PrePARED Report No. 006

Similarity assessment of offshore wind farms within UK marine habitats

University of Exeter

SMRU Consulting

PrePARED

Predators + Prey Around Renewable Energy Developments

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Similarity assessment of offshore wind farms within UK marine habitats

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Summary

The expansion of offshore wind energy in UK waters requires careful consideration of how marine predators and their prey interact with wind farm developments. The PrePARED project studies these ecological relationships at wind farms in the Moray Firth and Firth of Forth, Scotland. The wider broader applicability of these findings depends on how environmentally representative these sites are of other development areas. For example, if findings could be reliably transferred to environmentally similar locations, they may aid streamlining of future impact assessments and advance our understanding of cumulative effects across multiple wind farms.

To assess the potential for transferability, this report analyses environmental conditions at the PrePARED study sites in comparison to the wider UK marine area and other wind farms in the region. The analysis examined environmental data, across four seasons, on sea bottom temperature, salinity, water stratification, tidal speed, seabed slope, water depth, distance to shore and seabed substrate.

The east coast of Scotland and North Sea exhibited high similarity to the PrePARED study sites, with seasonal variations predominantly driven by sea bottom temperature and water vertical stratification. The Dogger Bank area revealed high year-round similarity to the Moray Firth PrePARED sites, suggesting that certain environmental characteristics persist across larger spatial scales, despite considerable geographical distance. Future planned wind farms in these areas were more like the PrePARED study sites than existing operational wind farms. Wind farms using grounded jacket system revealed significantly higher similarity to Firth of Forth PrePARED study sites in comparison to wind farms using floating and grounded monopile seabed attachment methods.

This report indicates potential transferability of PrePARED findings, based on environmental similarity, to other UK offshore wind farms, particularly off Scotland's east coast and in the North Sea. These regions are set to host many of the UK's future offshore wind farm developments.

Recommended Citation

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List of Acronyms

Acronyms	Definition
AP	Attribute Profiles
AV	Attribute Values
CEDA	Centre for Environmental Data Analysis
CMS	Copernicus Marine Service
DEP	Depth
DIS	Distance to Shore
EEA	European Environment Agency
EMODnet	European Marine Observation and Data Network
F	Floating (foundation type)
FoF	Firth of Forth, Scotland
GEBCO	General Bathymetric Chart of the Oceans
GJ	Grounded Jacket
GM	Grounded Monopile
InTOG	Innovation and Targeted Oil & Gas
ISO	International Organization for Standardization
MF	Moray Firth, Scotland
MSPS	Mean Spring Peak Speed
NNG	Neart Na Gaoithe
NOC	National Oceanography Centre
NWSPPE	Northwest Shelf Perturbed Parameter Ensemble
OWEC	Offshore Wind Evidence and Change Programme
PEA	Potential Energy Anomaly
PrePARED	Predicting the Impacts of Offshore Wind Farms on Marine Species
PSU	Practical Salinity Unit
SAL	Salinity
SLP	Slope
SUB	Substrate
TBC	To be confirmed
TEM	Temperature
TID	Tidal Speed
UK	United Kingdom
VS	Vertical Stratification

1. Introduction

The Northeast Atlantic is characterised by an array of marine habitats, ranging from shallow coastal waters to deep-sea environments. This diversity is underpinned by varying bathymetry, complex current systems, and geological features (Johnsen, Nygaard et al. 2002). Despite this heterogeneity, offshore wind farms are often constrained in their location due to geological, engineering and economic considerations (Díaz and Guedes Soares 2020).

The tendency for offshore wind farms to be in areas with shared environmental characteristics suggests that findings from PrePARED could be transferable to other future developments across the UK marine region, though this hypothesis remains untested. The strategic focus of PrePARED on predator-prey relationships and cumulative effects makes such transferability valuable - if species' responses can be robustly applied across environmentally similar sites, it could significantly advance our understanding of cumulative impacts and help overcome key barriers to sustainable offshore wind development.

This study assesses environmental similarities across the UK offshore wind farm network, using PrePARED project wind farms in the Moray Firth (MF) and Firth of Forth (FoF) as reference sites. We seek to improve understanding of the environmental context of UK wind farms and support discussions regarding transferability of findings from PrePARED sites to other offshore wind developments in the northeast Atlantic.

2. Methods

Study sites

PrePARED research in the Moray Forth focuses on the Beatrice, Moray East and Moray West development sites (Scotland, UK; Fig. 1). Depth ranges from 40 m to 58 m (chart datum), with a seabed predominantly covered by sand and mud habitats (Directorate 2021). The Beatrice Offshore Wind farm was constructed between 2017 and 2018, and Moray East Offshore Wind farm was constructed between 2019-2022. Both sites used grounded jacket foundations and are among the deepest globally.

The Firth of Forth PrePARED study site is situated off the east coast of Scotland. This study site comprises of two wind farms, including SeaGreen Phase 1 offshore wind farm (constructed 2021-2023) and Neart Na Gaoithe (NNG) offshore wind farm (construction began in 2020, completion expected in late 2024). Both wind farms have grounded jacket foundations, with SeaGreen being the world's deepest constructed commercial scale wind farm (deepest foundation 59 m below sea level (SeaGreen 2020)).

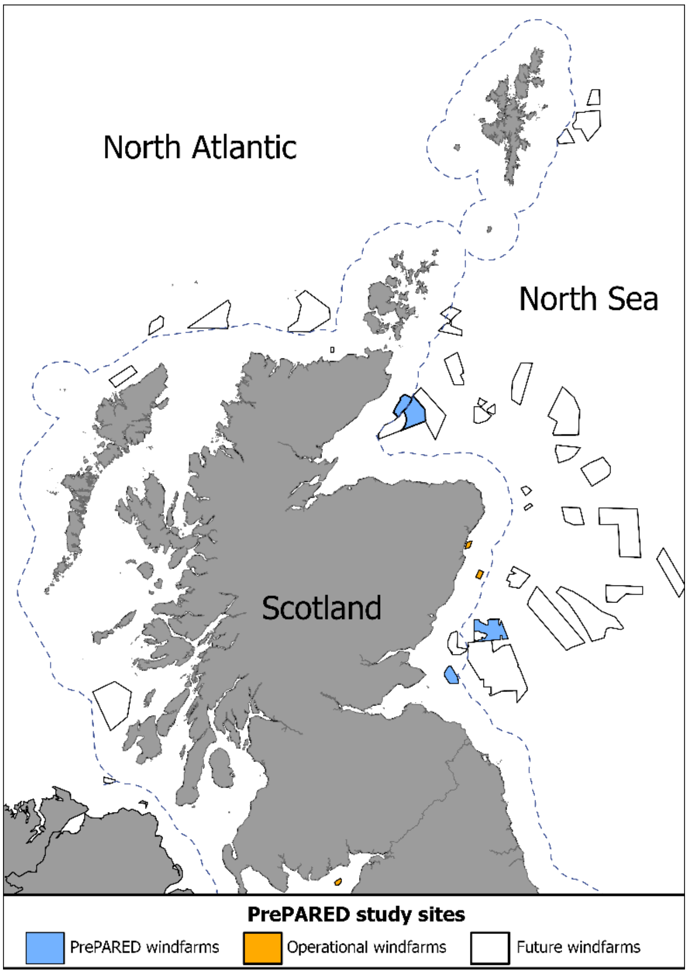

Figure 1. Map of Scotland showing the PrePARED study sites (light blue). United Kingdom's territorial water (12 nautical miles; dashed blue line).

Wind farm metadata

A database of offshore wind farms was compiled, which included all operational wind farms in the UK marine region, projects from The Crown Estate's Leasing Round 3 and Round 4 in England and Wales, as well as Crown Estate Scotland's ScotWind leasing round and Innovation and Targeted Oil and Gas (INTOG) leasing round[1]. For each wind farm, metadata were gathered, including foundation type, turbine number, age, operational status, and wind farm geographic location. These data sourced online, primarily from the 4COffshore database (https://www.4coffshore.com/) and cross-referenced with developer websites where available. For wind farms that have not yet been constructed, some details remain uncertain, including the foundation type and the final number of turbines to be installed. In such cases, these parameters were denoted as "to be confirmed" (TBC).

Environmental data

Data for several relevant environmental abiotic variables were investigated (see **Table 1**); these are summarised below. Seasons were specified as follows: winter (December-February), spring (March-May), summer (June-August), and autumn (September-November).

Sea bottom temperature (°C) *and Salinity* (PSU). Monthly mean average rasters were obtained from the Copernicus Atlantic Northwest Shelf–Ocean Physics Analysis and Forecast (cmems_mod_nws_phy_anfc_P1M-m model) at a 1.8 km resolution, spanning December 2021 to November 2023. These rasters were combined into four separate seasonal rasters.

Vertical stratification (J/m^3). A potential energy anomaly (PEA) raster, representing vertical stratification, was obtained from the Ensemble Statistics dataset calculated from the Northwest Shelf Perturbed Parameter Ensemble (NWSPPE). NWSPPE provided seasonal means for PEA (2000 to 2019) at 7 x 7 km resolution.

Tidal speed (m/s). Mean spring tide peak current speed (m/s) was obtained from the National Oceanographic Centre POLPRED model (CS20 depth-averaged model). This dataset was an average from 2006 to 2015 based on hourly values, with a horizontal resolution of 1.8 km.

Seabed depth (m). Seabed depth data were obtained from the GEBCO gridded bathymetry product, native resolution was 15 arc seconds.

Seabed slope (arc °). Seabed slope was derived from the GEBCO gridded bathymetry depth raster.

Distance to shore (km). A raster of minimum distance to shore was created (Fig. S2) using the European Environment Agency coastline vector with the Euclidean distance tool (ArcPro 3.0.1 (ESRI)). Spatial resolution of this product was inherited from the salinity dataset.

Seabed substrate. Data were sourced from EMODnet using the Seabed Substrate Multiscale-Folk 7 model. Data were required in a numeric form for modelling, ranging from 1 to 10 (increasing substrate size corresponding to larger numerical values (1 = fine mud, 4 = sand, 8 = rocks and boulders); these encoded EMODNet categorical descriptions.

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[1] INTOG is a leasing round for small scale (<100 MW) innovative offshore wind (IN) and power generation equipment wind connected to oil and gas infrastructure to reduce carbon emissions (TOG).

Table 1. Environmental variables: Variable and units / acronym, organisation, native spatial resolution, source URLs (validated 26-NOV-2024) and dataset name.

Variable (acronym)	Unit	Organisation (Org. acronym)	Native horizontal spatial resolution	Source URL	Dataset
Sea bottom temperature (**TEM**) and salinity (**SAL**)	°C / PSU	Copernicus Marine Service (CMS)	1.8 km	https://data.marine.copernicus.eu/product/NWSHELF_ANALYSISFORECAST_PHY_004_013/services	cmems_mod_nws_phy_anfc_0.027deg-3D_P1M-m
Vertical stratification (**VS**)	J/m3	Centre for Environmental Data Analysis (CEDA)	7 km	https://data.ceda.ac.uk/badc/deposited2023/marine-nwsclim/EnsStats	Wi - NWSClim_NWSPPE_EnsStats_clim_djf_2000-2019_gridT_stats.nc Sp - NWSClim_NWSPPE_EnsStats_clim_mam_2000-2019_gridT_stats.nc Su - NWSClim_NWSPPE_EnsStats_clim_jja_2000-2019_gridT_stats.nc Au - NWSClim_NWSPPE_EnsStats_clim_son_2000-2019_gridT_stats.nc
Seabed depth (**DEP**)	m	General Bathymetric Chart of the Oceans (GEBCO)	15 arc seconds	https://download.gebco.net	GEBCO 2023
Seabed slope (**SLP**)	arc °	General Bathymetric Chart of the Oceans (GEBCO)	500 m	https://download.gebco.net	GEBCO 2023
Distance to shore (**DIS**)	km	European Environment Agency (EEA)	Vector	https://www.eea.europa.eu/data-and-maps/data/eea-coastline-for-analysis-1/gis-data/europe-coastline-shapefile	European coastline shapefile
Tidal speed (**TID**)	m/s	National Oceanography Centre (NOC)	1.8 km	https://noc-innovations.com/services/tide-prediction-software/offshore-software	MSPS_MNPC_CS20_DA
Seabed substrate (**SUB**)	Ordinal	European Marine Observation and Data Network (EMODnet)	Vector	https://emodnet.ec.europa.eu/geoviewer	Seabed Substrate – Multiscale – folk 7

Spatial framework

A template gridded spatial layer (i.e. fishnet) was created to serve as a spatial framework for harmonising environmental data layers of varying spatial resolution. This spatial layer represented a grid of squares with common dimensions that encompassed the maximum spatial extents of all environmental data layers. The resulting grided spatial layer had a cell size of 12.5 km by 12.5 km (area 156.3 km^2). Cell size was predominantly influenced by the PEA dataset, which had the lowest spatial resolution. This template was replicated to create one template for each season, to which seasonally relevant environmental data were joined.

Raster-based environmental data (TEM, SAL, VS, DEP and SLP) were first converted to spatial point features, using minimum XY cell corners as the reference. These datasets, along with seabed substrate and tidal speed, were spatially joined to their respective seasonal gridded spatial layers. In cases where multiple data points occurred within a single grid cell, the mean value of those points was calculated and assigned to that cell.

Environmental values coincident to the MF and FoF wind farms were extracted from the seasonal gridded spatial layers. These values were averaged (mean) to obtain single values for each environmental variable at each study site for each season.

Assessing environmental collinearity

It is recommended practice that multicollinearity in explanatory data should be minimised (Dormann et al. 2013). Multicollinearity can complicate interpretations as correlated explanatory data make it challenging to distinguish the individual effect of each variable. Given this, we ascertained correlation between all environmental data at a seasonal level.

