembe.2017.01.020
Henley J (2023) European countries pledge huge expansion of North Sea wind farms. The Guardian. Retrieved June 18 from https://www.theguardian.com/environment/2023/apr/24/european-countries-pledge-huge-expansion-of-north-sea-wind-farms
Hernández C, OM, Shadman M, Amiri MM, Silva C, Estefen SF, La Rovere E (2021) Environmental impacts of offshore wind installation, operation and maintenance, and decommissioning activities: a case study of Brazil. Renew Sustain Energy Rev, 144. https://doi.org/10.1016/j.rser.2021.110994
Hofstede Rt, Driessen FMF, Elzinga PJ, Van Koningsveld M, Schutter M (2022) Offshore wind farms contribute to epibenthic biodiversity in the North Sea. J Sea Res 185. https://doi.org/10.1016/j.seares.2022.102229
Horton T, Kroh A, Ahyong S, Bailly N, Boyko CB, Brandão SN, Gofas S, Hooper JNA, Hernandez F, Holovachov O, Mees J, Molodtsova TN, Paulay G, Decock W, Dekeyzer S, Poffyn G, Vandepitte L, Vanhoorne B, Adlard R et al (2021) World Register of Marine Species (WoRMS). WoRMS Editorial Board. Retrieved March 12 from https://www.marinespecies.org/
Houziaux J S, Fettweis M, Francken F, Van Lancker V (2011) Historic (1900) seafloor composition in the Belgian-Dutch part of the North Sea: a reconstruction based on calibrated visual sediment descriptions. Cont Shelf Res 31(10):1043–1056. https://doi.org/10.1016/j.csr.2011.03.010
Huijbregts M A J, Steinmann Z JN, Elshout P M F, Stam G, Verones F, Vieira M, Zijp M, Hollander A, van Zelm R (2016) ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 22(2):138–147. https://doi.org/10.1007/s11367-016-1246-y
IEA (2019) Offshore Wind Outlook 2019. IEA, Paris
Jackson A, Hiscock K (2008) Sabellaria spinulosa Ross worm. Plymouth: Marine Biological Association of the United Kingdom. Retrieved July 29 from https://www.marlin.ac.uk/species/detail/1133
Kaiser D (2022) Dist2coast. GitHub. Retrieved May from https://github.com/Davidatlarge/dist2coast/blob/main/dist2coast.R
Kristensen LD, Støttrup JG, Svendsen JC, Stenberg C, Hansen OKH, Grønkjær P (2017) Behavioural changes of Atlantic cod (Gadus morhua) after marine boulder reef restoration: implications for coastal habitat management and Natura 2000 areas. Fish Manage Ecol 24(5):353–360. https://doi.org/10.1111/fme.12235
Krone R, Gutow L, Brey T, Dannheim J, Schröder A (2013) Mobile demersal megafauna at artificial structures in the German Bight – likely effects of offshore wind farm development. Estuar Coast Shelf Sci 125:1–9. https://doi.org/10.1016/j.ecss.2013.03.012
Kuipers KJJ, Hellweg S, Verones F (2019) Potential consequences of regional species loss for global species richness: a quantitative approach for estimating global extinction probabilities. Environ Sci Technol 53(9):4728–4738. https://doi.org/10.1021/acs.est.8b06173
Kuipers KJJ, Hilbers JP, Garcia-Ulloa J, Graae BJ, May R, Verones F, Huijbregts MAJ, Schipper AM (2021) Habitat fragmentation amplifies threats from habitat loss to mammal diversity across the world's terrestrial ecoregions. One Earth 4(10):1505–1513. https://doi.org/10.1016/j.oneear.2021.09.005
Kuipers KJJ, Melki A, Morel S, Schipper AM (2025) Relationships between mean species abundance (MSA) and potentially disappeared fraction of species (PDF) are consistent but also uncertain. Environ Sustain Ind 26. https://doi.org/10.1016/j.indic.2025.100652
Lacal-Arántegui R, Uihlein A, Yusta JM (2019) Technology effects in repowering wind turbines. Wind Energ 23(3):660–675. https://doi.org/10.1002/we.2450
Lemasson AJ, Somerfield PJ, Schratzberger M, McNeill CL, Nunes J, Pascoe C, Watson SCL, Thompson MSA, Couce E, Knights AM (2022) Evidence for the effects of decommissioning man-made structures on marine ecosystems globally: a systematic map. Environ Evid 11(1). https://doi.org/10.1186/s13750-022-00285-9
Lengkeek W, Bouma S (2010) Impacts of beam trawl fisheries in the North Sea. A summary of fifty-five publications
Leung B, Lodge DM, Finnoff D, Shogren JF, Lewis MA, Lamberti G (2002) An ounce of prevention or a pound of cure: bioeconomic risk analysis of invasive species. Proc Biol Sci 269(1508):2407–2413. https://doi.org/10.1098/rspb.2002.2179
Li D, Dorber M, Barbarossa V, Verones F (2022) Global characterization factors for quantifying the impacts of increasing water temperature on freshwater fish. Ecol Indic 142. https://doi.org/10.1016/j.ecolind.2022.109201
Li C, Coolen JWP, Scherer L, Mogollon JM, Braeckman U, Vanaverbeke J, Tukker A, Steubing B (2023) Offshore wind energy and marine biodiversity in the north sea: life cycle impact assessment for benthic communities. Environ Sci Technol. https://doi.org/10.1021/acs.est.2c07797
Lonka R, Verones F, Stadler K (2021) The MarINvaders toolkit. J Open Source Softw 6(64). https://doi.org/10.21105/joss.03575
Michaelis R, Hass HC, Mielck F, Papenmeier S, Sander L, Ebbe B, Gutow L, Wiltshire KH (2019) Hard-substrate habitats in the German Bight (South-Eastern North Sea) observed using drift videos. J Sea Res 144:78–84. https://doi.org/10.1016/j.seares.2018.11.009
Molnar JL, Gamboa RL, Revenga C, Spalding MD (2008) Assessing the global threat of invasive species to marine biodiversity. Front Ecol Environ 6(9):485–492. https://doi.org/10.1890/070064
Mortimer-Jones K (2007) Magelona filiformis: a bristleworm. Plymouth: Marine Biological Association of the United Kingdom. Retrieved August 2 from https://www.marlin.ac.uk/species/detail/21
NOAA (2024) What is a sponge? Retrieved August 2 from https://oceanservice.noaa.gov/facts/sponge.html
OBIS (2025) Ocean biogeographic information system. Intergovernmental Oceanographic Commission of UNESCO. Retrieved March 19 from https://obis.org/
Oginah S A, Posthuma L, Maltby L, Hauschild M, Fantke P (2023) Linking freshwater ecotoxicity to damage on ecosystem services in life cycle assessment. Environ Int 171:107705. https://doi.org/10.1016/j.envint.2022.107705
Olsen OT (1883) The piscatorial atlas of the North Sea, English and St. George's Channels: illustrating the fishing ports, boats, gear, species of fish (how, where and when caught), and other information concerning fish and fihseries. Taylor and Francis, London
Pysek P, Hulme PE, Simberloff D, Bacher S, Blackburn TM, Carlton JT, Dawson W, Essl F, Foxcroft LC, Genovesi P, Jeschke JM, Kuhn I, Liebhold AM, Mandrak NE, Meyerson LA, Pauchard A, Pergl J, Roy HE, Seebens H, van Kleunen M, Vilà M, Wingfield MJ, Richardson DM (2020) Scientists' warning on invasive alien species. Biol Rev Camb Philos Soc 95(6):1511–1534. https://doi.org/10.1111/brv.12627
Reubens JT, Degraer S, Vincx M (2014) The ecology of benthopelagic fishes at offshore wind farms: a synthesis of 4 years of research. Hydrobiologia 727(1):121–136. https://doi.org/10.1007/s10750-013-1793-1
Samal S, Swapnil P, Meena M (2019) Phylum. Springer, Cham. https://doi.org/10.1007/978-3-319-47829-6_1197-1

