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Universidad del País Vasco · Euskal Herriko Unibertsitatea

Ekosistemen Biodibertsitate, Funtzionamendu eta Kudeaketaren Gaineko Masterra

Máster en Biodiversidad, Funcionamiento y Gestión de Ecosistemas

AZTI

MEMBER OF BASQUE RESEARCH & TECHNOLOGY ALLIANCE

Assessment of the adequacy of the north-eastern Atlantic Marine Protected Areas for the conservation of fin whales

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Abstract:

The vast majority of the oceans are suffering increasing impacts of anthropogenic threats, causing the loss of biodiversity and its habitats. Highly-mobile species, such as fin whales (*Balaenoptera physalus*), are especially vulnerable as they face multiple threats over their extensive migrations. Thus, the implementation of conservation and management measures, such as the designation of marine protected areas (MPAs) become essential for the protection of the important areas where individuals aggregate. This study developed maximum entropy (MaxEnt) models using occurrence data from OBIS-SEAMAP and the JUVENA and BIOMAN oceanographic surveys for the period 1973-2021 and climatological environmental variables to identify suitable habitats for fin whales in the Northeast Atlantic. Then, the adequacy for the protection of fin whales of the designated MPAs within the northeast Atlantic was assessed by overlapping the predicted suitable habitats and the designated MPAs within the study area. Suitable habitats for fin whales were mainly located over the Macaronesia, off-shore waters of the Iberian Peninsula, north-western Africa, southern Iceland and Greenland and eastern waters of the British Islands. The assessment of the designated MPAs highlights that less than the 11% of the suitable habitat is protected, evidencing the need for further management and conservation measures to protect the species. This study supports the design and establishment of MPAs for the conservation of fin whales.

Keywords: Migratory predator; MaxEnt; Habitat suitability modelling; Marine Protected Areas; Habitats Directive; Biodiversity conservation.

ZUZENDARIAREN BAIMENA MAL AURKEZTEKO	AUTORIZACIÓN DEL/LA DIRECTORA/A PARA LA PRESENTACIÓN DE TFM

Biodibertsitate, Funtzionamendu eta Ekosistemen Gestioa **Masterra** / **Máster** Biodiversidad, Funcionamieno y Gestión de Ecosistemas

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La directora Isabel García Barón con DNI 71143800Q y la codirectora Maite Louzao Arsuaga con DNI 72474662Y dan su conformidad a la defensa del TFM titulado "**Assessment of the adequacy of the north-eastern Atlantic Marine Protected Areas for the conservation of fin whales**" realizado por Nerea Reyes Peñafiel bajo su dirección.

Data eta sinadura / Fecha y firma: 6 de septiembre de 2021

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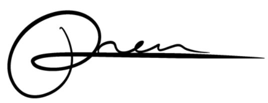

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1. Introduction

The global loss of biodiversity due to anthropogenic threats and climate change affect the ecosystems functioning reducing the provision of ecosystem services (Asaad et al, 2016). The vast majority of the oceans are experiencing a significant increase in the impacts of multiple human stressors causing a profound cumulative global impact, pushing many ocean regions beyond critical tipping points of sustainability (Halpern et al, 2008). In this context, as the pressures to biodiversity increase and more species become threatened, the need for an effective management of human activities become essential (Lascelles et al, 2014; Asaad et al, 2016). This is specially challenging in the case of wide-ranging species (*e.g.,* cetaceans, sharks, turtles) inhabiting the open oceans, where the effective management and conservation rely on understanding basic predator ecology and the processes driving their distribution (Game et al, 2009; García-Barón et al, 2019).

Among wide-ranging marine species, baleen whales are of special conservation interest since they have strong effects on community structure and function, playing key roles in ecosystem functioning (Pimiento et al, 2020). This is the case of fin whales (*Balaenoptera physalus*), which are widespread throughout the world's oceans, from temperate to polar latitudes, being the most abundant baleen whales in the northeast Atlantic (NE Atlantic, hereafter). Fin whales undertake large annual migrations from high latitude feeding grounds, where they spend the summer, to middle and low latitude breeding grounds during winter (Edwards et al, 2015; IUCN, 2018; Silva et al, 2013). Fin whales inhabit deep off-shore waters with high biological productivity (García-Barón et al, 2019; Laran et al, 2016) and as other baleen whale species, their diet is opportunistic, relying mainly on krill (mostly euphausiids) but also on small pelagic fishes (*e.g.*, *Sprattus sprattus* or *Clupea harengus*) (Solvang et al, 2021).

Fin whales are particularly vulnerable to multiple threats, especially during their annual migrations, since most of these threats are widely distributed and may have cumulative effects (Lascelles et al, 2014). In addition, their life-history traits, *i.e.* late maturity and low reproductive rate, make them particularly susceptible to several threats (Sahri et al, 2021). The main threats affecting fin whales have an anthropogenic origin: ship strikes, acoustic pollution (*e.g.,* sonar, seismic surveys), entanglement in fishing gears among others (Thomas, Reeves & Brownell, 2015). Fin whale population was reduced by 70% during the whaling era, and although appear to have recovered from the commercial whaling that took place in this area, the species remain classified as Vulnerable (IUCN, 2018). The increasing of fin whale population is not only due to the cessation of the commercial whaling, but to the implementation of protection measures, such as Marine Protected areas (MPAs) (Evans, 2018; Hoyt et al, 2005). MPAs are increasingly being used worldwide for the conservation and management of threatened species and habitats (Evans, 2018) however, only a 7.65% of the worldwide oceans is protected (UNEP-WCMC & IUCN, 2021). Most MPAs are small and delineated by exclusive economic zones (EEZs) and thus, restricted to national boundaries while ignoring the high seas (Lubchenco & Grorud-Colvert, 2015) hampering the effective conservation of highly mobile species (Harrison et al, 2018).

One of the most challenging aspects to protect highly migratory species, such as fin whales, is to understand their distribution and the underlying relationships with the environment (Becker et al, 2016). In this sense, the use of Species Distribution Models (SDMs) has become the best tool to overcome this issue and to support conservation and management measures (Correia, 2020; Tobeña et al, 2016; Sahri et al, 2021). The main limitation to model the distribution of marine species is the lack of reliable data, especially in the case of species inhabiting the open ocean (Smith et al, 2021) such as cetaceans. The collection of absence data can often be logistically difficult and expensive given the large spatial scales they occupy and the imperfect detection (*i.e.* individuals are often "unavailable" to observers due to a large proportion of their time spent underwater, which can lead to false absences (Smith et al, 2021). Hence, the use of presence-only models is particularly advantageous in the case of highly migratory species to predict their distribution and disentangle their relationships with the environment. As such, nowadays presence-only models have become a useful conservation tool to locate important/critical areas and fine-tune mitigation and conservation measures accordingly.

This study had three goals: (i) to develop SDMs to predict fin whale habitat suitability in the NE Atlantic; (ii) to identify important areas based on the suitable habitat; and (iii) to assess the adequacy of the MPAs implemented within the NE Atlantic for the protection of fin whales. Our spatial modelling approach relies on a presence-only modelling approach based on the maximum entropy principle (MaxEnt), a widely used approach in ecological studies when presence-only data is available to predict species distribution. The present study exemplifies a methodological approach to locate important areas for a species and provides an assessment of the importance of existing MPAs for the protection of a vulnerable highly migratory predator.

2. Material and methods

2.1 Study area

The study area was situated in the NE Atlantic region covering a surface of 14,742,618.7 km^2 (Figure 1). The study area was delimited south by the Macaronesian archipelagos (Azores, Madeira and Canary Islands), west-north by Greenland, east-south by the coasts of northwest Africa (hereafter, NW Africa) and east-north by Norway. The topography and dynamic oceanographic processes in this area enable the presence of different kind of habitats, which support high levels of marine biodiversity (Correia, 2020), including fin whales. In the northern part of the study area, around the British Isles steeply depths are reached (Breen et al, 2016). The eastern continental shelf of Greenland and the western coast of Iceland are characterized by their high productivity (Silva et al, 2013). In the southern part, the combination of several seamounts, canyons, abyssal plains and narrow continental platforms result in upwelling systems, stronger over the eastern Iberian and African coasts and weaker over Macaronesian waters, both with a marked seasonality (Correia, 2020). The oceanography of the NE Atlantic is dominated by the Gulf Stream and the North Atlantic Drift (Hoyt, 2005). Fin whales' foraging grounds are typically located in high latitudes (eastern Greenland and western Iceland), where primary production promote the accumulation of phyto- and zooplankton biomass (Silva et al, 2013; Breen et al, 2016). Whilst breeding grounds, are located towards middle and low latitudes (Azores, Madeira; Edwards et al, 2015) in tropical or sub-tropical oligotrophic areas (Silva et al, 2013).

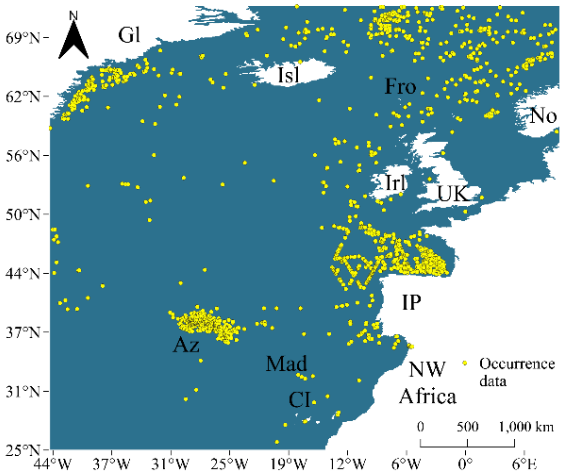


Figure 1. Map of the study area showing fin whale occurrence data and geographical references: Gl, Greenland; Isl, Iceland; Fro, Faroe Islands; No, Norway; Irl, Irland; UK, United Kingdom; IP, Iberian Peninsula; Az, Azores archipelago; Mad, Madeira archipelago; CI, Canary Islands archipelago; NW Africa, northwest Africa.