We created 1000 sets of 250 random locations across the marine study area and sampled the spatially coincident environmental data at these random locations. Spearman correlations were calculated in R using cor.test(). Correlations between variables were explored using diagonal matrices describing median rho from each set (n=1000) of environmental combinations. P values arising from individual correlations within each set were modified following Fishers' adjustment to determine statistical significance for each set for each environmental combination.

Similarity search

Similarity analyses were performed in ArcPro 3.0.1 (ESRI) using the Similarity Search tool. This tool calculated a similarity score for grid square across the study area in each seasonal gridded spatial layer, indicating how similar each grid square ("cell") was to a "feature to match" site, which were the PrePARED study sites (performed individually for MF and FoF). This process resulted in four similarity spatial layers, one for each season, where similarity was referenced to either MF or FoF. Three methods of similarity search are available: Attribute Values (AV), Attribute Profiles (AP), and Ranked Attribute Values.

- The Attribute Values (AV) method calculated similarity by standardising all environmental variables from the gridded surface and PrePARED wind farms placing them on the same scale. A similarity score was calculated by subtracting the standardised values of the PrePARED wind farms from each cell, squaring the differences, and then summing these squared differences.
- The Attribute Profiles (AP) method calculated similarity by standardising variables using the Attribute Values method. The method subsequently uses cosine similarity mathematics to compare the vectors of environmental variables for each cell to a PrePARED wind farm site. The cosine similarity index ranges from 1 (perfect similarity) to -1 (perfect dissimilarity).
- The Ranked Attribute Values was not used as ranking did not provide sufficient resolution on quantitative differences among sites. method was not deemed appropriate for analysing environmental similarity between two sites.

Preliminary analyses of AV and AP methods revealed comparable results; as such, the Attribute Profiles method was selected given the intuitive numerical scale result, ranging from 1 (most similar) to -1 (least similar). A score of 0 indicates these is no strong similarity or dissimilarity to the reference feature. It might mean that the similarities and dissimilarities across the various environmental variables cancel each other out, leading to a neutral score.

Descriptive terms were developed to aid interpretation and description of patterns emerging from the similarity analysis (Table 2).

Table 2. Similarity values and textual descriptors. Colours are consistent with symbology used in map figures showing similarity layers. *Similarity and dissimilarity, when assessed across numerous environmental variables cancel out.

Similarity values	Descriptor
> 0.6	Highly similar
> 0.4 to 0.6	Considerably similar
> 0.2 to 0.4	Moderately similar
> 0 to 0.2	Slightly similar
0	*Neutral
0 to > -0.1	Slightly dissimilar
-0.1 to > -0.4	Moderately dissimilar
-0.4 to > -0.6	Considerably dissimilar
-0.6 to -1	Highly dissimilar

Similarity mapping and wind farm comparisons

Eight maps (one per season for each of the two PrePARED sites, MF & FoF) were generated from similarity analyses and were inspected to identify patterns of similarity within and across seasons. Similarity scores were extracted from each of the eight similarity gridded layers for all UK wind farms. Wind farm specific similarity scores (with reference to each of the PrePARED sites) were assessed regarding wind farm age, status (i.e., approved, construction, operation, and planned), and foundation type (i.e., floating, grounded jacket, grounded monopile, and those where foundation type is not yet confirmed).

For each UK wind farm, the similarity scores from the four seasonally relevant similarity assessments were summed, and the mean similarity score calculated. This process was performed for both PrePARED sites, resulting in a seasonally averaged similarity score for each wind farm with respect to each PrePARED wind farm. Patterns in similarity between wind farms with differing foundation types and operational status were investigated using descriptive and frequentist statistics (including two-sample t-test, linear models and ANOVA); statistical analysis was performed in R.

Environmental drivers

Analyses were performed to identify which environmental variable, or combinations of variables, most strongly influenced environmental similarity between the PrePARED wind farms and all other UK offshore wind farms. Similarity searches were conducted for all unique combinations of environmental variables, resulting in 256 unique combinations of these variables, with a minimum of at least two variables per combination. From the resulting similarity gridded layers, similarity scores for each UK wind farm were determined and a median similarity score was subsequently calculated. This process identified vertical stratification as a potential key environmental driver. As such, all unique combinations of environmental variables were considered with respect to whether vertical stratification was present in that combination of variables or not. Results from these similarity searches were subsequently visually inspected. This approach enabled the assessment of how individual environmental variables and their interaction with vertical stratification affected the similarity scores to the Moray Firth sites across the wind farm network.

3. Results

Wind farm metadata

Information on 101 UK offshore current and future wind farms were sourced (Fig. 2; Table 3). Five wind farms were excluded later due to poor spatial alignment of environmental variables and the spatial extents of these wind farms. Of the 96 remaining wind farms, 36 were operational, with the majority planned for post-2024 construction (n=60). The age of operational wind farms in England ranged between 1.6 – 18.4 years, contrasting with winds farms in Scotland (0.5 – 5.7 years) and Wales (8.8 – 19.5 years). Foundations of operational wind farms were dominated by grounded monopiles (n=34; Table 3).

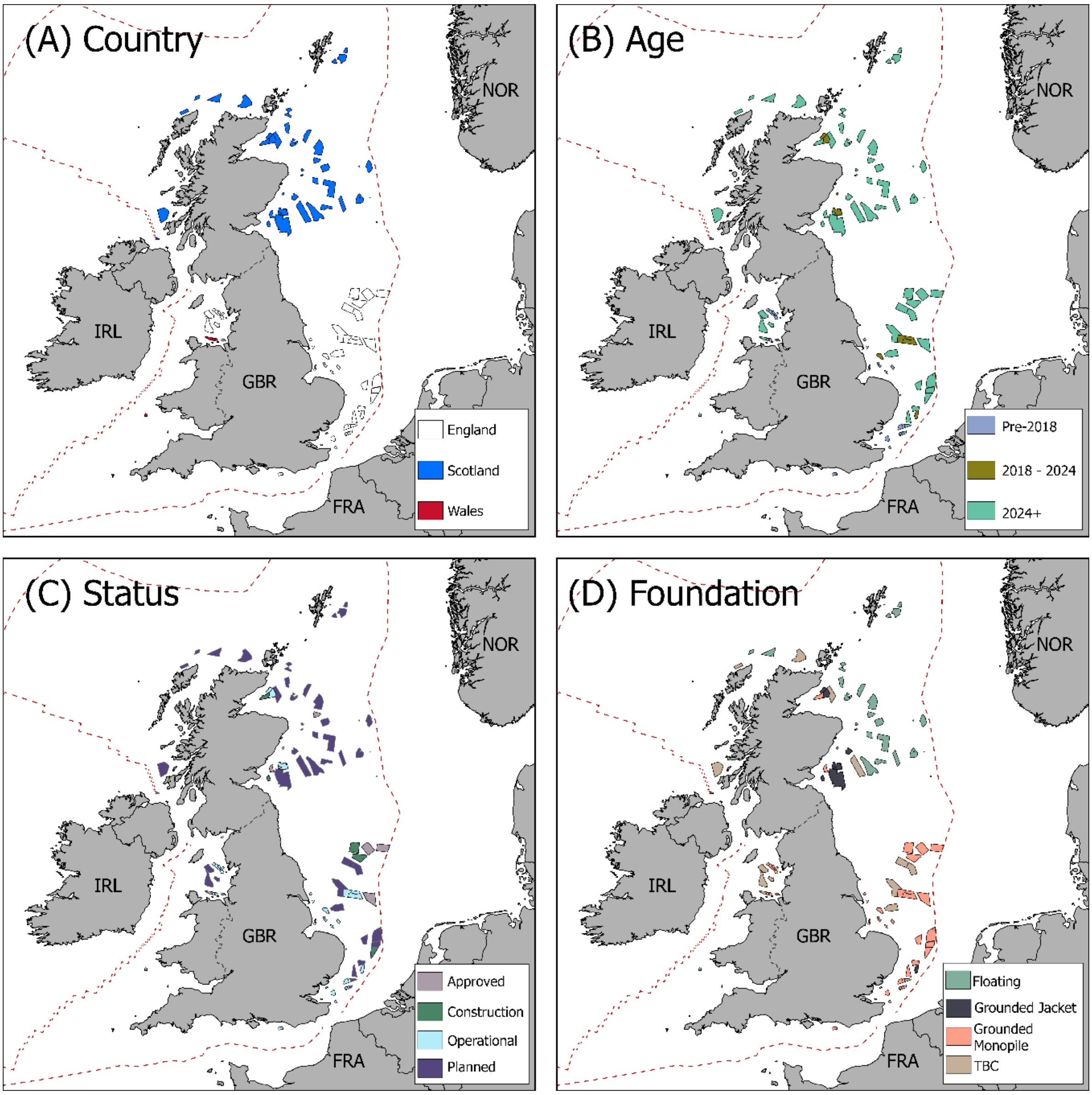

Figure 2. Wind farm database, described by meta data categories: (A) country, (B) age, (C) status and (D) foundation type.

Table 3. Characteristics of operational and future wind farms; grouped by PrePARED wind farms in Moray Firth and Firth of Forth (Scotland) and UK devolved administrations. Foundation types (GM: grounded monopile, GJ: grounded jacket, F: floating and TBC: to be confirmed). Characteristics of wind farms being studied in PrePARED shown in parentheses.

Region	Wind farms (PrePARED sites)	Operational wind farms	Future wind farms	Median age; years (range)	Foundation type	
					Operational	Future
Moray Firth	4 (2)	2	2	4.3 (2.4 – 6.1)	GJ = 2	GM = 1 TBC = 1
Firth of Forth	4 (2)	1	3	0.9 (0.9)	GJ = 1	GJ = 2 GM = 1
United Kingdom	96	36	60	9.2 (0.5 – 19.8)	GM = 34 GJ = 6 F = 1	GM = 13 GJ = 4 F = 29 TBC = 14
England	48	28	20	10 (1.6 – 18.4)	GM = 26 GJ = 2	GM = 11 GJ = 0 F = 1 TBC = 8
Scotland	43	5	38	4.8 (0.5 – 5.7)	GJ = 4 F = 1	GM = 2 GJ = 4 F = 27 TBC = 5
Wales	5	3	2	14.4 (8.8 – 19.5)	GM = 3	F = 1 TBC = 1
Northern Ireland	0	0	0	-	-	-

Multicollinearity of environmental data

Most environmental data were correlated within season and for the static environmental variables of distance from shore, depth, tide, seabed substrate and slope (Fig. 3). Distance to shore and depth were particularly strongly correlated with all other variables and given this consistency and strength of correlation (in both negative and positive directions), we choose to remove these two variables from further analysis as their explanatory power exists within the remaining datasets they correlate with. The strong negative correlation between depth and vertical stratification (> 0.65 in all seasons) was anticipated given depth data are explicitly incorporated into the derivation of vertical stratification. We chose to retain the remaining environmental variables, although significantly correlated to greater or lesser extent to each other (determined by Spearman rho), due to their importance for describing variation across the study area. It is challenging to eliminate such correlation in environmental analysis as these relationships fundamentally explain how the environment covaries in time and space.

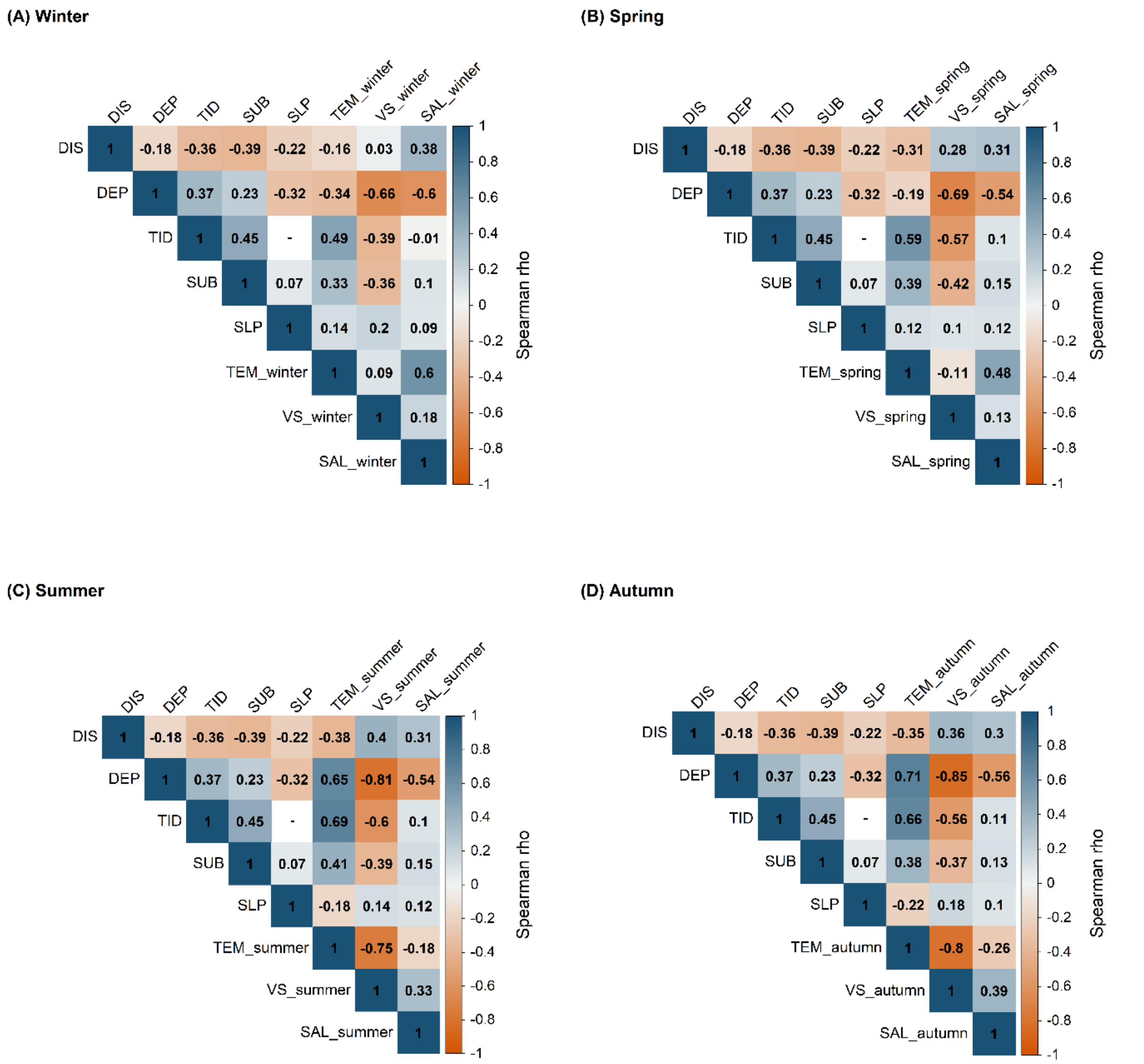

Figure 3. Seasonal environmental correlation matrices. Correlation matrices describing median rho from 1000 simulations of 250 random locations to sample spatially coincident environmental variables. Median rho shown for significant relationships ($p < 0.05$; with Fishers' adjustment). Seabed bottom temperature (TEM), salinity (SAL), vertical stratification (VS), tidal speed (TID), seabed depth (DEP), seabed slope (SLP), distance from shore (DIS), seabed substrate (SUB).

