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RESEARCH ARTICLE

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Come, tell me how you live: Habitat suitability analysis for *Ostrea edulis* restoration

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Abstract

1. Against the background of the UN decade on ecosystem restoration and the new EU Biodiversity Strategy for 2030, and in the context of marine spatial planning and complex maritime user conflicts, reliable information on habitat suitability for large-scale restoration is an important prerequisite for implementing conservation management and for supporting successful, sustainable, and ecologically efficient restoration measures.
2. In this study, habitat suitability was assessed using multicriteria decision analysis (MCDA) for the restoration of the European oyster, *Ostrea edulis*, in marine protected areas (MPAs) of the German Bight in the North Sea: Borkum Reef Ground (*Borkum Riffgrund*, BRG) and Sylt Outer Reef – Eastern German Bight (*Sylter Außenriff*, SAR).
3. Based on site selection criteria, exclusion and suitability factors for the MCDA were defined. Results were integrated with the available geodata to produce habitat suitability maps for oyster restoration in the area of interest.
4. Suitable as well as unsuitable habitats have been successfully identified for both MPAs: several hundred square kilometres (≥97.2% of BRG) or several thousand square kilometres (≥74.5% of SAR) were classified as ecologically and logistically suitable for oyster restoration measures in the respective MPAs. As oyster restoration is significantly limited by human activities (e.g. bottom trawl fisheries), the management of fisheries is an important prerequisite for successful oyster restoration in both MPAs. Results show that designated fishery management measures will increase the possibilities for oyster restoration.
5. In BRG, our results correspond to the known historical distribution. In SAR, our results significantly exceed the historically known distribution. The habitat suitability analysis will facilitate decision-making regarding ocean use, and will

reduce restoration costs through targeted management activities in areas of high suitability and expand species recovery by improving the survival of reintroduced individuals.

6. The habitat suitability analysis procedure is easily adaptable for application to other areas, other species, or other habitat restoration projects, or to other conservation management settings. The software applied is open source and the suitability calculation is described in detail to inform wider applications.

KEYWORDS

coastal, ecological restoration, ecosystem services, invertebrates, marine protected area, reef

1 | INTRODUCTION

The years 2021–2030 have been declared as the UN decade on Ecosystem Restoration (UNEP/FAO, 2020). From a global perspective, the political will and the ecological need for the successful implementation of large-scale restoration are well defined (e.g. Gann et al., 2019). The ecological restoration of terrestrial and freshwater ecosystems has advanced substantially over the last few decades but, worldwide, critically degraded and ecologically relevant marine habitats are now also moving into focus (Bekkby et al., 2020; Pogoda et al., 2020b). An example of ecological key habitats of temperate marine regions are oyster reefs: as ecosystem engineers, they provide food, shelter, and spawning grounds for many species, and create habitats considered to be hotspots of biodiversity. Moreover, they improve water quality through their capacity for filtration, consolidate loose sediments, and increase benthic–pelagic coupling (Hancock & zu Ermgassen, 2019; zu Ermgassen et al., 2020).

In Europe, the native oyster *Ostrea edulis* and the habitat it provides are considered as threatened and/or declining (OSPAR, 2008; OSPAR, 2013). *Ostrea edulis* is a key species, providing essential ecosystem functions and services, for which several conservation and restoration frameworks apply (Coen et al., 2007; Grabowski & Peterson, 2007; Pogoda et al., 2020b). Historically, it covered large areas of the North Sea and adjacent coastal waters. As a sublittoral species, it was found at depths of up to 50 m, forming biogenic reefs in the so-called offshore oyster grounds (Olsen, 1883; Airoldi & Beck, 2007; Pogoda, 2019). During industrialization and the transition to motor-driven dredging technologies, the exploitation of this valuable resource exceeded the natural capacities of recovery. In the course of the 20th century, massive fishing pressure led to a Europe-wide collapse of oyster populations and the total loss of these habitats in many European regions (Berghahn & Ruth, 2005; Lotze et al., 2005; Thurstan et al., 2013; Gercken & Schmidt, 2014; Pogoda, 2019).

Today, a number of restoration actions for the native oyster are underway. At the same time, the European Union calls for large-scale marine restoration (UNEP/FAO, 2020; EU COM, 2020b; EU COM, 2022b), with the new EU Biodiversity Strategy for 2030 (EU COM, 2020a) and the corresponding goals to establish a coherent and representative network of marine protected areas (EU COM, 2022a). As part of the strategy, the EU commission has proposed a new EU Nature Restoration law that includes binding restoration targets for specific habitats, including oyster reefs (EU COM, 2022b). This is also designed to achieve a good environmental status according to the Marine Strategy Framework Directive (MSFD) in European seas and a favourable conservation status in marine protected areas (MPAs) of the Natura 2000 network (European Parliament, 1992; European Parliament, 2008).

Germany has already defined so-called environmental targets in 2012 and 2018 as part of the implementation of the MSFD. One of the environmental targets includes the reintroduction of locally extinct or endangered species such as *O. edulis* (BMU, 2012; BMU, 2018). This comes with an obvious demand to identify appropriate areas where these restoration efforts can be realized (Pogoda, 2019; Pogoda et al., 2020a; Pogoda et al., 2020b).

In the German exclusive economic zone (EEZ), Borkum Reef Ground (*Borkum Riffgrund*, BRG) and Sylt Outer Reef – Eastern German Bight (*Sylter Außenriff*, SAR) are MPAs for which active conservation measures, including the restoration of biogenic reefs, namely of the native oyster, have been defined (BfN, 2020a). Pilot oyster reefs have been set up in BRG and have been constantly monitored, with the aim of providing the technological and biological background required for the necessary upscaling and further implementation process of such active restoration measures (Pineda-Metz et al., this issue). As part of the site selection process, a comprehensive list of site-selection criteria was compiled (Pogoda et al., 2020b): among those are abiotic (e.g. temperature and hydrodynamics) and biotic factors (e.g. food availability), as well as logistical factors (e.g. contraindicated other uses), and other aspects that have either positive or negative effects on the final suitability of habitats for reef restoration (Pogoda et al., 2020b). For example, fisheries with mobile bottom-contacting gears (e.g. bottom otter trawls, beam trawls, etc.), currently targeting other demersal species (e.g. plaice, sole or brown shrimp), are a major obstacle to the reintroduction of European oysters and the restoration of biogenic reefs, as the oysters are not able to withstand the physical impacts of bottom trawling (Beck et al., 2011; zu Ermgassen et al., 2012; Cook et al., 2013; Gillies et al., 2018). Bottom trawling is a widespread fishing practice in European MPAs (Dureuil et al., 2018), but designated European Common Fisheries Policy (CFP) measures will exclude bottom-contacting fishing gear from BRG and SAR (EU COM, 2023). Also, other user conflicts impact site selection: underwater cable laying and removal, or sand and gravel extraction put the logistical and ecological success of restoration at risk and must be considered when selecting sites (Pogoda et al., 2020b).

Against this background, the identification and designation of appropriate areas for such (larger) restoration measures within the MPAs are crucial next steps. Habitat suitability analysis is therefore an ideal tool if relevant (geo)data are available to inform the performance models (Questad et al., 2014; Puckett et al., 2018; zu Ermgassen et al., 2020; Pogoda et al., 2020b).

The aim of this study was to perform a habitat suitability analysis by applying multicriteria decision analysis (MCDA) for the identification of suitable habitat areas for the reintroduction of *O. edulis* within the BRG and SAR MPAs in the North Sea (Figure 1). MCDA relies on an analytical hierarchy process (AHP) for rational decision-making by including expert opinions and suitability data in the derivation of a quantitative decision formula (e.g. Saaty, 1977). Especially in recent years, the method has been widely applied in different scientific and practical fields with a spatial focus, such as the spatial planning of on- and offshore wind farms (Höfer et al., 2016; Sánchez-Lozano, García-Cascales & Lamata, 2016; Gkeka-Serpetsidaki & Tsoutsos, 2021; Kim et al., 2021), the calculation of risk maps for natural hazards (Pourghasemi, Pradhan & Gokceoglu, 2012; Ghosh & Kar, 2018; Saha et al., 2019), as well as water and soil management in agricultural applications (Romeijn et al., 2016; Saranya & Saravanan, 2020; Zandi et al., 2020; Dar, Rai & Bhat, 2021). The chosen approach provides suitability maps and is expected to be applicable beyond the marine geographic setting of this study.

2 | MATERIALS AND METHODS

2.1 | Site selection criteria and data acquisition

Relevant site selection criteria were adopted from the literature (e.g. Kamermans et al., 2018; Pogoda et al., 2020b; Hughes et al., 2023) and are displayed in Table 1. The listed criteria include ecologically relevant criteria, reflecting the ecological tolerance of the target species *O. edulis*, as well as specific logistically relevant criteria, affecting restoration implementation and long-term success. Several criteria were considered as exclusion factors (EFs; Table 1), e.g. salinity below or above the tolerance limits or areas with marine underwater cables (Pogoda et al., 2020b). All other criteria were considered as suitability factors (SFs; Table 1) and were applied in the AHP as described below.

