Supplementary material

Habitat suitability and future refugia for Vulnerable Marine ecosystems sea pens across European seas

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Summary

- Fig S19–S21 Climate scenario maps — SSP2-4.5, 2091–2100
- Fig S22–S24 Climate scenario maps — SSP5-8.5, 2041–2060

OCCURRENCE DATASET

List of surveys used, with definitions of acronyms :

MEDITS – Mediterannean International Bottom trawl Survey

CAMANOC - CAmpagne MANche OCcidentale pluridisciplinaire (West English channel pluridisciplinary survey)

CCFS – Channel Ground Fish Survey

NS-IBTS – North-sea, International Bottom trawl survey

EVHOE – EValuation Halieutique Ouest de l'Europe – (Western Eeurope fish survey)

SOLEMON – Adriatic SOLE and ground fish MONitoring beam trawl survey

NOURMED – NOUrriceries MEDiterannee (Mediterannean fish nurseries)

EPIBENGOL – Epibenthic survey in the channel and gulf of Lion

Demersales – International Bottom trawl survey of Northern Spain

Table SI : Source of data points used to create the three occurrence datasets.

SURVEY NAME	**TYPE**	**AREA**	**CITATION**	**YEARS**	**NB OF POINTS (Total)**	**NB OF POINTS (Filtered)**	***Pennatula phosphorea***	***Pennatula rubra***	***Pteroides griseum***

MEDITS	*Trawl survey*	*Mediterranean (EU countries)*	*Spedicato et al. (2020)*	*2001-2022*	*30576*	*2273*	*216*	*220*	*174*
CAMANOC	*Trawl survey*	*English Channel*	*Travers-Trolet & Verin (2014)*	*2014*	*88*	*0*	*0*	*0*	*0*
CGFS	*Trawl survey*	*English Channel*	*Girado (1988)*	*2006-2018*	*1283*	*0*	*0*	*0*	*0*
NS-IBTS	*Trawl survey*	*English Channel and North Sea*	*ICES (2024)*	*2006-2015*	*1081*	*340*	*30*	*0*	*0*
EVHOE	*Trawl survey*	*Bay of Biscay*	*Laffargue (1987)*	*2008-2021*	*3413*	*657*	*65*	*0*	*44*
SOLEMON	*Beam trawl survey*	*Adriatic Sea*	*Scarcella et al. (2019)*	*2005-2017*	*1059*	*105*	*3*	*1*	*4*
NOURMED	*Trawl survey*	*Gulf of Lion*	*Vaz et al. (2023)*	*2018-2019*	*216*	*88*	*3*	*1*	*4*
EPIBENGOL	*Towed video record*	*Gulf of Lion*	*Vaz (2018)*	*2018*	*10*	*5*	*2*	*1*	*2*
DEMERSALE	*Trawl survey*	*North Spain*	*ICES (2024a)*	*2008.2019*	*88*	*62*	*62*	*0*	*34*
OBIS JNCC	*Mixed*	*UK waters*	*JNCC (2021)*	*1984-2014*	*2286*	*350*	*350*	*0*	*0*
GBIF mixed	*Mixed*	*study area*	*GBIF (2024)*	*1968-2007*	*109*	*42*	*42*	*0*	*0*
ICES VME database	*Mixed*	*study area*	*ICES (2024b)*	*1900-2020*	*38*	*34*	*34*	*0*	*0*

ENVIRONNEMENTAL LAYERS

Table SII : Summary of environmental layers used in the modelling.

VARIABLE	*METRIC*	*CODE*	*CLIMATE PROJECTION*	*CITATION*	*NATIVE RESOLUTION*
TEMPERATURE	*Long-term maximum*	*Tethao_ltmax*	*YES*	*Assis et al. (2024)*	*0.05 decimal degrees (4-5 km)*
CURRENT VELOCITY	*Long-term maximum*	*Sws_ltmax*	*YES*		
CURRENT VELOCITY	*range*	*Sws_range*	*YES*		
DISSOLVED OXYGEN	*Long-term minimum*	*o2_ltmin*	*YES*		
SUBSTRATE AVERAGE GRAIN SIZE	*Log-transformed*	*Log_grain*	*NO*	*Millot & Vaz (2024); Vasquez et al. (2021)*	*None (Polygons)*
DEPTH	*mean*	*Bathymetry*	*NO*	*EMODnet Bathymetry Consortium (2020)*	*(200m) 0.002*

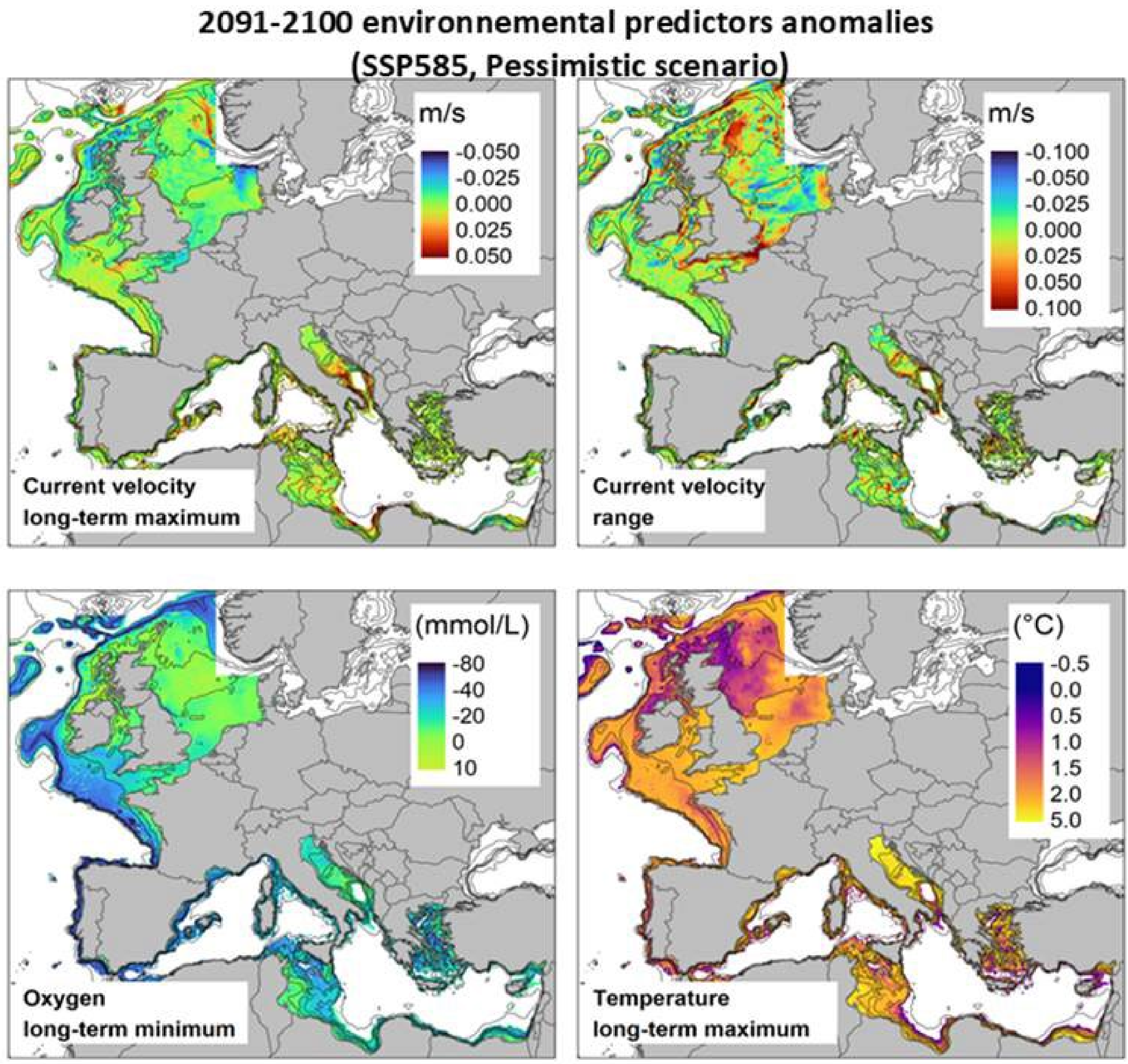

Figure S1 : Expected anomalies of environmental predictors with respect to the reference period for 2091-2100, according to the most pessimistic climate scenario (SSP 585).

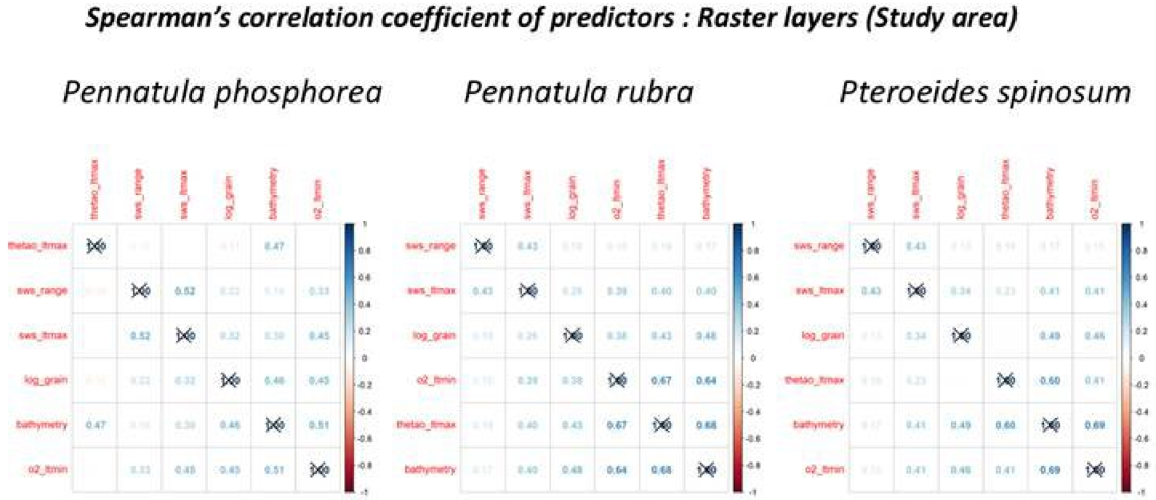

Figure S2 : Spearman's correlation coefficient for each raster layers (cropped to the species study area) used in the modelling.