Environmental data

Mapped environmental data (Fig. 4-9) revealed seasonal patterns for dynamic datasets, for example, during summer, sea bottom temperature, salinity and vertical stratification were warmer, with marginally more saline and with greater stratification than winter periods, which are cooler and with more vertical mixing energy. Seasonal variations in salinity were less pronounced, and the variation that occurs is most noteworthy in coastal regions. Environmental data with no, or limited seasonal variation, including seabed substrate, slope and tidal speed highlighted the shelf nature of the UK marine region, while revealing greatest tidal speeds around headlands, and in the English Channel.

Sea bottom temperature

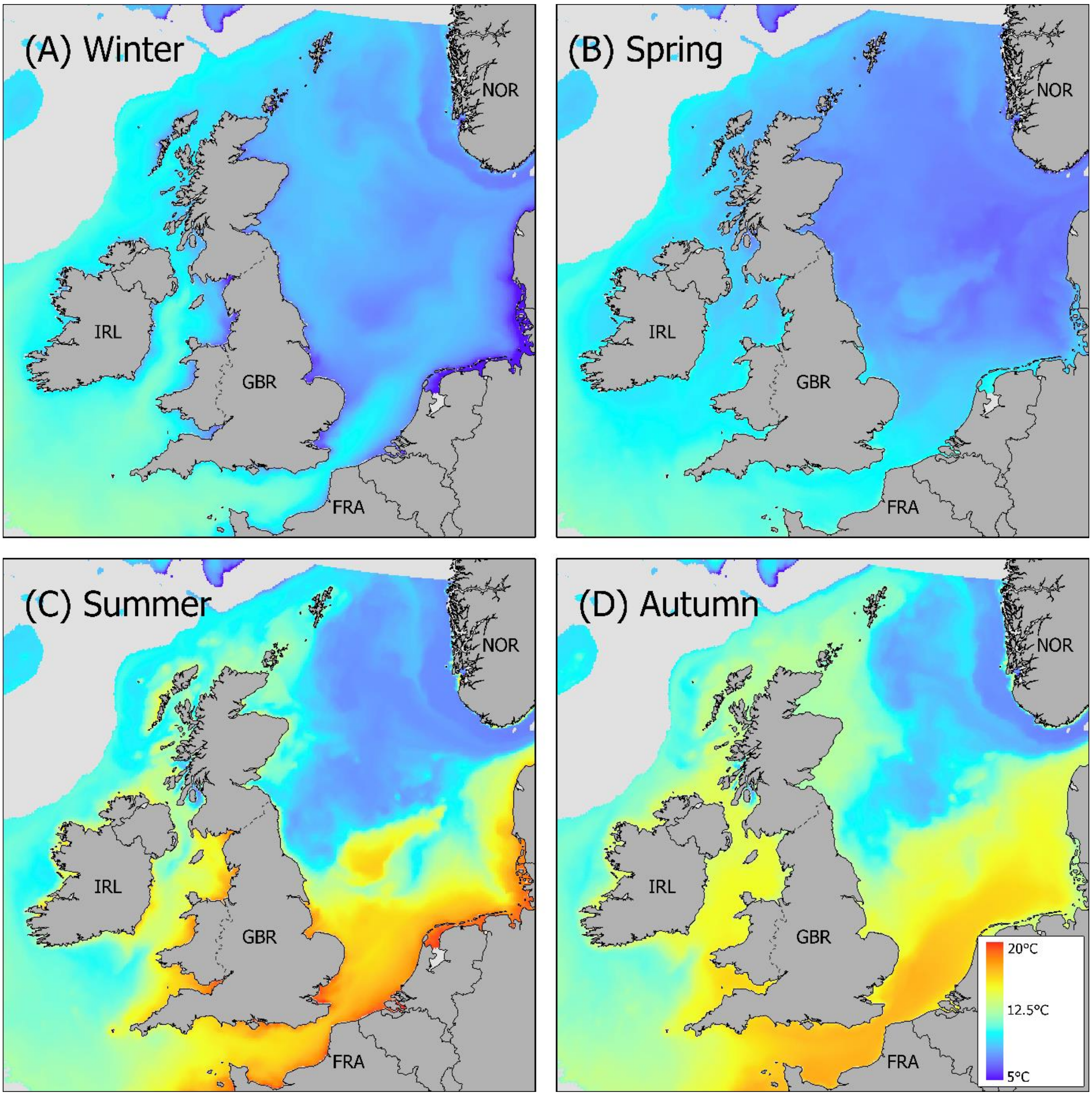

Figure 4. Sea bottom temperature (TEM; °C). Monthly mean average rasters were obtained from the Copernicus Atlantic Northwest Shelf–Ocean Physics Analysis and Forecast (cmems_mod_nws_phy_anfc_P1M-m model) at a 1.77 km resolution, spanning December 2021 to November 2023. Countries labelled with ISO 3166 three-character alpha codes.

Salinity

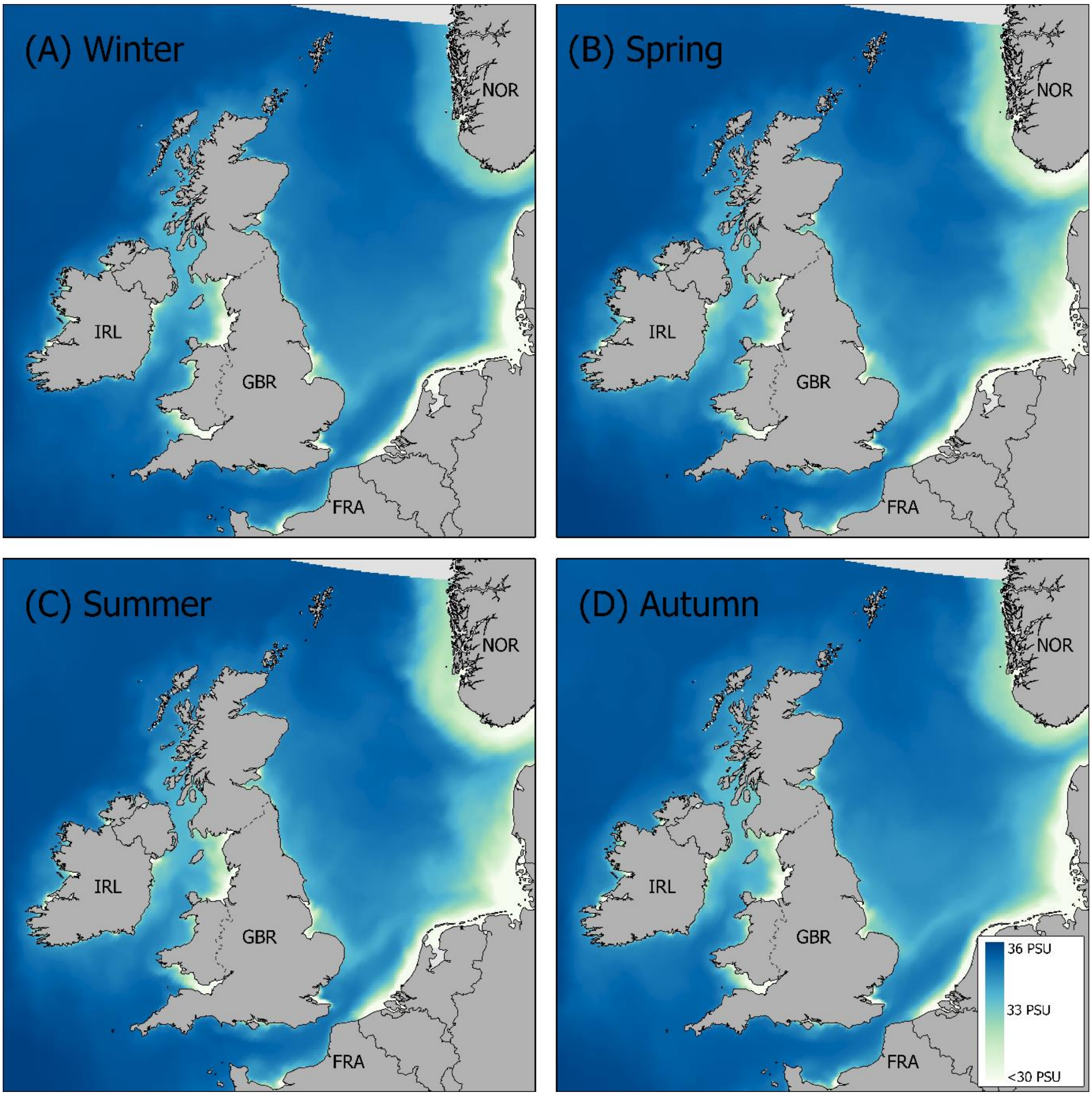

Figure 5. Salinity (PSU). Monthly mean average rasters were obtained from the Copernicus Atlantic Northwest Shelf–Ocean Physics Analysis and Forecast (cmems_mod_nws_phy_anfc_P1M-m model) at a 1.77 km resolution, spanning December 2021 to November 2023. Countries labelled with ISO 3166 three-character codes.

Vertical stratification

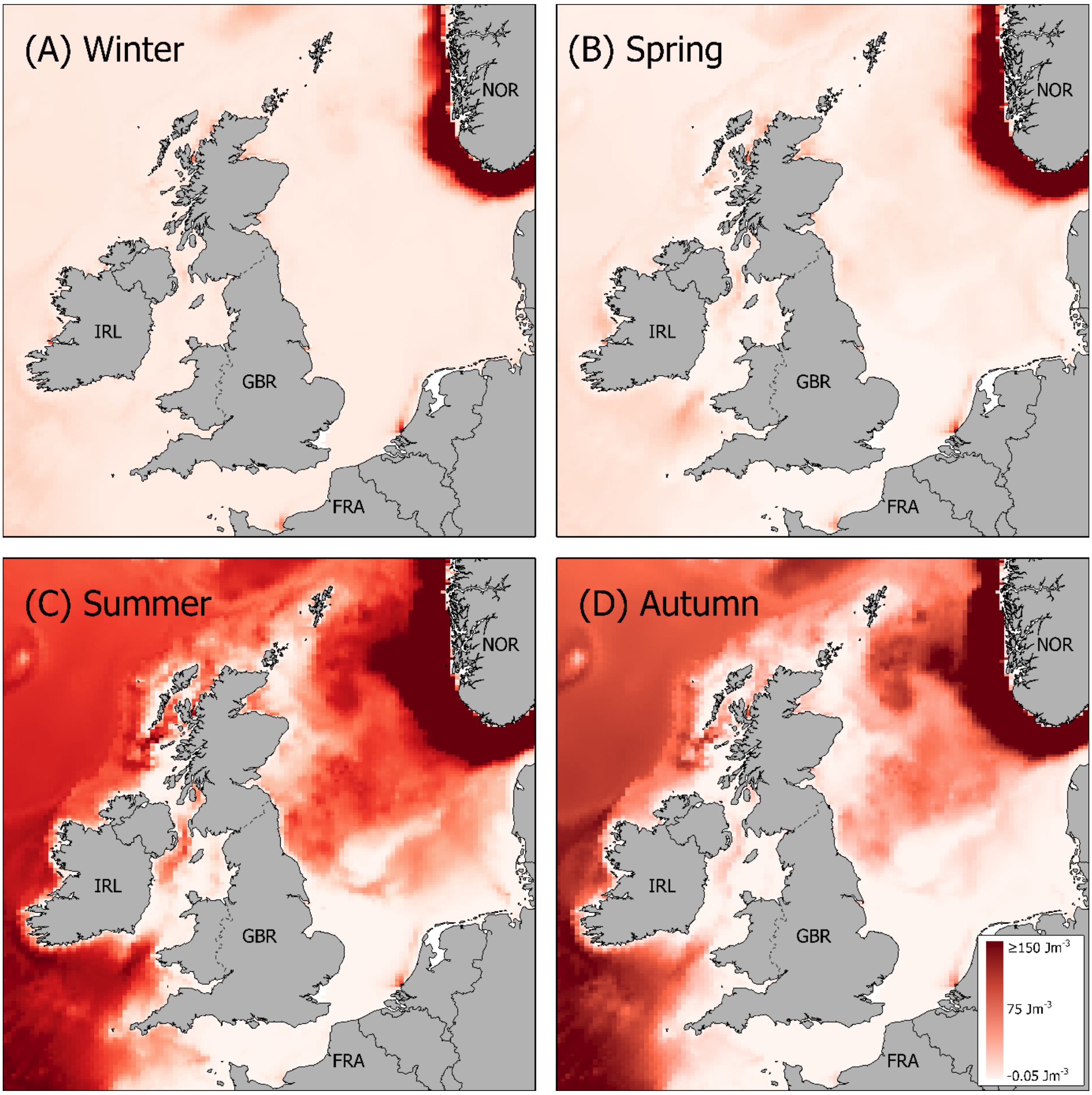

Figure 6. Vertical stratification (J/m3). The vertical stratification raster (potential energy anomaly) raster was obtained from the Ensemble Statistics dataset calculated from the Northwest Shelf Perturbed Parameter Ensemble (NWSPPE). The NWSPPE provided seasonal means for PEA from 2000 to 2019 at 7 x 7 km horizontal resolution. Countries labelled with ISO 3166 three-character codes.

