Biological Conservation 316 (2026) 111771

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Conservation potential of offshore windfarms for epibenthic invertebrates and fish communities in a heavily used regional sea

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ARTICLE INFO

Keywords:
Species distribution models
North Sea
Offshore wind farms
Marine protected areas network
Conservation planning
OECM

ABSTRACT

The Southern North Sea (SNS) has become a hub for installation of offshore renewables (OWF). Until 2040 large proportions of the SNS seascape will host fixed marine infrastructure for offshore wind farms. In parallel, the European Union urges member states to implement spatially conservation policies, leading to a network of marine protected areas (MPA). In MPA and OWF, demersal trawling will be restricted or prohibited and thereby could provide refuge for epibenthic invertebrates and demersal fish. Here we analysed the potential of the MPA and OWF networks to protect these two species groups by analysing the overlap between species' core areas (CA) and MPA/OWF sites. We defined core areas (CA) of species distributions based on modelled distributions of 177 epibenthic invertebrate and fish species, of which we identified 19 species of conservation concern. We further used a spatial optimisation algorithm to identify the areal demand for two coverage targets for the 19 species of conservation concern (10% and 30%). A 10%-CA coverage for all but three out of 19 species of could be achieved within the existing MPA network, a 30%-coverage could be achieved for only 13 species. Including existing and OWF planned until 2040 could help to achieve a coverage of 10% for all 19 species and would at least a 25%-coverage for all 19 species. Our results demonstrate the potential to co-locate areas of human activities with conservation areas by applying species distribution models in combination with spatial optimization tools to support regional conservation targets.

1. Introduction

The Southern North Sea (SNS) plays a central role in the economy and culture of its adjacent countries. Its waters have accommodated thriving fisheries, generation of energy, highly frequented shipping routes, diverse tourism, the exploration of sand, oil, and gas, and numerous other human activities (Halpern et al., 2008; Halpern et al., 2012; Emeis et al., 2015; OSPAR, 2023). However, the SNS ecosystem is also subject to multiple stressors ranging from climate change and overfishing to the expansion of maritime industries (McLean et al., 2019; Stelzenmüller et al., 2024). One of the most heavily growing industry in the SNS is the installation of offshore wind farms (OWF). The planned output of OWF is expected to increase substantially, from 20 GW in 2020 to ~200–300 GW by 2050 to cover the increasing demand for renewable energy (Gusatu et al., 2021; Stelzenmüller et al., 2022; Li et al., 2023). By then, OWF might occupy more than 23.000 km^2 in the SNS (based on the data on existing and planned offshore wind farms used in this study, 4C Offshore Ltd.). In parallel, a network of MPA (Natura 2000 network) was implemented based on the EU Habitats Directive (HD), the Bird Directive (BD) and the Oslo-Helsinki-Commission (OSPAR). This MPA network will be expanded based on goals defined through the EU Biodiversity Strategy 2030 and the EU Restoration Law (Bodenbender, 2024; EU, 2024), which require EU member states to define 10% to 30% of their national waters (and deteriorated and lost habitats therein) to be protected or restored by 2030 (EEA, 2015; EC, 2021; EC, 2023; OSPAR, 2023).

To accommodate spatial requirements of different human activities, countries bordering the SNS pursue marine spatial planning (MSP), which organises and manages activities in space and time in compliance with ecological, economic, and social policy objectives (Frazão Santos et al., 2019). MSP eventually results in spatial plans (i.e. maps), which allocate areas for human activities and conservation objectives and

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https://doi.org/10.1016/j.biocon.2026.111771
Received 26 March 2025; Received in revised form 13 November 2025; Accepted 18 February 2026
Available online 28 February 2026