2.2 Occurrence Data

Fin whale presence data were collected for the time-series 1973-2021 from two sources: (1) the available occurrence data set (1973-2021) provided by the Ocean Biogeographic Information System - Spatial Ecological Analysis of Megavertebrate Populations (OBIS-SEAMAP; http://seamap.env.duke.edu/) which is an interactive, spatially referenced online database collecting data of marine megafauna from contributors all over the world and (2) the multidisciplinary oceanographic surveys JUVENA (2012-2020) and BIOMAN (2016-2020) that took place in the Bay of Biscay every late summer and spring, respectively (Boyra et al, 2013; Santos et al, 2019). These oceanographic surveys included a standardized observer programme for marine megafauna data collection since 2012 and 2016, respectively. Whilst data from oceanographic surveys are systematic, with rigorous recording of effort and sightings so that species presence and absence are recorded; in the case of the OBIS-SEAMAP data, absence and effort data are not available. Thus, data from both sources were considered as presence-only data for the purpose of the present work. The full dataset was filtered to eliminate stranding records and duplicates. Finally, the dataset was spatially thinned to obtain one occurrence point per cell to minimize autocorrelation biases.

2.3 Environmental data

To study the NE Atlantic fin whale habitat preferences, we used remote sensing environmental data selected based on biological relevance and data availability. Three physiographic predictors, bathymetry (BAT), seabed slope (Slope) and the closest distance to the coast (DistCO) were selected based on their importance in previous studies examining fin whale distribution (Breen et al, 2016; Laran & Gannier, 2008; García-Barón et al, 2019). Furthermore, we selected three oceanographic predictors, sea surface temperature (SST), salinity (SAL) and current velocity (SW) and three biologically relevant predictors, chlorophyll-*a* concentration (Chl-*a*), phytoplankton (Phyto) and primary productivity (PP). All the predictors were used as climatological variables from the time-series 2000-2014 and were obtained from Bio-ORACLE (Tyberghein et al, 2012; Assis et al, 2017) and MARSPEC (Sbrocco & Barber, 2013). Environmental (and occurrence) data were either provided in, or modified so they were in, the geographical coordinate system WGS 1984, with a regular cell size of 0.08°. Before running the models, all the spatial information, both the occurrence data and the environmental variables to be tested in the model were prepared in the same format (with the same number, cell size and the same geographic extension). To obtain easily interpretable results, the predictive layers included in the model were restricted to the study area (Annex I, Figures S1-a-i).

Prior to modelling, we examined the collinearity between the 9 environmental predictors by means of Spearman rank correlation coefficients (r) to eliminate predictors with similar functions in explaining the species habitat suitability. For each pair of correlated variables ($r > |0.7|$), only the most informative one was kept for analysis (*i.e.*, the variable with the best explanatory power).

2.4 Habitat suitability modelling using MaxEnt

SDMs or *habitat suitability models* (Pearce & Boyce, 2006) are commonly used to understand species niche requirements and predict species suitable habitat relating occurrence observations data to a set of environmental variables. In the present work the maximum entropy (MaxEnt) algorithm was chosen to fit the fin whale habitat suitability model in the NE Atlantic given its statistical power and competitiveness with other well-established methods using presence-only data (Elith et al, 2006; Phillips et al, 2006). MaxEnt has been successfully applied in studies where absence data were not available (Elith et al, 2006, 2011), and was widely used when working with combined data collected through different methodologies (Elith et al, 2006; Sahri et al, 2021), as in the present study. Using species occurrence data (presence-only data), a set of associated environmental predictors and a sample of background locations, MaxEnt calculates the probability distribution of maximum entropy, *i.e.* the distribution that is closest to uniform across the study area.

2.4.1 Background point generation

We used a presence-background modelling approach using species occurrence as presence locations and randomly generating pseudo-absence points within the study area, which are known as background points. Background points are meant to be compared with the presence data and help differentiate the environmental conditions under which a habitat can or cannot be suitable for the species. MaxEnt generates a random sample of background points from the whole study area or from a given area (Philips et al, 2009; Elith et al, 2011). This selection may strongly affect the model if these points are extracted from areas far from the occurrence data, *i.e.* outside the environmental envelope of the species. We used a spatial filtering of the presences together with a spatial buffering strategy (*i.e.* a circular buffer of specified radius around each occurrence point) to refine background point selection and to correct for sampling bias. Doing so, we constrain the location and density of background point sampling to ensure that background points are generated from the same environmental space as the occurrence locations (Phillips et al, 2009). Background selection was carried out using a buffered local adaptive convex-hull using the function *buffer* from the *raster* R-package (package version 3.4-13, Hijmans, 2021). A range of buffers between 50 km and 150 km were tested. Finally, a 50 km buffer was chosen as this best restricted background point selection within the environmental envelope of the species (Annex II, Figure S2).

2.4.2 Model runs and settings

MaxEnt models were run using cross-validation with 60% of the occurrence data as training (model building) and 40% as testing (model validating). We ran 100 model replicates generating a maximum number of background points of 10,000, as the selection of more background points does not improve predictive ability (Phillips & Dudík, 2008). Only one background point per grid cell was permitted to prevent over-representation of environmental conditions (Elith et al, 2006). MaxEnt was run with a maximum of 5000 iterations, linear and quadratic relationships and a logistic output for easier interpretation. Additionally, we enabled the "fade by clamping" option to prevent extrapolations outside the environmental range of the training data (Owens et al, 2013). While the MaxEnt model is being trained, the program assigns the increase in the gain to the environmental variable(s) that the habitat suitability depends on (Phillips et al, 2006). At the end of the training process MaxEnt ran Jackknife analyses to get estimates of which variables are most important in the model by excluding one at a time ('leave-one-out' procedure) and creating a model with the remaining ones. Jackknife analysis can be used to show the importance of each variable in isolation, determine if a single variable could effectively predict the habitat suitability and delete variables which, if correlated, showed the worst explanatory power.

2.4.3 Model evaluation and prediction

To assess the MaxEnt models' performance, we used the Receiver Operating Characteristic (ROC) curve (Hirzel et al, 2006) to evaluate the sensitivity (true positive rate) and specificity (true negative rate) for training and testing data sets. Each point on the ROC curve represents the trade-off between making a true-positive prediction versus a false-positive prediction with increasing prediction threshold. The result produces an Area Under the receiver-operating-characteristic Curve (AUC), a measure of the ability of the predictions to discriminate presence from absence (or background). AUC values ranging from 0 to 1 (from negligible to perfect discriminatory power, respectively), where a value of 1 indicates that the presences and absences are perfectly discriminated, while a value of ≤0.5 indicates that discrimination is no better than random chance (Engler, Guisan & Rechsteiner, 2004). Finally, a map of the predicted habitat suitability index (HSI) was created as the mean HSI along with the standard deviation as a measure of predictive uncertainty from the 100 model replicates. Consequently, all the cells of the study area were categorized with a value from 0 to 1 (*i.e.* 0 for not suitable habitat and 1 for perfect suitable habitat). All statistical analysis including the use of MaxEnt model version 3.4.4 were performed using R software Version 1.2.1106 (RStudio Team, 2019).

2.5 Marine Protected Areas assessment

Since fin whales requires strict protection, we assessed whether currently designated MPAs could be relevant to aid in their conservation in NE Atlantic. To perform the assessment, we firstly identify the fin whale suitable habitat using a cut-off value (*i.e.* threshold) for the HSI. Thus, each cell was characterized as suitable or unsuitable given the cut-off value estimated as the average of the 100 cut-off values obtained from each model replicate. The cut-off value was calculated as the point on the ROC curve where specificity and sensitivity were maximized (Max SSS; where the total amount of misclassification is minimized). Thus, the HSI map (values ranging from 0 to 1; Figure 4A) was transformed into a binary map of suitable/non-suitable habitat.

Secondly, the fin whales' suitable habitat was overlapped with the existing MPAs to obtain the suitable habitat area under protection. This analysis was two-fold to obtain the amount of suitable habitat encompassed by MPAs designated: (1) under the Habitats Directive (hereafter, HD; Council Directive 92/43/EEC) as Special Areas of Conservation (SACs) and (2) under OSPAR (Oslo/Paris convention for the Protection of the Marine Environment of the NE Atlantic) as "Marine Protected Area" (Hübner & Nordheim, 2015). On one hand, we selected SACs designated within the *Natura 2000* as this programme was designed to provide a network of MPAs for those species listed under Annex II. Although in the case of cetacean species includes only the harbour porpoise, *Phocoena phocoena* and the bottlenose dolphin *Tursiops truncatus,* these areas could be relevant to aid in the conservation of fin whales. On the other hand, OSPAR MPAs was selected since OSPAR has developed a list of conservation features in need of protection in order to address gaps in existing European measures (*e.g.* HD). Information on the location of existing MPAs included within the study area was obtained from the World Database on Protected Areas (UNEP-WCMC & IUCN, 2021).