Available geodata were searched comprehensively for the selected criteria (Table 1). Data were retrieved from different sources,

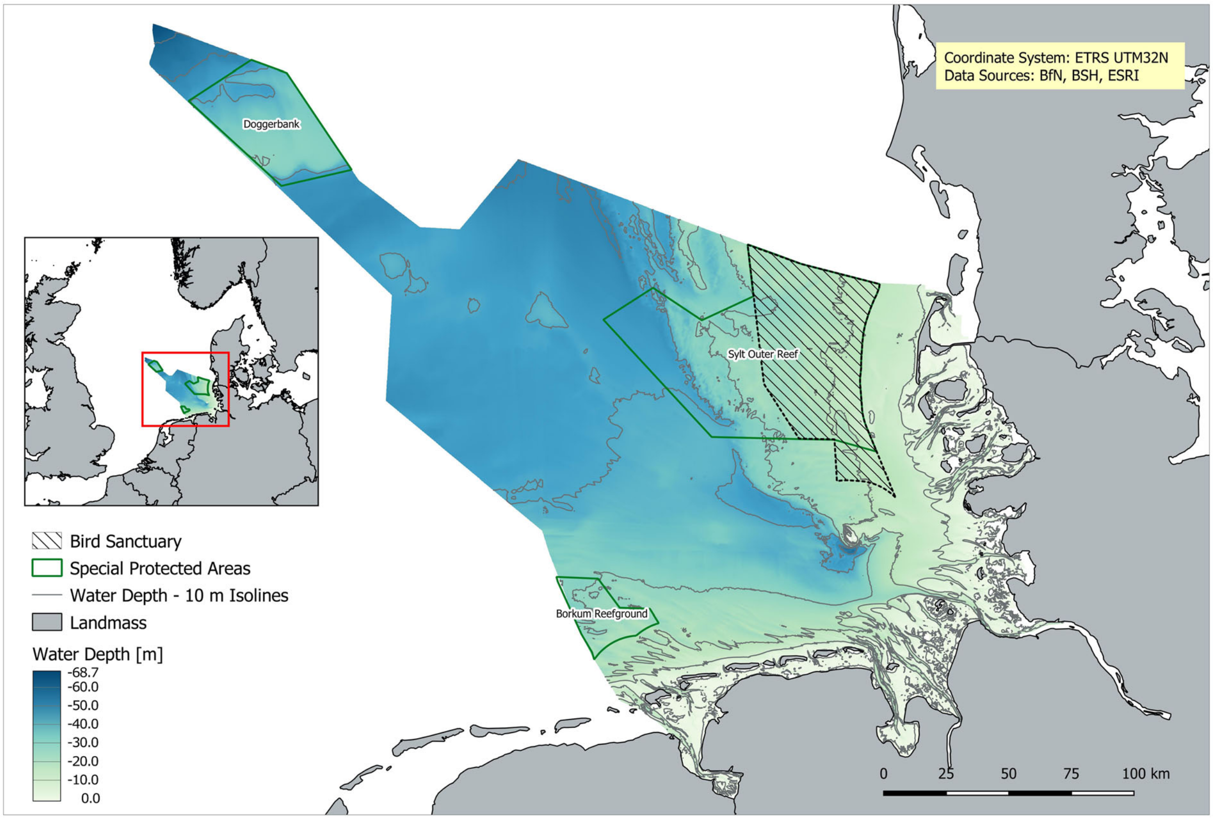

FIGURE 1 German Bight, with the marine protected areas (MPAs) Borkum Reef Ground (BRG) and Sylt Outer Reef – Eastern German Bight (SAR), including the bird sanctuary, and Doggerbank (DGB), in the German Exclusive Economic Zone (EEZ) of the North Sea.

TABLE 1 List of factors considered as site selection criteria relevant for native oyster reef restoration in the MPAs Borkum Reef Ground (BRG) and Sylt Outer Reef – Eastern German Bight (SAR). Factors were either defined and considered as exclusion factors (EF 1–7; A) for the analytical hierarchy process (AHP) or as suitability factors (SF 8–20) for the AHP. SF 8–18 (B) were considered in the AHP. SF 19–20 (C) were not considered in the AHP (limited data availability). For EF 4 only munition dumping areas were considered in the AHP. Three perception levels (level 1, ecologically suitable oyster restoration areas; level 2, logistically and ecologically suitable oyster restoration areas (without fishery); and level 3, logistically and ecologically suitable oyster restoration areas – right columns) include different combinations of factors.

A	EFs	Background	Reference(s) (data source)	Level 1	Level 2	Level 3
1 eco	Temperature <1.5 °C in winter >30 °C in summer	Winter minimum: 1.5 °C Summer maximum: 30 °C Optimal range: 7–25 °C *Ostrea edulis* starts feeding at >7–9 °C Spawning is induced at >15–16 °C.	(Korringa, 1952; Walne, 1979; Buxton, Newell & Field, 1981; Laing, 2005; Ashton & Brown, 2009; Kamermans et al., 2018; BSH, 2021; Colsoul et al., 2021)			
2 eco	Salinity <20 PSU >36 PSU	*O. edulis* survives down to 20 PSU (at temperatures of <20 °C). Optimal range: >30 PSU	(Hutchinson & Hawkins, 1992; Laing, Walker & Areal, 2005; HZG, 2013; Colsoul et al., 2021)			
3 eco	Oxygen < 3.5 mg L^{-1}	*O. edulis* may be relatively tolerant of low oxygen concentrations Hypoxia thresholds for short-term survival are 3.5 mg L^{-1}	(Laing, Walker & Areal, 2005; Vaquer-Sunyer & Duarte, 2008; Smaal et al., 2017; BSH, 2021)			
4 log	Military area and munition dumping	Potential impact of dangerous goods for operations and for ecological health of the habitat	(Brenner, Bostelmann & Kloepper, 2017; BSH, 2017; North.io GmbH, 2020; BSH, 2020b)			
5 log	Offshore cables and pipelines	Destruction and potential negative impact during installation, construction, and removal works	(BSH, 2017; BSH, 2020b; Pogoda et al., 2020b; EMODnet, 2021)			
6 log	Wind farms	Destruction and potential negative impact during installation, construction and removal works	(BSH, 2017; BSH, 2020b; Pogoda et al., 2020b; EMODnet, 2021)			
7 log	Wrecks	Underwater obstacles are defined as dangerous areas and must be avoided or passed at a safe distance	(Krone & Schröder, 2011; BSH, 2020a; Pogoda et al., 2020b)			
B	**SFs considered in AHP**	**Background**	**Reference(s) (data source)**			
8 log	Fishing intensity (mobile bottom-contacting gears)	Potential negative impact of mobile bottom-contacting fisheries habitat restoration and the ecological status of the habitat	(Pogoda et al., 2020b; Global Fishing Watch, 2021)			
9 log	Shipping (vessel density)	Potential impact of anchoring, noise, and pollutants for ecological health of the habitat. Potential impact of ship traffic for restoration operations	(Falco et al., 2019; Pogoda et al., 2020b)			
10 eco	Depth, 0–50 m	*O. edulis* is common at 0–30 m and is reported to live in depths up to 80 m. Information on preferred depth is not available	(Hutchinson & Hawkins, 1992; Laing, Walker & Areal, 2005; Hayward & Ryland, 2017; BSH, 2020a)			
11 eco	Slope	Remnant fossil oyster bed indicates preferences of *O. edulis* for certain sea bed gradients	(BSH, 2020a; Sander et al., 2021)			
12 eco	Roughness	Remnant fossil oyster bed indicates preferences of *O. edulis* for certain sea bed roughness	(BSH, 2020a; Sander et al., 2021)			
13 eco	Shear stress < 0.6 N m^{-2}	The development of flat oyster beds is not likely at a shear stress of >0.6 N m^{-2}	(HZG, 2014; Kamermans et al., 2018)			
14 eco	Chlorophyll concentration	Chl *a* to be considered for months with temperatures of >7 °C, because of filtration activity of *O. edulis*. Optimal concentration 2–3 µg L^{-1}	(Rogan & Cross, 1996; Laing, Walker & Areal, 2005; Ashton & Brown, 2009; BSH, 2021)			
15 eco	Substrate quality: sediment types	*O. edulis* is intolerant to high turbidity environments: silt and fine sand	(Kamermans et al., 2018; Bennema, Engelhard &			

TABLE 1 (Continued)