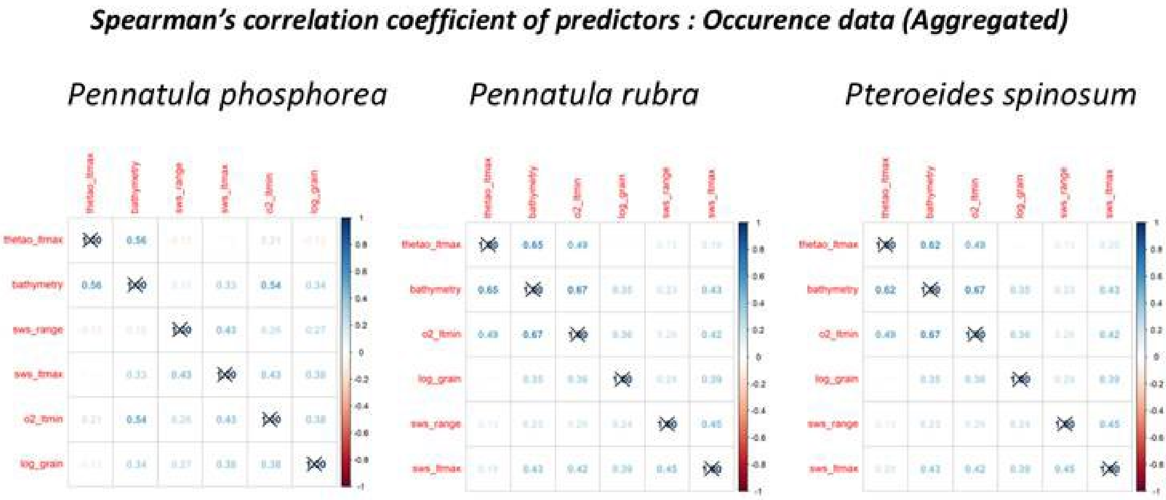

Figure S3 : Spearman's correlation coefficient for each occurrence dataset (values extracted from raster layers at points locations) used in the modelling.

SPATIAL AUTOCORRELATION AND CROSS-VALIDATION

To treat spatial autocorrelation of the models, the spatial partitions used for cross-validation require a set block size, which was selected by plotting the semivariograms of model residuals. As it needs to be selected prior to cross-validation, single models were fitted for each species/algorithm using the full datasets.

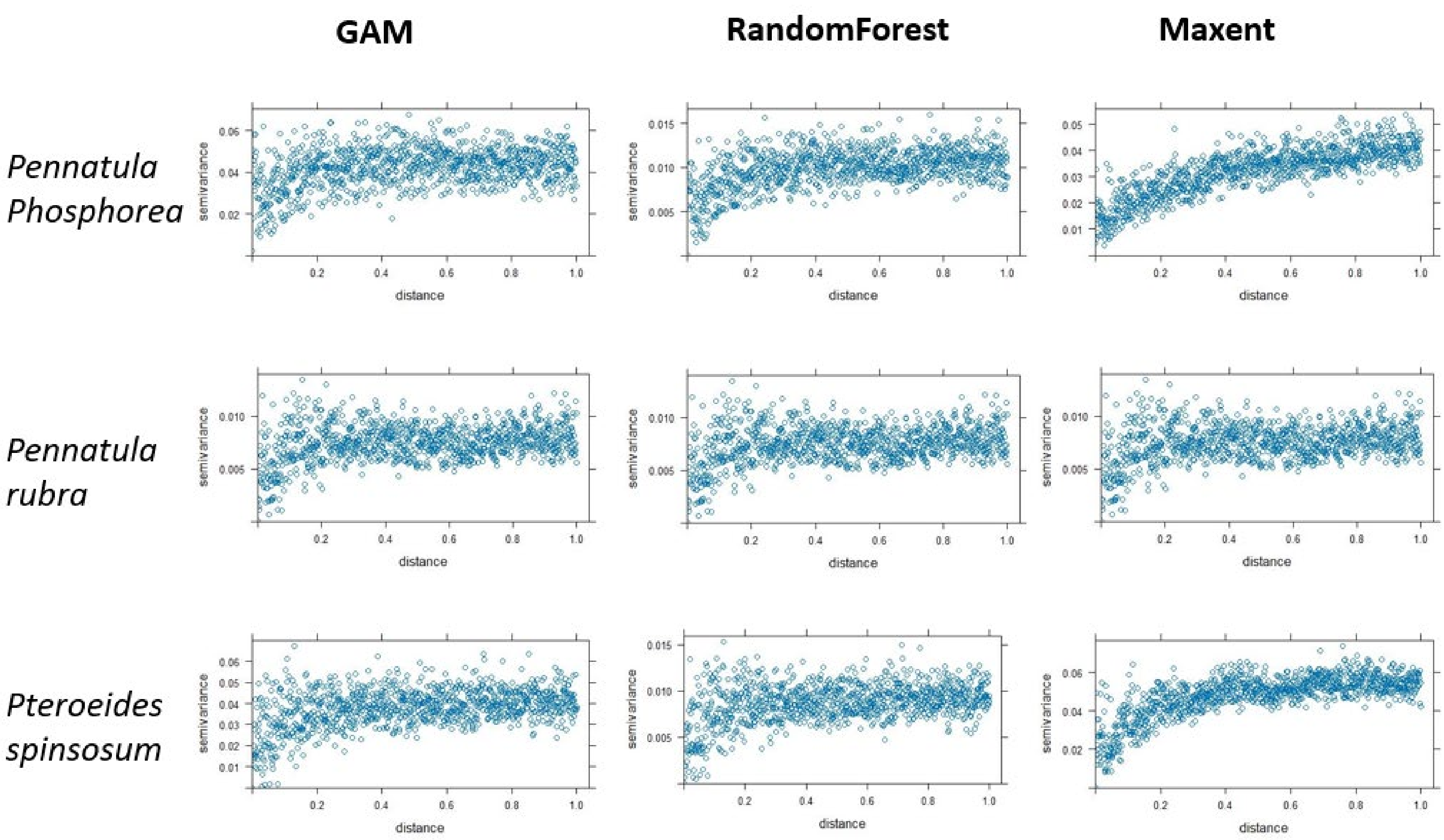
GAM
RandomForest
Maxent
Pennatula Phosphorea
Pennatula rubra
Pteroeides spinsosum
semivariance
distance

Figure S4 : Semivariograms of model residuals for full data models of each species/algorithm.

In Figure S4, semivariograms reach the sill between 0.1 and 0.3 decimal degrees, which amounts to between 15-25 km at our study areas' latitudes. Subsequently, the block size was set as 25 km.

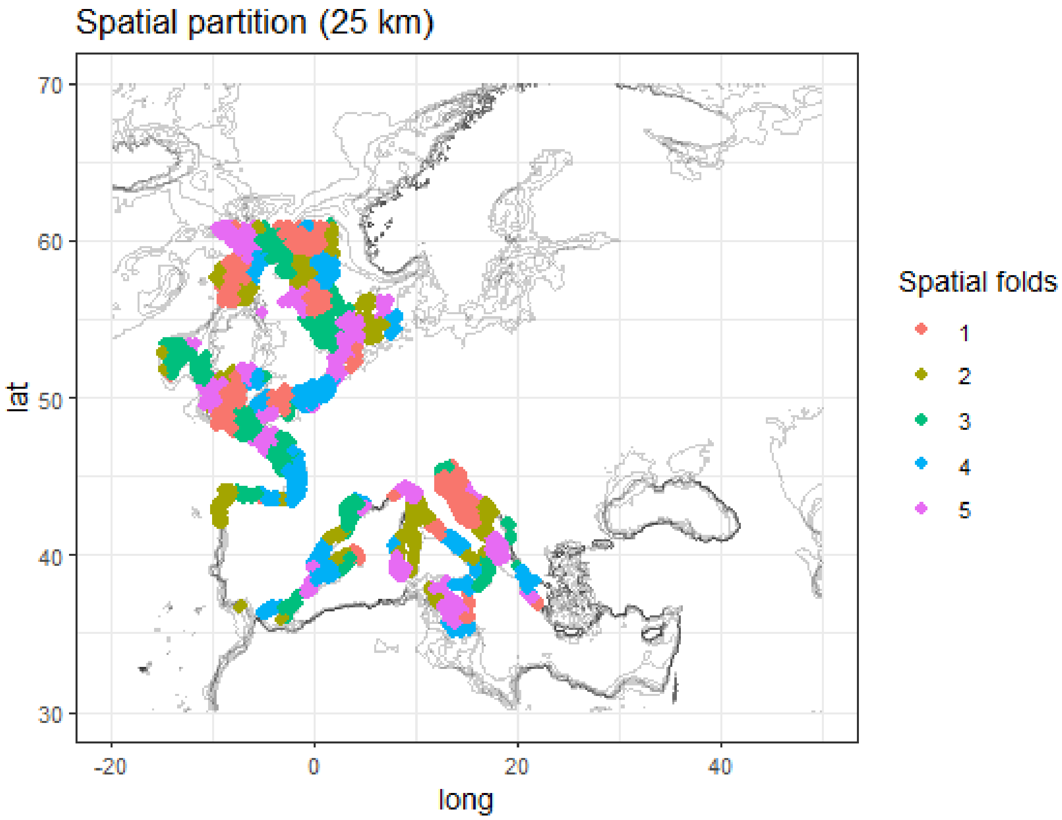

Figure S5 : Example of spatial partition using the blockCV R package, using 25 km blocks. Each "fold" will be used to test the evaluation dataset for models built using the remaining four folds.

MODEL OUTPUTS

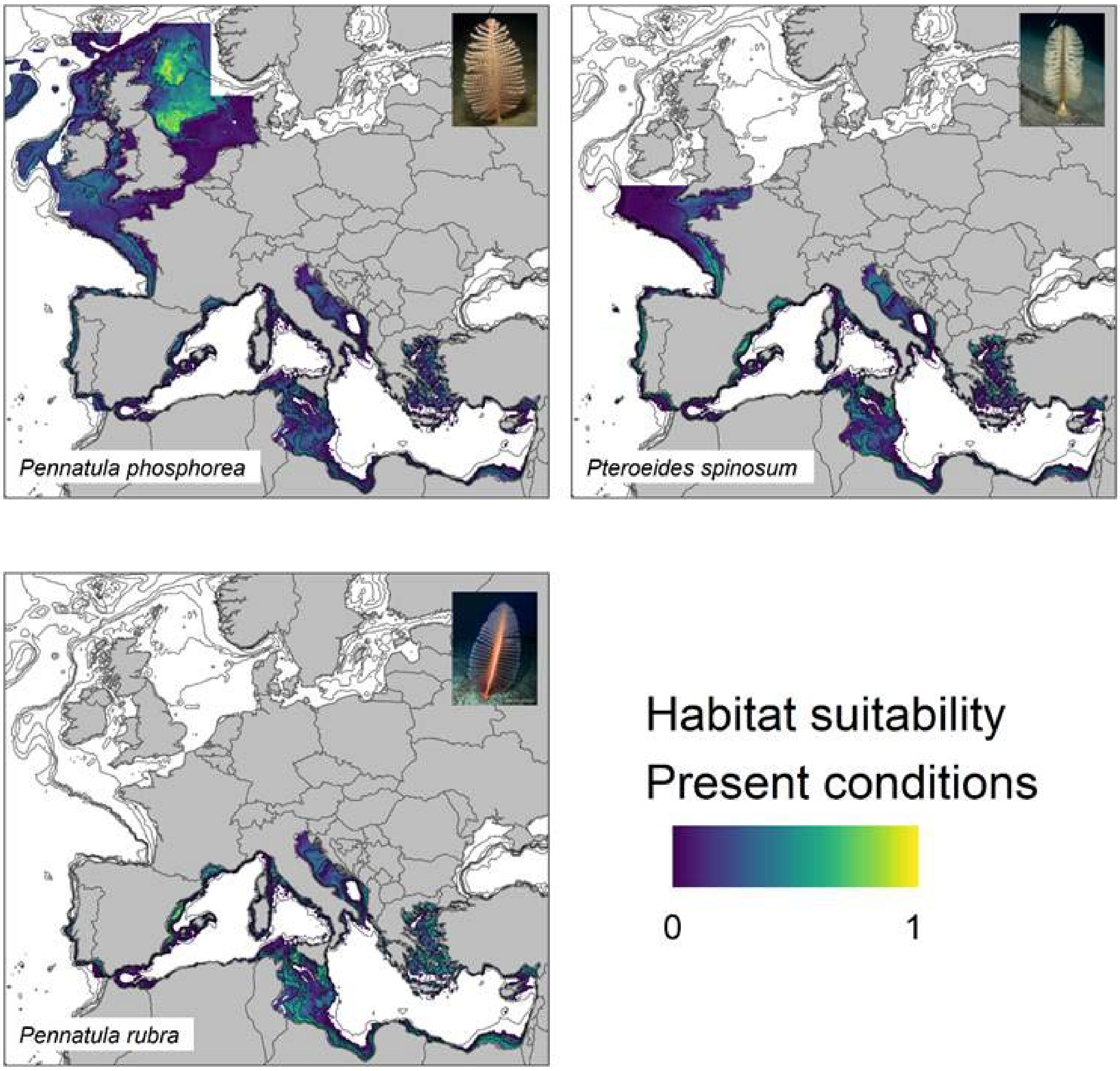

Figure S6 : Habitat suitability prediction (Ensemble) for each species, in current environmental conditions.