3. Results

A total of 18,848 and 220 occurrence points were obtained from OBIS-SEAMAP and JUVENA and BIOMAN surveys, respectively. After filtering the data (see section 2.2), a total of 1,421 occurrence points remained. Of the nine environmental variables selected a priori, collinearity analysis indicated that SAL and SST (r=0.89) were correlated, being SAL the variable with worst explanatory power and the variable deleted for further analysis (Annex III, Figure S3).

3.1 MaxEnt model results and performance

Habitat suitability models for fin whales showed a good performance (AUC score > 0.7), being the mean AUC score ± standard deviation calculated for the 100 replicate models 0.732 ± 0.0004 and 0.715 ± 0.0002 for testing and training data respectively (Figure 2).

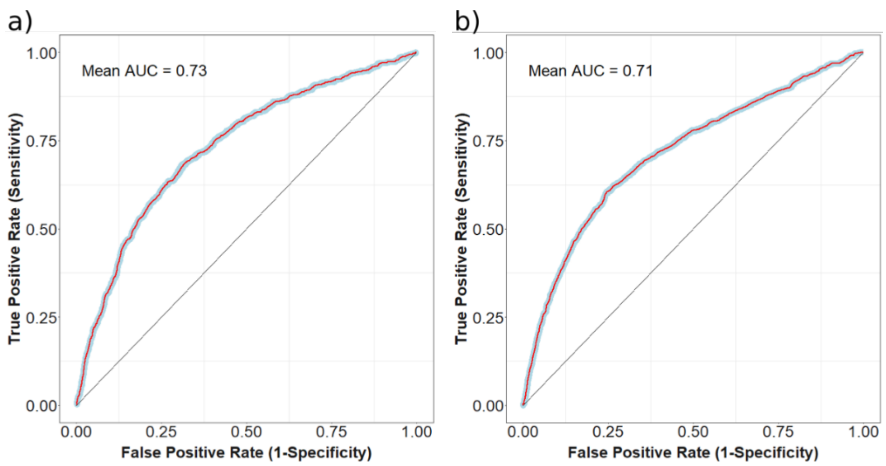


Figure 2. ROC curves of the 100 replicate models resulting from the fin whale's MaxEnt model for a) testing data and b) training data. Blue lines represent the ROC curve of the 100 model replicates and the red line the averaged ROC curve of the 100 model replicates. Note that the sensitivity (true positive rate) is plotted against the 1-specificity (false positive rate) for a range of threshold probabilities. A smooth curve is drawn through the points to derive the ROC curve. The 45° line represents the sensitivity and the false positive values expected to be reached by chance alone for each decision threshold.

The most important environmental variables in the MaxEnt model were DistCO, SST, Slope, and Chl-*a*. The Jackknife test showed that these variables were the most influential environmental predictors when using in isolation (Figure 3a) indicating that these environmental factors play an important role in the habitat suitability of fin whales. Furthermore, the Jackknife test also showed that DistCO, SST and Slope have most information that isn't present in the other variables since remove these variables from the analysis resulted in a reduction in training gain, *i.e.* a reduction in model performance (Figure 3a; Annex III, Figure S4-a-b).

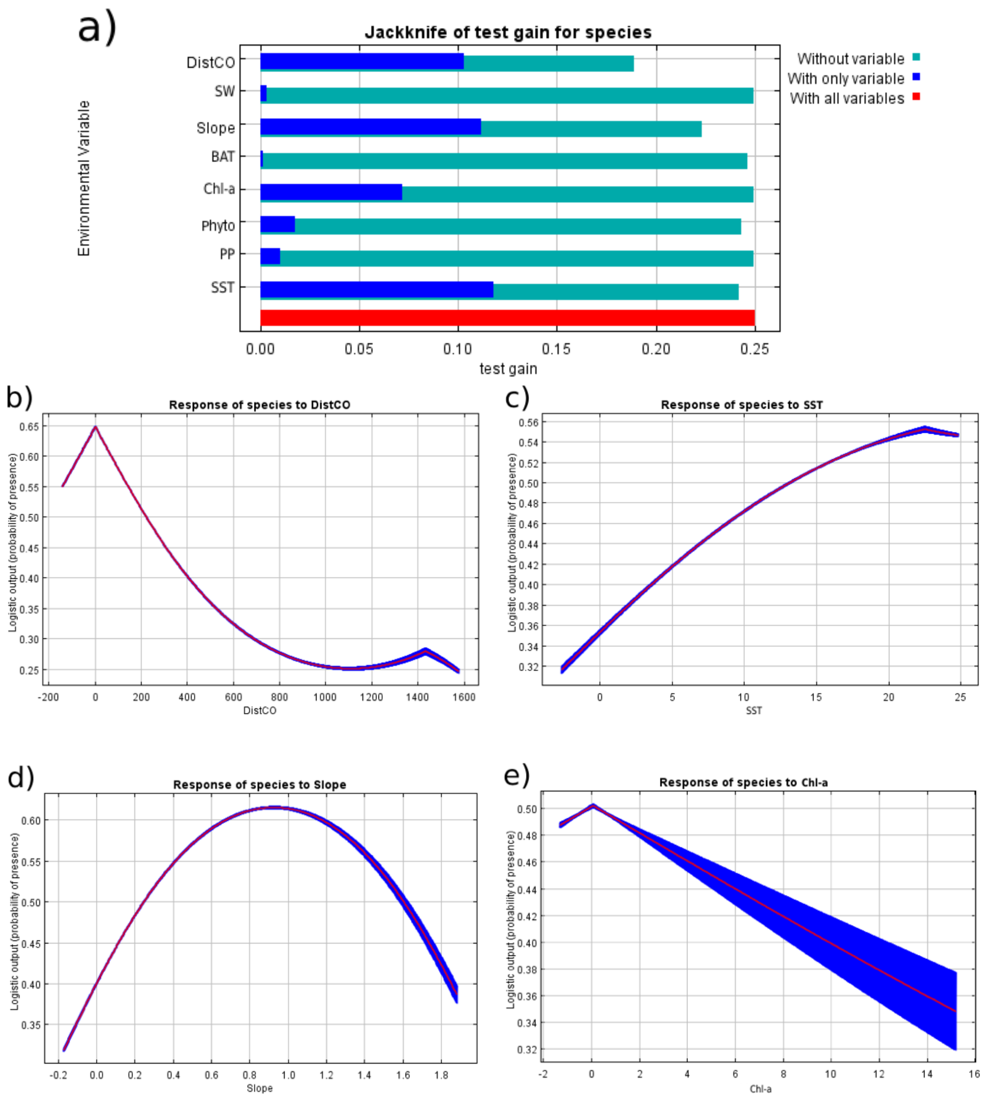


Figure 3. Results from the MaxEnt model a) Jackknife of regularized training gain for the environmental predictors of the model, where the contribution of each environmental predictor to the habitat suitability index prediction is estimated by the reduction of training gain after removing the variable (without variable vs. with all variables bars); Response curves of the most important environmental variables showing in blue the 100 replicate responses and in red the averaged response of b) DistCO: distance to the coast; c) SST: sea surface temperature; d) Slope: seabed slope e) Chl_a: chlorophyll-*a* concentration. The values shown in all figures are averages over 100 replicate runs in Maxent.

The response curves of the MaxEnt models (Figure 3 b-e; Annex III, Figure S5-a-d) regarding DistCO showed that the most suitable habitat conditions (HSI 0.6-0.65) for fin whales were located when distance is short, 0-60 Km from shore. When DistCO increase, occurrence probability decrease. The response curve of the SST showing a positive relationship between HSI and SST being the HSI highest (HSI ~0.55) when temperature is ~24ºC. The response curve of the Slope indicates that the most suitable habitat conditions (HSI ~0.62) where located at intermediated values. Finally, the response curve of the Chl-*a* indicates that the most suitable habitat conditions (HSI ~0.51) where located at lower concentrations of Chl-*a*.

3.2 Suitable habitat for fin whales

The HSI map showed higher values (higher suitable areas) over the Macaronesian archipelagos, off-shore waters of the Iberian Peninsula, NW Africa, southern Iceland and Greenland and eastern waters of the British Islands whilst less suitable areas were located over the inner North Sea and areas beyond national jurisdictions between 50-56ºN and 22-44ºW (Figure 4). The average cut-off value (Max SSS) obtained from the 100 model replicates and used as threshold for the HSI to define the suitable/non-suitable habitats was 0.65. By using this threshold (2.64% of the study area was classified as suitable habitat (map cells with HSI > 0.65) whilst 97.36 % was classified as non-suitable habitat (map cells with HSI < 0.65). The resulting map (Figure 5) showed suitable habitats mainly located over Macaronesia archipelagos, off-shore waters of the Iberian Peninsula, NW Africa, southern Iceland and Greenland, eastern waters of the British Islands and eastern Norway.