B	SFs considered in AHP	Background	Reference(s) (data source)
			Lindeboom, 2020; Colsoul et al., 2020; Pogoda et al., 2020b)
16 eco	Substrate quality: grain size > fine sand	Settled *O. edulis* are found from medium sand to hard substrates Mud content (as the relative fraction with grain sizes of <63 µm or mud%) is correlated with grain size, historical flat oyster beds in the North Sea were located in areas with mud% of approx. 1%–50%	(Kamermans et al., 2018; Bennema et al., 2020; Colsoul et al., 2020; Pogoda et al., 2020b)
17 eco	Benthic communities	*O. edulis* may favour areas of the soft bottom community *Goniadella–Spisula*	(Schönrock, 2016; Pogoda et al., 2020b)
18 eco	Biotopes	*O. edulis* may favour areas of species-rich coarse sand, gravel, and shell gravel (CGS) biotopes	(BfN, 2017; Kamermans et al., 2018; Colsoul et al., 2020; Pogoda et al., 2020b)
C	**SFs not considered in AHP (no data available for target areas)**	**Background**	**Reference(s)**
19 eco	Turbidity low	*O. edulis* is not tolerant to high turbidity environments: e.g. silt or fine sand	(Korringa, 1952; Yonge, 1960; Hutchinson & Hawkins, 1992)
20 eco	Current velocity range 0.05–0.45 m s^{-1}	Minimum current velocities of 0.05–0.1 m s^{-1} are necessary to avoid sedimentation and sediment accumulation. High (daily tidal) current velocities (0.45 m s^{-1}) result in low growth rates of *O. edulis*	(Ashton & Brown, 2009; Pogoda, Buck & Hagen, 2011)

Abbreviations: Eco, ecologically relevant factors; log, logistically relevant factors.

such as national monitoring programmes (e.g. BSH, 2020a; EMODnet, 2021), and in different formats and resolutions (Table 1). The data comprise constraint and threshold (exclusion) and decision or suitability variables of both categorical and metric scales. Corresponding geodata were acquired as vector data, tabular event tables, and raster data. Raster resolutions range from 50 m for bathymetry data to approximately 3,200 m for shear stress data. The vector data provided are documented for a spatial scale range from 1:10,000 (sediment types derived from backscatter data) to 1:200,000 (sediment types derived from sample data).

For the identification of exclusion zones for oyster restoration, corresponding delineation data of the respective EFs were acquired (Table 1). Both line and point data were buffered with a distance of 25 m, leading to a 50-m-wide raster cell representation of offshore cables, pipelines, and wrecks. Together with the data on offshore wind farms and munition dumping grounds, a set of Boolean raster data sets was integrated as constraint variables in the suitability mapping procedure.

Areas that exceed critical environmental thresholds were identified with raster data: whereas data on salinity were available as gridded points of approximately 3,200-m spacing, data on water temperature and dissolved oxygen were provided as tabular data with coordinates (Table 1). The data were classified according to winter and summer months, integrated in R (R Core Team, 2019), transformed to point vector data, and then interpolated to raster data via geostatistical methods.

Identified SFs served as decision variables (Table 1) and were included in the AHP procedure: fishing activity was quantified by data from Global Fishing Watch (Merten et al., 2016). Tracking data were processed together with satellite imagery data via machine learning procedures to model the fishing pressure on a spatial resolution of 1 km as hours of fishing within a raster cell of 0.01°. Data sets for 2019 and 2020 were filtered for gear types flagged as bottom trawling and averaged (Figure S2). For shipping density, modelled data on vessel densities were acquired from the Environmental Monitoring and Observation Network – Lot Human Activities at a resolution of 1,000 × 1,000 m (Falco et al., 2019). The map illustrates the total ship presence time on a 1-km grid per year. Here, the average of 2019 and 2020 observations was considered. Bathymetry data were acquired at a resolution of 50 × 50 m. From this, slope and roughness were derived according to Burrough and McDonnell (1998) and Wilson et al. (2007), respectively, and then included in the AHP procedure as SFs. A modelled data set for sea bed shear stress was acquired in N/m^2 at a resolution of approximately 3,200 m (HZG, 2014) to represent current effects on the sea floor and benthic communities. Data on chlorophyll *a* content in the upper water column were acquired as tabular data with coordinates covering the entire North Sea area (BSH, 2021), and were then transformed to point vector data, interpolated using geostatistical methods, and clipped to the areas of interest. Median grain sizes were derived from Bockelmann et al. (2018), and grain size parameters and distributions in North Sea surface sediments were integrated via geostatistical techniques. Historical data on former flat oyster beds indicate the importance of muddy sand sediments (Bennema, Engelhard & Lindeboom, 2020). In this study, grain size data with mud content as a trend variable were acquired (Bockelmann et al., 2018), including the correlation between median grain sizes and mud content. The data were accessed with a spatial resolution of 0.06°. Data on sediment types were available in different spatial resolutions. For BRG and parts of SAR, high-resolution vector data on sediment types were produced and provided by Propp et al. (2016), based on side-scan sonar mosaics, according to a hierarchical sediment classification system at a resolution of 1:10,000 (Richter et al., 2019; Holler et al., 2019a; Holler et al., 2019b; Holler et al., 2020; Richter et al., 2020). For data gaps, a sediment-type polygon map created by Laurer, Naumann & Zeiler (2013) was applied (documented scale: 1:200,000). Data on benthic communities were available at a resolution of 100 × 100 m for BRG (Pesch et al., 2016; Pogoda et al., 2020b) and of 1,000 × 1,000 m raster for SAR (Schönrock, 2016), which had been identified from benthic infauna sample data by fuzzy clustering and spatially predicted by random forests: two communities for BRG (*Goniadella–Spisula* and *Tellina fabula*) and four communities for SAR (*Goniadella–Spisula*, *Nucula nitidosa*, *Phoronis*, and *T. fabula*). For the predicted occurrence of the biotope type 'species-rich coarse sands, gravel, and shell gravel' (CGS), polygon data at a 230 × 230 m resolution was derived from both infauna and sediment sample data and full coverage data on bathymetry, slope, grain size ranges, and sediment types, using a machine learning approach (Schuchardt et al., 2017).

2.2 | Data processing and standardization

All data processing and standardization steps were performed using the statistical open-source software R and Python programming language. Important packages for (spatial) data processing included sp, raster, rgdal, rgeos, pandas and geopandas.

For the AHP calculations, all geodata were transformed into an identical raster of 50 × 50 m resolution for the UTM32 N coordinate system (ETRS89) and then converted into a suitability score system, scored between 1 (optimal for oyster restoration) and 6 (unsuitable for oyster restoration). Whereas for all raster data sets (including tabular ASCII data) resampling procedures were applied, the polygon vector data were transformed to a raster data set by polygon-to-raster transformation. Here, the category was assigned to the respective cell exhibiting the highest area coverage.

Except for the fisheries data, all metrically scaled variables were reclassified into the six suitability classes using equally sized intervals followed by an assignment of categorial suitability scores (1–6): 1, 1.00–1.49; 2, 1.50–2.49; 3, 2.50–3.49; 4, 3.50–4.49; 5, 4.50–5.49; 6, 5.50–6.00. For fishing activity (here, bottom trawling), a manual classification was applied because of the great impact of this variable on the decision process (see below). Based on fishing hours per year and a 0.01° grid cell, six classes were defined: 1, 0 h/a; 2, <1 h/a; 3, 1–2 h/a; 4, 2–3 h/a; 5, 3–4 h/a; 6, >4 h/a).

Both sediment classifications comprise a multitude of different sediment types, which were assigned to suitability scores for the AHP calculations by expert judgement. Solid sea floor was judged to be a score of 1, being preferred over loose sediments. Accordingly, higher scores were assigned to sediment types with decreasing grain size. Raster data on benthic communities were grouped into two suitability scores for *Goniadella–Spisula* (suitability score = 1) and all other communities (suitability score = 6). For the CGS biotopes a score of 1 was assigned if the biotope was present, otherwise a score of 6 was assigned to the respective raster cell. Data ranges, units, and distributions of suitability factors considered in the AHP are provided in Pogoda et al. (2022).