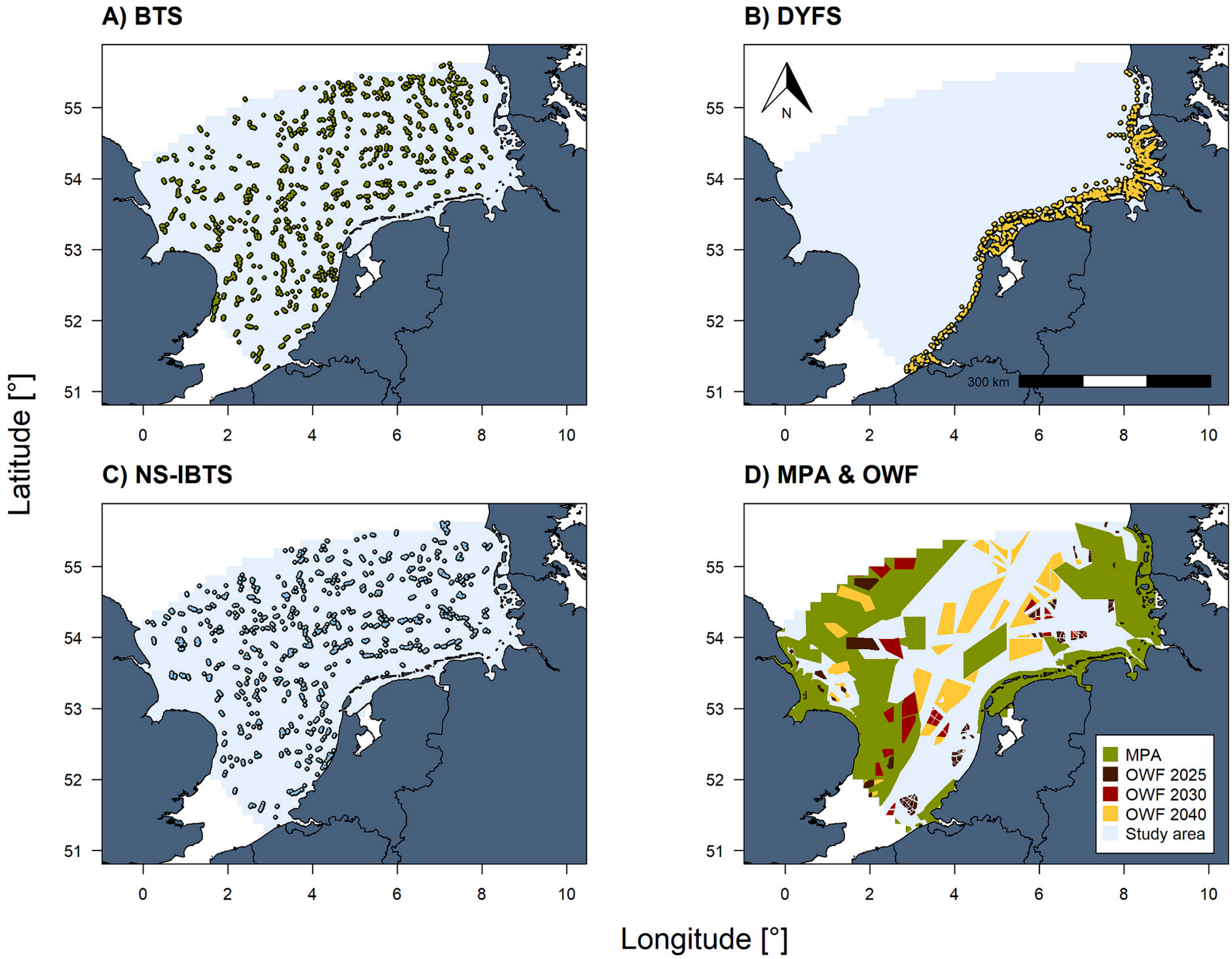

Fig. 1. Location of samples (fishing hauls) from three scientific surveys in the Southern North Sea conducted between 2014 and 2023. A) Beam trawl survey [BTS], B) Demersal Young Fish Survey [DYFS], C) North Sea International Bottom Trawl Survey [NS-IBTS]; all data are available via the ICES DATRAS data portal. For details see Table 1. D) Location of offshore windfarms (OWF) in 2025, 2030 and 2040 and marine protected areas (MPA) in the study area.

other aspects of ecosystem-based management (Katsanevakis et al., 2011). To inform MSP on spatial conservation aspects, the knowledge of the distribution of relevant ecosystem features is therefore key. However, several ecosystem features that are relevant for marine conservation policies such as birds, marine mammals or fish are mobile are widely distributed (Probst et al., 2021) and perform daily and seasonal migrations (Harden Jones, 1968; Hunter et al., 2003; Gilles et al., 2009; Schaber et al., 2022; Schwemmer et al., 2023). Our study therefore analyses the spatial overlap between core areas (CA) of occurrence of benthic and demersal marine species with the network of MPA and OWF. We focus on OWF as potential candidate sites for providing additional CA-coverage, as in many countries bordering the SNS, other human activities such as fishing and shipping are already banned from these areas. OWF may thereby provide refuge and new habitats for sensitive, endangered and rare fish and epibenthic invertebrate species (Fock, 2014; Fock et al., 2014; Degraer et al., 2020).

The distribution of mobile species can be characterised by core areas (CA) of their distribution, which convert a species' distributional ranges into comprehensive binary information on their most likely presence (Osborne and Suárez-Seoane, 2006; Probst et al., 2021). Probst et al. (2021) identified CA of demersal fish species in the North Sea, demonstrating that CA of species of conservation concern or areas of increased species richness were not consistently covered by the MPA network. The authors propose to consider OWF sites as additional conservation areas to facilitate the re-establishment of locally extirpated species such as rays and sharks (see also Fock, 2014; Fock et al., 2014). Hence OWF are expected to provide potential conservation benefits for marine species. As such, areas which are not primarily designated for marine conservation, but have been demonstrated to benefit conservation objectives, are also labelled as 'other effective area-based conservation measures' (OECM, CBD, 2018; FAO, 2022).

An OECM ("other effective area-based conservation measures" (OECM, CBD, 2018; FAO, 2022) is defined by the Convention on Biological Diversity (CBD) as "*geographically defined area*[*s*] […][*managed to*] *achieve positive and sustained long-term outcomes for the* in situ conservation of biodiversity" (CBD, 2018; IUCN, 2019). As such, OECM are recognized as tools for supporting biodiversity conservation (Shabtay et al., 2019). However, whether and how OWF could be designated as OECM in the SNS (Claudet et al., 2022; NABU, 2023) is an ongoing matter of debate, as they would need to meet several criteria (IUCN, 2019; FAO, 2022). One of these criteria, *the sustained and effective contribution to* in situ *conservation of biodiversity* (IUCN, 2019) demands for the overlap between OECM and conservation features (e.g. for the occurrence of a single species or a species community). Hence this study addresses the spatial potential for OWF-MPA synergies by applying overlap analyses of species' CA and MPA/OWF.

In this study, we combined data from three scientific fisheries surveys covering the years 2014 to 2023 to compute 179 species distribution models (SDM) for epibenthic invertebrates and fish in the SNS. We used a spatial prioritization approach to evaluate how networks of MPA and OWF could coverage of species' CA of 10% and 30%, under the assumption that such areas still present a suitable habitat regardless of the construction or presence of OWF. These targets were based on the EU Biodiversity Strategy 2030 and the EU Nature Restoration Law, which aim to strictly protect 10% of national marine waters and to recover 30% of marine benthic habitats by 2030 (EC, 2021; EU, 2024). The second coverage target of 30% follows also the argumentation of Gaines et al. (2010), who conclude that generically at least 30% of the distributional range of a species' population should be protected by an MPA to become an effective conservation measure. We hypothesize that OWF sites, due to the exclusion of trawl fisheries, could complement existing MPA networks to meet EU conservation targets. To this end, we apply the first quantitative, transboundary integration of MPA and OWF for multi-species conservation in the SNS.

2. Methods

The study used distributions from single species distribution models (SDM) to define core areas (CA) of species' distributions, to analyse the overlap between species' CA and MPA/OWF and to identify spatially optimised solutions for policy targets using the spatial optimization tool *prioritzR* in R.

2.1. Data compilation and processing

Averaged monthly means of dissolved oxygen, maximum shear stress, particulate organic carbon, temperature, zooplankton carbon at the sea floor, dissolved phosphate and nitrate in the water column, light attenuation and sea surface salinity (Fig. S2, Table S2) were obtained for the time period 2004–2012 from a high resolution model simulation (Wirtz et al., 2024), where the ecosystem model MAECS (Wirtz, 2019) was coupled to the hydrodynamic model GETM and other earth system modular components such as benthic biogeochemistry through the coupling framework MOSSCO (Lemmen et al., 2018). The original resolution of this data was 0.125° longitude × 0.125° latitude.

Spatial information on installed and planned OWF (up to and including 2042) was obtained from 4Coffshore Ltd. (www.4coffshore.com). OWF marked with the status “cancelled”, “failed proposal” or “dormant” were excluded. For the calculation of the distance to OWF, used as a predictor for the SDMs, only OWF installed until 2022 were considered. The overlay analysis of current and future OWF sites was made by combining installed and projected OWF until 2025, 2030 and 2040 into unified shapefiles.