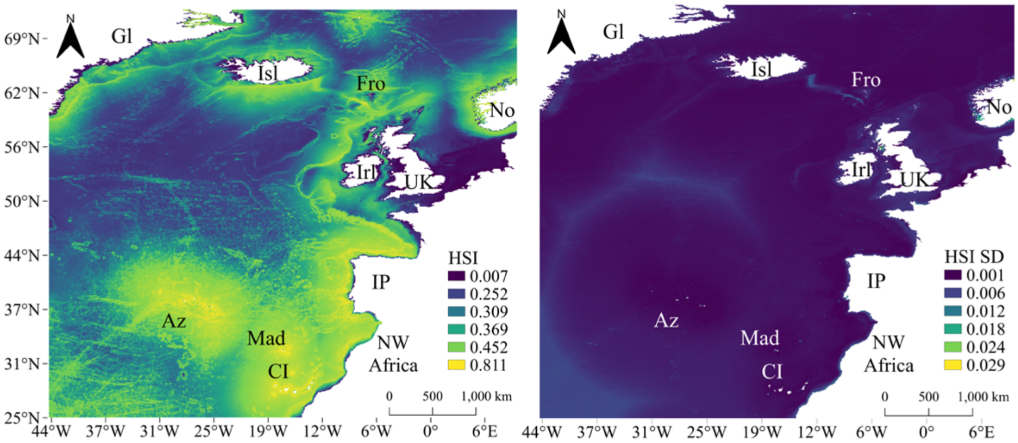


Figure 4. MaxEnt modelling results showing the averaged habitat suitability index (HSI) (left map) and the standard deviation (SD) of the HSI from the 100 MaxEnt replicated models.

3.3 Suitability of Marine Protected Areas for fin whales

The assessment of the suitability of the MPAs designated within the NE Atlantic for the protection of fin whales (Table 1) showed that if we consider all the MPAs designated within the study area, these MPAs encompassed 10.86% of the predicted suitable areas (Figure 5) whilst SACs encompassed 7.65% and the OSPAR MPAs encompassed 1.44% of the predicted suitable areas. On the other hand, if we only consider the suitable habitat encompassed by the MPAs designated within the study area, 70.49% was encompassed within SACs whilst 13.27% was encompassed within OSPAR MPAs.

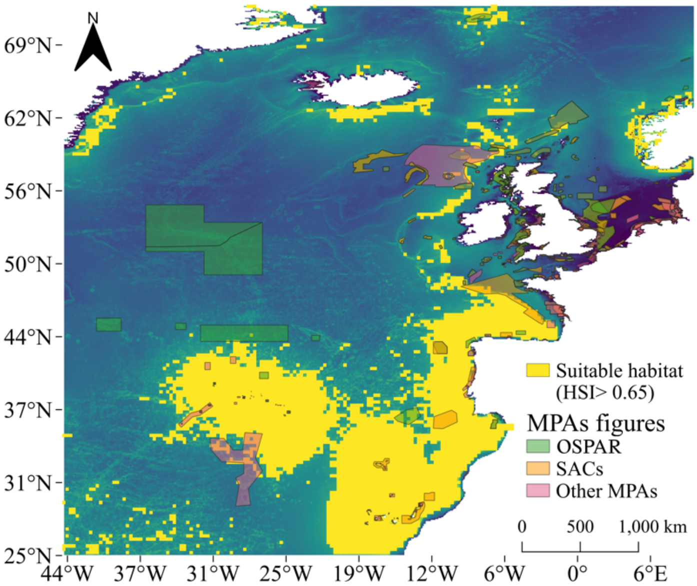


Figure 5. Map showing the different areas classified as suitable habitat [habitat suitability index (HSI) >0.65] and the designated Marina Protected Areas (MPAs) within the study area as: OSPAR: MPAs designated by OSPAR; SACs:

Special Areas of Conservation (SACs) designated under the Habitats Directive; and Other MPAs: the remaining MPAs designated under different national/international agreements. The map background showed the HSI predicted for fin whales.

Table 1. Extension and proportion of the fin whales' suitable habitat encompassed by the MPAs designated in the NE Atlantic respect to: i) the whole study area (Study area) and ii) the area encompassed within all the MPAs designated in the NE Atlantic (Within designated MPAs). SACs: Special Areas of Conservation designated under the Habitats Directive; OSPAR: MPAs designated under the OSPAR Convention.

Area	MPAs figures	Proportion (%)	Extension (km^2)
Study area	All MPAs	10.86	42,309.46
	SACs	7.65	29,822.56
	OSPAR	1.44	5,616.305
Within designated MPAs	SACs	70.49	29,822.56
	OSPAR	13.27	5,616.305

4. Discussion

The current knowledge of highly mobile species habitat preferences over wide scales is still limited despite its necessity for effective conservation management. Although MPAs have been shown to be a tool for species conservation (Evans, 2018) their effectiveness needs to be adequately addressed through the employment of spatial approaches such as the one presented here (Geijer & Jones, 2015; Breen et al, 2016). The multi-decadal, ocean basin-scale modelling approach performed in this work helps the advance on fin whales' conservation in the NE Atlantic by identifying their suitable habitats and assessing the adequacy of the existing MPAs.

4.1 Fin whales' suitable habitat in the NE Atlantic

Habitat suitability models have previously been used to identify the geographic range and environmental niche of species (*e.g.* Sahri et al, 2021). In the case of cetacean species, for which lack of information on species absence data is very common, there has been increasing focus on developing methods to model presence-only data (Smith et al, 2021; Pearce & Boyce, 2006; Prieto, Tobeña & Silva, 2016). Although multiple presence-only SDMs approaches exists, the model used in this work (MaxEnt) provided a robust approach for evaluating the importance of environmental characteristics influencing species distribution patterns to identify high suitable areas (Elith et al, 2011; Phillips & Dudík, 2008). Overall, we found that areas with highest suitability for fin whales were predicted in the Bay of Biscay, Azores, Madeira, Canary Islands, east cost of Greenland and Norwegian sea, which is consistent with some areas with higher density of occurrence records and indicates that these areas represent an important habitat for fin whales in the NE Atlantic. Our results showed that fin whales' suitable habitat was associated with temperate/cold both offshore and near coastal waters with steeper slopes where primary productivity is enhanced and therefore attracted the species. In accordance with previous studies, SST was one of the most important variables explaining fin whales' habitat suitability (and distribution) (*e.g*. Tobeña et al, 2016, García-Barón et al, 2019, Laran et al, 2008). Our results showed that most part of the predicted suitable habitats is located in areas with temperate SST values (15-21ºC) towards lower latitudes (García-Barón et al, 2019; Alessandrini, 2016), but also in areas of colder waters (4-10ºC) towards higher latitudes (Solvang et al, 2021; Bérubé et al., 1998). The disparity of suitable habitats either in temperate and colder waters makes sense if we consider that fin whales inhabit temperate latitudes during the breeding season and high latitudes with lower SST values during the feeding season. As in Breen et al (2016), slope was relevant to define fin whales' suitable habitat, as areas with high topographic complexity and sea currents create upwelling events, stimulating primary productivity and in consequence, promoting the aggregation of small pelagic species on which large predators, such as fin whales, rely (Sahri et al, 2021). Previous studies show that fin whales' potential habitat differed seasonally, mainly driven by temporal variations in the primary productivity. Although, the results showed a negative relationship between Chl-*a* concentration and habitat suitability due to highest values of Chl-*a* over near-shore waters, this variable may provide a proxy for areas of enhanced biological production contributing to prey aggregations (Tobeña et al, 2016; Prieto, Tobeña & Silva 2016).

Our findings highlight suitable areas for fin whales and, by implication more important for their conservation. In low-latitudes over Azores and Madeira, reflecting the breeding grounds and over the Canary Islands and NW Africa where high presence of fin whales has been reported. In high-latitude areas, over southern Iceland and Greenland reflecting the foraging grounds and, in mid-latitudes over off-shore Iberian Peninsula waters and the eastern of the British Islands reflecting possible migratory corridors and feeding grounds. Prieto, Tobeña & Silva (2016) and Tobeña et al (2016), although using a finer temporal scale (monthly and seasonal, respectively), showed that Azores represent an important breeding area for fin whales where temporal variations in primary production due to the strong seasonal warming also become a feeding ground prior to departing to wintering grounds (Silva et al, 2013). In the Bay of Biscay, studies like Laran et al (2016) and García-Barón et al (2019) discussed the presence of fin whales during summer, where the species showed a clearly oceanic distribution, as this area is presumably one of the foraging grounds outside polar and subpolar areas (García-Barón et al, 2019). Conversely, northern suitable areas corresponded to previously reported feeding grounds where high abundances of krill are available during summer (Lydersen et al, 2020).

The MaxEnt model performance is good (AUC = 0.73), although the northeastern part of the study area was not predicted as suitable despite the presence of occurrence points. This is not surprising since we are modelling annual data of a wide-ranging seasonally migrant species using climatological environmental predictors. In contrast with daily or monthly environmental products, climatological products may hide the inter-annual variation (*i.e.* monthly or seasonal) of the suitable environmental conditions for fin whales depending on the breeding or feeding season which affects the predictive model performance but still has the ability to locate biophysical hotspots (*i.e.* high suitable areas) (Smith et al, 2021). Hence, there can be a mismatch in predicted high suitable habitat and current knowledge of fin whales' distribution, such as over the northern regions (feeding grounds) of the study area, where wider suitable habitat areas were expected (Solvang et al, 2021; Breen et al, 2016; Edwards et al, 2015). Another possible reason for that mismatch may be explained by the restriction of the background data selection to a buffer of 50 km (as in Correia, 2020). This buffer size was selected to avoid over spatial predictions and to produce models that exclude suitable habitats considerably outside the occurrence range. Conversely, wider buffers to select background data across a broad spatial scale may result in increased model performance and overestimated suitable habitats but may not be the most appropriate approach for understanding finer scale patterns of habitat selection (Hazen et al, 2021). Hence, since the aim of this work was to assess the adequacy of the MPAs for the protection of important areas for fin whales, a finer scale pattern of suitable habitat was desired. In fact, most biologically realistic models were not always those that performed best according to model performance metrics (Hazen et al, 2021) sometimes failing to identify environmental gradients relevant for the species*, e.g.* near-shore *vs.* off-shelf waters where fin whales tend to occur. Despite the aforementioned limitations, our results provide crucial insights to support conservation and management strategies for fin whales in the NE Atlantic.