2.3 | Analytical hierarchy process

The AHP was performed in R with the R package ahpsurvey. It is a general technique that allows decision-making based on multiple criteria (Saaty, 1977). Within the algorithm, the subjective importance of each factor is estimated against every other factor separately and stepwise, resulting in pairwise factor comparisons (e.g. sediment types vs fisheries pressure). To quantify pairwise importance, an arbitrary scale spanning nine points was introduced (Saaty, 1987). Numerals >1 express relative significance, whereas fractions express relative insignificance, in a given comparison (Figure 2): 1/9, one-ninth relative insignificance of factor A compared with factor B; 1, equal importance between factors A and B; and 3, a three times stronger relative importance of factor A compared with factor B (Eastman, 1999). Resulting factor comparisons are integrated into a $n \times n$ matrix, with n being the number of factors (Figure 2). As reverse relative factor weights are reciprocal and the major diagonal is filled with ones, a total number of $1/2\ n(n-1)$ pairwise weights need to be compiled. In this study, Saaty's original approach of solving n factorial weights (using the matrix's principal eigenvector) was adapted to an arithmetical approach: Matrix values were first normed by the column sum and then were averaged row-wise producing the final set of weights (Eastman, 1999). In order to compare spatially distributed factors of different scales, it is essential to standardize the factors into a (convenient) numeric scale, from 1 (optimal) to 6 (unsuitable). The suitability of a certain location x can be expressed as a summation of n linear combinations of the standardized factor values $X(x)$ and the obtained weights w_i as in equation 1 (Eastman, 1999). By the product, m excluding attributes can constrain the summation to a suitability of $S(x) = 0$, when the constraining data set $C(x)_j$ is set to 0.

$$S(x) = \sum_{i=1}^{n} w_i X(x)_i \times \prod_{j=1}^{m} C(x)_j, \quad C(x)_j \in \{0,1\}$$

FIGURE 2 (a) Extract of a pairwise comparison questionnaire: 1/9 = relative insignificance; 1 = equal importance; 3 = a three times stronger relative importance. Please note: salinity was considered a suitability factor (SF) earlier in the analysis, and hence was included for comparison against other SFs, but was later defined as an exclusion factor (EF) and not included in the weighting. (b) Example of a cross table resulting from one pairwise comparison of suitability criteria.

(a)

			Feature 1 is x times important as Feature 2								
No	Feature 1	Feature 2	1/9	1/7	1/5	1/3	1	3	5	7	9
1	Depth	Slope						x			
2	Depth	Roughness									
3	Depth	Sediment_type		x						x	
4	Depth	Median_Grain_Size		x							
5	Depth	Modelled_biotopes					x				
6	Depth	Benthic_communities					x				
7	Depth	Chlorophyll-A			x						
8	Depth	ShearStress		x							
9	Depth	Salinity								x	
10	Depth	Ship_density							x		
11	Depth	Fishing	x								
57	Chlorophyll-A	ShearStress		x							
58	Chlorophyll-A	Salinity								x	
59	Chlorophyll-A	Ship_density							x		
60	Chlorophyll-A	Fishing	x								
61	ShearStress	Salinity								x	
62	ShearStress	Ship_density								x	
63	ShearStress	Fishing		x							
64	Salinitiy	Ship_density			x						
65	Salinitiy	Fishing	x								
66	Ship_density	Fishing	x								

(b)

	Benthic communities	Biotopes	Chlorophyll	Depth	**Fishery**	Roughness	Sediment types	Shear stress	Slope	Substrate grain size	**Vessel density**
Benthic communities	1	3	1	1	1/9	7	5	1/7	7	5	5
Biotopes	1/3	1	1/3	1	1/9	5	3	1/7	7	3	3
Chlorophyll	1	3	1	5	1/9	7	1/3	1/7	9	1/3	5
Depth	1	1	1/5	1	1/9	7	1/7	1/7	3	1/7	5
Fishery	9	9	9	9	1	9	9	7	9	9	9
Roughness	1/7	1/5	1/7	1/7	1/9	1	1/5	1/7	5	1/5	1/5
Sediment types	1/5	1/3	3	7	1/9	5	1	1/3	5	1	5
Shear stress	7	7	7	7	1/7	7	3	1	9	3	7
Slope	1/7	1/7	1/9	1/3	1/9	1/5	1/5	1/9	1	1/5	1/5
Substrate grain size	1/5	1/3	3	7	1/9	5	1	1/3	5	1	5
Vessel density	1/5	1/3	1/5	1/5	1/9	5	1/5	1/7	5	1/5	1

For the assessment of weights between all factors, a spreadsheet survey form was prepared for respective experts actively engaged in oyster restoration projects. The six qualified biologists (with expertise in marine biology, zoology, and ecology, as well as in marine spatial planning and conservation management) provided their ranking for the 11 continuous marine features in a set of 55 pairwise comparison weightings (Figure 2). The median average of the six individual sets of AHP weights resulting from AHP matrices was considered to reduce the influence of single diverging expert judgements with the arithmetic mean.

2.4 | Automatization and implementation

To achieve applicability of the procedure for future suitability calculations in corresponding projects at national or international scales, all operations were set up in R language with additional tools built in Python and published as a commented notebook on GitHub: https://github.com/markorothe/oyster_restauration_mcda.

3 | RESULTS

Comparing the corresponding raster values of the environmental parameters of salinity, water temperature, in respective winter and summer months, and dissolved oxygen in summer months with the identified thresholds (Table 1), no areas within the investigated MPAs exceeded these thresholds. Hence, EFs only demonstrated relevance for logistical criteria (Table 1). By applying the R script (Figure S1), weights for each of the decision variables (SFs) were derived from the AHP. The survey answers diverged for some criteria, but fishing density, shear stress, and chlorophyll *a* were identified as being most

TABLE 2 Resulting weights of the 11 suitability factors (SFs) after applying the R script in the analytical hierarchy process (AHP).

SF	Weights
Fishing intensity (mobile bottom contacting gears)	0.3319
Shear stress	0.1618
Chlorophyll a	0.1225
Benthic communities	0.0672
Median grain size	0.0671
Sediment type	0.0630
Depth	0.0483
Shipping (vessel density)	0.0478
Coarse sand, gravel, and shell gravel (CGS) biotopes	0.0416
Slope	0.0193
Roughness	0.0188

relevant, whereas roughness and slope were weighted as least relevant (Table 2).

Considering EFs as well as weighted SFs, sets of suitability maps were calculated and produced for both of the MPAs investigated, BRG and SAR, providing three different perception levels by differentiating ecologically relevant factors against logistically relevant factors (Table 1). Level 1 includes ecologically relevant features only, indicating all ecologically suitable oyster restoration areas and explicitly not considering other marine uses (Figures 3a and 4a, Table 3). Level 2 includes ecologically relevant features plus all existing user groups with respective occupied or inadequate areas, indicating technically and ecologically suitable oyster restoration areas, but excluding bottom trawling activity (Figures 3b and 4b; Table 3). Level 3 includes all identified factors: ecologically relevant features and all existing marine uses, including bottom trawl fisheries,