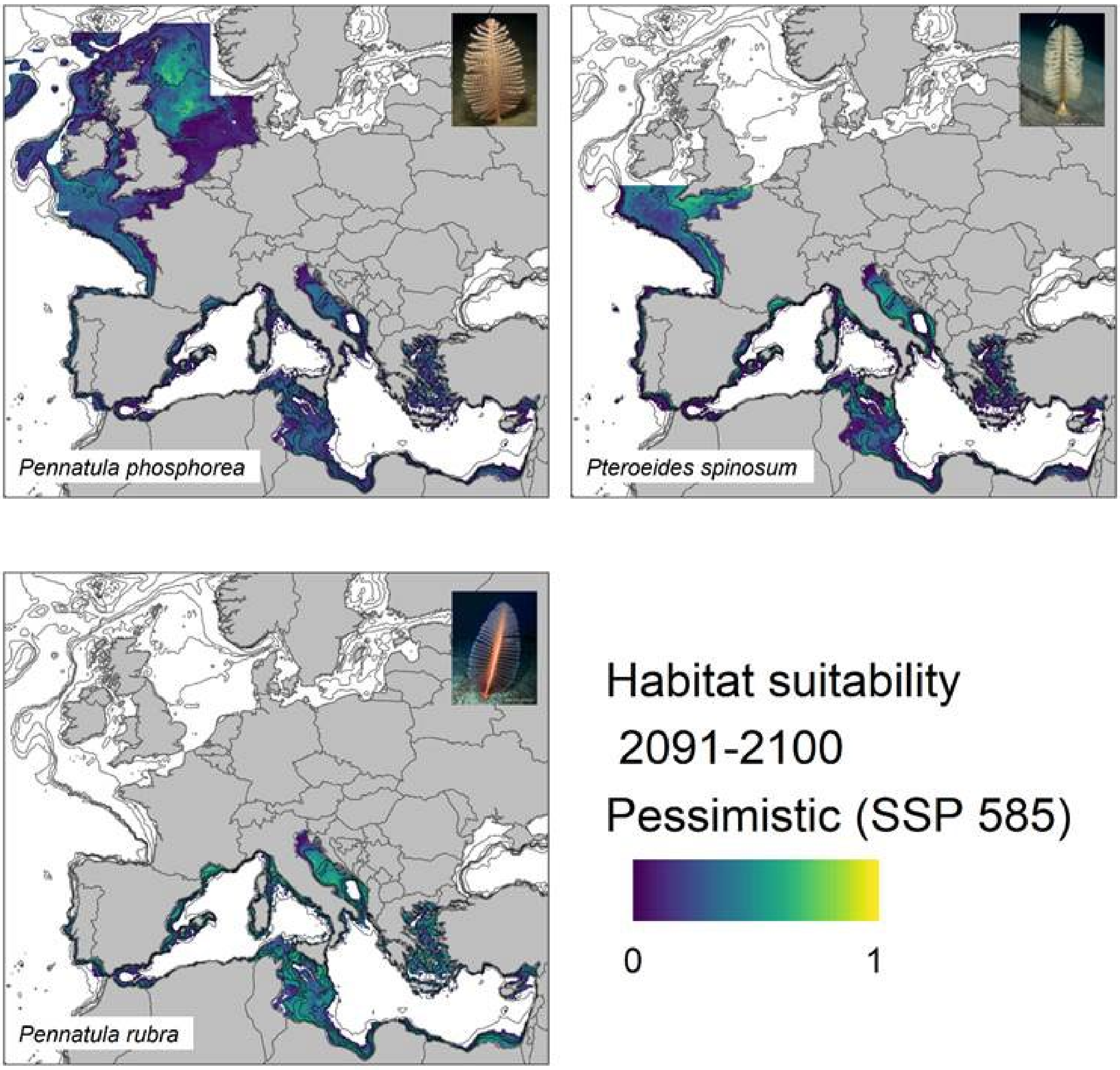

Figure S7 : Habitat suitability prediction (Ensemble) for each species, in 2100 environmental conditions following the most pessimistic scenario (SSP 585).

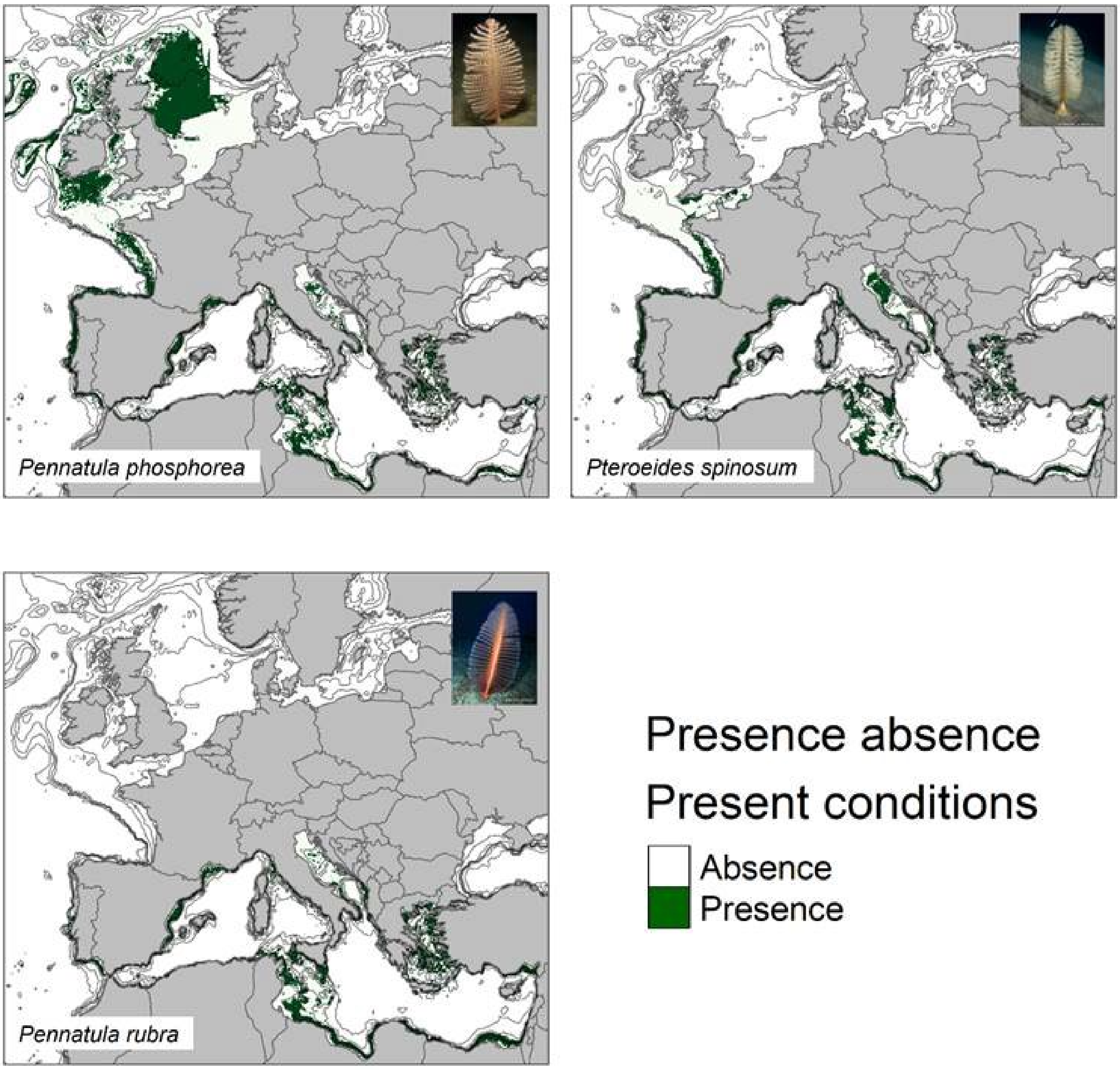

Figure S8 : Presence absence binarization (Ensemble) for each species, in current environmental conditions.