Fishing intensity, expressed as swept area ratios (SAR), was downloaded from the International Council for the Exploration of the Sea (ICES) including subsurface and surface SAR averaged from 2009 until 2020 (ICES, 2021). SAR represents the proportional area of a grid cell that was touched by any towed mobile fishing gear (surface SAR) and gear that digs into the seafloor (subsurface SAR, Gerritsen et al., 2013; Eigaard et al., 2016; ICES, 2021). Surface and subsurface SAR were averaged across all years.

MPA shapefiles were downloaded from the World Database on Protected Areas provided by the UN Environmental Programme and the International Union for Conservation of Nature (UNEP-WCMC and IUCN, 2024, www.protectedplanet.net).

All predictor variables were transformed to raster format on a rectangular raster grid with a resolution of 0.025° longitude × 0.025° latitude, which corresponds to a rectangle roughly 1.6 km × 2.8 km edge length, or an average distance between grid cell centres of around 3 km and an average cell size of 4.5 km^2.

We tested for collinearity by pairwise correlation of the predictor variables. We excluded collinearity as a substantial source of bias to the SDM, since none of the predictor correlation coefficients was above $R > 0.7$ (Dormann et al., 2013). The size and extent of the spatial grid in this analysis was constrained by the spatial GETM-SNS model domain ranging from −1°W to 9°E longitude and 51°N to 56°N latitude.

Table 1
Overview of survey data from 2014 to 2023 used to model distributions of 179 epibenthic and fish species.

Survey	Abbreviation	Used gear	Data source	Sample frequency	No. of samples
Demersal Young Fish Survey	DYFS	Beam trawl	ICES DATRAS	Annually	4.590
International Bottom Trawl Survey in the North Sea	NS-IBTS	Otter board trawl	ICES DATRAS	Twice a year (winter and summer)	1.541
International Beam Trawl Survey	BTS	Beam trawl	ICES DATRAS	Annually	1.438

Demersal fish and epibenthic occurrence data were obtained from (i) the Demersal Young Fish Survey DYFS, (ii) the North Sea International Bottom Trawl Survey NS-IBTS, and (iii) the beam trawl survey BTS (Fig. 1). The three surveys were conducted annually in the SNS between 2014 and 2023 using beam or otter board trawls (Table 1).

All surveys are coordinated by ICES and the data including records on haul length and survey information are available through the ICES DATRAS data portal (https://www.ices.dk/data/data-portals/Pages/DATRAS.aspx, accessed on 02.08.2024). Samples without occurrence of any given species were considered as zero occurrence.

2.2. Selection of species

We identified 179 demersal fish and epibenthic invertebrate species that were recorded in at least 20 samples (fishing hauls) between 2014 and 2023 (Table S1). Even though some authors suggest considering only species with at least 50 occurrences (Virgili et al., 2018) we decided to implement a smaller cut-off threshold to include rare species, which often are of conservation concern, e.g. sea horses *Hippocampus* spp.

While the environmental data covered a time period from 2004 to 2012 (see supplements Table S2), we chose to use survey data from the most recent decade (2014–2023) to get a current estimate of the species' distributions. Assuming that the spatial patterns in oceanographical predictors from 2004 to 2012 remained comparable to the period of 2014–2023, we considered this temporal mismatch to have minor implications for the modelled distributions.

To address the objectives of this study, we defined different ensembles of species containing i) demersal fish, ii) epibenthic invertebrates, iii), species of conservation concern and iv) all species. Species of conservation concern were identified as species that were listed either by the regional European IUCN list as “near threatened”, “vulnerable”, “endangered” or “critically endangered”, under the OSPAR red list of species, in Annex II of the EU Habitats Directive or were considered of national conservation relevance in Germany (i.e., the Norway lobster *Nephrops norvegicus*, the European lobster *Homarus gammarus*, and the mud lobster *Upogebia deltaura*).

2.3. Modelling and evaluating species distributions

For each species, the probability of occurrence (P_{occ}) was estimated using random forests (RF, Breiman, 2001) implemented in the R-package ‘randomForest’ (version 4.7-1.1). Among other tested SDM methods, RF were found to be a versatile machine learning algorithm allowing the inclusion of dependent and predictor variables of all types (continuous, categorical, nominal variables, Breiman, 2001; Rongcheng et al., 2025). The RF used the spatial predictors as shown supplements S2 and