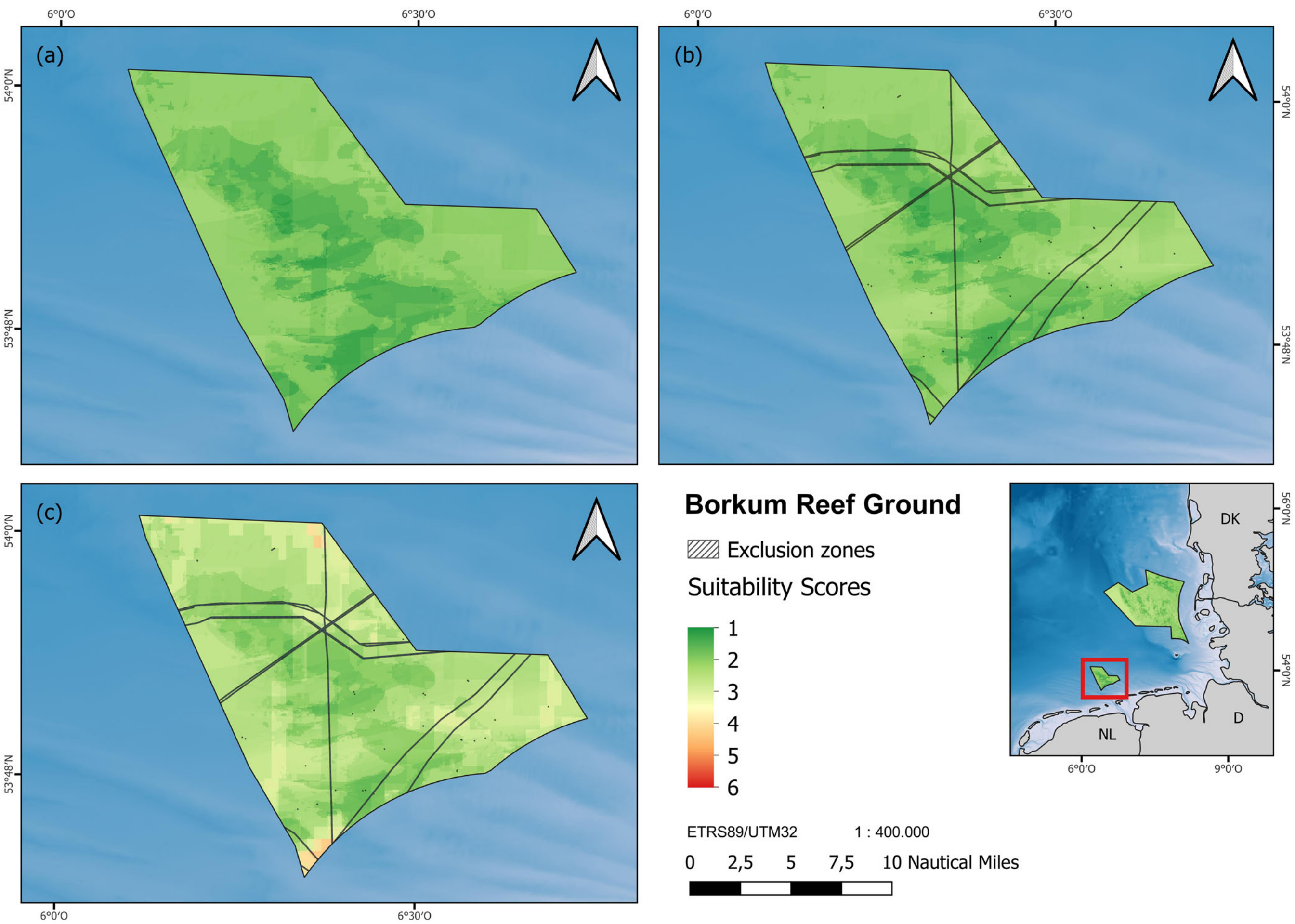

FIGURE 3 (a–c) Suitability maps of the Borkum Reef Ground marine protected area (MPA), indicating: (a) level-1 areas, suitable for the restoration of *Ostrea edulis*, considering only ecologically relevant factors; (b) level-2 areas, suitable for the restoration of *O. edulis*, by considering all factors (ecologically relevant factors and existing marine uses, e.g. offshore cables, with respective occupied or inadequate areas), but not considering bottom trawl fisheries; and (c) level-3 areas, suitable for the restoration of *O. edulis*, by considering all factors (ecologically relevant and existing marine user groups with respective occupied or inadequate areas, e.g. offshore cables), including bottom trawl fisheries (Table 1). Suitability maps indicate suitability in green (optimal, very good, and good), yellow (moderate), orange (poor), and red (unsuitable), based on suitability scores: 1, 1.00–1.49; 2, 1.50–2.49; 3, 2.50–3.49; 4, 3.50–4.49; 5, 4.50–5.49; 6, 5.50–6.00 (also see Table 3). Exclusion zones are offshore cables (black lines) and wrecks (black dots).

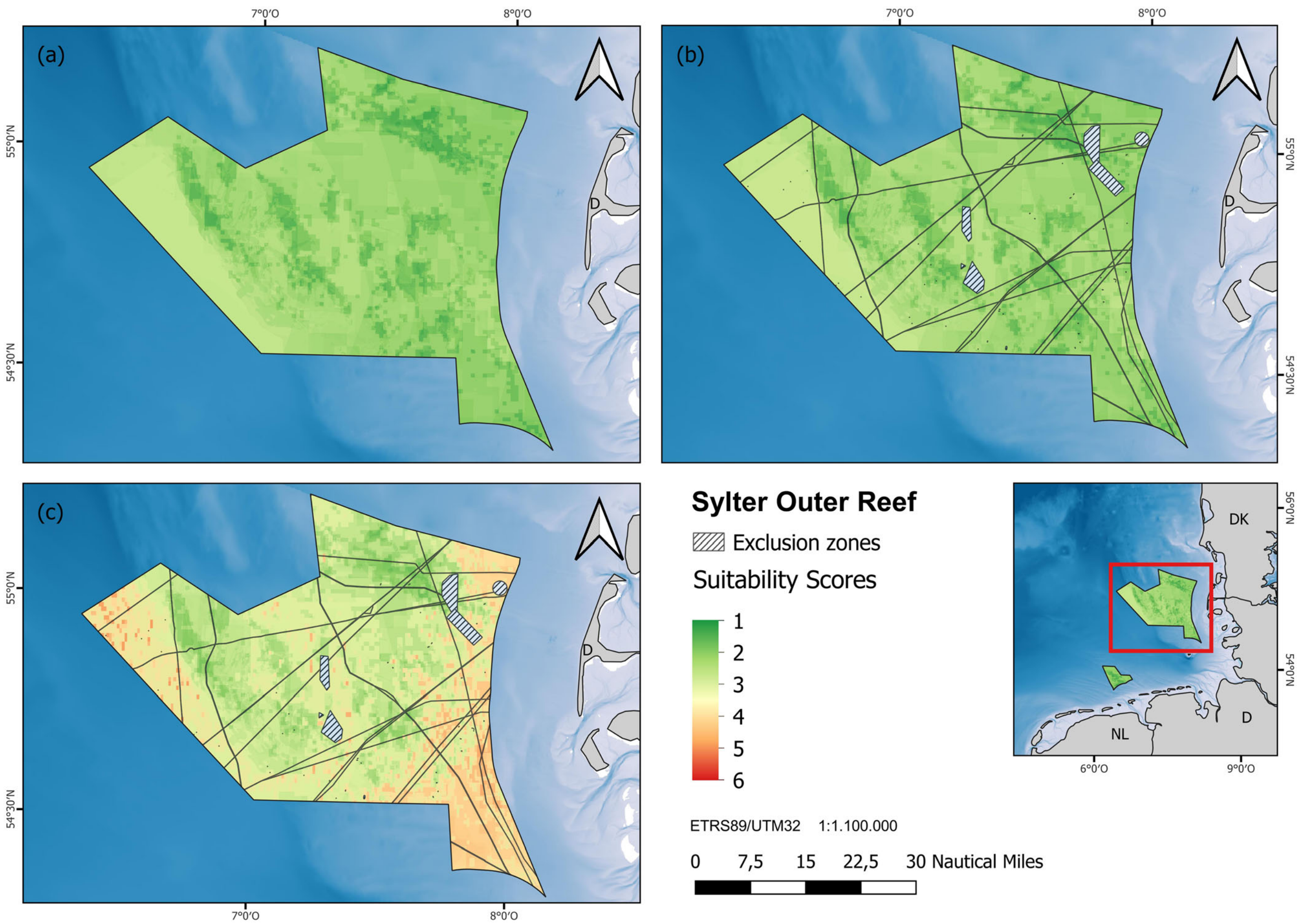

FIGURE 4 (a–c) Suitability maps of the Sylt Outer Reef marine protected area (MPA), indicating: (a) level-1 areas, suitable for the restoration of *O. edulis*, considering only ecologically relevant factors; (b) level-2 areas, suitable for the restoration of *O. edulis*, by considering all factors (ecologically relevant factors and existing marine user groups, e.g. offshore windfarms, offshore cables, wrecks, with respective occupied or inadequate areas), but not considering bottom trawl fisheries; and (c) level-3 areas, suitable for the restoration of *O. edulis*, by considering all factors (ecologically relevant and existing marine user groups with respective occupied or inadequate areas, e.g. offshore cables), including bottom trawl fisheries (Table 1). Suitability maps indicate suitability in green (optimal, very good, and good), yellow (moderate), orange (poor), and red (unsuitable), based on suitability scores: 1, 1.00–1.49; 2, 1.50–2.49; 3, 2.50–3.49; 4, 3.50–4.49; 5, 4.50–5.49; 6, 5.50–6.00 (also see Table 3). Exclusion zones are offshore windfarms (shaded areas), offshore cables (black lines), and wrecks (black dots).

with respective occupied or inadequate areas, indicating logistically and ecologically suitable oyster restoration areas (Figures 3c and 4c).

Suitable areas for the restoration of European oyster reefs were identified for both of the MPAs investigated and for all applied perception levels. Colour codes indicate particularly suitable areas in green and less suitable areas in orange–red in dynamic web suitability maps (Figures 3 and 4). For this study, suitability scores are defined as: 1, optimal; 2, very good; 3, good; 4, moderate; 5, poor; 6, unsuitable. Suitability scores 1–3 are considered suitable for oyster restoration and scores 4–6 are considered as not suitable for oyster restoration. The highest value of suitability score was 1.096787, located at 54.78181°N, 6.89241°E in SAR.

At level 1, the complete area of BRG is suitable for oyster restoration, achieving scores of 1–2 (optimal and very good suitability). Central and southern parts showed optimal and very good suitability, resulting in a total of 624.94 km^2 (100% of MPA) of ecologically suitable area (Figure 3a; Table 3). In SAR, the complete area is suitable for oyster restoration, achieving scores of 1–3 (optimal, very good, and good suitability). The central, north-western, north-eastern, and southern parts show optimal and very good suitability for oyster restoration, achieving scores of 1–2. In some western parts, as well as in some central areas, scores of 3 are achieved, resulting in a total of 5,599.71 km^2 (100% of MPA) of ecologically suitable area (Figure 4a; Table 3).

At level 2, exclusion zones with buffer zones around wrecks and offshore cables (Figures 3b and 4b: black lines and spots) are considered not suitable for oyster restoration. The remaining BRG area is suitable for oyster restoration, achieving scores of 1–3. Central and southern parts show optimal and very good suitability, resulting in a total of 614.90 km^2 (98.4% of MPA) of ecologically and logistically suitable area (Figure 3b; Table 3). In SAR, offshore wind farms exist as additional exclusion zones. The central, north-western, north-eastern,

TABLE 3 Areal proportions of suitability scores in square kilometres (km^2) and in percentage of total MPA area, identified for level 1 (only ecologically relevant features), level 2 (ecologically relevant features plus all existing user groups, except fishery), level 3 (all factors, including fishery).