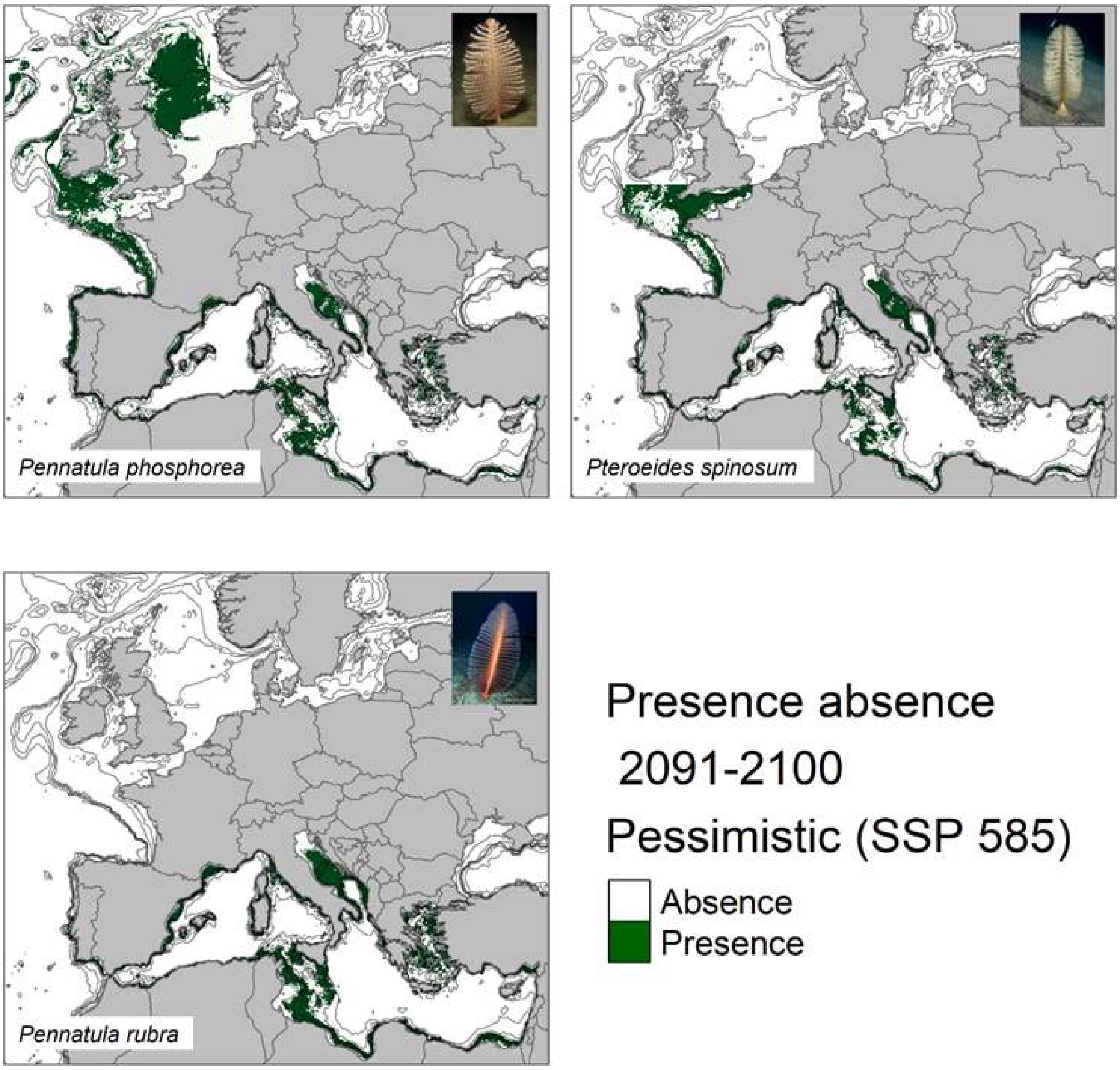

Figure S9 : Presence absence binarization (Ensemble) for each species, in 2100 environmental conditions following the most pessimistic scenario (SSP 585).

Cross Validation uncertainty shows the variation of habitat suitability by cell depending on the spatial fold fitting. The metric is computed using :

CVU = standard deviation / (standard deviation + Habitat suitability)

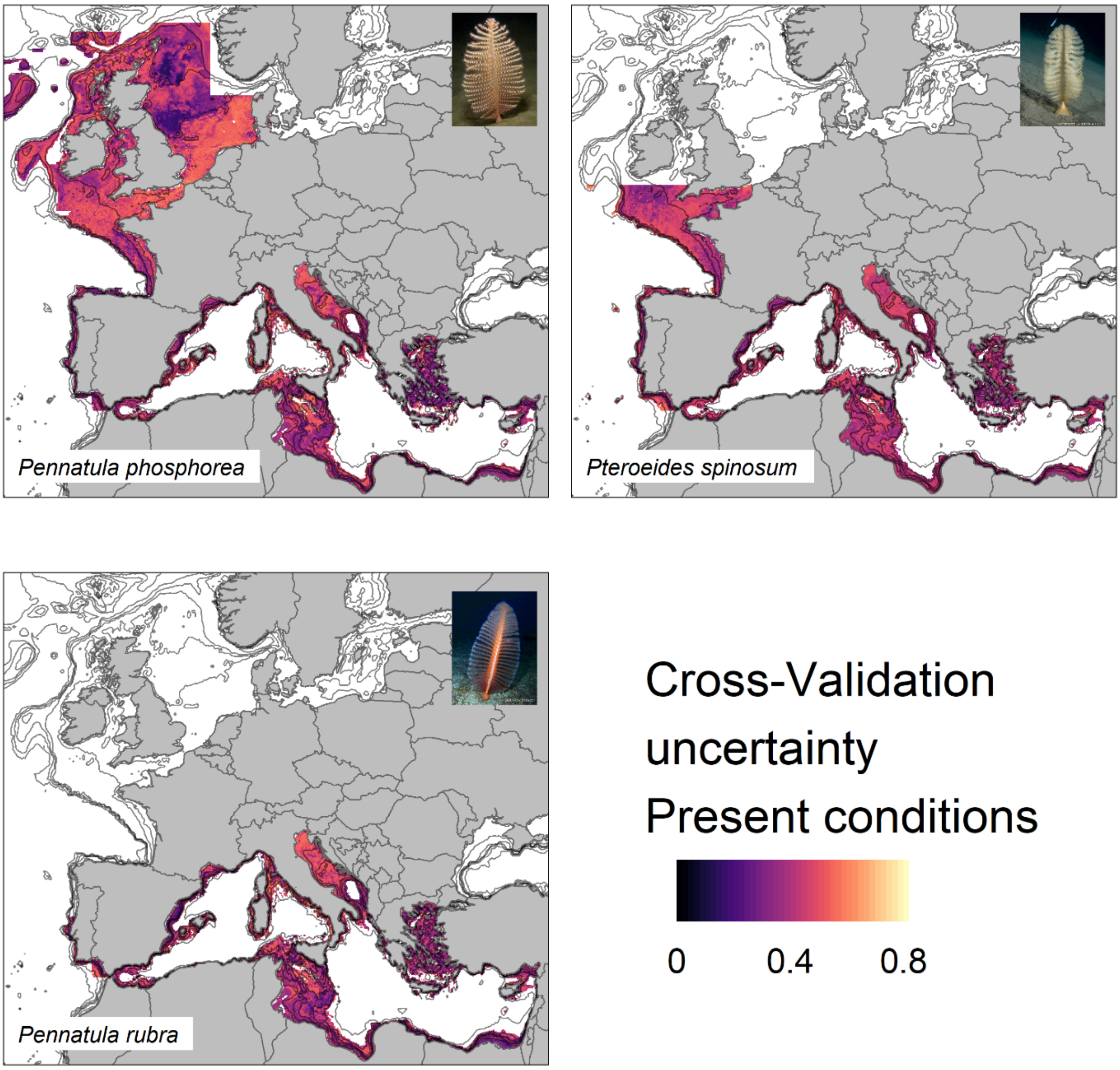

Figure S10 : Cross-Validation uncertainty (Ensemble) for each species, in current environmental conditions.

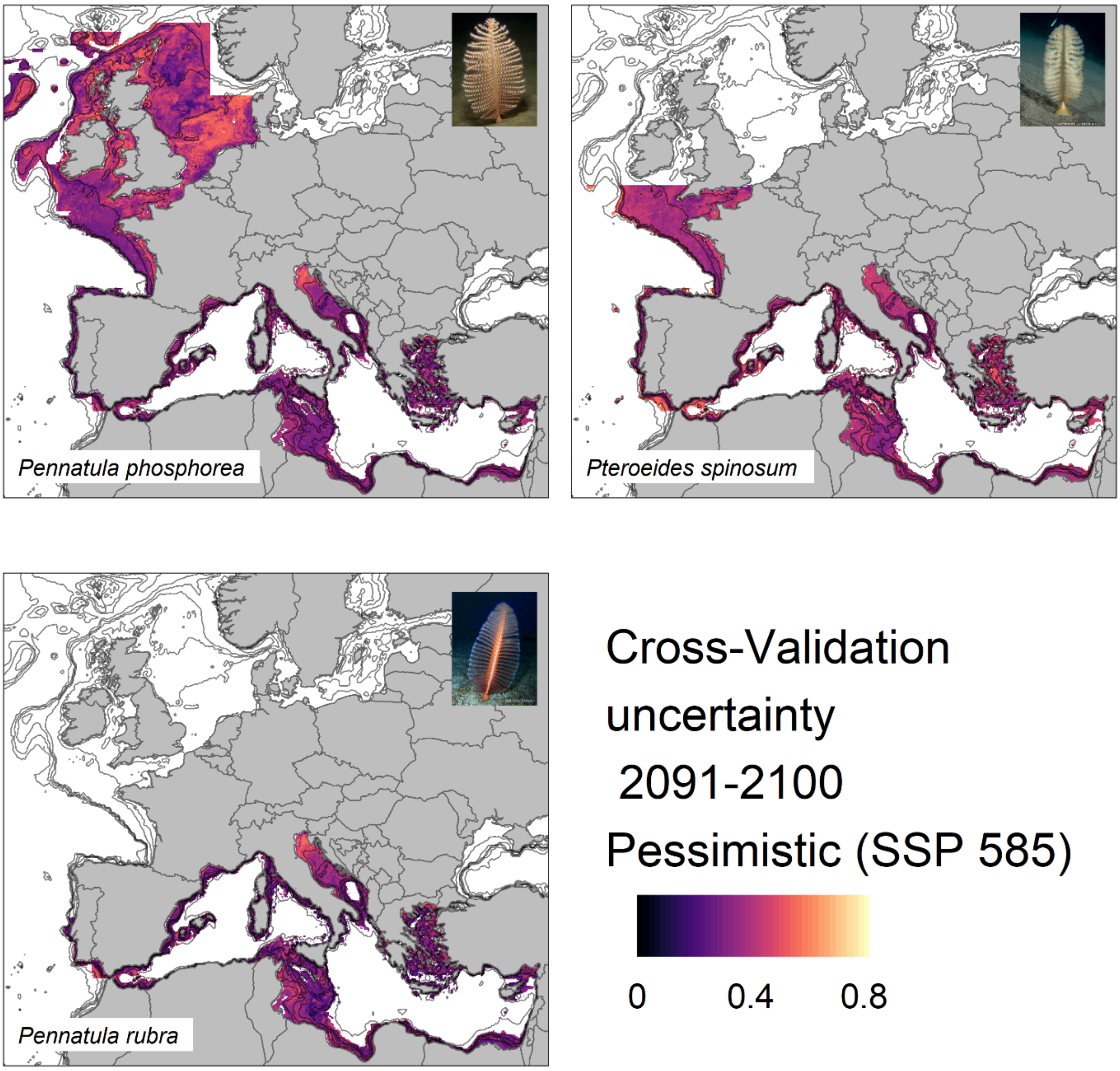

Figure S11 : Cross Validation uncertainty (Ensemble) for each species, in 2100 environmental conditions following the most pessimistic scenario (SSP 585).