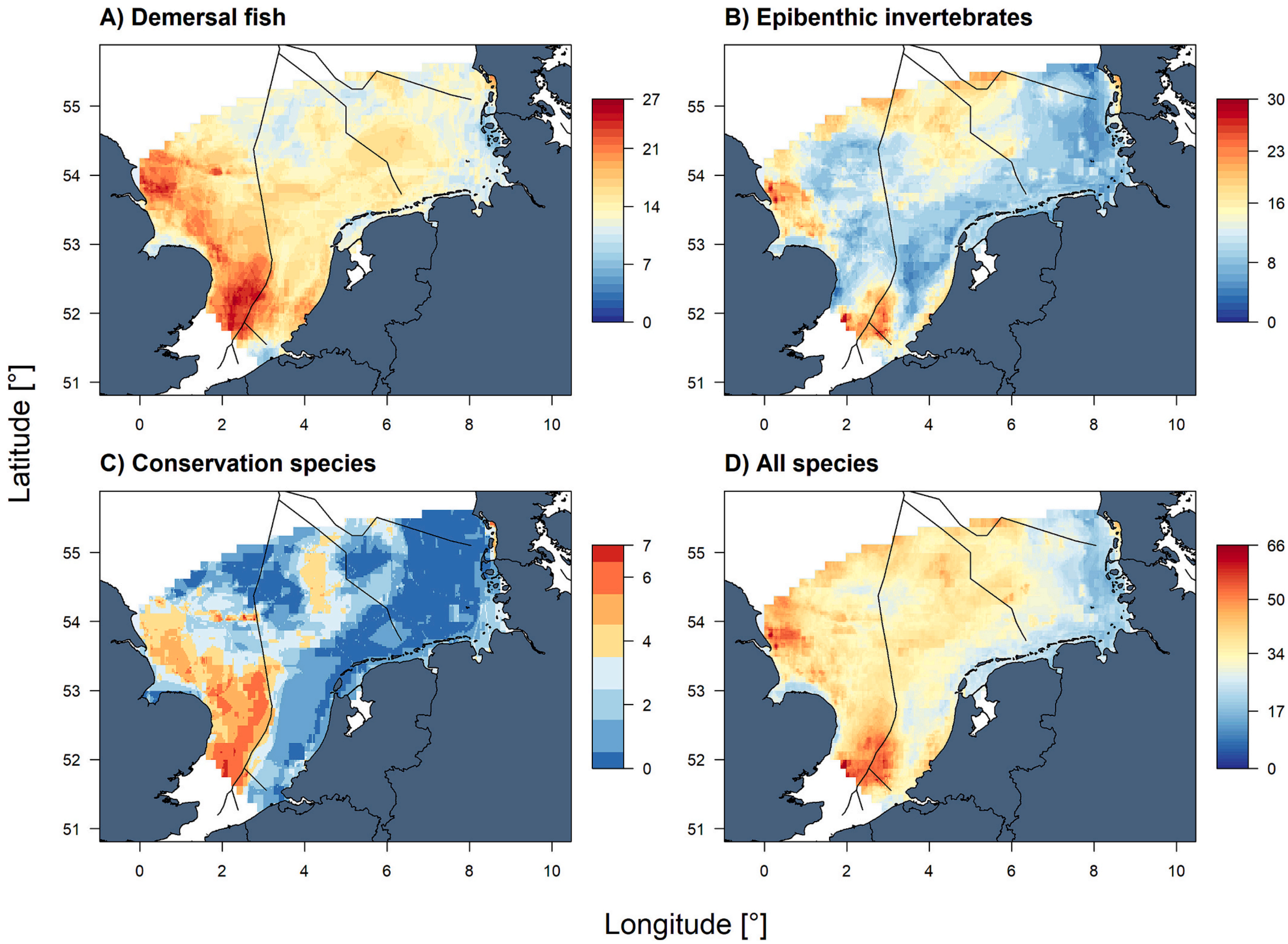

Fig. 2. Overview of hotspots as number of overlapping species' core areas per grid cell. A) Demersal fish ($N = 63$), B) epibenthic invertebrates (N = 90), C) species of conservation concern ($N = 21$) and D) all species ($N = 179$). Black lines indicate national borders (on land) and of exclusive economic zones (EEZ, on water).

Table S2 and were parametrized with default parameters except for setting 'nodesize' = 10, 'maxnodes' = 5 and ntree = 1000 to prevent overfitting (Probst et al., 2019). To account for the effects of different fishing gears used in the surveys, the gear category (small beam trawl with a width of 3–4 m, large beam trawl with a width of 6–8 m, and otter board trawls) was included as a predictor variable. To account for spatial autocorrelation, the local Moran's I for occurrence was calculated based on a spatial smoothing of observed occurrences (see supplements S3, Anselin, 1995) and included as a predictor in the RF (Georgian et al., 2019).

For each SDM, the data set was randomly divided into a training (75%) and validation data set (25%) to obtain independent evaluation metrics from the validation data set. As evaluation metrics we used the area-under-the-curve (AUC), true skill statistic (TSS), and the mean average error (MAE). We used an AUC-threshold of 0.6 to include as many species as possible into the analysis. This threshold led to the exclusion of two species (twait shad *Alosa fallax* and lump sucker *Cyclopterus lumpus*). All evaluation metrics are shown in supplements S1.

2.4. Defining core areas and overlap analysis

The probability of occurrence (P_{occ}) was used to identify core areas (CA) of each species' distribution. CA were defined as POC values that were above the mid-range of all modelled POC values of a species, indicating areas where species were found with the highest probability. This approach allowed the inclusion of rare species, which were found with low POC value and for which no CA could have been identified with by an absolute threshold.

The CAs of all species were overlaid with locations of OWF and MPA to identify regions of overlap for single species' CA and the suite of 19 species of conservation concern. The percentage of overlap between MPA/OWF and CA as well as the proportion of each CA that did not overlap with any MPA or OWF were calculated by summing the area of all grid cells that overlapped with the according shapefiles (see Fig. 5 for an example on mud lobster *Upogebia deltaura*).

2.5. Analysing MPA and OWF networks

To test the potential of the MPA/OWF network to protect the 19 species of conservation concern in the SNS, we addressed two questions using the *prioritizR*-package in R. *PrioritzR* is a conservation planning tool that optimises the spatial costs of predefined conservation targets (Hanson et al., 2025):

- How much CA-coverage can be achieved with the network of existing MPA and existing and projected OWF until 2025, 2030 and 2040?
- How much additional area outside the existing and projected networks would be needed to meet the targets of covering 10% and 30% of each species' CA?

To address the first question, we overlayed the core areas of the 19 species of conservation concern with the MPA and OWF networks. To

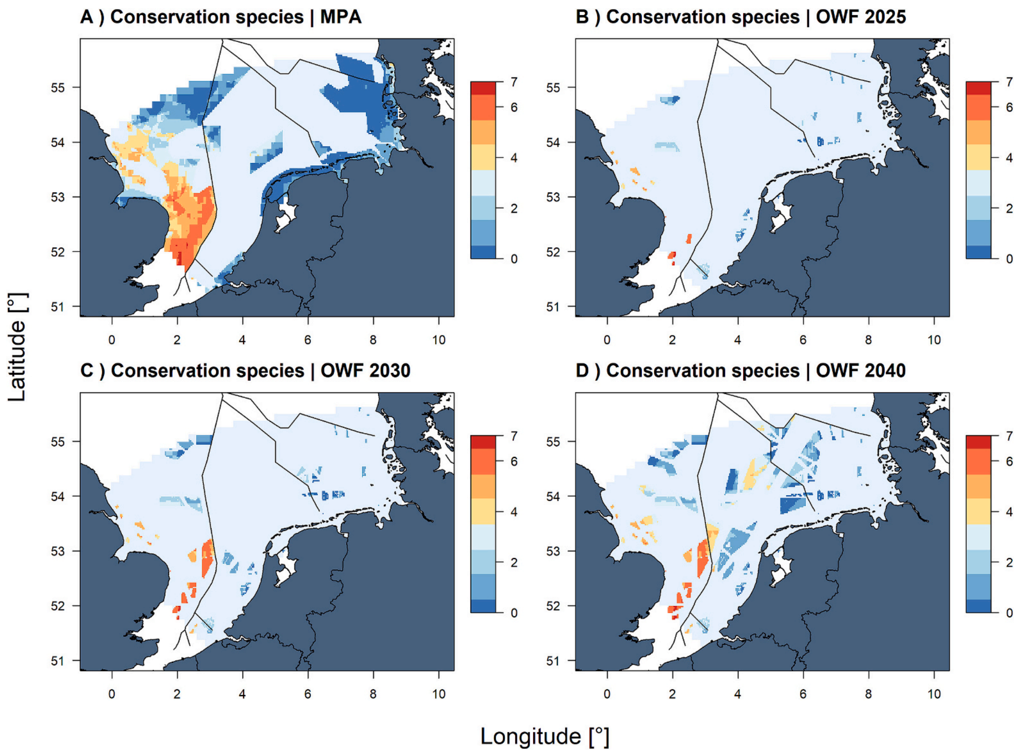

Fig. 3. Overlap between core areas of species of conservation concern and A) designated marine protected areas (MPA), B) offshore wind farms until 2025 OWF, C) offshore windfarms until 2030 and D) offshore windfarms until 2040.

this end, we used the *prioritzR*-package, however, without any coverage target and locked-in-constraints, and using the 'eval_target_coverage_summary'-function to extract overlaps. This essentially resulted in a simple overlap analysis of single species CAs and MPA/OWF areas without any spatial optimisation and was applied for convenience purposes (for R-code see Table S1).