4.2 Adequacy of Marine Protected Areas for fin whales

Conserving the marine environment on the high seas is a challenging task, since efforts to establish protection measures are constrained to the limitations of international governance and legal framework pertaining to the high seas (Gjerde et al, 2003). Moreover, transboundary cooperation between countries is needed in the case of areas located over more than one EEZ. Nonetheless, the large-scale movements of fin whales, show the need for protection of important high seas areas where individuals aggregate either during breeding, foraging, or migrating (Baines, Reichelt & Griffin, 2017). The designation of MPAs encompassing these important areas can help species conservation however, appropriate management and conservation measures needs to be implemented within these MPAs to ensure an effective protection and prevent them from becoming 'paper parks' (Di Minin & Toivonen, 2015). In this sense, our results showed that only 10.86% of the suitable habitat was encompassed within the currently designated MPAs. This suggests that important areas for fin whales (breeding, calving, nursing, feeding or migration areas) may not be adequately addressed by the currently designated NE Atlantic MPAs. Furthermore, from all the predicted suitable habitat, only 7.65% and 1.44% was encompassed by SACs and OSPAR MPAs, respectively, whilst the remaining 1.77% was encompassed by other figures of MPAs. Most of the study area considered in this work belongs to EU waters, where the HD through the *Natura 2000*, conform the largest network of MPAs worldwide, protecting nowadays more than 9.7% of the EU marine territory (EEA, 2020). In fact, 70.49% of the MPAs considered in this work belongs to the HD (*i.e.* SACs) however, only a small part of the suitable habitat for fin whales was represented within these MPAs. This result showed that the currently designated *Natura 2000* network is not adequate for the protection of NE Atlantic fin whale suitable habitat. Even though the *Natura 2000* network was not designated specifically for most cetacean species (accounting only for those listed under the HD Annex II) the adequacy of these MPAs for the protection of the critical habitats of fin whales would be crucial. Indeed, additional conventions and agreements such as ecologically or biologically significant areas (EBSAs) and important marine mammal areas (IMMAs) (Di Sciara et al, 2016) acknowledges the need to protect other threatened species. Regarding OSPAR MPAs, most of them overlapped with SACs despite some of these MPAs area located in the high seas aiming to protect areas disregarding by the *Natura 2000* network. However, the percentage of fin whales' suitable habitats encompassed by OSPAR MPAs is also very low showing the inadequacy of the designated MPAs for the protection of fin whales within the NE Atlantic.

This assessment reveals underprotection of important suitable areas over Macaronesian waters which overlap with oil and gas exploration activities and high maritime traffic, posing a high risk for fin whales (Sahri et al, 2021). These areas are jeopardized by the growing impact of human activities and maritime traffic, due to the human population growth, truistic attraction of the region and fisheries (Alessandrini, 2016). For instance, there are reports on cases of collision with cetaceans caused by the increasing of the traffic and the high presence of fast ferries in the Canary Islands (Carrillo & Ritter, 2010), and on the interaction between cetaceans and fisheries in the Azores (Silva et al, 2013). Despite having evidence of all these threats, a very small part of the fin whale's suitable habitat is covered by some figure of protection or management measure.

As this study demonstrated, the level of protection of the high suitable habitats for fin whales in the NE Atlantic needs to be increased. We show that despite the numerous advantages of a network of well-managed MPAs, such as *Natura 2000,* to protect and connect critical habitats of wide-ranging species, it is still discussed if these networks are an important tool in the conservation and management of migratory cetaceans (Geijer & Jones, 2015; Hoyt, 2005). The identification of high suitable habitats along with the assessment of the adequacy of existent MPAs reveals that further studies are necessary to improve the management and conservation of fin whales in the NE Atlantic. This work not only identify important areas for fin whales to advance in their conservation, but also highlight the inadequate global degree of protection of these suitable habitats and advise where the focus should be put for future conservation and management measures.

5. Conclusions

1- The most important variables describing fin whales' habitat suitability over the NE Atlantic were distance to the coast, sea surface temperature, seabed slope and chlorophyll-*a* concentration, but the use of trophic variables for habitat suitability predictions improvement is recommended for further studies.
2- Predicted fin whales' suitable habitat were located around the Macaronesian archipelagos, northwest Africa, off-shore waters of the Iberian Peninsula, southern area of Iceland and Greenland and eastern waters of the British Islands.
3- The assessment of the adequacy of the NE Atlantic MPAs for the protection of fin whales showed that overall less of the 11% of the suitable habitat was encompassed within designated MPAs evidencing the need for further management and conservation measures to protect the species.
4- Additional studies of highly-migratory species, such as the fin whale, to assess the current status of the populations, distribution and the threats they are facing, are needed to improve the management and conservation measures at their critical areas.

6. Acknowledgments

This work is a contribution to the project EVALRENAT "Evaluación espacial de la adecuación de la red Natura 2000 para la conservación de especies de interés comunitario en la Demarcación Noratlántica" funded by Fundación Biodiversidad and to FutureMARES Project, a European Union's Horizon 2020 research and innovation programme under grant agreement No. 869300. I would like to thanks AZTI BRTA for giving me the opportunity to work with them and, especially, to my mentors Isabel García Barón and Maite Louzao for their dedication, effort and encouragement through all this period.

7. Bibliography

Alessandrini, A. (2016). Movements of short-finned pilot whales *(Globicephala macrorhynchus)* in the Macaronesian biogeographical region: a photo-identification analysis. Doctoral dissertation. Universidade do Algarve, Faro. Retrieved from https://sapientia.ualg.pt/handle/10400.1/9850

Asaad, I., Lundquist, C. J., Erdmann, M. V., & Costello, M. J. (2016). Ecological criteria to identify areas for biodiversity conservation. *Biological Conservation*, 1–8. https://doi.org/10.1016/j.biocon.2016.10.007

Assis, J., Tyberghein, L., Bosch, S., Verbruggen, H., Serrão, E. A., & De Clerck, O. (2017). Bio-ORACLE v2.0: Extending marine data layers for bioclimatic modelling. *Global Ecology and Biogeography*, *27*(3), 277–284. https://doi.org/10.1111/geb.12693

Baines, M., Reichelt, M., & Griffin, D. (2017). An autumn aggregation of fin (*Balaenoptera physalus*) and blue whales (*B. musculus*) in the Porcupine Seabight, southwest of Ireland. *Deep-Sea Research Part II: Topical Studies in Oceanography*, *141*, 168–177. https://doi.org/10.1016/j.dsr2.2017.03.007

Becker, E. A., Forney, K. A., Fiedler, P. C., Barlow, J., Chivers, S. J., Edwards, C. A., … Redfern, J. V. (2016). Moving towards dynamic ocean management: How well do modeled ocean products predict species distributions? *Remote Sensing*, *8*(149), 1–26. https://doi.org/10.3390/rs8020149

Boyra, G., Martínez, U., Cotano, U., Santos, M., Irigoien, X., & Uriarte, A. (2013). Acoustic surveys for juvenile anchovy in the Bay of Biscay: Abundance estimate as an indicator of the next year's recruitment and spatial distribution patterns. *ICES Journal of Marine Science*, *70*(7), 1354–1368. https://doi.org/10.1093/icesjms/fst096

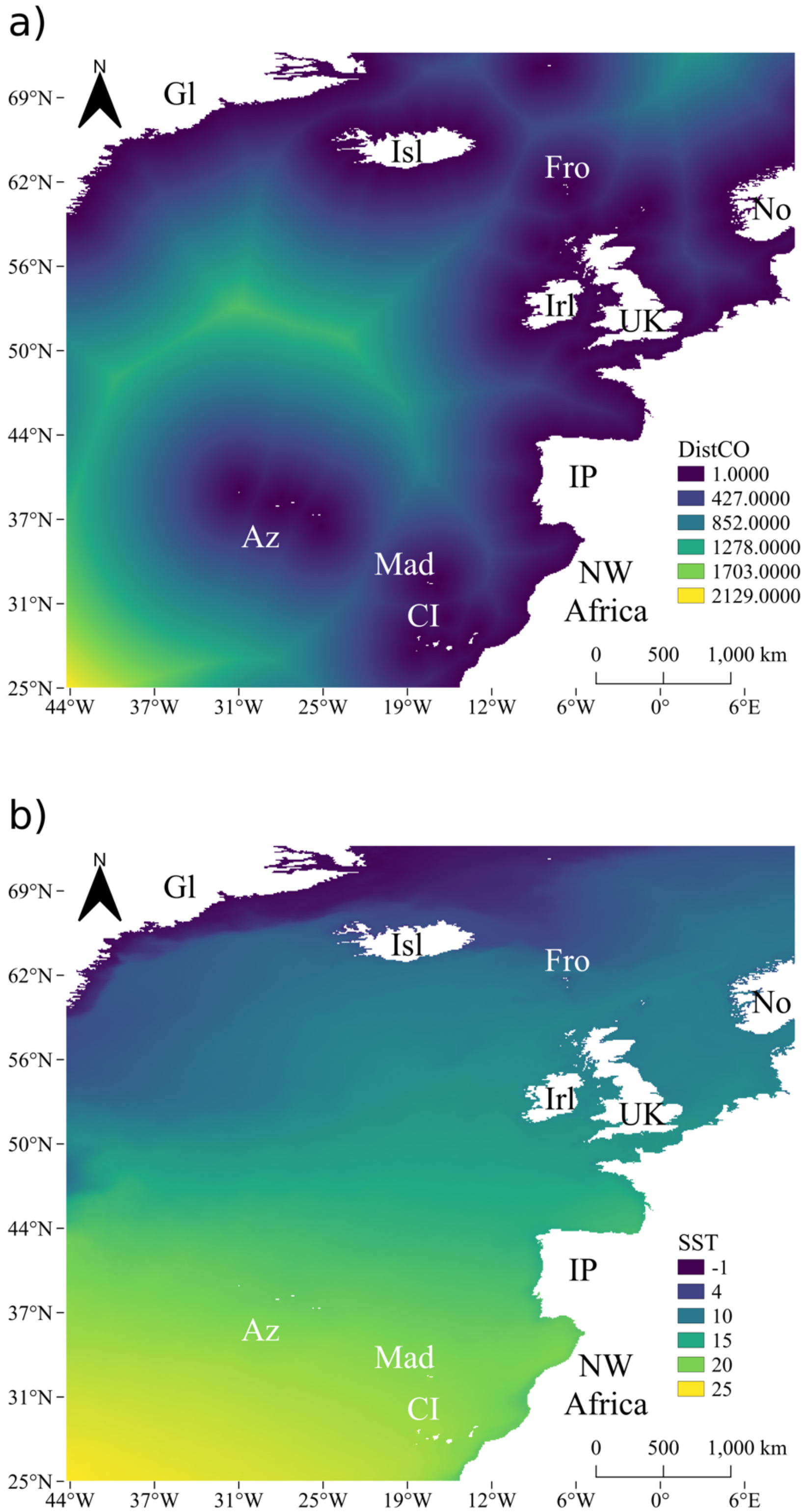
Breen, P., Brown, S., Reid, D., & Rogan, E. (2016). Modelling cetacean distribution and mapping overlap with fisheries in the northeast Atlantic. *Ocean and Coastal Management*, *134*, 140–149. https://doi.org/10.1016/j.ocecoaman.2016.09.004