BRG Suitability score	Level 1		Level 2		Level 3	
	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)	Area (km^2)	Percentage [%]
1	49.74	8.0	23.66	3.8	0.00	0.0
2	575.20	92.0	586.77	93.9	304.94	48.8
3	0.00	0.0	4.48	0.7	302.59	48.4
4	0.00	0.0	0.00	0.0	7.37	1.2
5	0.00	0.0	0.00	0.0	0.00	0.0
6	0.00	0.0	0.00	0.0	0.00	0.0
Suitable restoration area	624.94	100.0	614.90	98.4	607.53	97.2
SAR Suitability score	**Level 1**		**Level 2**		**Level 3**	
	Area (km^2)	**Percentage (%)**	**Area (km^2)**	**Percentage (%)**	**Area (km^2)**	**Percentage (%)**
1	33.87	0.6	15.46	0.3	0.00	0.0
2	4,612.53	82.4	4,252.19	75.9	620.77	11.1
3	953.32	17.0	1,154.33	20.6	3,549.48	63.4
4	0.00	0.0	0.00	0.0	1,200.79	21.4
5	0.00	0.0	0.00	0.0	50.93	0.9
6	0.00	0.0	0.00	0.0	0.00	0.0
Suitable restoration area	5,599.71	100.0	5,421.97	96.8	4,170.25	74.5

Note: in the calculation of raster data, areal values can slightly differ from geographical values. Suitability scores: 1 = 1.00–1.49; 2 = 1.50–2.49; 3 = 2.50–3.49; 4 = 3.50–4.49; 5 = 4.50–5.49; 6 = 5.50–6.00.

and southern parts show optimal and very good suitability for oyster restoration, achieving scores of 1–2. In some western parts, as well as in some spots in the centre, scores of 3 are achieved, resulting in a total of 5,421.97 km^2 (96.8% of MPA) of ecologically and logistically suitable area (Figure 4b; Table 3).

At level 3, fishing activity (bottom trawling) is included and resulted in no areas with scores of 1 in both MPAs. In BRG, some areas were identified as not suitable for oyster restoration, such as in the north east and in the south west, achieving moderate scores of 4. The centre, northern, and southern parts show very good and good suitability, achieving scores of 2–3, resulting in 607.53 km^2 (97.2% of MPA) of ecologically and logistically suitable area (Figure 3c; Table 3). In SAR, eastern areas with bottom trawl fisheries (beam trawling), mainly targeting the brown shrimp *Crangon crangon*, show moderate (4) and poor scores (5). North-eastern, some north-western, and some central areas show very good and good suitability for oyster restoration, achieving scores of 2–3. The remaining southern and north-north-western parts show moderate or poor suitability, achieving scores of 4–5, resulting in 4,170.25 km^2 (74.5% of MPA) of ecologically and logistically suitable area (Figure 4c; Table 3).

4 | DISCUSSION

Habitat suitability index (HSI) models are increasingly used to guide ecological restoration (Puckett et al., 2018). This study demonstrates the application of a straightforward method of habitat suitability analysis for marine restoration to facilitate site selection and to create a knowledge base for site managers and decision makers. Suitable areas for European oyster habitat have been identified in the selected MPAs using MCDA and AHP. By calculating suitability scores, geographic information system (GIS)-based suitability maps were developed (Figures 3 and 4): the presented scenarios reveal several hundreds of square kilometres (BRG) and up to several thousands square kilometres (SAR) of suitable habitats for the reintroduction of *O. edulis* and the restoration of biogenic reef habitat within the two investigated MPAs in the North Sea.

Three different scenarios have been calculated and explored in this study: level 1, considering ecological suitability exclusively (Figures 3a and 4a); level 2, considering the ecological as well as the logistical suitability, factoring in potentially contraindicated uses or occupied areas but excluding bottom trawl fishing activities (Figures 3b and 4b); and level 3, considering all factors, including bottom trawl fishing (Figures 3c, 4c).

Level 1 is a theoretical exercise: fully neglecting existing usages indicates the natural capacity of the BRG and SAR MPAs and the German Bight ecosystem to host and sustain biogenic reef habitat with all the goods and services that these could theoretically provide (e.g. Coen et al., 2007; Grabowski & Peterson, 2007; Smaal et al., 2019). Moreover, it indicates their potential role in achieving the goals of the EU Biodiversity Strategy for 2030, the Marine Strategy Framework Directive, and the Habitats Directive by contributing to a favourable conservation status and to a good environmental status (European Parliament, 1992; European Parliament, 2008).

With level 1, no human activities and the related demand for areas are taken into account in the MPAs, resulting in 100% of the area suitable for oyster restoration, both in BRG and SAR (Figures 3a and 4a; Table 3). Against this background, an integration of conservation measures with existing human activities should be discussed and explored to achieve optimized ecological performance under present and future spatial limitations, to ensure that conservation targets can be reached. Marine co-use (or multi-use) can be implemented as a tool to enhance conservation options and scale, e.g. by integrating restoration measures into priority areas for shipping. The restoration of oyster reef habitat is currently realized through the deployment of a flat stone layer (reef base), to counteract sediment dynamics in offshore environments, and through the deployment of young oysters thereon (Pineda-Metz et al., this issue). The elevation from the sea floor does not exceed 1 m and therefore, in areas with water depths of >20 m, does not present any hindrance for shipping in terms of traffic and manoeuvring (La Peyre et al., 2014; Gillies et al., 2015; Sawusdee et al., 2015; Pineda-Metz et al., this issue). Also, anchoring in emergency situations does not hinder large-scale restoration. We suggest further investigation of the potential implementation of restoration measures in such shipping areas, taking into account other protected features, e.g. resting and wintering seabirds.

Level 2 provides an all-in scenario (except bottom trawling): including all user groups in the current marine spatial plan and related logistical restrictions, but at the same time not taking into account fishing activity with bottom-contacting gear, results in 98.3% and 96.8% of the MPA considered suitable for oyster restoration in BRG and SAR, respectively (Figures 3b and 4b; Table 3). Here, only exclusion zones such as wrecks, offshore cables, and wind farms (only in SAR) contribute to the reduced area suitable for oyster restoration. This scenario considered recent developments regarding the management of fishing activities in the two MPAs in the context of the European Common Fisheries Policy (CFP): a delegated regulation under the CFP is currently being reviewed and conservation measures regulating bottom-contacting fisheries are likely to come into force in 2022 (Pogoda et al., 2020b, EU COM, 2023; Pusch/Bundesamt für Naturschutz (BfN) pers. comm./joint recommendation). These measures foresee the year-round exclusion of all bottom-contacting gears in BRG and in large areas of SAR (Figures 5 and 6). The main objective is the protection of the habitat types 'sandbanks' and 'reefs' (according to the EU Habitat Directive) from negative impacts of fisheries with mobile bottom-contacting gears. The presented results confirm that both MPAs are highly suitable for the designated restoration measures, be it within MPA management (BfN, 2020a), within implementation of EU restoration goals (EU COM, 2022b), or through area-based measures for the compensation of interventions in nature (BfN & BMU, 2021).

In SAR, the proposed fisheries management measures will result in a closed area of 3,399 km^2 for all mobile bottom-contacting fishing gears (e.g. bottom otter trawls, beam trawls, dredges, etc.). This area corresponds to 61% of the MPA with optimal suitability for oyster restoration. In the eastern part of the SAR covering an area of 857 km^2, all bottom-contacting fishing gears will be excluded, with the exception of beam trawls targeting brown shrimp (Figure 6). Beam trawls targeting shrimp are equipped with rubber disks on the ground rope and are less invasive than beam trawls targeting flat fish (e.g. plaice and sole) that use tickler chains to flush out fish buried in the sea floor. Nevertheless, even beam trawls targeting shrimps will have some detrimental effects on oysters and restored biogenic habitat, and therefore these areas are not suitable for oyster restoration. For the northern part of the Amrumbank, located in the eastern part of the SAR MPA, a complete exclusion of all fishing activities is foreseen. This no-take area of 48 km^2 will have, after being successfully implemented, a high potential for the restoration of oysters and of biogenic reef habitat (Figure 6).

Level 3 provides the current all-in scenario: to date, no fishery exclusion measures are in place. Mobile bottom-contacting fishing activities were identified as the most relevant factor counteracting habitat suitability for restoration (Table 2). Depending on the fishing intensity, areas with fishing activity achieved good, moderate, or poor scores. Hence, by considering all existing marine uses, related logistical restrictions, and accepting fishing activity as the main limiting driver, 97.2% of the total area of BRG (low fishing activity) and 74.5% of the total area of SAR (intense trawling activity, where boulders on the sea floor do not prevent bottom-contacting gear) are classified suitable for oyster restoration (Figures 3c and 4c; Table 3). Considering the fragile features of biogenic structures, bottom-contacting fisheries will have severe destructive effects and cannot be combined with habitat restoration in multi-use approaches.