The second question applied *prioritizR* to identify the smallest areas which would achieve the 10%- and 30%-coverage targets for the suite of 19 species of conservation concern. To this end, we developed six *prioritizR*-solutions identifying the minimal areas which were required to cover 10% and 30% of each conservation species' CA (R-code in supplements S6.2).

The 10%- and 30%-targets were aligned with the aims of the EU Biodiversity Strategy 2030 and the EU Restoration Law, which aim to protect and restore 30% of each member states' marine area by 2030. However, both policies do not consider single species and hence the 10%- and 30%-targets were also based on the generic rationale that a substantial spatial conservation measure should at least cover 1/3 of a species distributional range (Gaines et al., 2010).

Each *prioritizR*-solution used the area of the grid cells as cost layer (area size of grid cells varied across the study area, mean grid cell size $=4.545$ km^2 $\pm$ 0.105 km^2 S.D., minimum size = 4.355 km^2, maximum size = 4.824 km^2) and was constrained (using the 'add_locked_in_constraints'-function, see supplements S6.1 & S6.2) by either the network of existing MPA, existing MPA + existing OWF until 2025, MPA + existing and planned OWF by 2030 or MPA + existing and planned OWF by 2040. 'Locked-out' constraints were also included in a sixth solution to exclude OWF-2040 sites as part of a potential conservation network. This solution was supposed to calculate the area demands for a 30%-coverage of the species of conservation concern under the premises that OWF could not function as spatial conservation units (in sensu OECM). A boundary penalty of 50 was included into all *prioritizR*-solutions to avoid the fragmentation of the solution polygons. This penalty value was chosen based on visual inspection by different solutions and aiming for consistent and coherent solutions.

3. Results

3.1. SDM performance

The SDM for P_{occ} had an average AUC of 0.850 ($\pm$0.097 S.D.), an average TSS of 0.626 ($\pm$0.118 S.D.) and an average MAE of 0.227 ($\pm$0.121 S.D.) (Table S1, Fig. S4). Only two SDM had an AUC < 0.6 (twait shad *Allosa fallax* and lump sucker *Cyclopterus lumpus*), which demonstrates an adequate overall performance of the SDM. Both species were excluded from the subsequent analysis.

3.2. Distribution of CA hotspots

We found a maximum number of species which had CA overlap in any single grid cell of 27 ($N = 62$) for demersal fish, 30 ($N = 90$) for epibenthic invertebrates, 7 ($N = 19$) for species of conservation concern, and 66 for the full species suite ($N = 177$). The overlay of CA from different species suites indicated hotspots in the Belgian, British, and Dutch Exclusive Economic Zone (EEZ) and to a lesser extent in the German EEZ (Fig. 2).

3.3. Species richness in MPA & OWF

The overlap between CA hotspots of species of conservation concern and MPA indicated that in the British EEZ a maximum of seven species of conservation concern fell within MPA boundaries, whereas in the Dutch and the German EEZ, MPA overlapped only with a maximum of two species of conservation concern (Fig. 3A). The same pattern held true for OWF until 2025 and 2030 (Fig. 3B & C). Only the OWF-2040 network, which reaches out further into the offshore areas of the Dutch and German EEZ, included a higher species richness for species of conservation concern (Fig. 3D).

For the total of all 177 included species, the average overlap of CA with MPA was 51.14% ($\pm$21.14% S.D.). Including OWF until 2040 increased this figure to 60.59% ($\pm$19.07% S.D.).

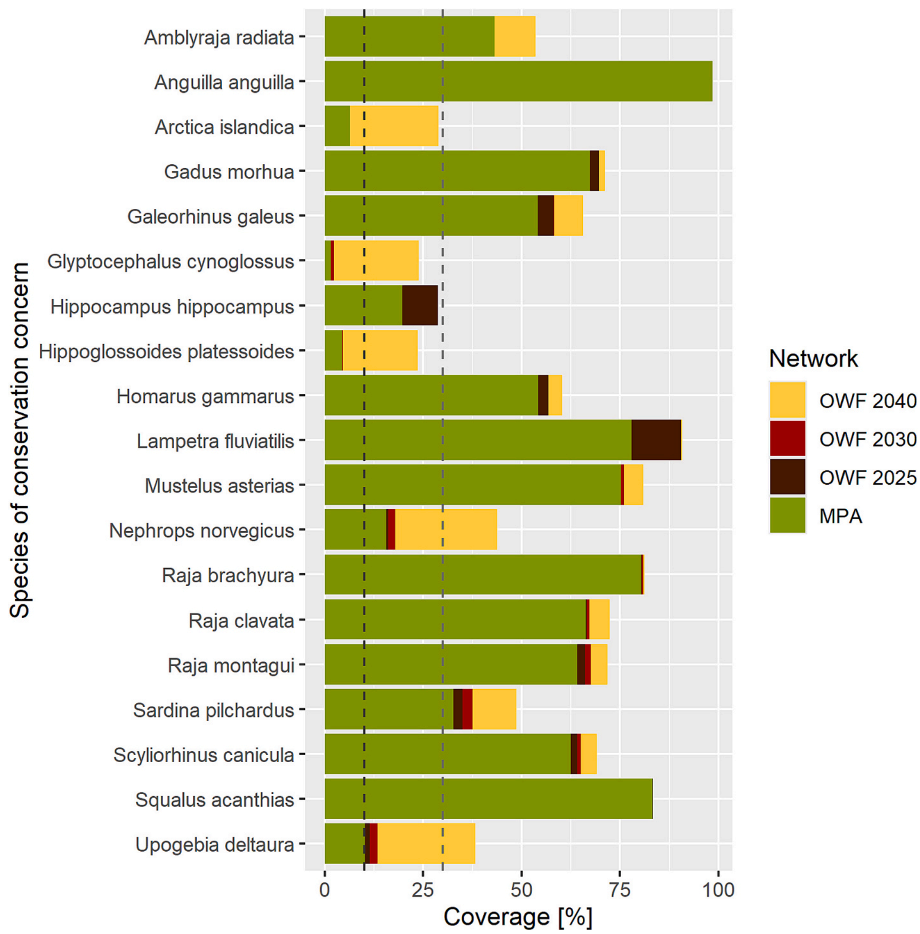

Fig. 4. Coverage of core areas (CA) of species of conservation concern with the network of marine protected areas (MPA) and additional overlap with offshore windfarms (OWF) installed by 2030 and 2040 in the Southern North Sea (SNS). Vertical dashed lines indicate 33% and 50% coverage targets.