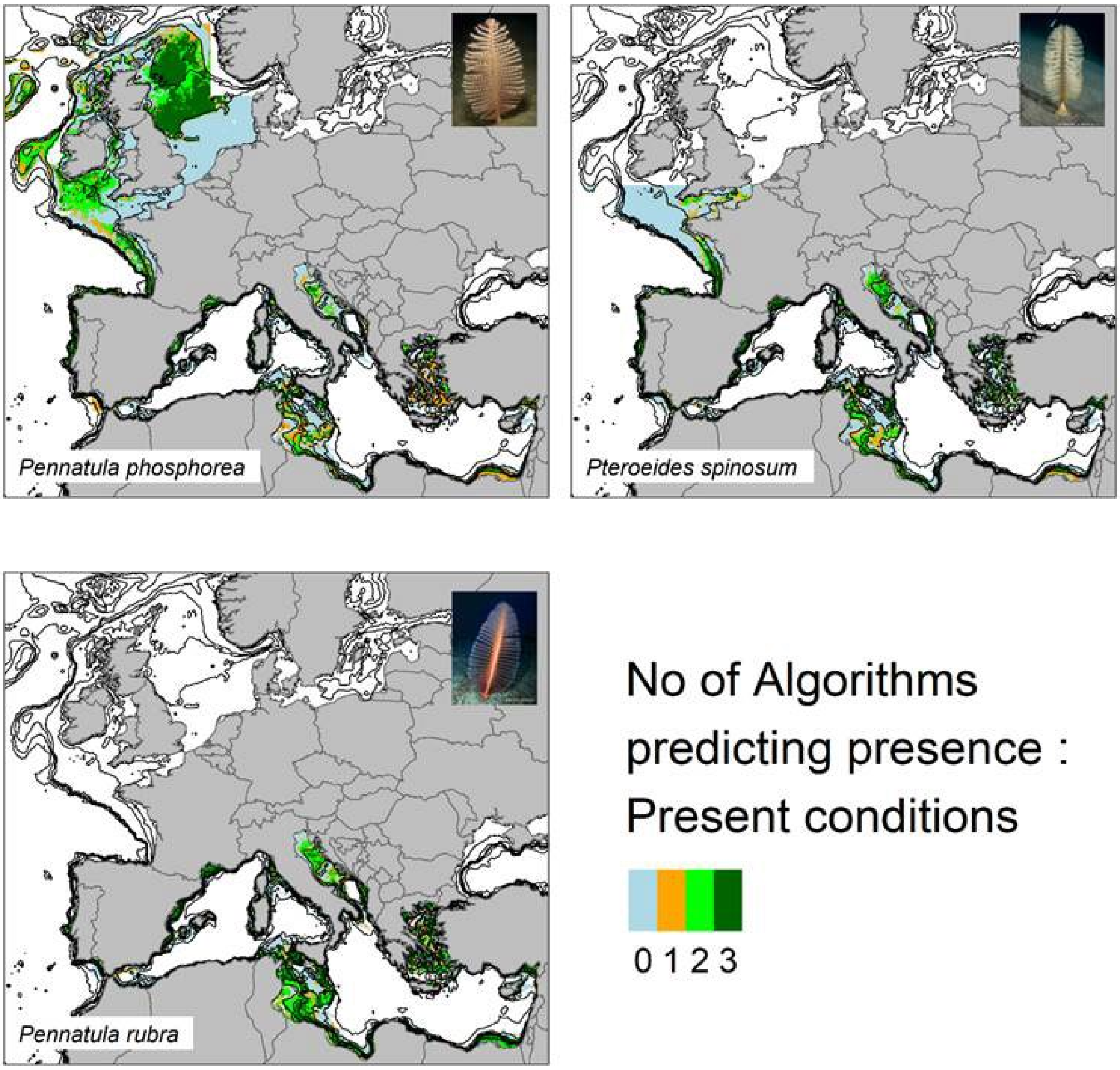

Figure S12 : Algorithm agreement on presences for each species, in current environmental conditions.

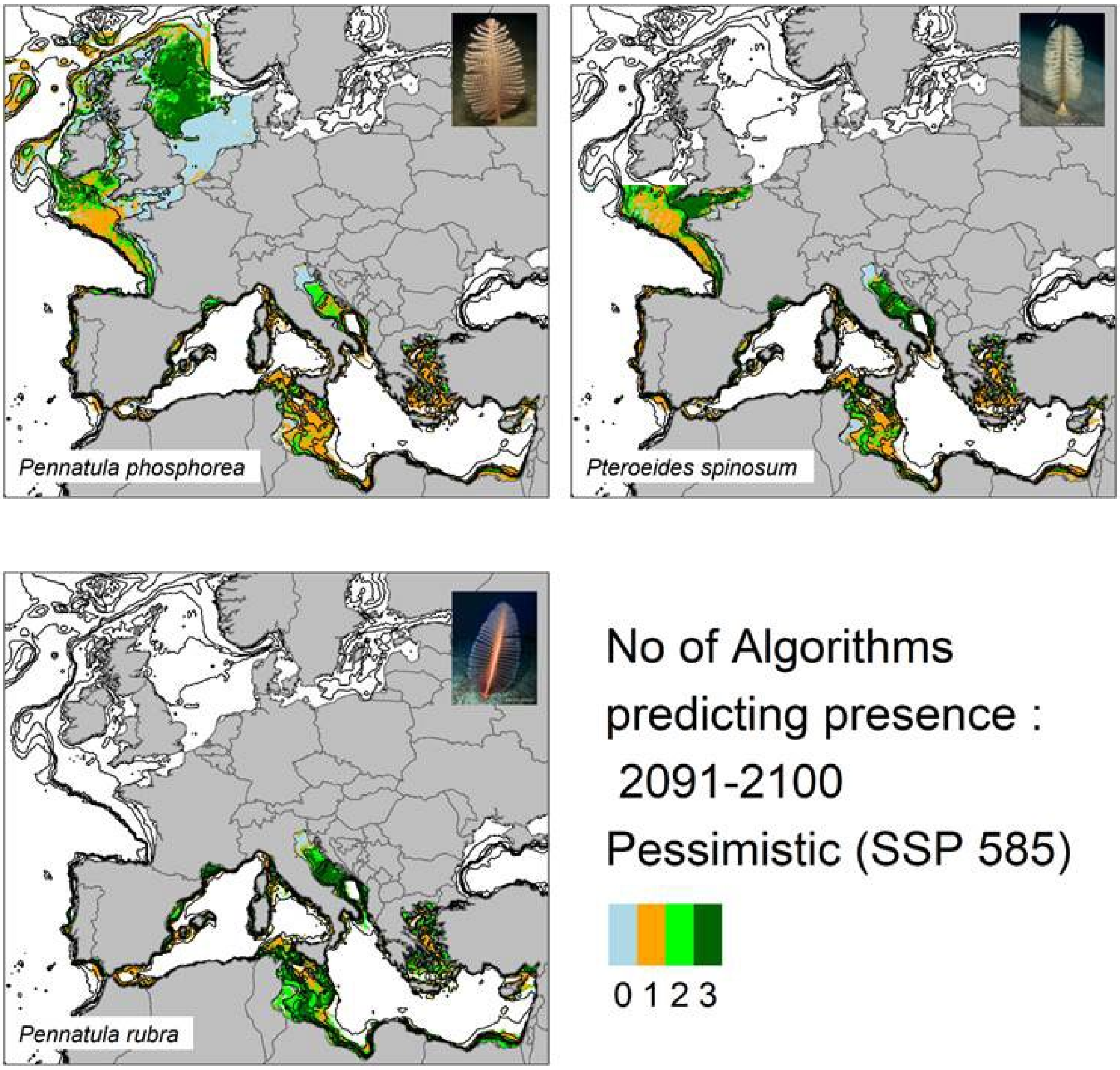

Figure S13 : Algorithm agreement on presences for each species, in 2100 environmental conditions following the most pessimistic scenario (SSP 585).

Extrapolation uncertainty

Extrapolation uncertainty is computed using the dsm extra R packages (Bouchet *et al*., 2020; Mesgaran *et al*., 2014). It classifies cell values in three different categories, depending on how similar the cell conditions are with respect to the observed covariates range in the occurrence dataset

Analogue = Predictors are within the range of the dataset values.

Univariate = at least one predictor is outside of the range of the dataset values (Extrapolation)

Combinatorial = no single predictors is outside its range, but new combinations of covariate are present.

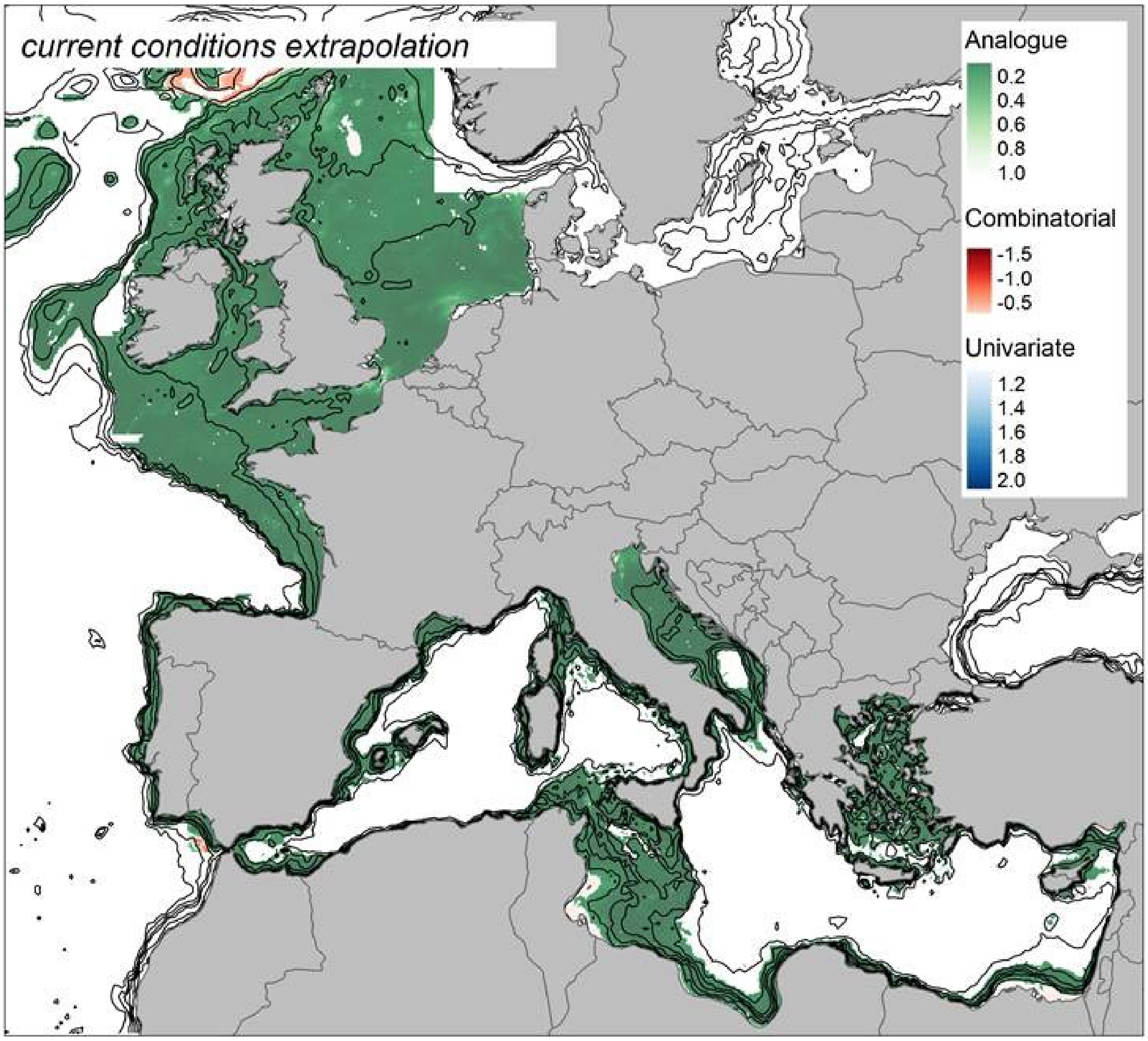

Figure S14 : Extrapolation uncertainty, in current environmental conditions.