Limited historical records (Gercken & Schmidt, 2014; Pogoda, 2019, Thurstan et al., unpubl.) indicate the widespread distribution of oyster habitats in the German Bight with the respective relevance for ecosystem functions and services of these ecosystem engineers (Coen et al., 2007; Grabowski & Peterson, 2007; Beck et al., 2011; Pogoda, 2019; Pogoda et al., 2020b). These records appear to be consistent with the habitat suitability predicted here for BRG. The habitat suitability predicted for the SAR MPA exceeds the known historical distribution (Figure 1). As a sound historical baseline is lacking, it remains an open question of whether oysters were historically present in SAR or whether other factors limited the natural distribution at that time (Pogoda, 2019). Current conditions in the MPA have a high suitability for oyster restoration.

The presented results also support the EU 2030 Biodiversity Strategy target to achieve a legal protection of at least 30% and a strict protection of 10% of European seas: to address the 10% target, only limited and well-controlled activities that do not interfere with natural processes or contribute to their improvement will be allowed. In addition, strictly protected areas may also be areas in which active management sustains or enhances natural processes (EU COM, 2022a). Suitable oyster habitats in MPAs could contribute to this, as management activities should be limited to restoration and/or habitat and species conservation actions (EU COM, 2020b). In the context of the MSFD, some countries, e.g. Germany, have reported the reintroduction of locally extinct or endangered species

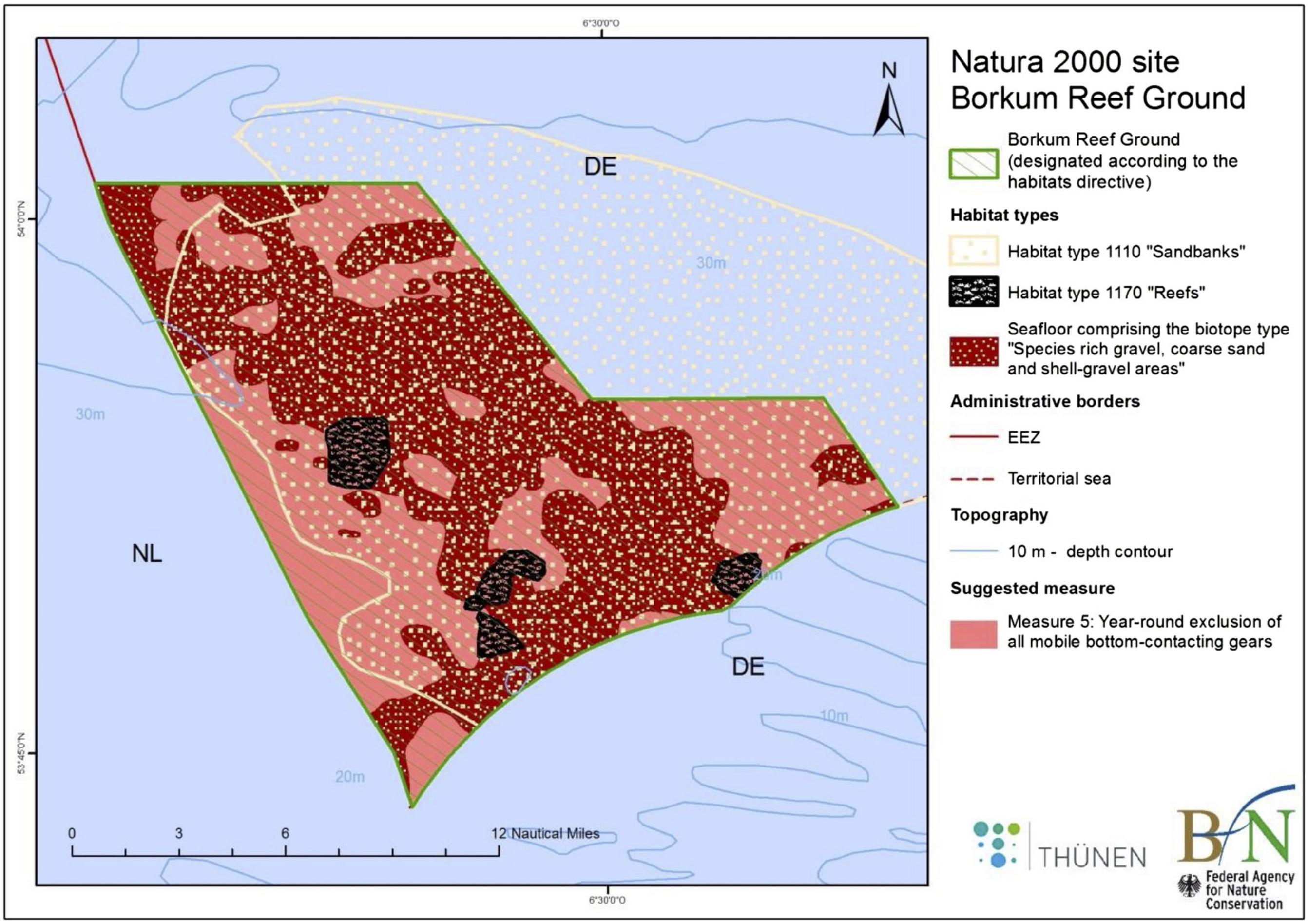

FIGURE 5 Designated European Common Fisheries Policy (CFP) measures for Borkum Reef Ground marine protected area (MPA). Year-round exclusion of all mobile bottom-contacting gears from the entire MPA Borkum Reef Ground to protect the habitat types 1110 'Sandbanks' and 1170 'Reefs' and sea floor areas comprising the biotope type 'Species-rich gravel, coarse sand and shell-gravel areas' (Joint Recommendation regarding Fisheries Management Measures 21 March 2021, EU COM, 2023).

such as *O. edulis* as so-called environmental targets to the EU Commission (BMU, 2012; BMU, 2018). Legal obligations or proposals to compensate human activities and establish restoration measures (BfN, 2020a; BfN, 2020b; BfN & BMU, 2021; EU COM, 2022b) were defined to address the poor environmental status of the German Bight (BMU, 2012; BMU, 2018). Considering the constantly increasing pressures on biodiversity through human activity and climate change, on one hand, and the vast historical extent of oyster reefs in the southern North Sea, on the other, with their important role for the ecosystem, oyster restoration is an effective and important conservation measure in both MPAs.

Against the background of conservation management and restoration practice, new restoration sites for biogenic reefs should be at least 4 ha in size (Westby, Geselbracht & Pogoda, 2019; Fitzsimons et al., 2020; Preston et al., 2020). Considering the role of reefs as hotspots of biodiversity (Boudreaux, Stiner & Walters, 2006; Shervette & Gelwick, 2008; Smyth & Roberts, 2010; Humphries et al., 2011), the restoration of biogenic reef habitat will increase habitat quality and quantity for other endangered species, e.g. sharks and rays, or for those relevant for ecosystem functions, e.g. intact trophic relations (Barrios-O'Neill, Bertolini & Collins, 2017; Zidowitz et al., 2017).

Despite the very good suitability of both MPAs, even the full restoration potential will not meet the ecological scale of the historical oyster reef habitat (Gercken & Schmidt, 2014). Increasing economic activity in the North Sea, and related stressors on the ecosystem, underline the relevance of restoration measures in both MPAs, despite the historical distribution being only documented for BRG. As historical information comes largely from oyster fisheries, and knowing that large areas of SAR were not accessible for fishing activities because of stone reefs and boulders, it is possible that oyster reefs did exist in the area (Pogoda, 2019; Thurstan et al., unpubl.). It is possible that SAR oyster populations may have been sustained by larvae originating from the offshore oyster grounds that have been overfished and extirpated (Gercken & Schmidt, 2014; Colsoul et al., 2021; Pogoda et al., in prep), and thus eliminating the source of oyster larvae to SAR reefs may have led to their disappearance. Today, the entire SAR area is considered ecologically suitable for oyster