3.4. Evaluating MPA & OWF networks

The overlay analysis addressing the question of how much CA-coverage could be achieved within different networks of MPA and OWF revealed that the CA of all but three species (ocean quahog *Arctica islandica*, witch *Glyptocephalus cynoglossus* and American plaice *Hippoglossus platessoides*) of conservation concern had a coverage of at least 10% by the existing MPA network (Fig. 4). A 30%-coverage by MPA was achieved for all but six species (ocean quahog, witch, American plaice, short-snouted seahorse *Hippocampus hippocampus*, Norway lobster *Nephrops norvegicus* and mud lobster *Upogebia deltaura*). Including the OWF 2040 network allowed to increase the coverage for Norway lobster and mud lobster to above 30%, and ocean quahog, witch and American plaice to above 25%. Short-snouted seahorse *Hippocampus hippocampus* was the only species which would benefit from the OWF 2025 network to come close to the 30%-coverage target.

On average, the OWF-2025 network could provide 2.0% (±3.4% S.D.), the OWF-2030 network 2.7% (±3.3% S.D.) and the OWF-2040 11.4% (±9.0% S.D.) additional CA-coverage. For the lobster *Upogebia deltaura*, for instance, the OWF-2040 network could additionally cover 24.9% of its CA, reaching a total coverage of 38.3% when combined with MPA network (Fig. 5).

The *prioritizR*-solutions showed that (i) a 10%-coverage of each species' CA could be achieved almost exclusively within the existing MPA network (except for 153 km^2 additional area needed, Fig. 6A & Table 2), while (ii) various extents of additional area would be required to achieve the 30%-coverage target (Fig. 6B–E & Table 2). If OWF are explicitly excluded from the conservation network, the largest demand of extra area of 1743 km^2 (S_{OUT}) would be needed to achieve the 30%-coverage target outside the OWF-2040 network (Fig. 6F & Table 2).

The additional area demands to reach the 10%- and 30%-coverage targets indicated a clear trade-off between the total extent of protected area (SA_{TOT}), area inside OWF (SA_{OWF}) and outside OWF (SA_{OUT}): When increasing S_{OWF} by including the OWF networks 2025, 2030 or 2040, the less S_{OUT} was required to achieve the 30%-coverage target, while S_{TOT} was increasing (Table 2 & Fig. 6).

4. Discussion

Our study provides the first regional assessment of the potential of MPA and window networks to contribute to spatial conservation targets for fish and epibenthic species. We show that the current transboundary MPA network covers 10% of the core areas (CA) for the majority of species of conservation concern. Furthermore, the areas designated to offshore wind development by 2040 could add substantially to the CA-coverage of these species allowing 15 out of 19 species to achieve the 30%-coverage target (with the other four species achieving more than 25% coverage). In particular species like mud lobster or Norway lobster, which are a habitat forming species of a sensitive habitat type defined by OSPAR ('Sea pen and deep burrowing mega-fauna communities', Gutow et al., 2020) might benefit from exclusions of trawled fisheries inside OWF.

In the SNS, the existing network of MPA seems to have a coverage gap in the northern and central parts of the SNS (Probst et al., 2021), which could be closed in different ways. One way would be to use OWF areas planned until 2040 to complement the existing MPA network to

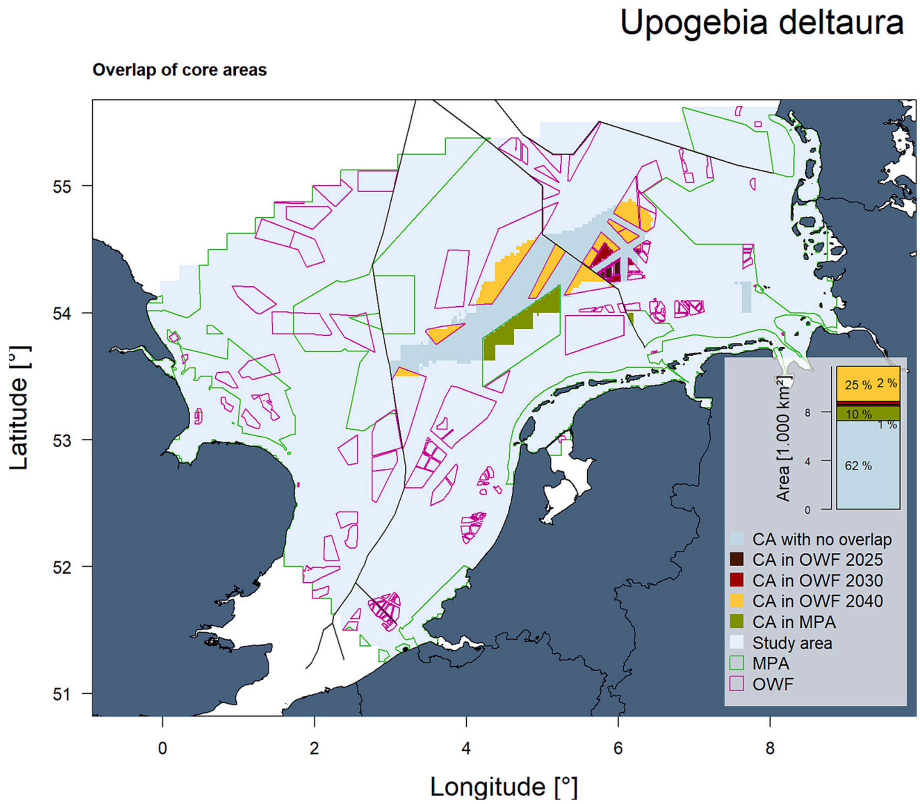

Fig. 5. Core area (CA) coverage of the mud lobster *Upogebia deltaura* by the network of marine protected areas (MPA) and offshore windfarms (OWF) installed by 2025, 2030 and 2040 in the Southern North Sea (SNS). The inset bar plot shows the absolute and relative areal coverage of the CA.

achieve a 30%-coverage of the majority of species of conservation concern. By contrast, if a 30%-coverage of these species should be achieved outside existing and planned OWF, 1743 km^2 of additional area were needed for spatial conservation measures, exacerbating the decrease in remaining space for other human activities such as shipping and fishing (Stelzenmüller et al., 2022; Kruse et al., 2024).