Tidal speed

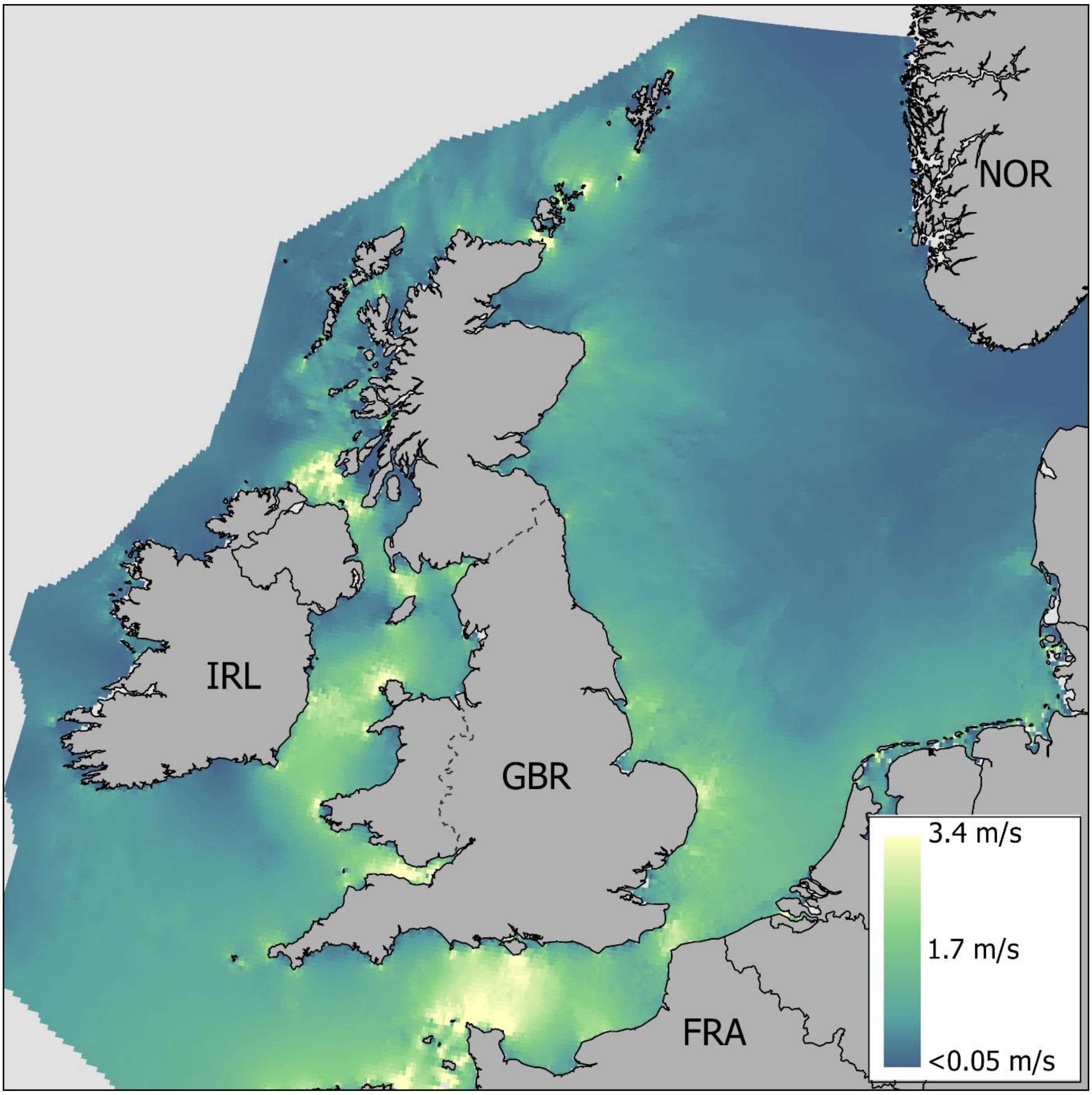

Figure 7. Tidal speed (m/s). POLPRED CS-20. Mean spring tide peak current speed (m/s) was obtained from the National Oceanographic Centre POLPRED model (CS20 depth-averaged model). This dataset was an average from 2006 to 2015 based on hourly values, with a horizontal resolution 1.8 km. Countries labelled with ISO 3166 three-character codes.

Seabed slope

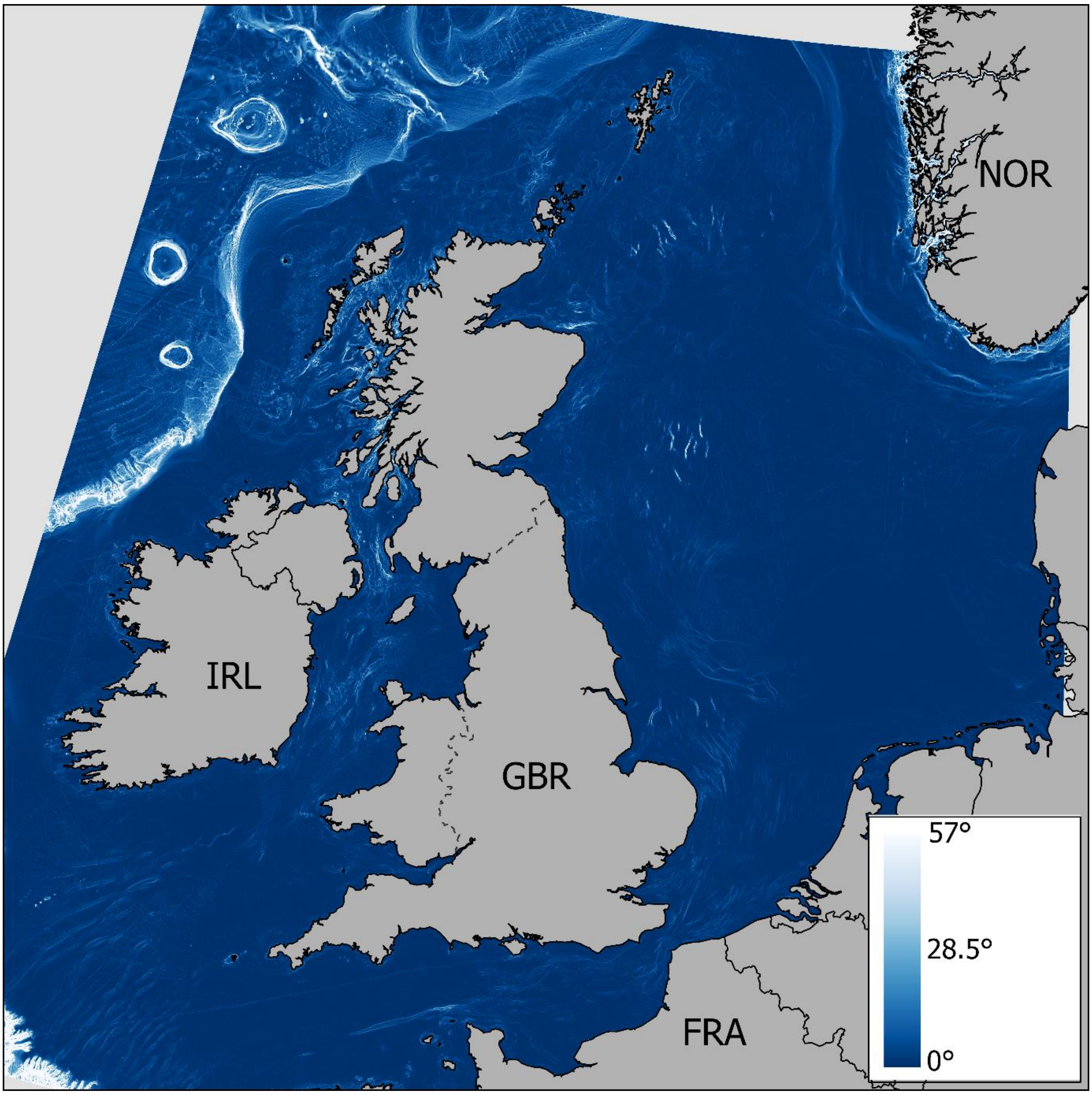

Figure 8. Seabed slope (arc °). Seabed slope was derived from the GEBCO gridded bathymetry depth raster (Fig. S1) at a 0.5 km horizontal resolution. Countries labelled with ISO 3166 three-character codes.

Seabed substrate

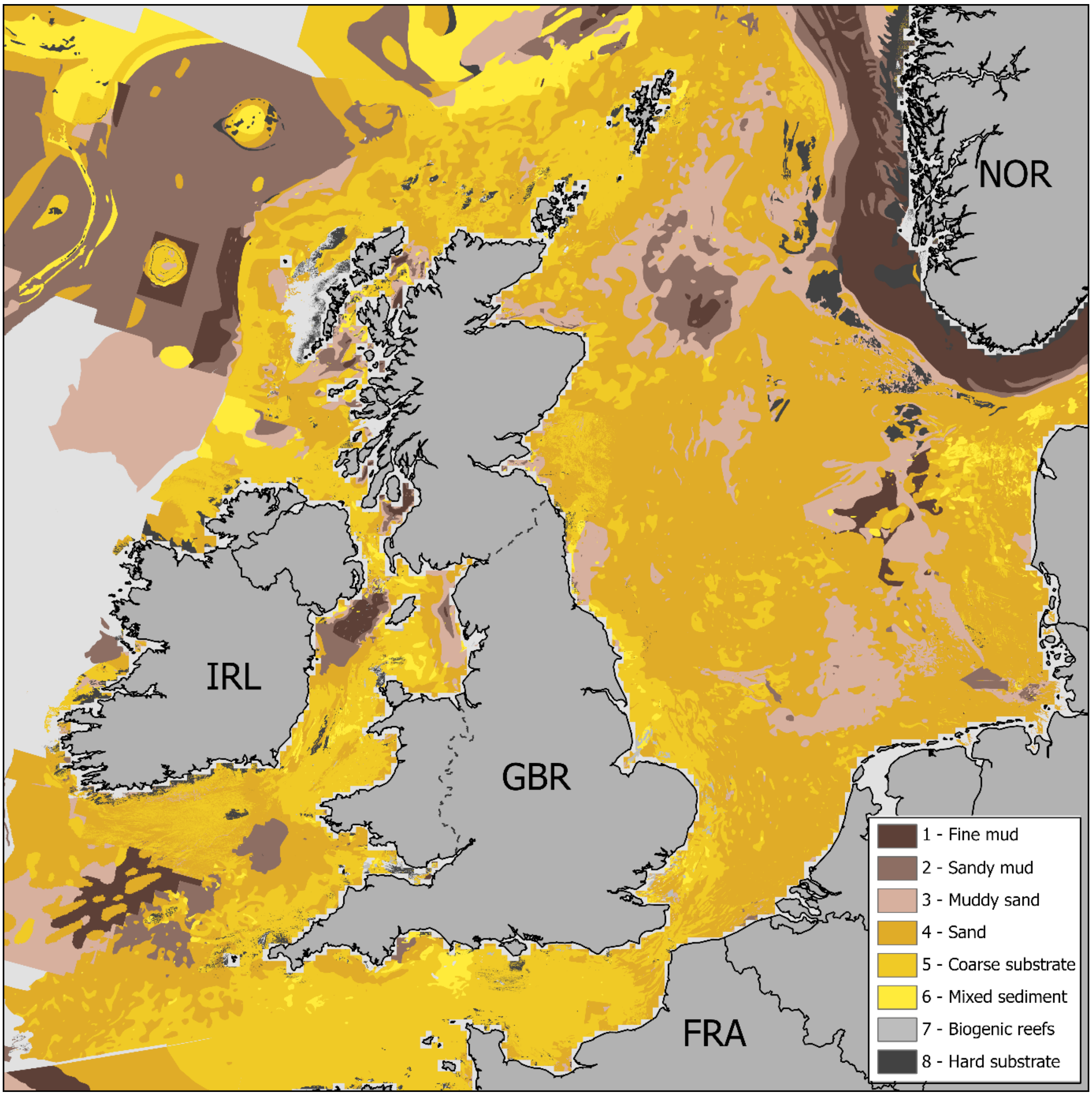

Figure 9. Seabed substrate classification based on the EUNIS Multiscale – Folk 7 system categorises the seabed into eight types. Mud (1) consists predominantly of fine particles, such as silt and clay. Sandy mud (2) is a mixture of sand and mud, with mud as the dominant component. Muddy sand (3) is a mixture where sand is the dominant component. Sand (4) is composed mostly of granular particles, ranging from very fine to coarse sand grains. Coarse substrate (5) includes larger particles such as gravel, pebbles, cobbles, and boulders. Mixed sediment (6) contains a mix of different particle sizes, including sand, gravel, mud, and occasionally coarser materials. Biogenic reefs (7) are solid, usually elevated structures on the seabed, formed by biological activity. Hard substrate (8) is composed of solid bedrock or large boulders and stones. Countries labelled with ISO 3166 three-character codes.