Carrillo, M., & Ritter, F. (2010). Increasing numbers of ship strikes in the Canary Islands: Proposals for immediate action to reduce risk of vessel-whale collisions. Journal of Cetacean Research and Management, 11(2), 131–138.
Correia AM. (2020). *Distribution and habitat modelling for cetacean species in the eastern north Atlantic Ocean*. University of Porto.
Di Minin, E., & Toivonen, T. (2015). Global Protected Area Expansion: Creating More than Paper Parks. *BioScience*, *65*(7), 637–638. https://doi.org/10.1093/biosci/biv064
Di Sciara, G. N., Hoyt, E., Reeves, R., Ardron, J., Marsh, H., Vongraven, D., & Barr, B. (2016). Place-based approaches to marine mammal conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *26*(S2), 85–100. https://doi.org/10.1002/aqc.2642
Edwards, E. F., Hall, C., Moore, T. J., Sheredy, C., & Redfern, J. V. (2015). Global distribution of fin whales *Balaenoptera physalus* in the post-whaling era (1980-2012). *Mammal Review*, (45), 197–214. https://doi.org/10.1111/mam.12048
Elith, J., H. Graham, C., P. Anderson, R., Dudík, M., Ferrier, S., Guisan, A., … E. Zimmermann, N. (2006). Novel methods improve prediction of species' distributions from occurrence data. *Ecography*, *29*(2), 129–151. https://doi.org/10.1111/j.2006.0906-7590.04596.x
Elith, J., Phillips, S. J., Hastie, T., Dudík, M., Chee, Y. E., & Yates, C. J. (2011). A statistical explanation of MaxEnt for ecologists. *Diversity and Distributions*, *17*(1), 43–57. https://doi.org/10.1111/j.1472-4642.2010.00725.x
Engler, R., Guisan, A., & Rechsteiner, L. (2004). An improved approach for predicting the distribution of rare and endangered species from occurrence and pseudo-absence data. Journal of Applied Ecology, 41(2), 263–274. https://doi.org/10.1111/j.0021-8901.2004.00881.x
Evans, P. G. H. (2018). Marine Protected Areas and marine spatial planning for the benefit of marine mammals. *Journal of the Marine Biological Association of the United Kingdom*, *98*(5), 973–976. https://doi.org/10.1017/S0025315418000334
Game, E. T., Grantham, H. S., Hobday, A. J., Pressey, R. L., Lombard, A. T., Beckley, L. E., … Richardson, A. J. (2009). Pelagic protected areas: the missing dimension in ocean conservation. *Trends in Ecology and Evolution*, *24*(7), 360–369. https://doi.org/10.1016/j.tree.2009.01.011
García-Barón, I., Authier, M., Caballero, A., Vázquez, J. A., Santos, M. B., Murcia, J. L., & Louzao, M. (2019). Modelling the spatial abundance of a migratory predator: A call for transboundary marine protected areas. *Diversity and Distributions*, *25*, 346–360. https://doi.org/10.1111/ddi.12877
Geijer, C. K. A., & Jones, P. J. S. (2015). A network approach to migratory whale conservation: Are MPAs the way forward or do all roads lead to the IMO? *Marine Policy*, *51*, 1–12. https://doi.org/10.1016/j.marpol.2014.06.002
Gjerde, K. M. (2003). Towards a Strategy for High Seas Marine Protected Areas. In: Proceedings of the IUCN, WCPA and WWF Experts Workshop on High Seas Marine Protected Areas. IUCN: Gland, Switzerland.
Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., … Watson, R. (2008). A global map of human impact on marine ecosystems. *Science*, *319*, 948–952. https://doi.org/10.1126/science.1149345
Harrison, A. L., Costa, D. P., Winship, A. J., Benson, S. R., Bograd, S. J., Antolos, M., … Block, B. A. (2018). The political biogeography of migratory marine predators. *Nature Ecology and Evolution*, *2*, 1571–1578. https://doi.org/10.1038/s41559-018-0646-8
Hazen, E. L., Abrahms, B., Brodie, S., Carroll, G., Welch, H., & Bograd, S. J. (2021). Where did they not go? Considerations for generating pseudo-absences for telemetry-based habitat models. *Movement Ecology*, *9*(5), 1–13. https://doi.org/10.1186/s40462-021-00240-2
Hijmans, R.J. (2021) Raster Geographic Data Analysis and Modeling. R Package Version 3.4-13.
Hirzel, A. H., Le Lay, G., Helfer, V., Randin, C., & Guisan, A. (2006). Evaluating the ability of habitat suitability models to predict species presences. *Ecological Modelling*, *199*(2), 142–152. https://doi.org/10.1016/j.ecolmodel.2006.05.017
Hoyt, E. (2005). *Marine Protected Areas for Whales, Dolphins And Porpoises: a world handbook for cetacean habitat conservation*. Earthscan.
Hübner K., Nordheim H von. (2015). 2014 Status Report on the OSPAR Network of Marine Protected Areas Biodiversity and Ecosystems Series.
Laran, S., Authier, M., Blanck, A., Doremus, G., Falchetto, H., Monestiez, P., … Ridoux, V. (2016). Seasonal distribution and abundance of cetaceans within French waters- Part II: The Bay of Biscay and the English Channel. *Deep-Sea Research Part II: Topical Studies in Oceanography*, *141*, 31–40. https://doi.org/10.1016/j.dsr2.2016.12.012
Laran, S., & Gannier, A. (2008). Spatial and temporal prediction of fin whale distribution in the northwestern Mediterranean Sea. *ICES Journal of Marine Science*, *65*(7), 1260–1269. https://doi.org/10.1093/icesjms/fsn086
Lascelles, B., Notarbartolo Di Sciara, G., Agardy, T., Cuttelod, A., Eckert, S., Glowka, L., … Tetley, M. J. (2014). Migratory marine species: Their status, threats and conservation management needs. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *24*(S2), 111–127. https://doi.org/10.1002/aqc.2512