At this time, however, our analysis should be considered as a first approach to finding a spatially optimised solution for reaching the 10%- and 30%-coverage targets of the EU Biodiversity Strategy 2030 within SNS, as the following issues remain:

- The 10%- and 30%-coverage targets do not refer to single species, but benthic habitat groups. Seeking spatially optimised solutions for benthic habitat groups single species will therefore not yield the same results as for single species.
- The MPA network of SNS does not restrict human activities within its entire extent (Aminian-Biquet et al., 2024) and fisheries closures are only implemented in some parts of the MPA network (EC, 2023), while in other areas certain types of fishing with e.g. passive demersal or active pelagic gears might still be allowed, Also, many spatial management measures within MPA are still being negotiated between adjacent countries of the SNS. Hence a comprehensive compilation of the factual spatial extent and content of the spatial conservation measures within the MPA network is not yet available.
- The fulfilment of both coverage targets is the obligation of each single country, whereas our study implemented a comprehensive, transboundary approach. Thus, each country has to find the solutions to the 10%- and 30%-targets within its own national waters and accordingly, the final political solutions might deviate substantially from the solutions identified in our study. However, transboundary and cross-country cooperation has been acknowledged as an important aspect of effective MSP and our results provide a sound basis to identify priority sites for diversity hotspots or CA of single species within the MPA and OWF networks across the SNS (see Figs. 2 & 3).

While our results suggest that OWF have the potential to contribute to species conservation and may be beneficial in reaching biodiversity targets, it remains unresolved whether OWF could be designated as spatial conservation measures and contribute towards the protection and enhancement of biodiversity. Some non-governmental nature conservation agencies (NGO) argue that in spite of the restriction of fishing and shipping within OWF, the impacts through alterations to the natural seabed, changes in atmospheric and oceanographic currents and impacts of the construction and operation activities are too severe to consider OWF as OECM (NABU, 2023). Fish and epibenthic communities associated with OWF are expected to be impaired by the introduction of noise, pollution, particle motion and turbidity, or the establishment of electro-magnetic fields (Hasselman et al., 2023; Watson et al., 2024). Accordingly, OECM have been warned to be used as "blue-washing" machines for marine conservation, becoming nice-sounding labels to areas without any net-gain to biodiversity or in which the conservation of one species or ecological unit may mask threats to other components of the ecosystem (Claudet et al., 2022). Up to date it is therefore unclear if and how OWF could fulfil the criteria for becoming OECMs and according literature is scarce (but see Stephenson, 2023).

However, studies reveal that OWF can have beneficial impacts on the marine environment, stemming particularly from the artificial reef effect associated with the introduction of hard structures into habitats dominated by soft sediments and the reduction of mortality through the exclusion of fisheries from OWF (Degraer et al., 2020; Watson et al., 2024). Demonstrated ecological benefits are increased abundances of brown crab *Cancer pagurus* and Atlantic cod *Gadus morhua* around wind mill foundations (Stelzenmüller et al., 2021; Gimpel et al., 2023; Werner et al., 2024) as well as an increase in species richness for benthic invertebrate communities (Li et al., 2023). However, several marine bird

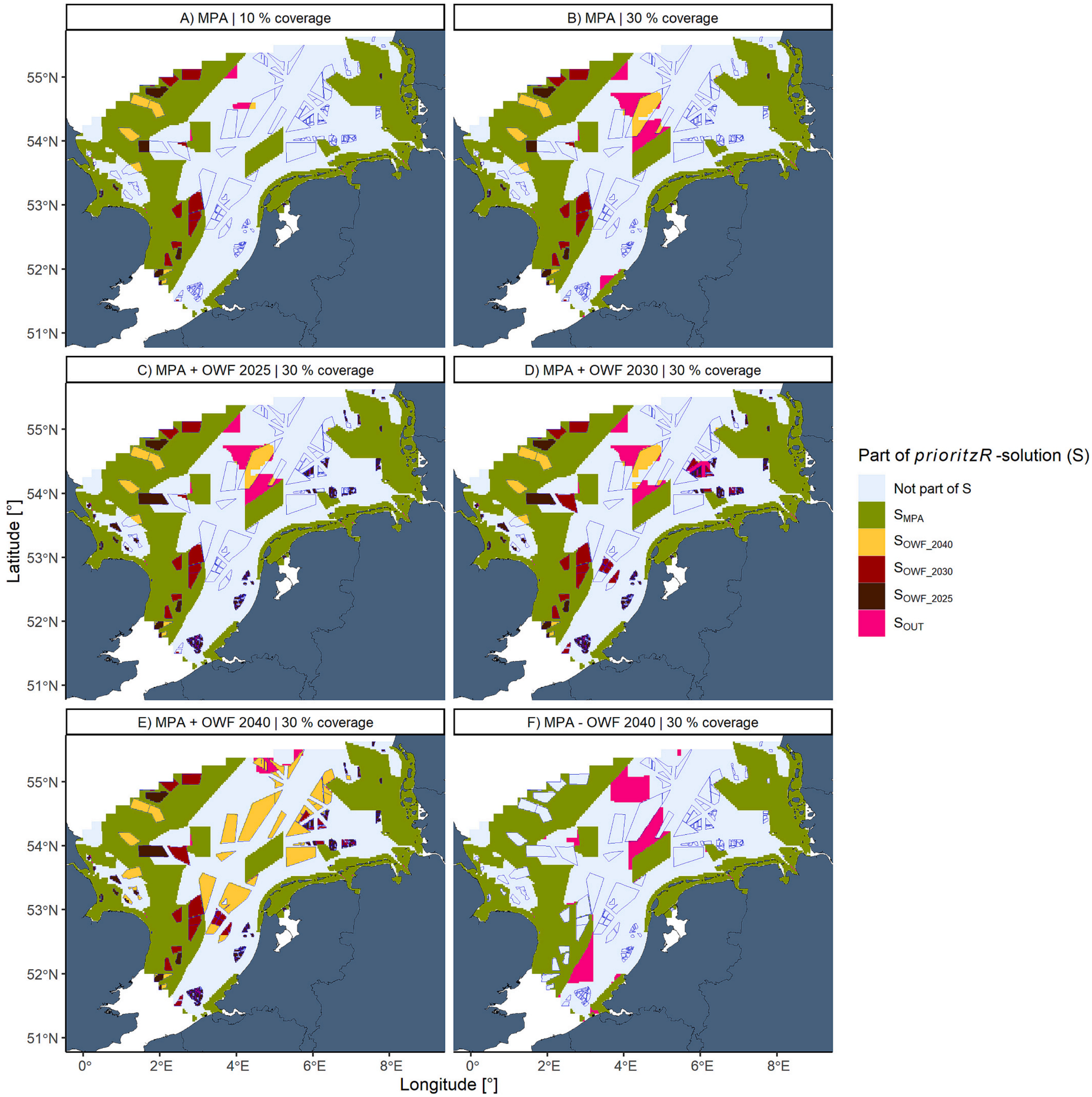

Fig. 6. Solutions (S) of the spatial optimisation problem (*prioritizR* in R) to achieve proportional coverage-targets within marine protected areas (S_{MPA}), within offshore windfarms (S_{OWF}) and outside either (S_{OUT}) for 19 species of conservation concern. A) 10%-coverage target within and outside the MPA network, (B-E) 30%-coverage target within and outside MPA the OWF network (blue outlines). F) Solution for 30%-coverage target within MPA but outside OWF. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