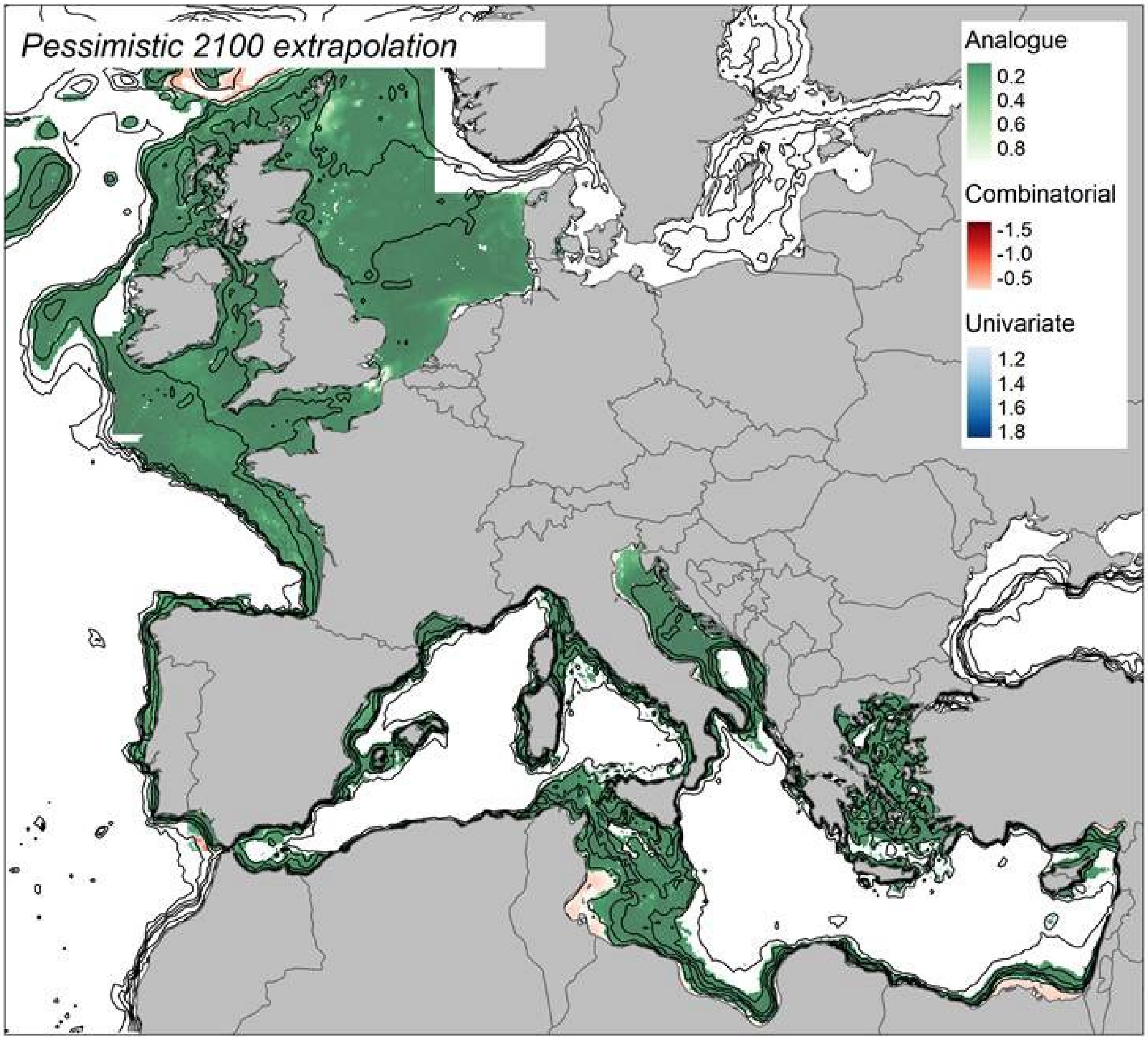

Figure S15 : Algorithm agreement on presences for each species, in 2100 environmental conditions following the most pessimistic scenario (SSP 585).

INTERMEDIATE CLIMATE PROJECTIONS

Figures S16–S24 present climate scenario maps (habitat gain, habitat loss, and refugia) for each of the three sea pen species under two additional projection scenarios: SSP2-4.5 at the 2041–2060 horizon, SSP2-4.5 at 2091–2100, and SSP5-8.5 at the 2041–2060 horizon. These projections were produced as deliverables of the REDRESS project (https://redress-project.eu/). Distributional shifts are qualitatively similar in direction to those reported in the main text, but of lower magnitude under intermediate forcing. The SSP5-8.5 2091–2100 scenario is presented in the main manuscript (Figures 4–6) and is not repeated here.

SSP2-4.5 — 2041–2050

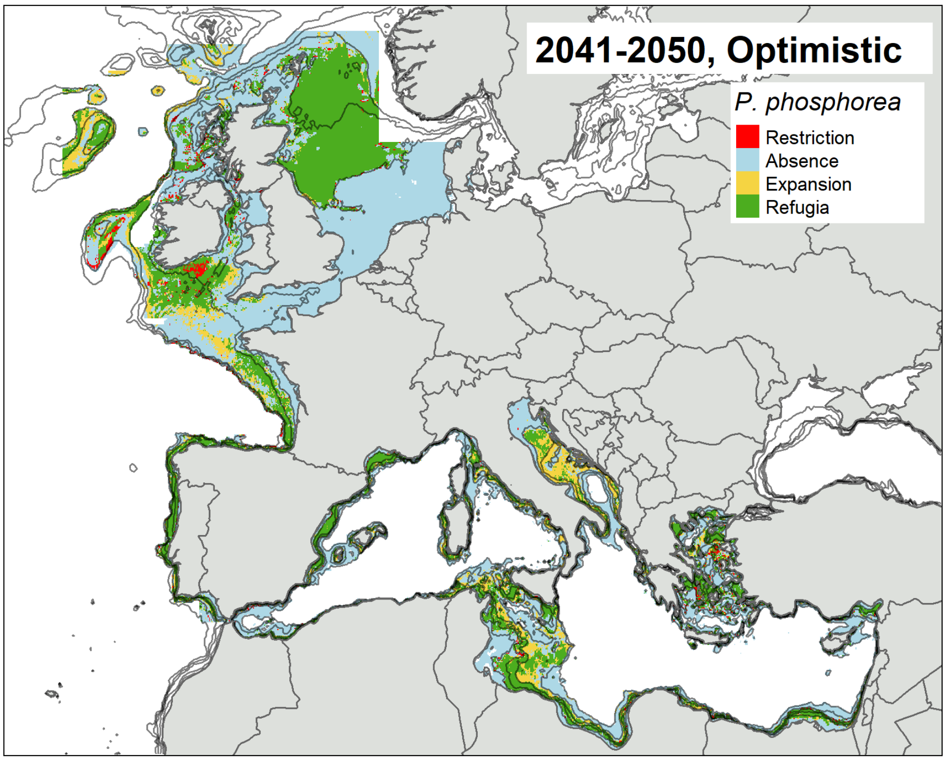

Figure S16: Climate scenario map for *Pennatula phosphorea*, SSP2-4.5, 2041–2050. Habitat gain (yellow), habitat loss (red) and refugia (green) relative to current conditions.

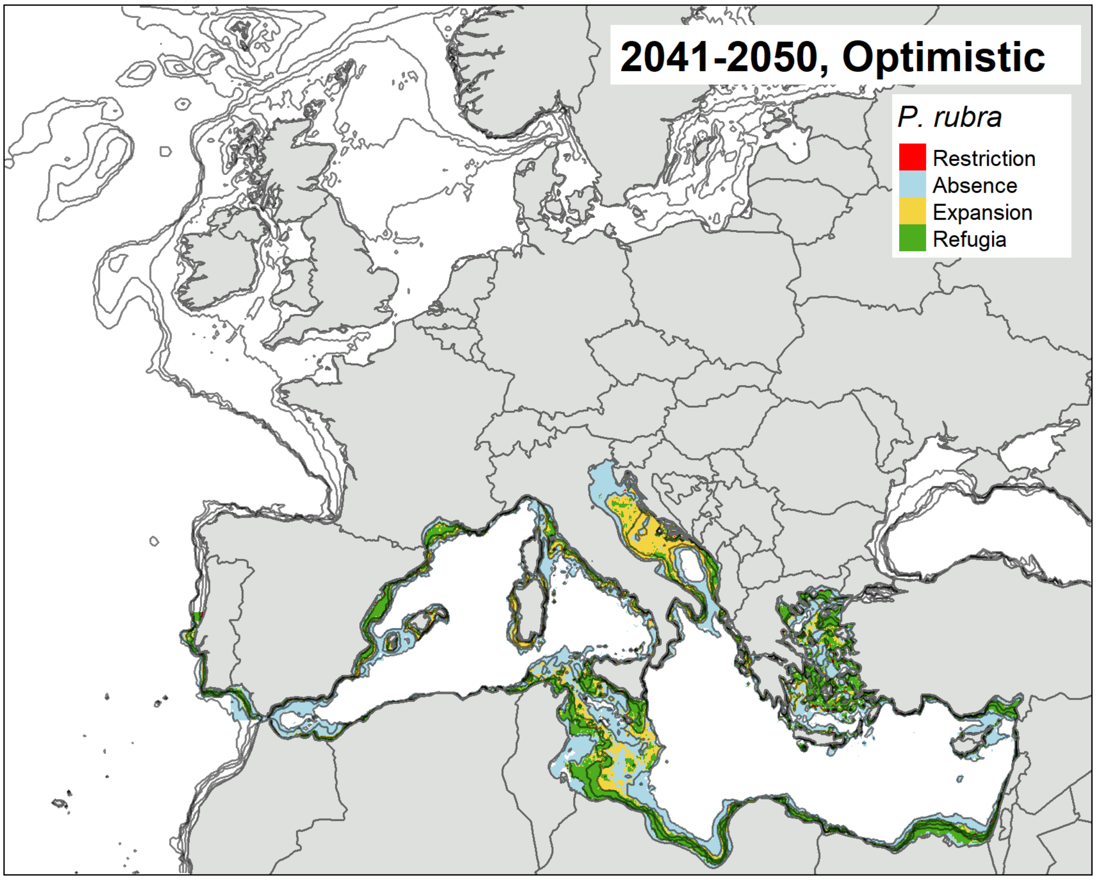

Figure S17: Climate scenario map for *Pennatula rubra*, SSP2-4.5, 2041–2050. Habitat gain (yellow), habitat loss (red) and refugia (green) relative to current conditions.