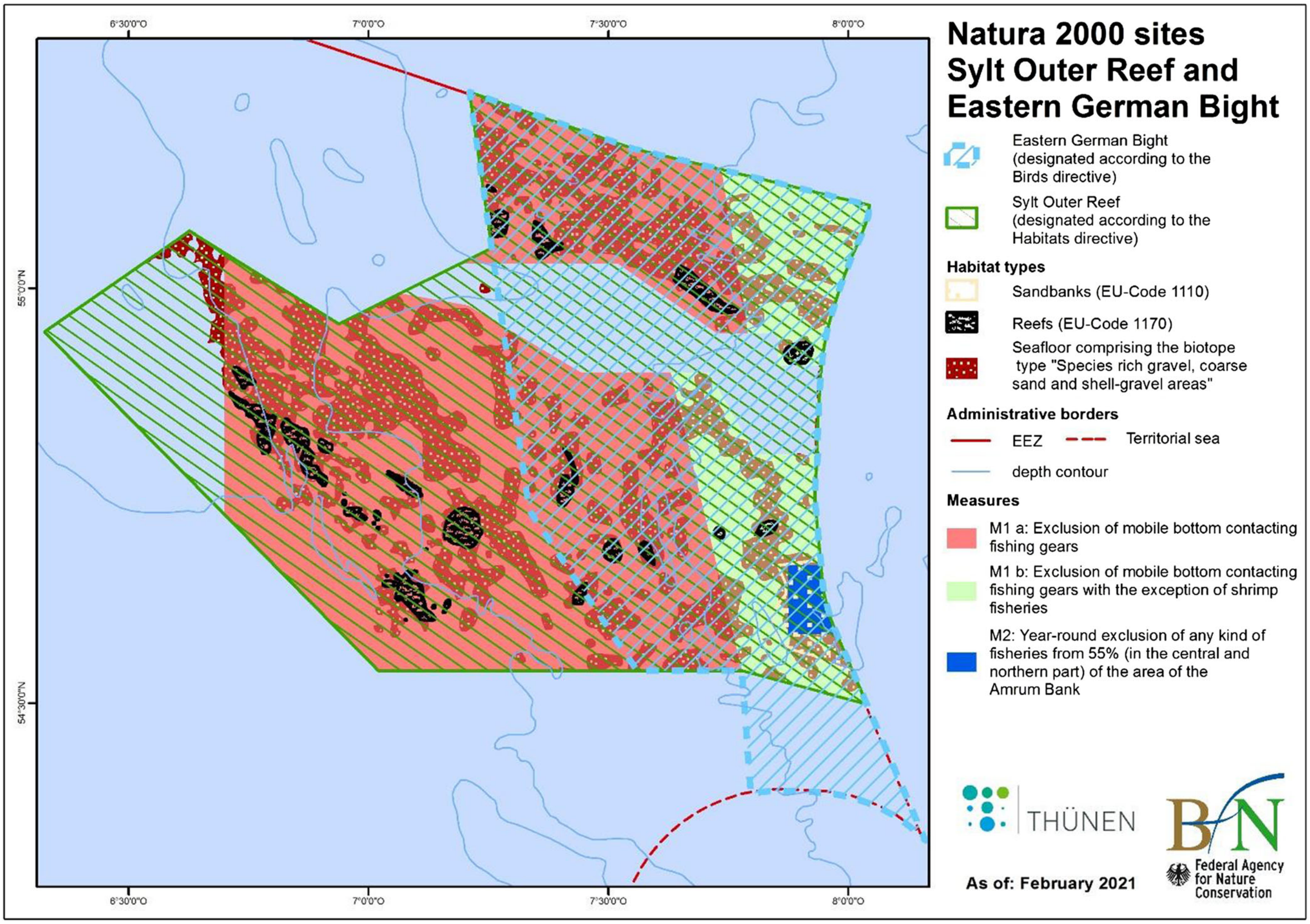

FIGURE 6 Designated European Common Fisheries Policy (CFP) measures for Sylt Outer Reef – Eastern German Bight marine protected area (MPA). Measure 1a: year-round exclusion of all mobile bottom-contacting gears in two management zones. Measure 1b: year-round exclusion of mobile bottom-contacting gears in two management zones, with the exception of brown shrimp fisheries with beam trawls within the Natura 2000 site Sylt Outer Reef (joint recommendation regarding Fisheries Management Measures, 17 March 2021; EU COM, 2023).

restoration, and hence the MPA can potentially play an important role in the restoration of European oyster populations, even under conditions of climate change with rising seawater temperatures, because of the tolerance of the species to a wide temperature range (Huthnance et al., 2016; Colsoul et al., 2021; Pörtner et al., 2021). Connectivity and recruitment remain key features for the long-term recovery of oyster populations and should be carefully investigated and considered when planning restoration efforts.

Successful restoration will only be achieved through multicriteria approaches, integrating physical and biological processes with permit schemes and logistical restrictions (Puckett et al., 2018). Some aspects of the presented method need consideration, as habitat suitability is based on site-selection factors, which have been defined for European oyster habitat restoration (Kamermans et al., 2018; Pogoda et al., 2020b; Hughes et al., 2023), although not all factors have been verified in the field and for some, the species-specific ecological thresholds are lacking. Taking bottom shear stress as an example, hydrodynamics and related mechanical stressors certainly affect filter-feeding, shell growth, and reef formation (Richardson, 2001; Pogoda, Buck & Hagen, 2011; Whitman & Reidenbach, 2012; Kamermans et al., 2018), but the degree to which conditions are favourable or limiting is not yet fully understood (Kamermans et al., 2018; Pogoda et al., 2020b). The historical flat oyster beds were sited in areas characterized by relatively low bed shear stress (Bennema, Engelhard & Lindeboom, 2020). Other crucial factors, e.g. median grain size (sediment type) and mud content (relative proportions of the grain size fraction of <63 μm) are correlated and influence oyster distribution (Bockelmann et al., 2018; Bennema, Engelhard & Lindeboom, 2020). Hence, the weighting of the respective criteria used for AHP is based on the best available knowledge and informed estimations from experts. Some factors that are not relevant in the study area (e.g. gravel extraction and dumping), or for which data were not accessible (e.g. turbidity and current velocity), were not considered in the weighting. Predation was explicitly not considered here, as potential predators of *O. edulis* are highly mobile species, such as *Asterias rubens*, *Cancer pagurus*, and *Homarus gammarus* (Whilde, 1985; Mascaró & Seed, 2001; Ellrich & Pogoda, in prep), and reef restoration is assumed to attract these predators during the initial stages of reef implementation, independent of the selected sites (Krone et al., 2013; Pogoda et al., 2020b; Pineda-Metz et al., this issue). During the development and application of the presented analysis, we defined suitability scores of 1–6, with scores 1–3 (optimal, very good, good) regarded as suitable for oyster restoration. These categories provide a dynamic scale or indication for restoration success. Future ground truthing will elucidate adaptation potential, especially against the background of existing knowledge gaps related to *O. edulis* ecology, e.g. by refining the applied factors.

In general, habitat suitability models intend to quantify the value of habitats when considering management alternatives in species-specific, as well as habitat-specific, conservation and restoration (Questad et al., 2014; Theuerkauf & Lipcius, 2016). The suitability analysis approach can be adapted to wider conservation management objectives and even the facilitation of complex decision-making procedures across different stakeholders, often representing different goals and views. Different conservation goals such as biodiversity enhancement as well as recently developing climate change mitigation measures can be addressed by integrated habitat suitability analyses. Current research shows that marine sediments serve as relevant blue carbon habitats if left undisturbed, for example, within the framework of MPAs (Roberts et al., 2017; Dunkley & Solandt, 2021). Intact ecosystems are more resilient to climate change than anthropogenically weakened ecosystems, and therefore could play a critical role in mitigating the negative impacts of climate change (EU COM, 2022b). The exclusion of bottom trawling will enhance their carbon storage capacity (Duplisea et al., 2001; Luisetti et al., 2019), whereas oyster reefs increase sedimentation rates and organic carbon accumulation through the provision of 3D structure (Fodrie et al., 2017; Lee et al., 2020; Veenstra et al., 2021). Such suitable potential future ‘climate protection areas’ (CPAs) are in some areas likely to overlap with suitable areas for oyster restoration, both identifiable by combined and adapted habitat suitability approaches (Smale et al., 2018; Dunkley & Solandt, 2021).

AUTHOR CONTRIBUTIONS

Bernadette Pogoda: Conceptualization; investigation; project administration; resources; writing—original draft. **Tanja Hausen:** Writing—original draft. **Marko Rothe:** Methodology; software; writing—original draft. **Felix Bakker:** Methodology; software; writing—original draft. **Sarah Hauser:** Methodology; software; writing—original draft. **Bérenger Colsoul:** Writing—original draft. **Manuel Dureuil:** Writing—original draft. **Jochen Krause:** Writing—original draft. **Kathrin Heinicke:** Writing—original draft. **Simone Eisenbarth:** Writing—original draft. **Christian Pusch:** Writing—original draft. **Axel Kreutle:** Writing—original draft. **Corina Peter:** Writing—original draft. **Roland Pesch:** Conceptualization; methodology; software; writing—original draft.

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CONFLICT OF INTEREST STATEMENT

The authors declare no potential conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are either available from the corresponding author upon reasonable request or are openly available in BSH Database at https://www.bsh.de/DE/DATEN/daten_node.html;jsessionid=EFA5B275F24055EBABC80BDA8448BDF5.live21304 and in HZG Coastmap at https://coastmap.hzg.de/server/rest/services.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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