Schläppy ML, Robinson LM, Camilieri-Asch V, Miller K (2021) Trash or treasure? Considerations for future ecological research to inform oil and gas decommissioning. Front Mar Sci 8. https://doi.org/10.3389/fmars.2021.642539

Sedano F, Tierno de Figueroa JM, Navarro-Barranco C, Ortega E, Guerra-Garcia JM, Espinosa F (2020) Do artificial structures cause shifts in epifaunal communities and trophic guilds across different spatial scales? Mar Environ Res 158:104998. https://doi.org/10.1016/j.marenvres.2020.104998

Smyth K, Christie N, Burdon D, Atkins JP, Barnes R, Elliott M (2015) Renewables-to-reefs? - decommissioning options for the offshore wind power industry. Mar Pollut Bull 90(1–2):247–258. https://doi.org/10.1016/j.marpolbul.2014.10.045

Spielmann V, Dannheim J, Brey T, Coolen JWP (2023) Decommissioning of offshore wind farms and its impact on benthic ecology. J Environ Manage 347:119022. https://doi.org/10.1016/j.jenvman.2023.119022

Støttrup JG, Dahl K, Niemann S, Stenberg C, Reker J, Stamphøj EM, Göke C, Svendsen JC (2017) Restoration of a boulder reef in temperate waters: strategy, methodology and lessons learnt. Ecol Eng 102:468–482. https://doi.org/10.1016/j.ecoleng.2017.02.058

Stranddorf L, Colley T, Delefosse M, Svendsen JC, Irving Olsen S (2024) Marine biodiversity impact pathways for offshore wind farm decommissioning: implications for life cycle impact assessment development. Ecol Indic 167. https://doi.org/10.1016/j.ecolind.2024.112613