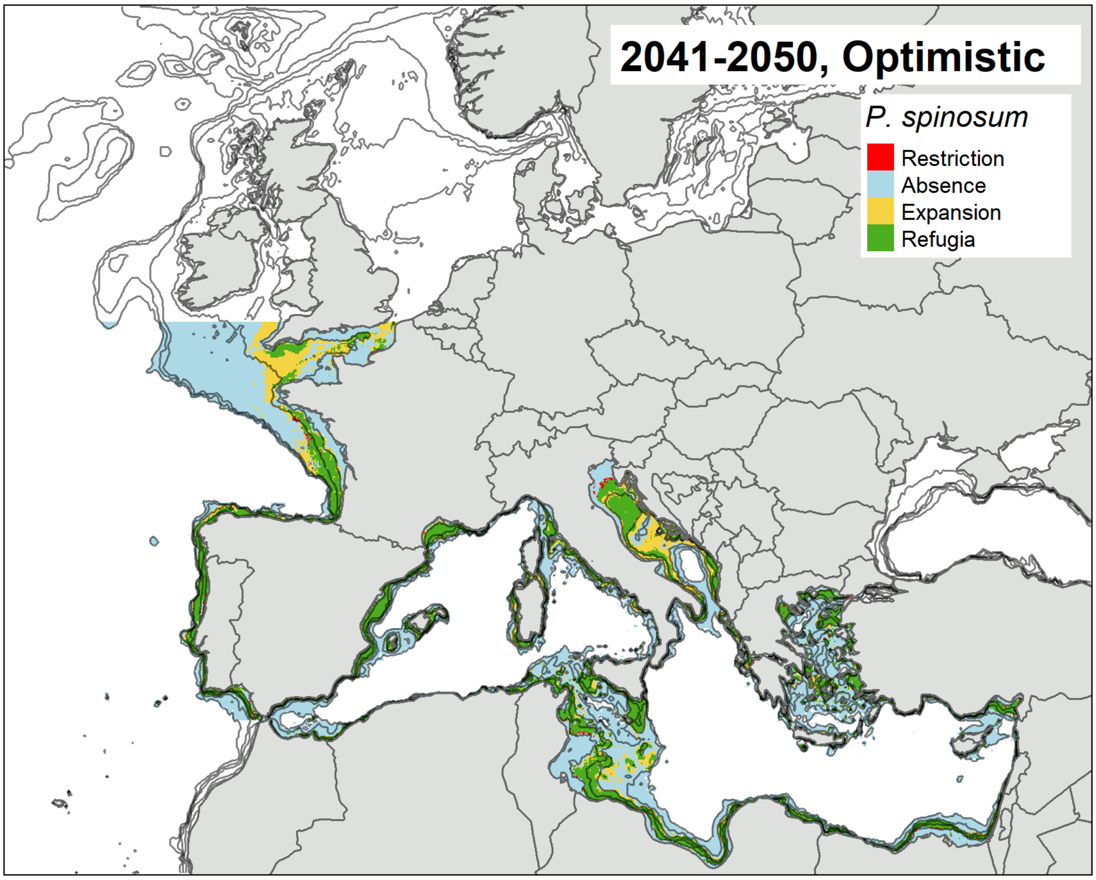

Figure S18: Climate scenario map for *Pteroeides griseum*, SSP2-4.5, 2041–2050. Habitat gain (yellow), habitat loss (red) and refugia (green) relative to current conditions.

SSP2-4.5 — 2091–2100

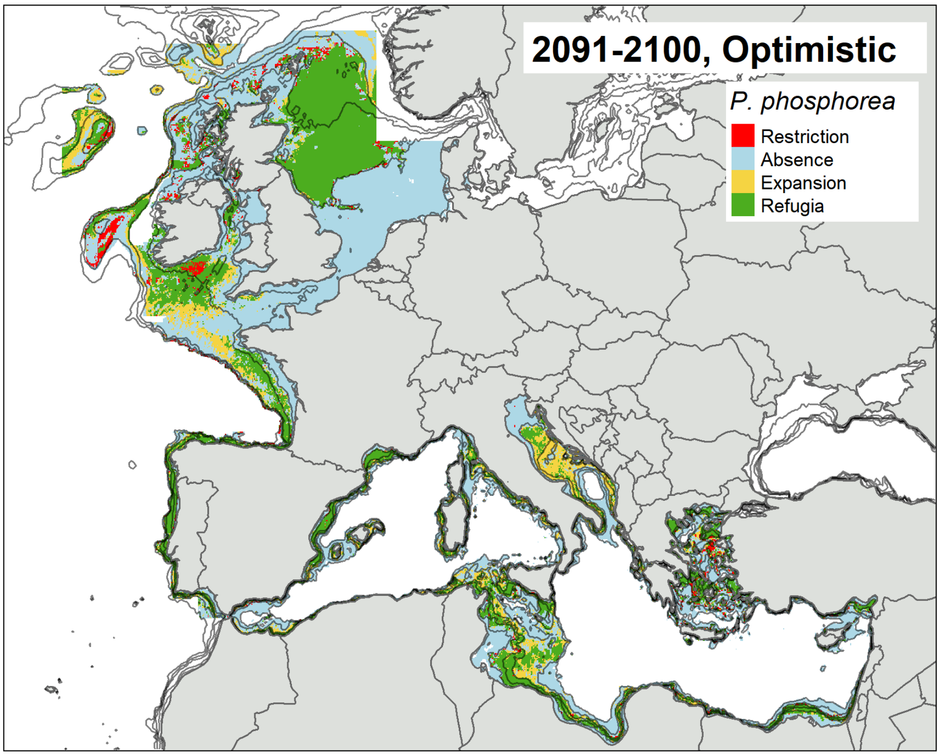

Figure S19: Climate scenario map for *Pennatula phosphorea*, SSP2-4.5, 2091–2100. Habitat gain (yellow), habitat loss (red) and refugia (green) relative to current conditions.

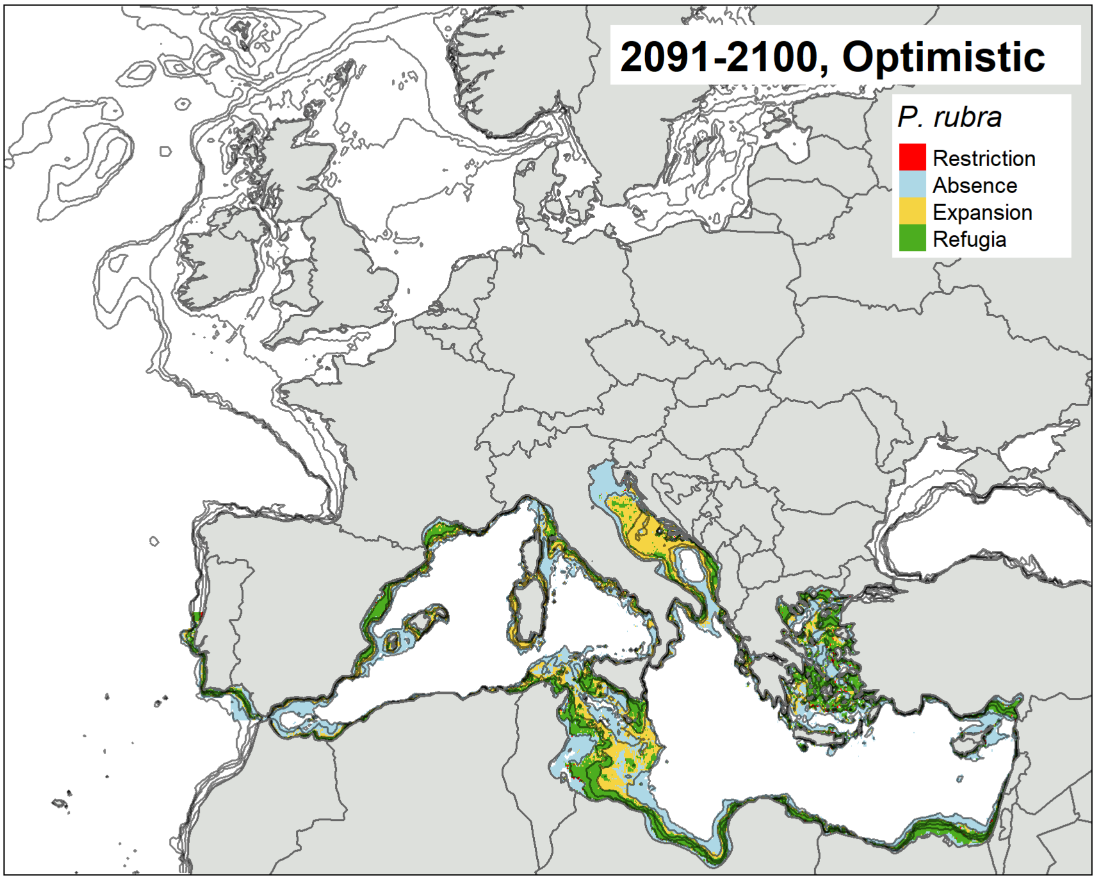

Figure S20: Climate scenario map for *Pennatula rubra*, SSP2-4.5, 2091–2100, habitat gain (yellow), habitat loss (red) and refugia (green) relative to current conditions.

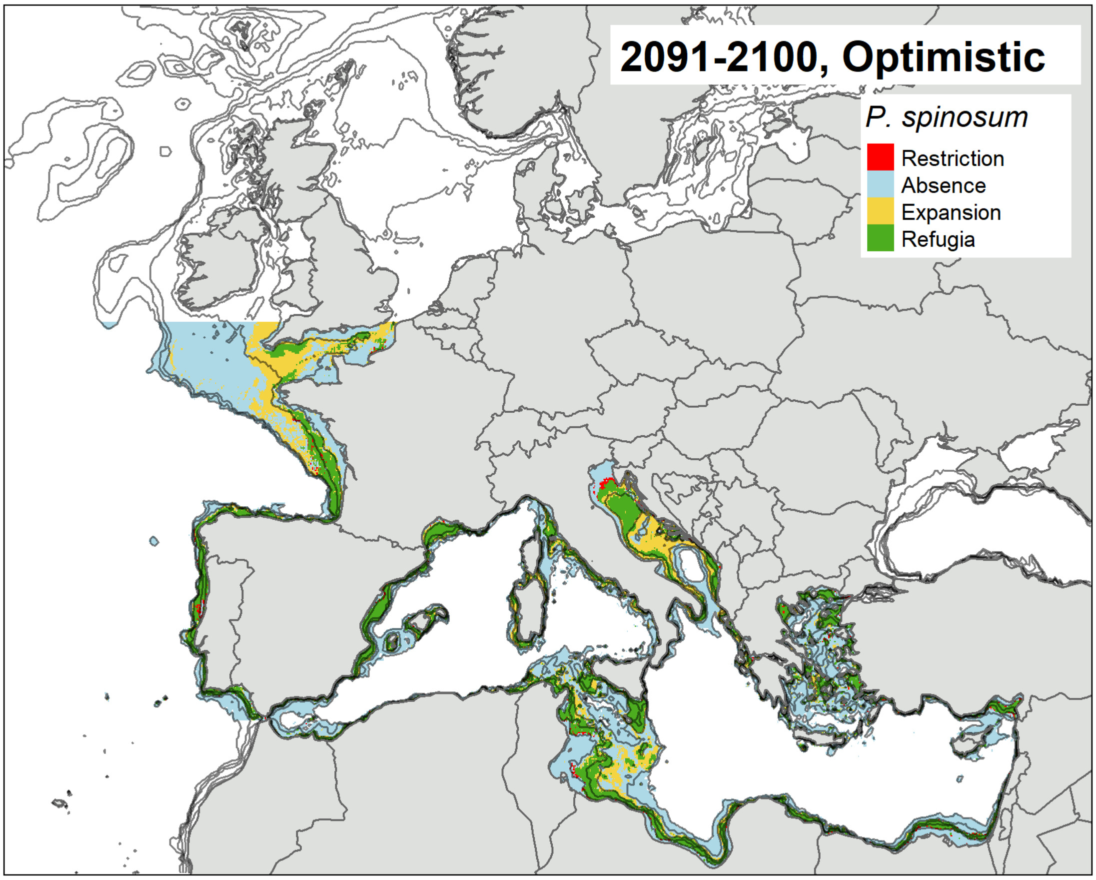

Figure S21: Climate scenario map for *Pteroeides griseum*, SSP2-4.5, 2091–2100. Habitat gain (yellow), habitat loss (red) and refugia (green) relative to current conditions.