Seasonal similarity mapping

Moray Firth

Similarity of the UK seascape to the Moray Firth PrePARED wind farms was influenced by season (Fig. 10, Table 4). The North Sea showed consistently high similarity scores (> 0.6) in winter and spring, particularly between the UK, Denmark and Norway, though these similarity values decreased (< -0.1) during summer and autumn across much of the region. Some areas maintained high similarity year-round (> 0.6), particularly off the east coast of Scotland and in parts of the North Sea (e.g. Dogger Bank region, Fig. 11). The Irish Sea demonstrated dissimilar to neutral similarity to MF throughout the year. In contrast, off southern England, there was greater dissimilarity to MF (< -0.1) in winter and spring, transitioning to moderately similar habitats in summer and autumn.

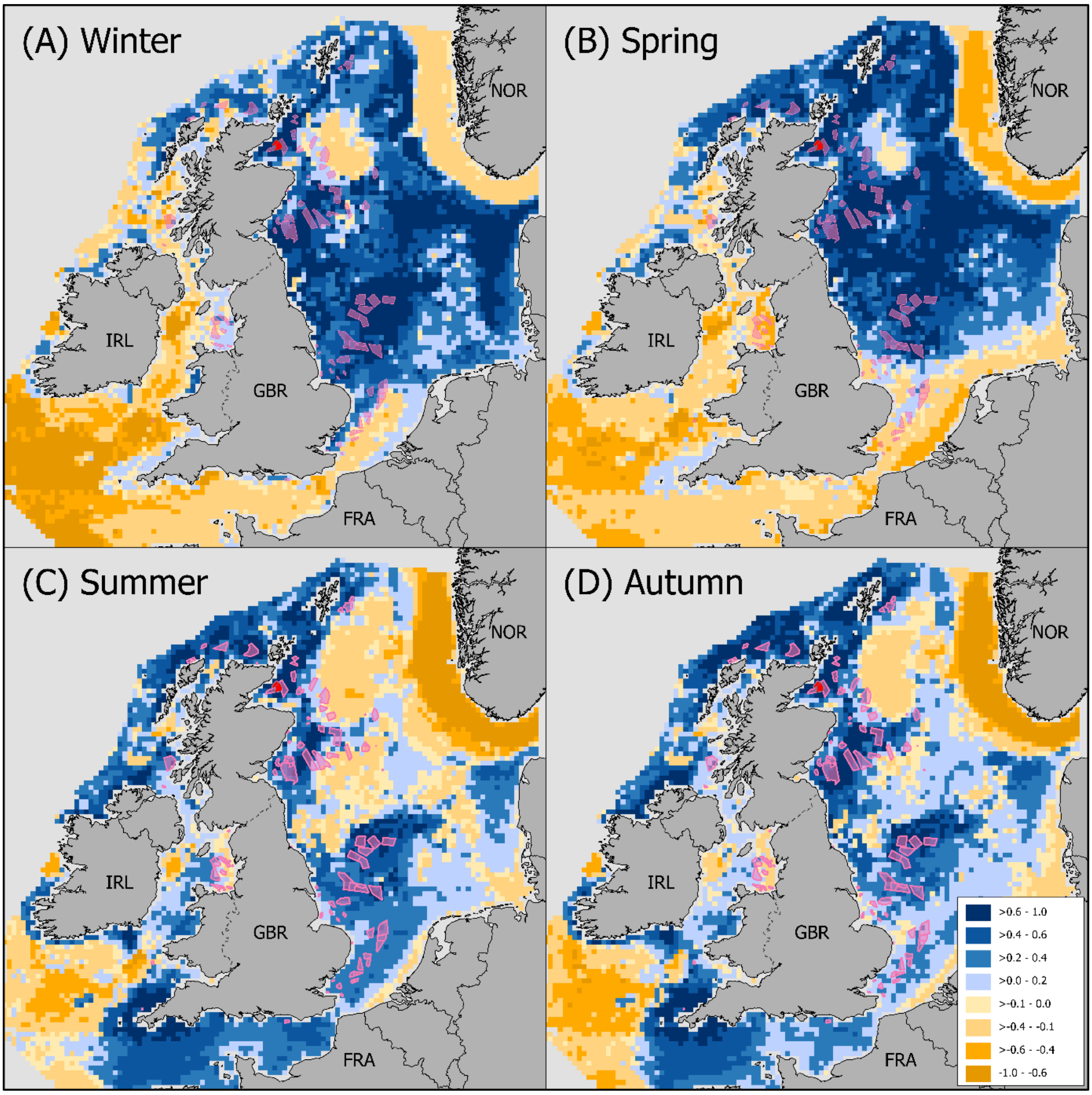

Figure 10. Seasonal similarity maps of the northeast Atlantic with respect to the Moray Firth study site. The similarity scores range from -1.0 to 1.0, with darker blue indicating cells that are more similar to the Moray Firth site (red filled polygon) and darker orange indicating cells that least similar. Current and future UK wind farms (pink edge polygon). Countries labelled with ISO 3166 three-character codes.

Limited variation occurred in seasonal mean environmental values across the wind farm network in comparison to those at the Moray Firth PrePARED sites, apart from vertical stratification (Table 4). Wind farms occurring in the upper quartile of similarity scores, exhibited sea bottom temperatures, salinity, tidal speed and slope more closely aligned with MF than all wind farms, although the differences were typically minor. Seasonal patterns were evident, with summer often showing the largest differences between groups, for example in vertical stratification.

Future wind farms (i.e. planned, approved, under construction) exhibited the highest similarity scores to the Moray Firth PrePARED wind farms (Fig. 12a). Of 60 planned, approved or under construction wind farms, 67% (n=40) had similarity scores above the grand median (0.22). In contrast, 74% (n=25) of operational wind farms had similarity scores occurring below the grand median. There was a significant difference in mean similarity scores between future and operational wind farms (two-sample t-test; n=60 vs 34; group means 0.379 vs 0.0959, t=5.4478, df=87, p<0.001).

Differences in similarity among farms in comparison to MF were investigated using a linear modelling framework with respect to foundation type; no statistically significant differences in similarity were detected ($F(3,90) = 2.11$, $p = 0.105$, $R^2 = 0.066$).

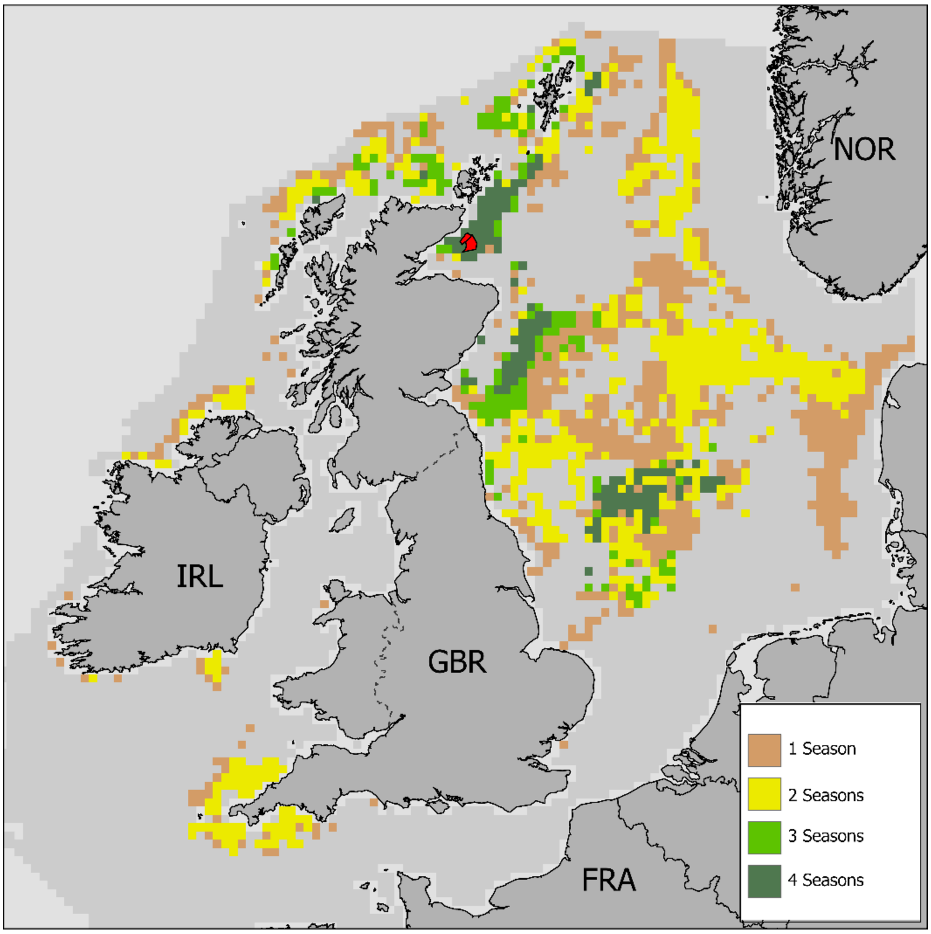

Figure 11. Year-round persistent areas of highly similar environmental conditions to Moray Firth PrePARED wind farms. Sum of seasonal similarity maps (Figure 9) where environmental similarity scores > 0.6. 4 (all seasons score highly similar for a particular cell); 3 (at least seasons score highly similar); 2 (any two seasons score highly similar); 1 (a single season scores highly similar). No seasons scored highly similar (mid-grey). Countries labelled with ISO 3166 three-character codes.

Table 4. Moray Firth. Seasonal variation of environmental variables at wind farms with **upper quartile** similarity scores in comparison to Moray Firth. Showing the Moray Firth (MF) reference values and corresponding wind farm data. The number of wind farms (n) above the median similarity score. Variables include, slope (degrees), seabed substrate, spring tide current speed (m/s), sea bottom temperature (°C), salinity (PSU), vertical stratification (Jm^{-3}).

Moray Firth	N	Sea bottom temperature (°C) (median; range)	Salinity (PSU) (median; range)	Vertical stratification (Jm^{-3}) (median; range)	Spring tide (m/s) (median; range)	Slope (degrees) (median; range)	Seabed substrate (median; range)
Winter (MF)	**2**	**8.5 (8.4 – 8.6)**	**34.6 (34.5 – 34.6)**	**0.1 (0.0 – 4.7)**	**0.5 (0.3 – 0.6)**	**0.2 (0.1 – 0.3)**	**5 (5 – 5)**
Upper quartile	26	8.2 (7.1 – 9.3)	34.5 (33.4 – 35.1)	0.0 (-0.1 – 10.6)	0.4 (0.2 – 1.0)	0.2 (0.1 – 0.4)	5.9 (4.5 – 8.7)
All wind farms	94	8.6 (6.4 – 11.4)	34.5 (30.3 – 35.1)	0.1 (-0.1 – 10.6)	0.5 (0.2 – 1.7)	0.2 (0.1 – 0.8)	5.7 (2.9 – 8.7)
Spring (MF)	**2**	**7.9 (7.8 – 7.94)**	**34.7 (34.7 – 34.7)**	**2.7 (2.1 – 12.9)**	**0.5 (0.3 – 0.6)**	**0.2 (0.1 – 0.3)**	**5 (5 – 5)**
Upper quartile	26	7.7 (7.2 – 8.8)	34.6 (33.7 – 35.2)	4.3 (0.1 – 26.9)	0.4 (0.2 – 0.6)	0.2 (0.1 – 0.5)	5.8 (4.5 – 8.7)
All wind farms	94	8.0 (7.2 – 11)	34.5 (30.8 – 35.2)	3.6 (0.0 – 26.9)	0.5 (0.2 – 1.7)	0.2 (0.1 – 0.8)	5.7 (2.9 – 8.7)
Summer (MF)	**2**	**11.8 (11.5 – 11.9)**	**34.7 (34.7 – 34.7)**	**12.6 (10.2 – 40.4)**	**0.5 (0.3 – 0.6)**	**0.2 (0.1 – 0.3)**	**5 (5 – 5)**
Upper quartile	26	12.4 (8.7 – 17.6)	34.5 (33.7 – 35.1)	19.5 (0.1 – 73.9)	0.5 (0.2 – 1.0)	0.2 (0.1 – 0.4)	5.8 (4.5 – 8.4)
All wind farms	94	11.9 (7.7 – 19)	34.5 (30.8 – 35.2)	21.8 (0.0 – 107.7)	0.5 (0.2 – 1.7)	0.2 (0.1 – 0.8)	5.7 (2.9 – 8.7)
Autumn (MF)	**2**	**12.4 (12.4 – 12.4)**	**34.7 (34.7 – 34.7)**	**2.0 (1.1 – 9.7)**	**0.5 (0.3 – 0.6)**	**0.16 (0.12 – 0.3)**	**5 (5 – 5)**
Upper quartile	26	12.4 (9.1 – 15.1)	34.6 (34.1 – 35.2)	4.3 (0.0 – 52.2)	0.4 (0.2 – 0.8)	0.2 (0.1 – 0.6)	6 (4.5 – 8.7)
All wind farms	94	12.7 (8.7 – 17.2)	34.6 (30.5 – 35.2)	2.89 (0.0 – 72.3)	0.5 (0.2 – 1.7)	0.2 (0.1 – 0.8)	5.7 (2.9 – 8.7)