Thurstan R, McCormick H, Preston J, Ashton E, Bennema F, Bratoš CA, Brown J, Cameron T, Da Costa F, Donnan D, Ewers C, Fortibuoni T, Galimany E, Giovanardi O, Grancher R, Grech D, Hayden-Hughes M, Helmer L, Jensen K, Zu Ermgassen P (2023) The world was our oyster: records reveal the vast historical extent of European oyster reef ecosystems. https://doi.org/10.32942/X20W43

UNEP (2019) Global guidance on environmental life cycle impact assessment indicators, Volume 2

van der Molen J, Smith HCM, Lepper P, Limpenny S, Rees J (2014) Predicting the large-scale consequences of offshore wind turbine array development on a North Sea ecosystem. Cont Shelf Res 85:60–72. https://doi.org/10.1016/j.csr.2014.05.018

Vandepitte L, Vanhoorne B, Decock W, Dekeyzer S, Trias Verbeeck A, Bovit L, Hernandez F, Mees J (2015) How aphia—the platform behind several online and taxonomically oriented databases—can serve both the taxonomic community and the field of biodiversity informatics. J Mar Sci Eng 3(4):1448–1473. https://doi.org/10.3390/jmse3041448

Verones F, Hellweg S, Antón A, Azevedo LB, Chaudhary A, Cosme N, Cucurachi S, Baan L, Dong Y, Fantke P, Golsteijn L, Hauschild M, Heijungs R, Jolliet O, Juraske R, Larsen H, Laurent A, Mutel CL, Margni M, Núñez M, Owsianiak M, Pfister S, Ponsioen T, Preiss P, Rosenbaum RK, Roy P-O, Sala S, Steinmann Z, van Zelm R, Van Dingenen R, Vieira M, Huijbregts MAJ (2020) LC-IMPACT: a regionalized life cycle damage assessment method. J Ind Ecol 24(6):1201–1219. https://doi.org/10.1111/jiec.13018

Verones F, Kuipers K, Núñez M, Rosa F, Scherer L, Marques A, Michelsen O, Barbarossa V, Jaffe B, Pfister S, Dorber M (2022) Global extinction probabilities of terrestrial, freshwater, and marine species groups for use in Life Cycle Assessment. Ecol Indic 142. https://doi.org/10.1016/j.ecolind.2022.109204

Verones F, Gjedde P, Koslowski M, Woods JS, Lonka R, Stadler K (2023) MarINvaders: a web toolkit of marine species for use in environmental assessments. Ecosphere 14(11). https://doi.org/10.1002/ecs2.4697

Watson R, Revenga C, Kura Y (2006) Fishing gear associated with global marine catches. Fish Res 79(1–2):103–111. https://doi.org/10.1016/j.fishres.2006.01.013

Watson SM, McLean DL, Balcom BJ, Birchenough SNR, Brand AM, Camprasse ECM, Claisse JT, Coolen JWP, Cresswell T, Fokkema B, Gourvenec S, Henry LA, Hewitt CL, Love MS, MacIntosh AE, Marnane M, McKinley E, Micallef S, Morgan D, Nicolette J, Macreadie PI (2023) Offshore decommissioning horizon scan: research priorities to support decision-making activities for oil and gas infrastructure. Sci Total Environ 878:163015. https://doi.org/10.1016/j.scitotenv.2023.163015

Whitehouse RJ, Harris JM, Sutherland J, Rees J (2011) The nature of scour development and scour protection at offshore windfarm foundations. Mar Pollut Bull 62(1):73–88. https://doi.org/10.1016/j.marpolbul.2010.09.007

Wilhelmsson D, Malm T (2008) Fouling assemblages on offshore wind power plants and adjacent substrata. Estuar Coast Shelf Sci 79(3):459–466. https://doi.org/10.1016/j.ecss.2008.04.020

Williams R, Zhao F (2023) Global offshore wind report

Wilson JC, Elliott M (2009) The habitat-creation potential of offshore wind farms. Wind Energ 12(2):203–212. https://doi.org/10.1002/we.324

Woods JS, Verones F (2019) Ecosystem damage from anthropogenic seabed disturbance: a life cycle impact assessment characterisation model. Sci Total Environ 649:1481–1490. https://doi.org/10.1016/j.scitotenv.2018.08.304

Woods JS, Veltman K, Huijbregts MA, Verones F, Hertwich EG (2016) Towards a meaningful assessment of marine ecological impacts in life cycle assessment (LCA). Environ Int 89–90:48–61. https://doi.org/10.1016/j.envint.2015.12.033

Authors and Affiliations

Liv Stranddorf[1,2,3] · Francesca Verones[4] · Stig Irving Olsen[1,3]

✉ Liv Stranddorf
livks@dtu.dk

[1] Section for Quantitative Sustainability Assessment, Department of Environmental and Resource Engineering, Technical University of Denmark (DTU), Bygningstorvet, Building 115, 2800 Kgs Lyngby, Denmark

[2] Environment and Sustainability Unit, Vattenfall Vindkraft, 6000 Kolding, Denmark

[3] Centre for Absolute Sustainability Assessment, Technical University of Denmark (DTU), 2800 kgs. Lyngby, Denmark

[4] Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), Trondheim 7491, Norway