SSP5-8.5 — 2041–2050

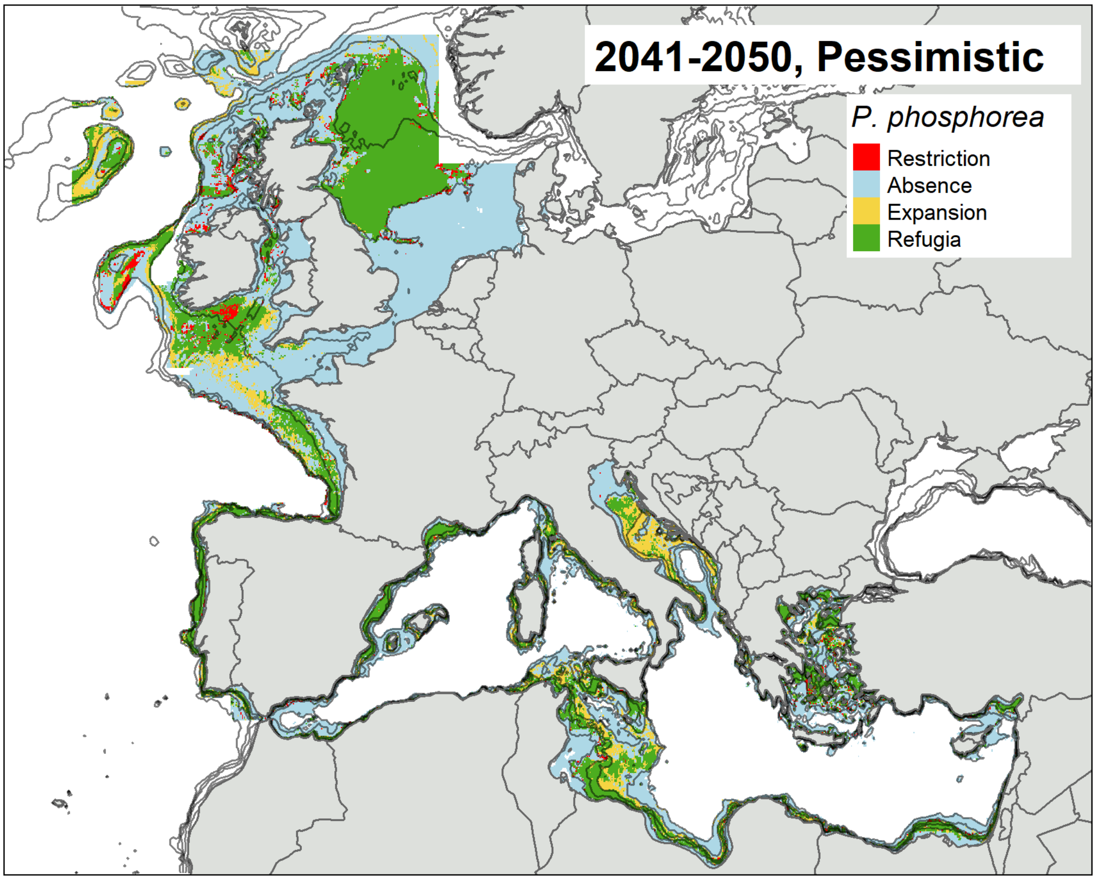

Figure S22: Climate scenario map for *Pennatula phosphorea*, SSP5-8.5, 2041–2050. Habitat gain (yellow), habitat loss (red) and refugia (green) relative to current conditions.

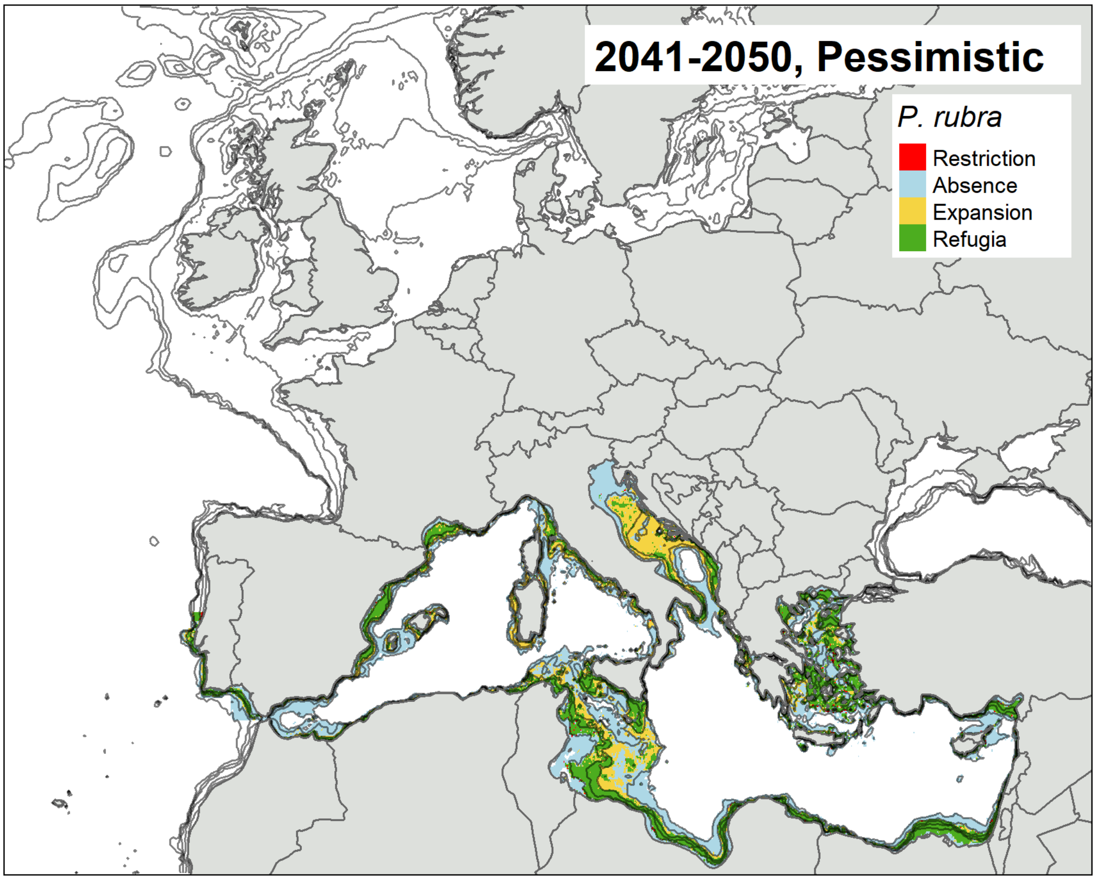

Figure S23 : Climate scenario map for *Pennatula rubra*, SSP5-8.5, 2041–2050. Habitat gain (yellow), habitat loss (red) and refugia (green) relative to current conditions.

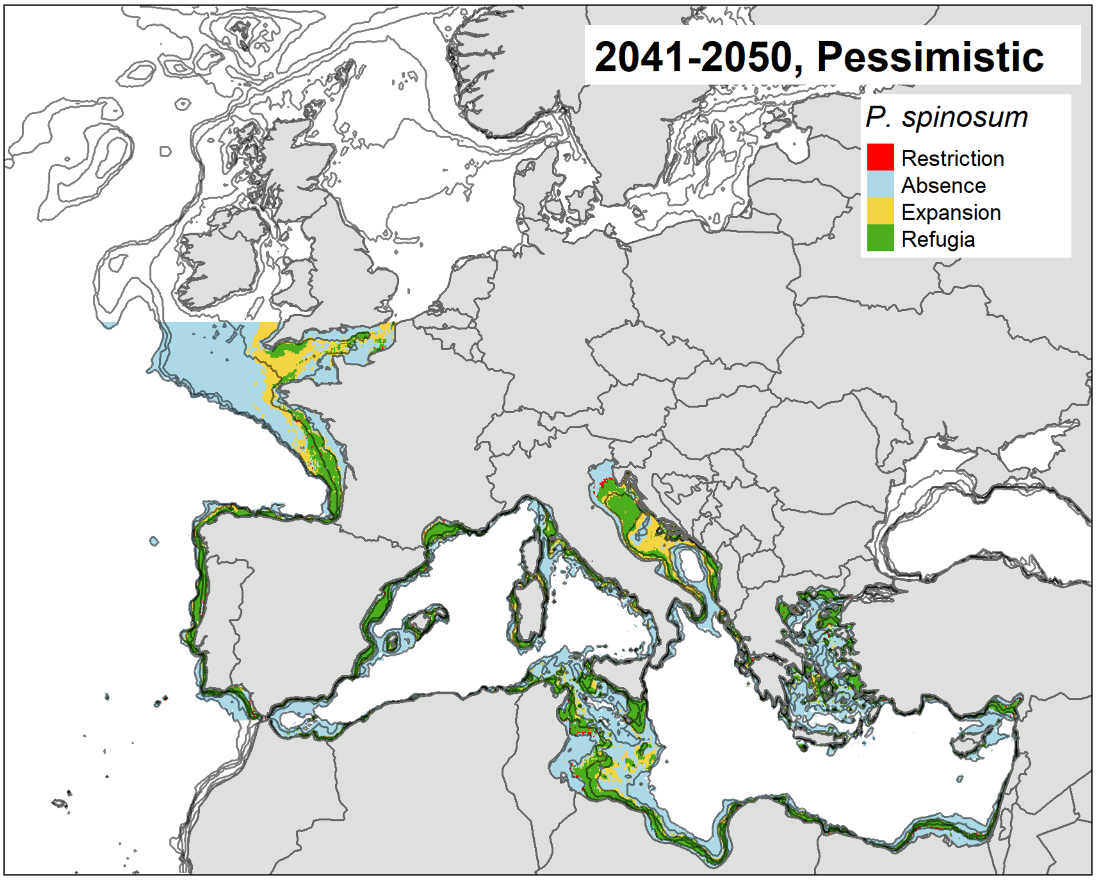

Figure S24 : Climate scenario map for *Pteroeides griseum*, SSP5-8.5, 2041–2050. Habitat gain (yellow), habitat loss (red) and refugia (green) relative to current conditions.

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