species such as loons are particularly affected by OWF and might pose serious challenges to biodiversity conservation targets (Garthe et al., 2023; Garthe et al., 2025).

Withstanding the unresolved issue of whether OWF could be designated as OECM, we argue that within an ecosystem-based approach to MSP additional functional layers such conservation measures for certain species should be added to OWF. For example, OWF might provide refuge for species vulnerable to demersal fishing and thereby complement the existing network of MPA by providing stepping stones for the recolonization of habitats in which species have become extirpated (Fock, 2014; Fock et al., 2014). Further, the implementation of nature-inclusive designs might support the re-establishment of once common species, e.g. oyster beds of the European flat oyster *Ostrea edulis*, which have been common and widespread in the SNS until the beginning of the 20th century (Bennema et al., 2020; Hermans et al., 2020). OWF can also provide new habitat to commercially attractive species such as brown crab *Cancer pagurus*, Atlantic cod *Gadus morhua* or European lobster *Homarus gammarus* (Stelzenmüller et al., 2021; Gimpel et al., 2023; Thatcher et al., 2023). OWF and marine conservation should therefore be thought more in conjunction by not only considering the mitigation of adverse effects during construction, operation and decommissioning, but also through the inclusion of active solutions that

Table 2
Area requirements for *prioritizR*-solutions (S) with different locked-in constraints (network) and relative spatial coverage targets in percent (for R-code see supplements S6.1). SA_{tot} = total area of solution, SA_{MPA} = Area of solution within marine protected areas, $SA_{OWF25/OWF30/OWF40}$ = area of solution within the network of offshore wind farms until 2025, 2030 & 2040. Colour shades represent area value from low (blue) to high (red).

Network	Coverage target	S_{TOT} [km²]	S_{MPA} [km²]	S_{OWF25} [km²]	S_{OWF30} [km²]	S_{OWF40} [km²]	S_{OUT} [km²]
MPA	10 %	15,605	14,034	307	984	1,418	153
MPA	30 %	16,730	14,034	307	984	1,827	869
MPA + OWF 25	30 %	17,191	14,034	857	1,534	2,361	796
MPA + OWF 30	30 %	17,540	14,034	857	1,938	2,708	798
MPA + OWF 40	30 %	19,425	14,034	857	1,938	5,136	255
MPA - OWF 40	30 %	15,777	14,034	0	0	0	1,743

support single species, species communities and biodiversity as a whole (Hermans et al., 2020).

This study designated CA to mobile demersal fish species and benthic epifauna by combining data from 10 years and three different scientific surveys. This allowed us to obtain comprehensive information on species distributions in space and time, which in turn allowed us to transform habitat preferences of mobile species into spatially explicit entities. However, it should be noted that location of CA of single species is also influenced by climate change (Perry et al., 2005; Dulvy et al., 2008; Núñez-Riboni et al., 2019; Oesterwind et al., 2022) and this has not been taken into account by this study. Hence, a new analysis using SDM and future climate data is pending, but might help to identify MPA and OWF areas with future conservation value.

The identification of CA for mobile species is an important prerequisite for their consideration into MSP (and likewise terrestrial conservation planning). Our study thereby provides a contribution to transboundary, regional MSP by identifying spatial entities for mobile ecosystem features such as demersal fish species and epibenthos. We also provide an empirical framework to evaluate OWF as spatial conservation instruments in MSP, thereby establishing coherence to EU biodiversity policy targets. Spatial overlap between OWF and a species' CA is a direct metric for the OECM criterion of sustained and effective contributions to in situ conservation. To allow for a comprehensive assessment on the full potential (and eventual caveats) of OWF as spatial conservation tools in MSP, we recommend to extend this analysis to a comprehensive suite of relevant ecosystem features including benthic habitats (Kenny et al., 2018), pelagic habitats, sea birds (Garthe et al., 2023; Schwemmer et al., 2023; Garthe et al., 2025) and marine mammals (Gilles et al., 2009). Our three-step-workflow of defining core areas of relevant ecosystem components, analyse the overlay of core areas and potential conservation sites and finding optimised solutions for spatial conservation targets could be adapted to other marine regions to facilitate the alignment of MSP and biodiversity policy targets.

CRediT authorship contribution statement

W. Nikolaus Probst: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jennifer Rehren:** Writing – review & editing, Writing – original draft, Formal analysis. **Casper Kraan:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Holger Haslob:** Writing – review & editing, Data curation. **Hermann Neumann:** Writing – review & editing, Data curation. **Carsten Lemmen:** Writing – review & editing, Writing – original draft, Data curation. **Shubham Krishna:** Writing – review & editing, Project administration, Data curation. **Maren Kruse:** Writing – review & editing, Formal analysis. **Kai Wirtz:** Writing – review & editing, Writing – original draft, Project administration, Data curation. **Vanessa Stelzenmüller:** Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgements

This study was funded by the German Federal Ministry of Education and Research as part of the FONA-project "Multiple Stressors on North Sea Life" (MuSSeL, grant numbers 03F0862A, 03F0862D www.mussel-project.de). This work was also supported by the European Union's Horizon 2020 research and innovation programme HORIZON-CL6–2021-BIODIV-01–12 under grant agreement No 101059407 "MarinePlan – Improved transdisciplinary science for effective ecosystem-based maritime spatial planning and conservation in European Seas". The comments and suggestions by two anonymous reviewers to improve this manuscript were highly appreciated.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2026.111771.

Data availability

Data on modelled species distributions (POC) and core areas (CA between 2014 and 2023 are available at Zenodo (https://zenodo.org/records/15279371). Survey data is publicly available at the ICES DATRAS portal (https://datras.ices.dk).

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