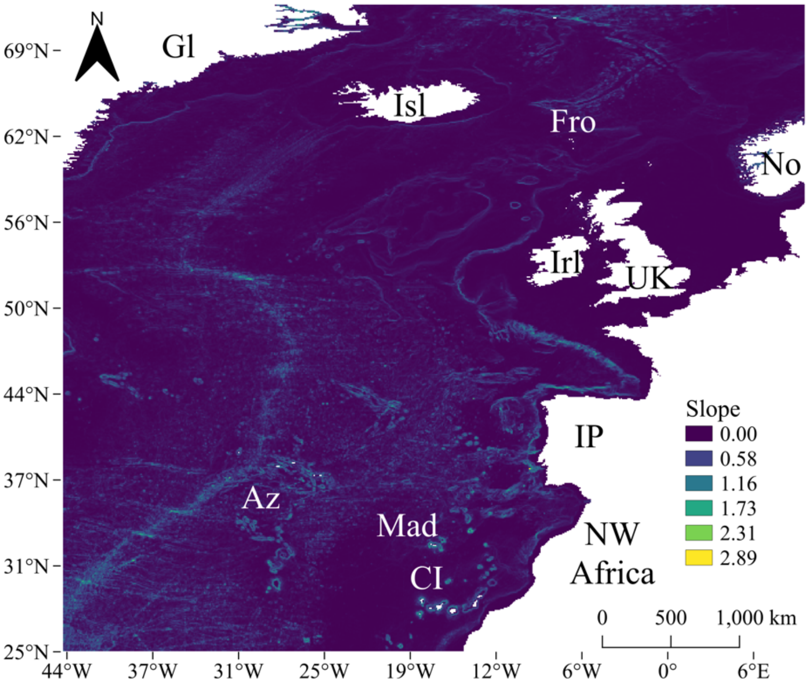
Lubchenco, J., & Grorud-Colvert, K. (2015). Making waves: The science and politics of ocean protection. *Science*, *350*, 1–11. https://doi.org/10.1126/science.aad5443
Lydersen, C., Vacquié-Garcia, J., Heide-Jørgensen, M. P., Øien, N., Guinet, C., & Kovacs, K. M. (2020). Autumn movements of fin whales (*Balaenoptera physalus*) from Svalbard, Norway, revealed by satellite tracking. *Scientific Reports*, *10*(16966), 1–13. https://doi.org/10.1038/s41598-020-73996-z
OSPAR. (2020). *Status of the OSPAR Network of Marine Protected Areas in 2019*. Retrieved from https://oap-cloudfront.ospar.org/media/filer_public/8c/21/8c2101bb-7ef7-406a-8633-c6b8870f3195/assessment_sheet_mpa_status_2019.pdf
Owens, H. L., et al. 2013. Constraints on interpretation of ecological niche models by limited environmental ranges on calibration areas. Ecological Modelling 263:10–18.
Pearce, J. L., & Boyce, M. S. (2006). Modelling distribution and abundance with presence-only data. *Journal of Applied Ecology*, *43*(3), 405–412. https://doi.org/10.1111/j.1365-2664.2005.01112.x
Phillips, S. B., Aneja, V. P., Kang, D., & Arya, S. P. (2006). Modelling and analysis of the atmospheric nitrogen deposition in North Carolina. *International Journal of Global Environmental Issues*, *6*, 231–259. https://doi.org/10.1016/j.ecolmodel.2005.03.026
Phillips, S. J., & Dudík, M. (2008). Modeling of species distributions with Maxent: New extensions and a comprehensive evaluation. *Ecography*, *31*(2), 161–175. https://doi.org/10.1111/j.0906-7590.2008.5203.x
Phillips, S. J., Dudík, M., Elith, J., Graham, C. H., Lehmann, A., Leathwick, J., & Ferrier, S. (2009). Sample selection bias and presence-only distribution models: Implications for background and pseudo-absence data. *Ecological Applications*, *19*(1), 181–197. https://doi.org/10.1890/07-2153.1
Pimiento, C., Leprieur, F., Silvestro, D., Lefcheck, J. S., Albouy, C., Rasher, D. B., … Griffin, J. N. (2020). Functional diversity of marine megafauna in the Anthropocene. *Science Advances*, *6*(16), 1–12. https://doi.org/10.1126/sciadv.aay7650
Prieto, R., Tobeña, M., & Silva, M. A. (2016). Habitat preferences of baleen whales in a mid-latitude habitat. *Deep-Sea Research Part II: Topical Studies in Oceanography*, *141*, 155–167. https://doi.org/10.1016/j.dsr2.2016.07.015
RStudio Team (2020). RStudio: Integrated Development for R. RStudio, Inc., Boston, MA UR.
Sahri, A., Herwata Putra, M. I., Kusuma Mustika, P. L., Kreb, D., & Murk, A. J. (2021). Cetacean habitat modelling to inform conservation management, marine spatial planning, and as a basis for anthropogenic threat mitigation in Indonesia. *Ocean and Coastal Management*, *205*, 1–30. https://doi.org/10.1016/j.ocecoaman.2021.105555
Santos M., Serrano N., Rubio A., Perez C., Louzao M., Korta M., … (2019). Enfoque ecosistémico para la investigación pesquera. ECOPES. Informe para Eusko Jaurlaritza – Gobierno Vasco, Dirección de pesca y acuicultura. 1-45.
Sbrocco, E. J., & Barber, P. H. (2013). MARSPEC: ocean climate layers for marine spatial ecology. *Ecology*, *94*(4), 979–979. https://doi.org/10.1890/12-1358.1
Silva, M. A., Prieto, R., Jonsen, I., Baumgartner, M. F., & Santos, R. S. (2013). North Atlantic Blue and Fin Whales Suspend Their Spring Migration to Forage in Middle Latitudes: Building up Energy Reserves for the Journey? *PLoS ONE*, *8*(10), 1–15. https://doi.org/10.1371/journal.pone.0076507
Smith, J. N., Kelly, N., & Renner, I. W. (2021). Validation of presence-only models for conservation planning and the application to whales in a multiple-use marine park. *Ecological Applications*, *31*(1), 1–14. https://doi.org/10.1002/eap.2214
Solvang, H. K., Haug, T., Knutsen, T., Gjøsæter, H., Bogstad, B., Hartvedt, S., … Lindstrøm, U. (2021). Distribution of rorquals and Atlantic cod in relation to their prey in the Norwegian high Arctic. *Polar Biology*, (0123456789), 22. https://doi.org/10.1007/s00300-021-02835-2
Thomas, P. O., Reeves, R. R., & Brownell, R. L. (2015). Status of the world's baleen whales. *Marine Mammal Science*, *32*(2), 682–734. https://doi.org/10.1111/mms.12281
Tobeña, M., Prieto, R., Machete, M., & Silva, M. A. (2016). Modeling the potential distribution and richness of cetaceans in the Azores from fisheries observer program data. *Frontiers in Marine Science*, *3*(202), 1–19. https://doi.org/10.3389/fmars.2016.00202
Tyberghein, L., Verbruggen, H., Pauly, K., Troupin, C., Mineur, F., & De Clerck, O. (2012). Bio-ORACLE: A global environmental dataset for marine species distribution modelling. *Global Ecology and Biogeography*, *21*(2), 272–281. https://doi.org/10.1111/j.1466-8238.2011.00656.x
UNEP-WCMC & IUCN. (2021) Protected Planet: The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WD-OECM). Cambridge, UK: UNEP-WCMC and IUCN. Available at: www.protectedplanet.net.