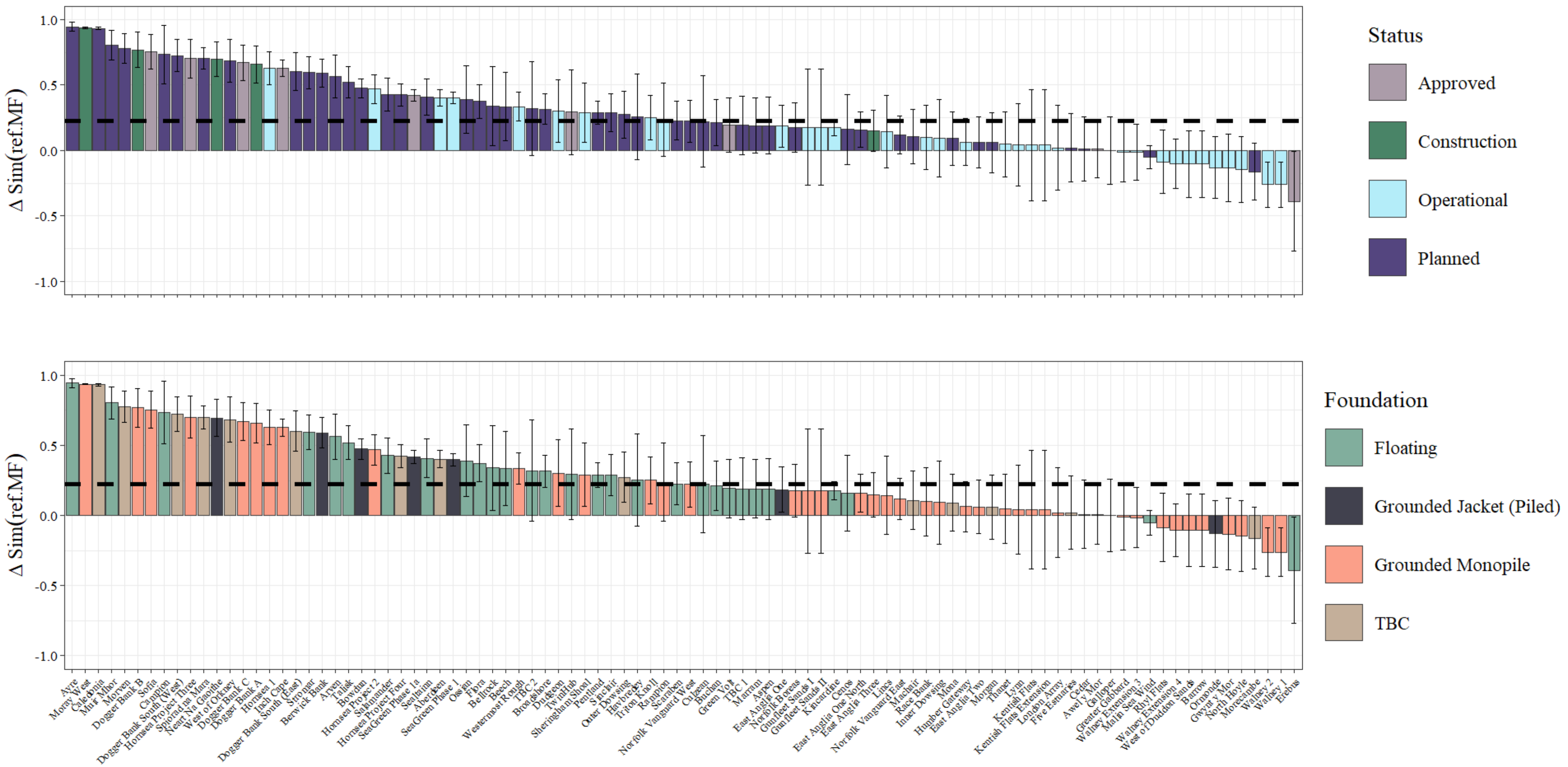

Figure 12. Similarity scores of offshore wind farms compared to the Moray Firth study site, categorised by the wind farm's status and foundation type. Similarity scores can range from -1.0 to 1.0. Sites with bar ordered greatest to least similarity to the Moray Firth study site. Each bar represents a wind farm mean similarity score across the four seasons, with error bars indicating the standard deviations across the seasons. The dashed horizontal line represents the grand median line (0.22) of all the wind farms' similarity score (horizontal dashed line). Top panel: wind farm categorised by status - Approved, Construction, Operational, and Planned. Bottom panel: wind farms categorised by foundation type - Floating, Grounded Jacket (Piled), Grounded Monopile, and TBC (to be confirmed).

Firth of Forth

Seasonally consistent high similarity (> 0.6) to the Firth of Forth PrePARED sites was predominantly observed along the east coast of the UK (Fig. 13). Seasonal variations were apparent, occurring mostly in summer and autumn off the northeast coast of England, where similarity declined. Summer and autumn also demonstrated moderate and above similarity (> 0.2) in the Irish Sea and along the west coast of Scotland. Persistent highly similar habitats (year-round) occurred exclusively off the east coast of Scotland (Fig. 14). There is a small region of persistent similarity off the central north England coast, though less substantial than the region occurring in the Central North Sea (e.g. Dogger Bank region, Fig. 11) as part of the Moray Firth similarity analysis.

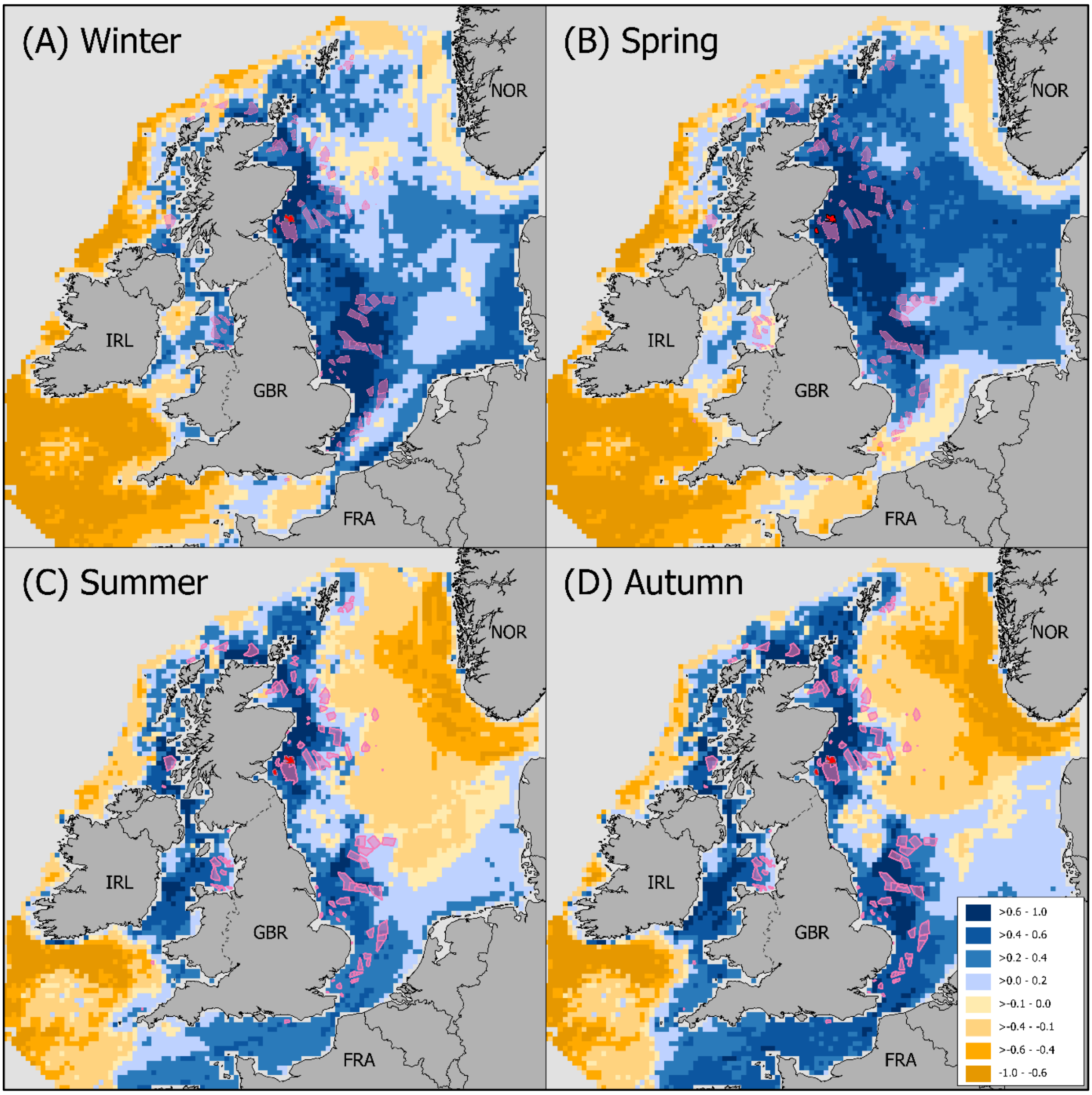

Figure 13. Seasonal similarity maps of the northeast Atlantic with respect to the Firth of Forth study site. The similarity scores range from -1.0 to 1.0, with darker blue indicating cells that are most similar to the Firth of Forth site (red filled polygon) and darker orange indicating cells that least similar. Current and future UK wind farms (pink edge polygon). Countries labelled with ISO 3166 three-character alpha codes.

Although wind farms occurring in upper quartile group of similarity scores (Table 5) tended to align more closely with FoF values, as would be expected, the degree of similarity varied across environmental parameters and seasons. Seasonal patterns were evident, with summer often showing the largest differences.

Sea bottom temperatures in the upper quartile group closely matched FoF across seasons, while salinity at FoF was consistently at the lower end of the range for all groups (Table 5). Vertical stratification showed the most significant differences, with values at FoF often at the lower end of the range and the greatest seasonal variation. Spring tide speeds at FoF sites were generally lower than other sites, while slope values were at the higher end of the range across all groups.

Similarity scores with respect to wind farm status (in comparison to the Firth of Forth PrePARED sites; Fig. 15), were more broadly distributed, with a wider spread of scores across both future and operational wind farms. There was no statistically significant difference in mean similarity scores between future and operational farms (two-sample t-test; n=96; group means 0.362 vs 0.369, t=-0.147, df = 85, p = 0.8833). There was a highly significant effect of foundation type on similarity scores (One-way ANOVA; $F_{(3,92)}$ = 4.165, p < 0.005). Grounded Jacket (Piled) had a significant positive effect (p = 0.05) on similarity scores when compared to other foundation types (Post hoc Tukey test).

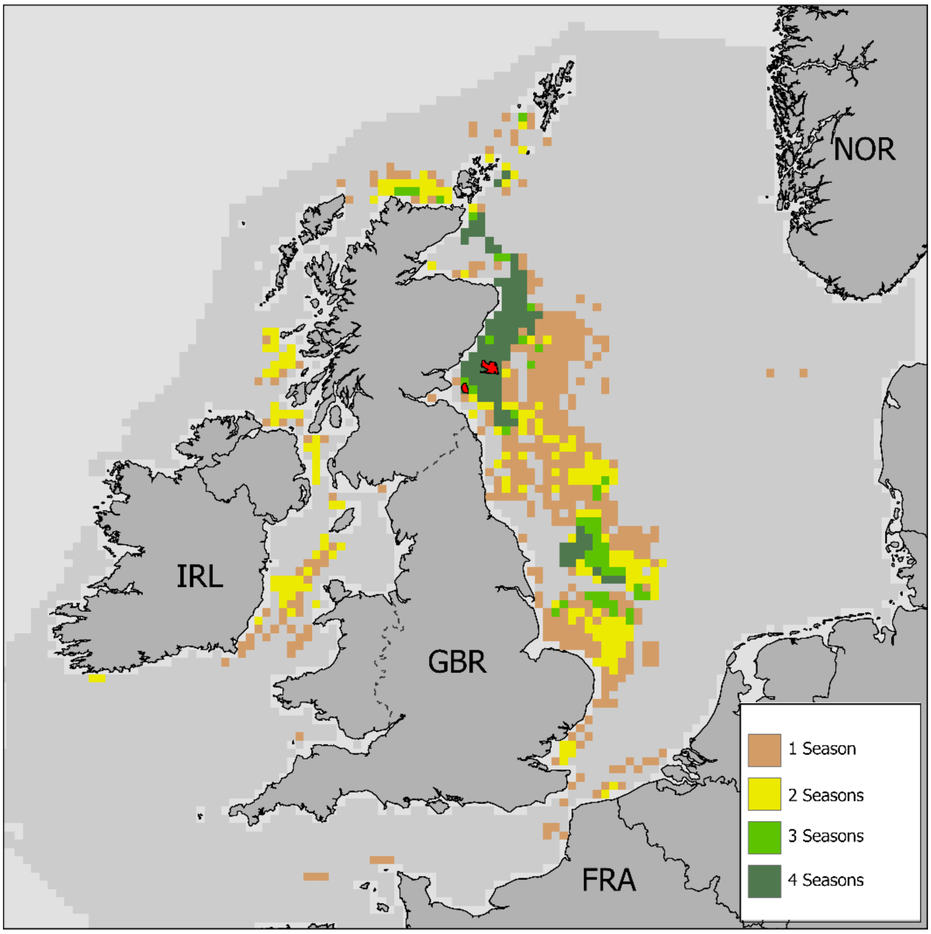

Figure 14. Year-round persistent areas of highly similar environmental conditions to Firth of Forth PrePARED wind farms. Sum of seasonal similarity maps (Figure 13) where environmental similarity scores > 0.6. 4 (all seasons score highly similar for particular cell); 3 (at least seasons score highly similar); 2 (any two seasons score highly similar); 1 (a single season scores highly similar). No seasons scored highly similar (mid-grey). Countries labelled with ISO 3166 three-character alpha codes.

Table 5. Forth of Firth. Seasonal variation of environmental variables at wind farms with **upper quartile** similarity scores in comparison to Forth of Firth. Showing the Forth of Firth (FoF) reference values and corresponding wind farm data. The number of wind farms (n) above the median similarity score. Variables include, slope (degrees), seabed substrate, spring tide current speed (m/s), sea bottom temperature (°C), salinity (PSU), vertical stratification (Jm^{-3}).

Firth of Forth	N	Sea bottom temperature (°C) (median; range)	Salinity (PSU) (median; range)	Vertical stratification (Jm^{-3}) (median; range)	Spring tide (m/s) (median; range)	Slope (degrees) (median; range)	Seabed substrate (median; range)
Winter (FoF)	**2**	**8.4 (8.2 – 8.4)**	**34.5 (34.0 – 34.5)**	**0.11 (0.0 – 9.5)**	**0.6 (0.4 – 0.7)**	**0.2 (0.2 – 0.4)**	**5 (5 – 7)**
Upper quartile	26	8.1 (6.4 – 9.4)	34.3 (32.4 – 34.7)	0.0 (0.0 – 10.6)	0.6 (0.3 – 1.1)	0.2 (0.1 – 0.6)	5.7 (4.8 – 7.0)
All wind farms	94	8.6 (6.4 – 11.4)	34.5 (30.3 – 35.1)	0.1 (-0.1 – 10.6)	0.5 (0.2 – 1.7)	0.2(0.1 – 0.8)	5.7 (2.9 – 8.7)
Spring (FoF)	**2**	**7.3 (7.2 – 7.4)**	**34.4 (33.7 – 34.4)**	**2.5 (2.3 – 17.9)**	**0.6 (0.4 – 0.7)**	**0.2 (0.2 – 0.4)**	**5 (5 – 7)**
Upper quartile	26	7.4 (7.2 – 8.5)	34.6 (33.9 – 34.9)	5.0 (0.1 – 16.3)	0.5 (0.3 – 0.7)	0.2 (0.1 – 0.8)	5.5 (3.0 – 7.0)
All wind farms	101	8.0 (7.2 – 11.0)	34.5 (30.8 – 35.2)	3.6 (0.0 – 26.7)	0.5 (0.2 – 1.7)	0.2 (0.1 – 0.8)	5.7 (2.9 – 8.7)
Summer (FoF)	**2**	**11.0 (10.8 – 11.1)**	**34.4 (33.7 – 34.4)**	**21.4 (11.3 – 33.6)**	**0.6 (0.4 – 0.7)**	**0.2 (0.2 – 0.4)**	**5 (5 – 7)**
Upper quartile	23	11.6 (9.3 – 16.9)	34.3 (32.3 – 35.0)	17.4 (0.0 – 55.3)	0.6 (0.3 – 1.7)	0.2 (0.1 – 0.8)	6 (4.5 – 8.5)
All wind farms	92	11.9 (7.7 – 19.0)	34.5 (30.8 – 35.2)	21.8 (0.0 – 107.7)	0.5 (0.2 – 1.7)	0.2 (0.1 – 0.8)	5.7 (2.9 – 8.7)
Autumn (FoF)	**2**	**12.6 (12.5 – 12.6)**	**34.6 (34.2 – 34.6)**	**2.2 (1.2 – 10.1)**	**0.6 (0.4 – 0.7)**	**0.2 (0.2 – 0.4)**	**5 (5 – 7)**
Upper quartile	23	12.7 (11.7 – 17.1)	34.4 (33.0 – 34.8)	2.9 (0.0 – 32.74	0.5 (0.3 – 1.7)	0.2 (0.1 – 0.8)	5.8 (4.9 – 8.5)
All wind farms	90	12.7 (8.7 – 17.2)	34.6 (30.5 – 35.2)	2.9 (0.0 – 72.3)	0.5 (0.2 – 1.7)	0.2 (0.1 – 0.8)	5.7 (2.9 – 8.7)

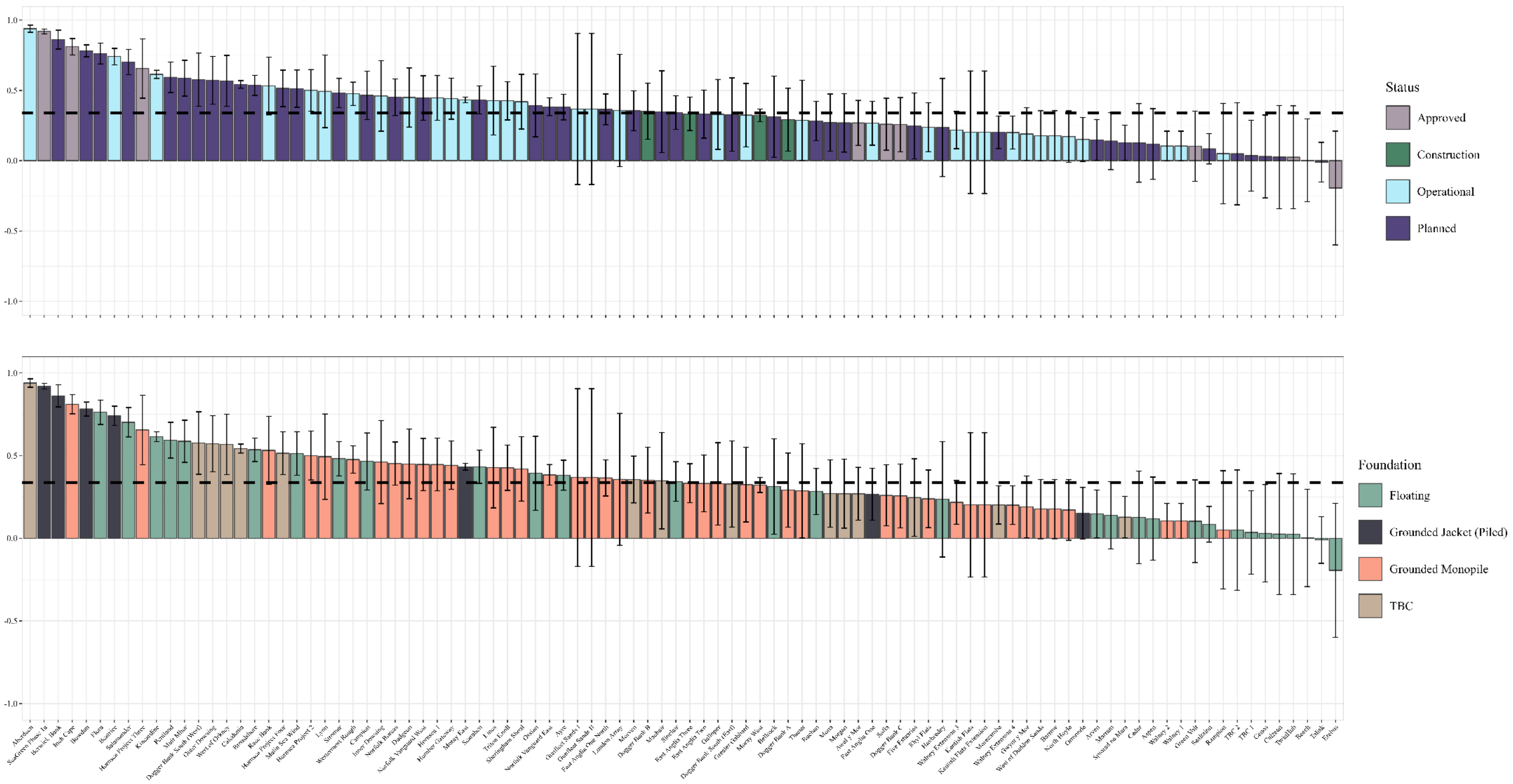

Figure 15. Similarity scores of offshore wind farms compared to the Firth of Forth study site, categorised by the wind farm's status, and foundation type. The plots show similarity scores can ranging from -1.0 to 1.0., Sites with bar ordered in by greatest to least similarity to the Firth of Forth study site. Each bar represents a wind farm mean similarity score across the four seasons, with error bars indicating the standard deviations across the seasons. The dashed horizontal line represents the grand median line (0.34) of all the wind farms' similarity score (horizontal dashed line). Top panel: wind farm categorised by status - Approved, Construction, Operational, and Planned. Bottom panel: wind farms categorised by foundation type - Floating, Grounded Jacket (Piled), Grounded Monopile, and TBC (To be confirmed)

Environmental drivers of similarity

A sensitivity analysis was conducted to determine the relative strength of the differing environmental datasets for determining environment similarity between the PrePARED wind farms and all other UK sites. Variance in grand mean seasonal similarity scores (calculated across all wind farms; Fig. 16) decreased as the number of variables incorporated into similarity analyses increased. Some seasonal variation was evident, which appears to be driven by the incorporation of vertical stratification, which itself has strong a seasonal pattern.

During summer and autumn, vertical stratification is the primary driver of similarity scores. There was a statistically significant divergence between similarity analyses that incorporate vertical stratification and those without it (Fig. 16C & D; two-sample t-test on median scores between similarity analyses that include and exclude vertical stratification, $p < 2.2e-16$).

During winter and spring (Fig. 16A & B), sea bottom temperature becomes an important contributing variable to driving similarity scores. For analyses including sea bottom temperature, median similarity scores become strongly positive with less spread across the full scale (-1 to 1). Further, scores arising from similarity analyses including sea bottom temperature, which both incorporate and exclude vertical stratification, become less divergent as sea bottom temperatures influence on driving similarity grow.

In contrast, during winter and spring (Fig. 16A & B), sea bottom temperature becomes the dominant factor influencing similarity patterns. When sea bottom temperature is included in the analyses, median similarity scores shift strongly positive and become more aggregated. During these seasons, the inclusion or exclusion of vertical stratification has less impact on the overall similarity scores, as sea bottom temperature exerts a stronger influence on environmental similarity.

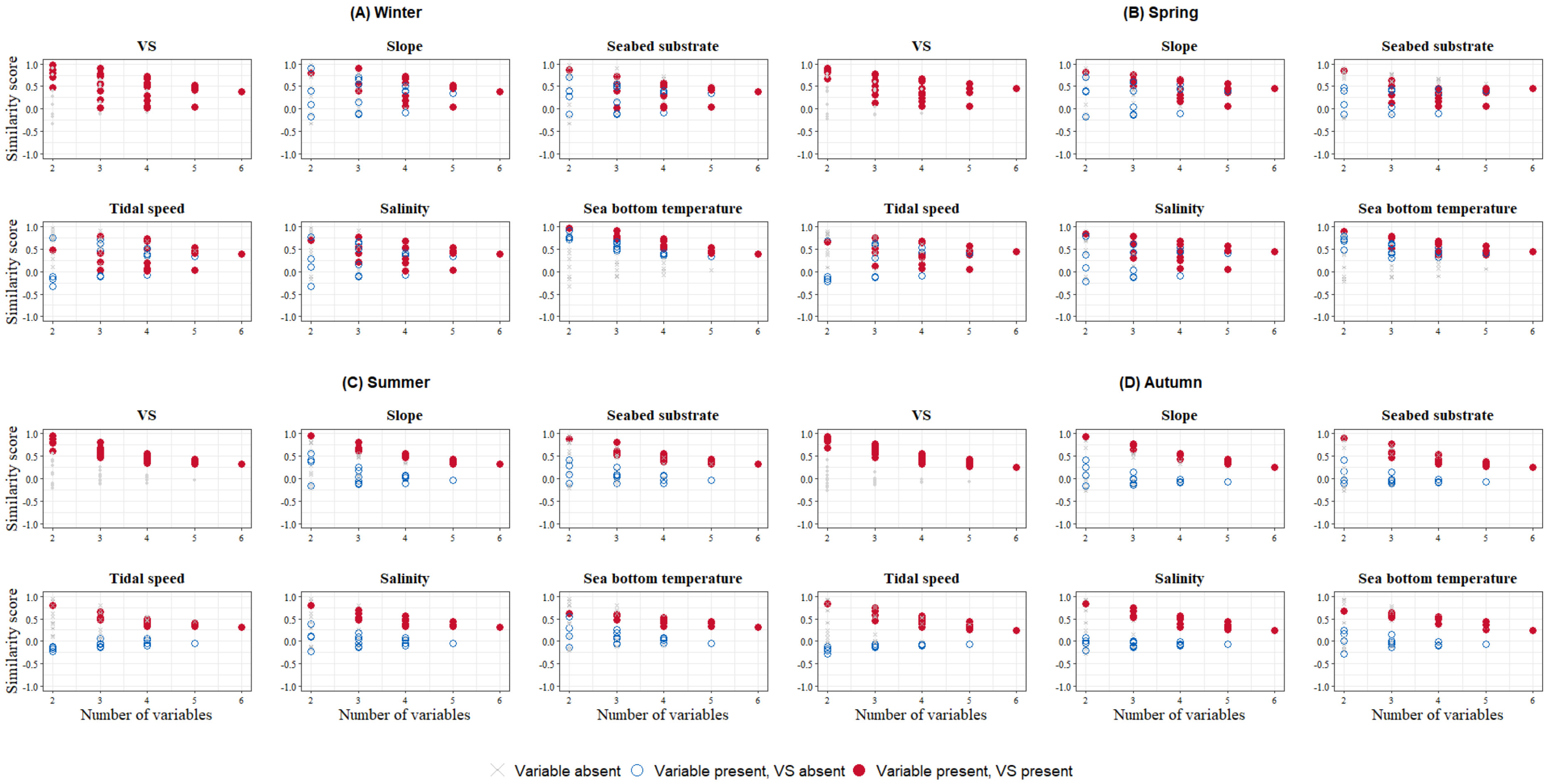

Figure 16. Sensitivity analysis of similarity scores for all combinations of environmental variables across four seasons (Winter, Spring, Summer, Autumn). Data points represent median similarity scores extracted from wind farm locations for each variable combination. Number of environment variables incorporated into similarity search (x-axis). Similarity score (-1.0 to 1.0; y-axis). Colour coding: red circles - variable present with PEA; blue circles - variable present without PEA; grey cross - variable absent. This visualisation demonstrates the relative importance of each variable in driving similarity scores and its interaction with PEA across seasons. Top left: combinations that occurred in Winter; Top right: combinations that occurred in Spring; Bottom left: combinations that occurred in Summer; Bottom right: combinations that occurred in Autumn.

4. Discussion

Similarity analysis of UK offshore wind farms with respect to the PrePARED study sites in the Moray Firth (MF) and Firth of Forth (FoF) revealed complex spatio-temporal patterns across the UK seascape. The findings reported here can feed into discussions regarding transferability of research outcomes from the PrePARED sites to other offshore wind farms.

Spatial patterns of similarity

The east coast of Scotland revealed high similarity to both MF and FoF sites across all seasons. This finding is unsurprising given the geographical proximity and shared regional characteristics. Yet, it underscores the potential for application of PrePARED findings to other Scottish east coast developments, which could help to streamline future environmental assessments and regulatory processes in this region.

Most of the North Sea, particularly the Dogger Bank area, emerged as a region with high year-round similarity to the MF PrePARED sites. This finding is interesting given the distance from the PrePARED sites and suggests that certain environmental characteristics persist across larger spatial scales in the North Sea. The implication here is that PrePARED findings, if appropriately caveated, could be applied to a broader geographical area, extending beyond the immediate vicinity of the study sites. This premise does, however, rely on a premise that environmental similarity may in some part influence the potential for ecological and biological similarity.

Seasonality

Seasonal changes in similarity scores were observed, particularly for the MF comparisons. The central North Sea revealed higher similarity in winter and spring compared to summer and autumn. This seasonal variability was primarily driven by differences in sea bottom temperatures and PEA. These findings highlight the importance of considering seasonal effects when assessing the potential transferability of research outcomes. The results here suggest that the applicability of PrePARED findings may vary across a year, necessitating a more nuanced, season-specific approach to environmental impact assessments and management strategies.

Areas of seasonal high similarity, such as southwest England, northeast England, and the north coast of Scotland, present opportunities and challenges. Whilst these regions offer potential for the application of PrePARED findings, the seasonal nature of their similarity underscores the need for careful consideration and potentially additional research, such as further surveys, are undertaken across other seasons to validate the transferability of results.

Wind farm characteristics

Our analysis revealed planned future offshore wind farms demonstrated statistically significantly higher similarity to the MF sites compared to existing operational wind farms. However, conversely, there was no significant difference detected between future and operational wind farms when considered from the perspective of FoF sites. The reasons underlying this divergence are potentially linked to geographic proximity, differences in foundation types across both built and planned farms and that constraints on site selection can change through time as technology improves.

Wind farms with grounded jackets revealed significantly higher similarity to FoF sites compared to floating and grounded monopile wind farms. This finding suggests a potential relationship between environmental conditions and the selection of foundation types. Further investigation is needed to disentangle these relationships and understand their implications for the transferability of ecological findings between sites with different foundation types.

Environmental drivers

Our analysis investigated the relative importance of different environmental variables in driving similarity scores. We identified key factors influencing similarity, including vertical stratification and sea bottom temperature. The examination of these environmental drivers provides additional context for understanding the patterns of similarity observed across the UK seascape. While this analysis offers insights, it should be noted that the relationships between these drivers and overall site similarity are complex and environmental data are rarely independent of each other. Interpretation of our results warrants careful consideration when applying these findings across different locations.

Methodological considerations and future directions

Whilst similarity analysis provides useful context, it is important to acknowledge the associated limitations. The similarity scores are useful for comparative purposes but are relative measures and should be interpreted cautiously.

The reduction of complex marine environments to a single similarity score, while providing a useful comparative tool, oversimplifies the multifaceted nature of these ecosystems. This approach may obscure nuanced differences between sites that could be ecologically significant. Additionally, the use of grid cells (156 km^2) in our analysis introduces limitations in capturing fine-scale environmental variability, potentially masking important local variations in environmental conditions.

There is uncertainty surrounding future developments, particularly in emerging technologies like floating wind farms. The potential environmental effects arising from these new technologies are not yet fully understood, which could affect the validity of our similarity comparisons for future sites.

Our analysis considered several abiotic environmental factors, which represent ecologically informed, yet limited, characteristics of an ecosystem. The exclusion of biotic factors and ecosystem dynamics limits the assessment of site similarity. Ecosystem characteristics, species distributions, and ecological interactions can vary between sites, even when abiotic conditions are similar.

The analysis presented here could be extended by incorporating biotic factors alongside abiotic data and might provide a more holistic assessment of site similarity. While the current approach simplifies complex marine environments, adding biological data such as marine mammal distributions, seabird foraging and migratory areas, would enhance the ecological relevance of the findings, but increase model complexity and may require more complex modelling frameworks, such as Ecopath, Ecospace or Ecosim (https://ecopath.org/).

Conclusion

This analysis provides context for the discussion regarding potential transferability of PrePARED findings to other UK offshore wind farms. The results highlight opportunities for broader application, especially for future wind farm projects. By identifying environmental similarities across the UK seascape, we identify regions where PrePARED findings might be extendable with the associated caveats described. This analysis offers one approach for connecting site-specific research to broader applications, hence helping to support evidence-based offshore wind farm development.

5. References

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Supplementary Material

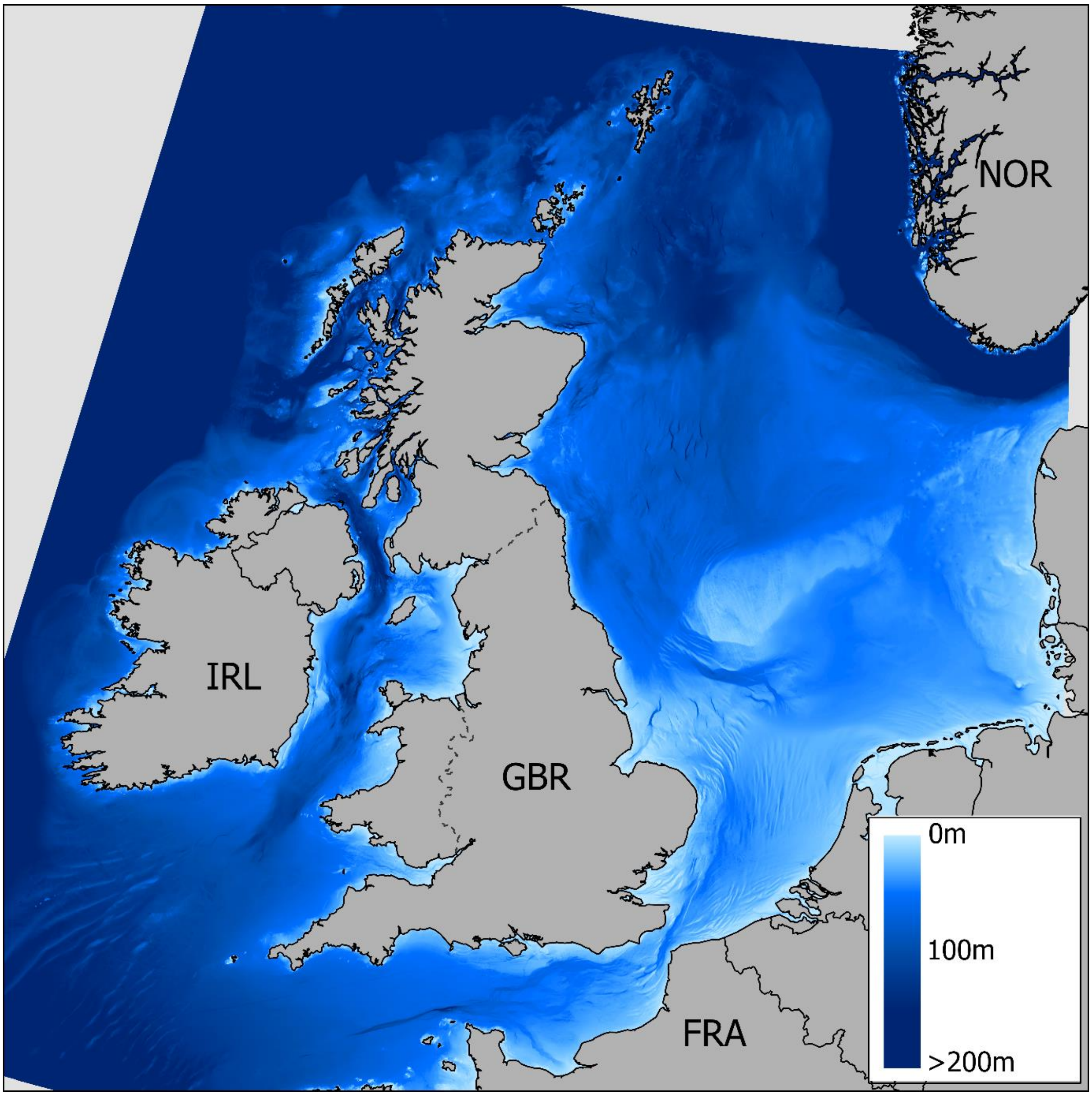

Figure S1. Seabed depth (m). GEBCO gridded bathymetry depth raster at a 0.5 km horizontal resolution. Countries labelled with ISO 3166 three-character codes.

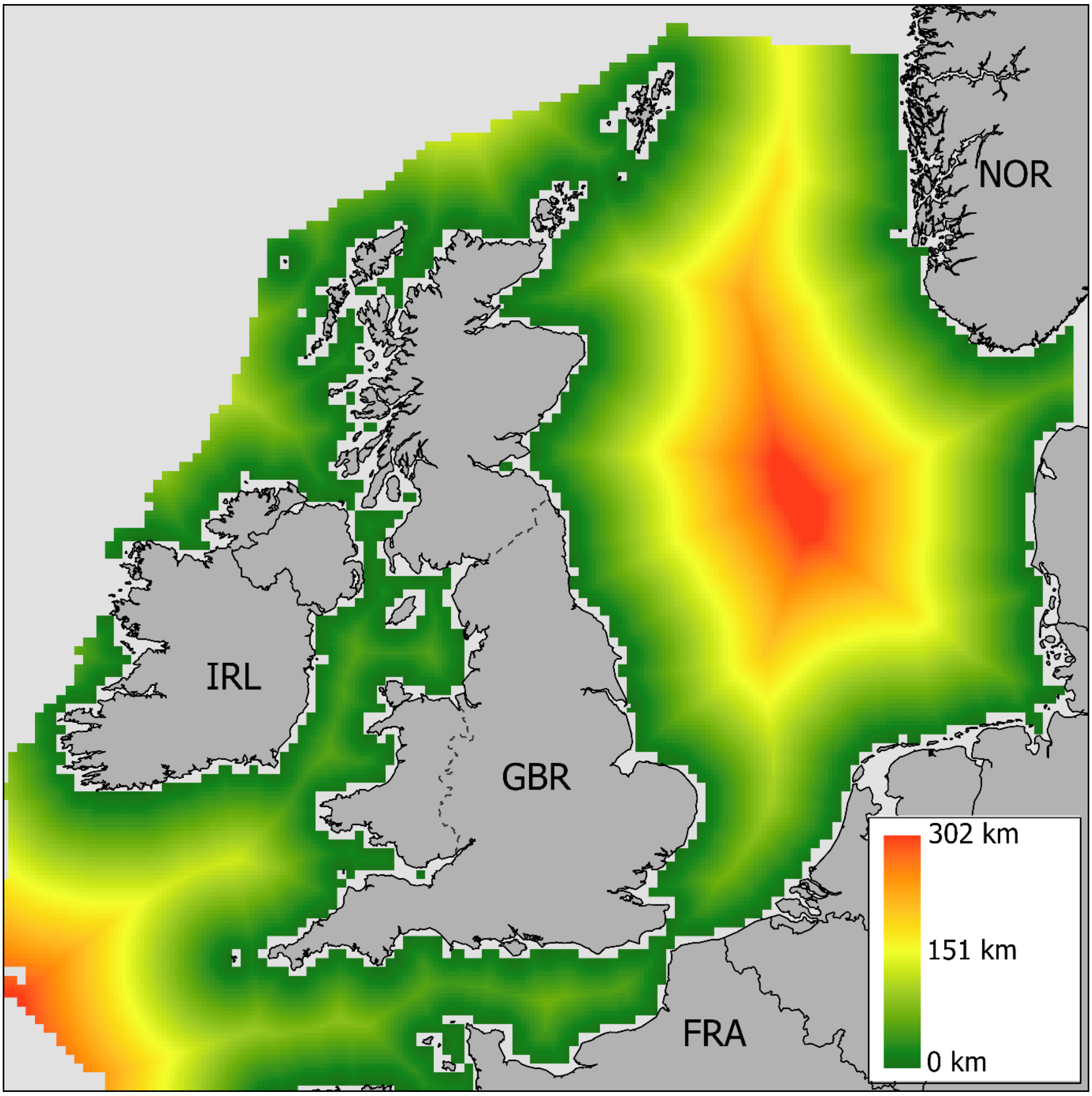

Figure S2. Distance to shore (km). Derived from EEA coastline shapefile using geodesic distance shown at a 1.8 km spatial resolution. Countries labelled with ISO 3166 three-character codes.