Supplementary material

Annex I: Environmental data



c)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19°W
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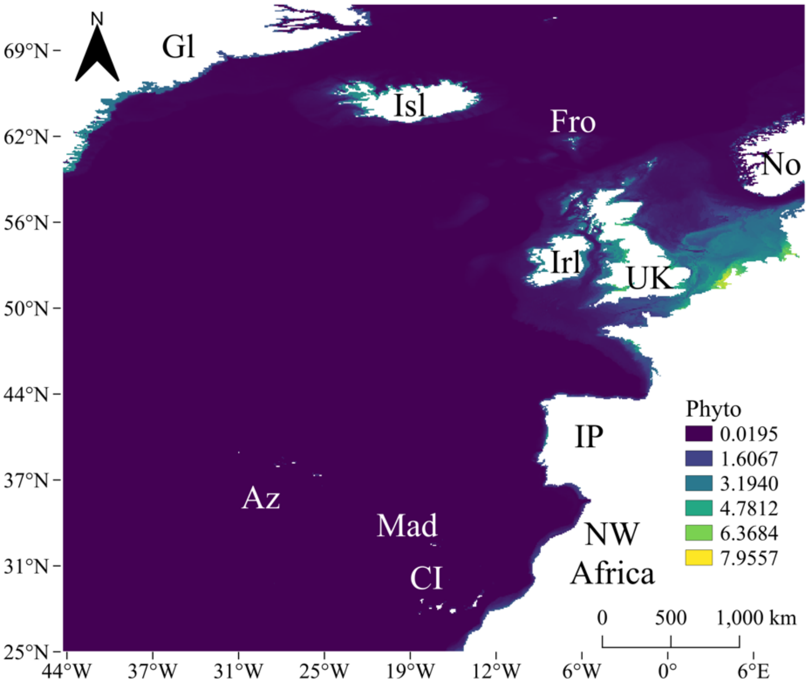
d)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6°W
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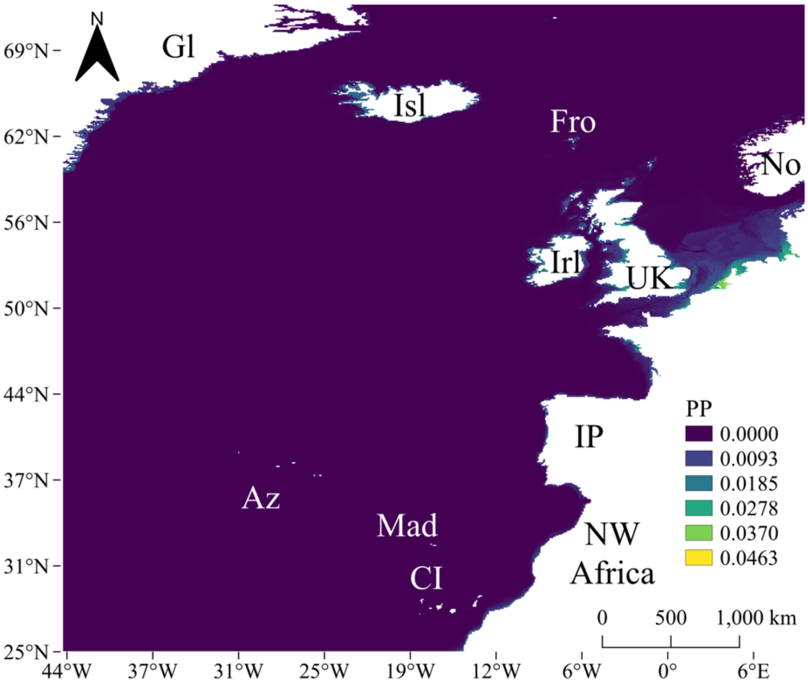
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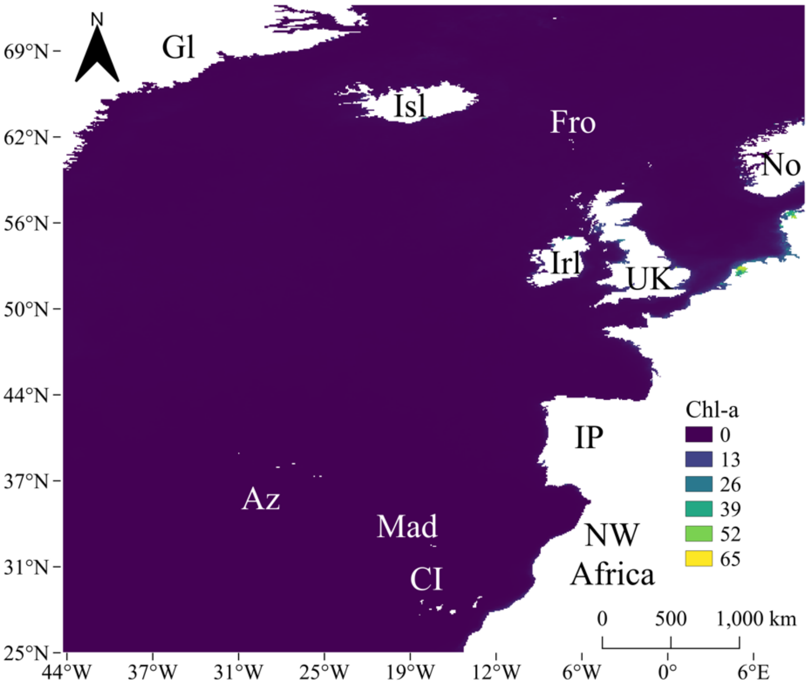
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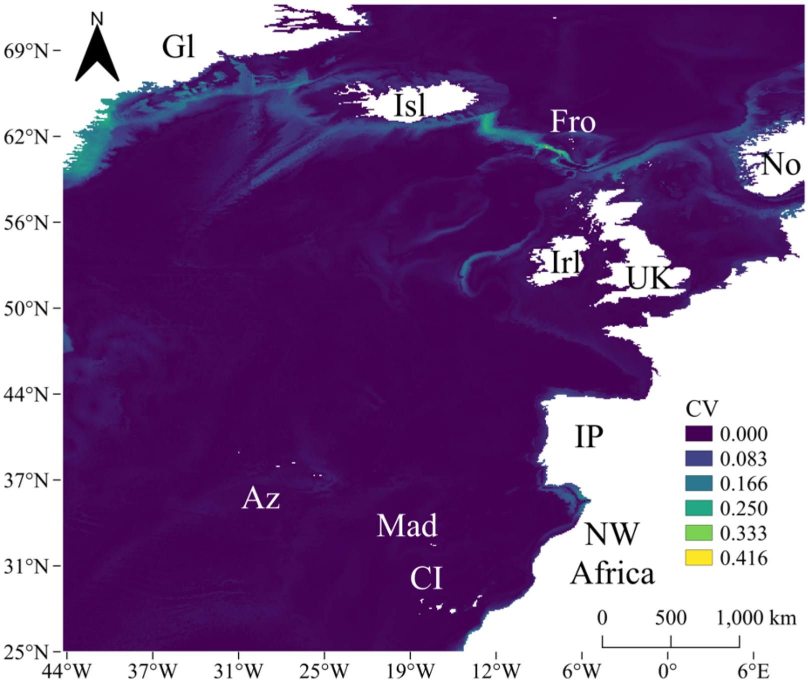
g)



h)

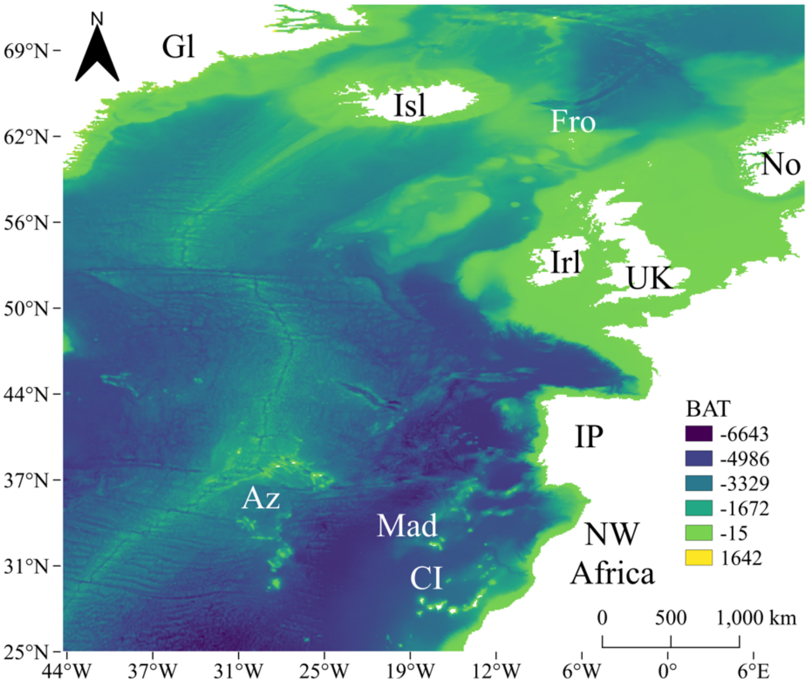


Figure S1. map of every environmental variable used in the model. a) map showing DistCO, distance to the coast. b) map showing SST, sea surface temperature. c) map showing Slope, seabed slope. d) map showing Phyto, phytoplankton concentration. e) map showing PP, primary productivity. f) map showing Chl-*a*, chlorophyll-a concentration. g) map showing CV, and current velocity. h) map showing BAT, bathymetry.

Annex II: Background data

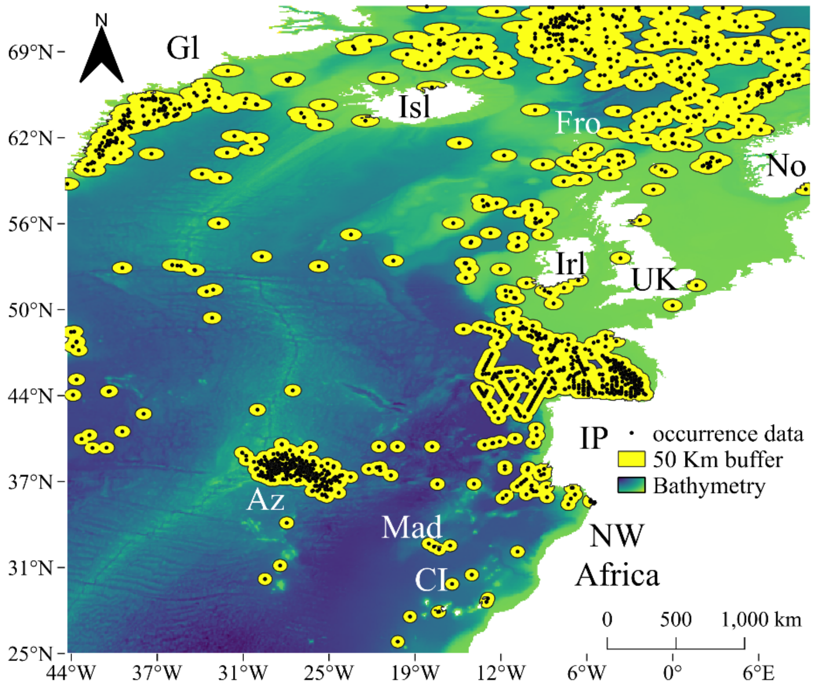


Figure S2. Map of the study area showing fin whale occurrence data (black points) and the 50 Km buffer (surrounding the occurrence data) from which background data were sampled (yellow).

Annex III: MaxEnt model results

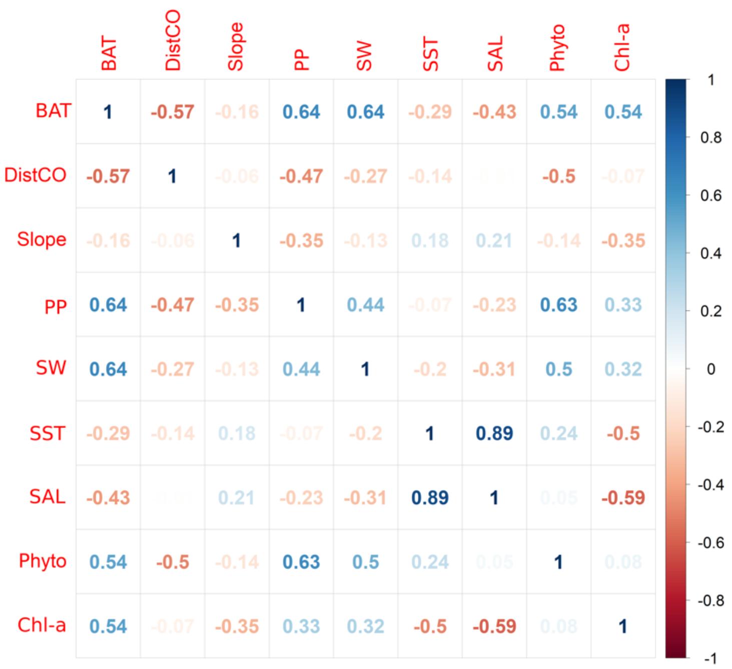
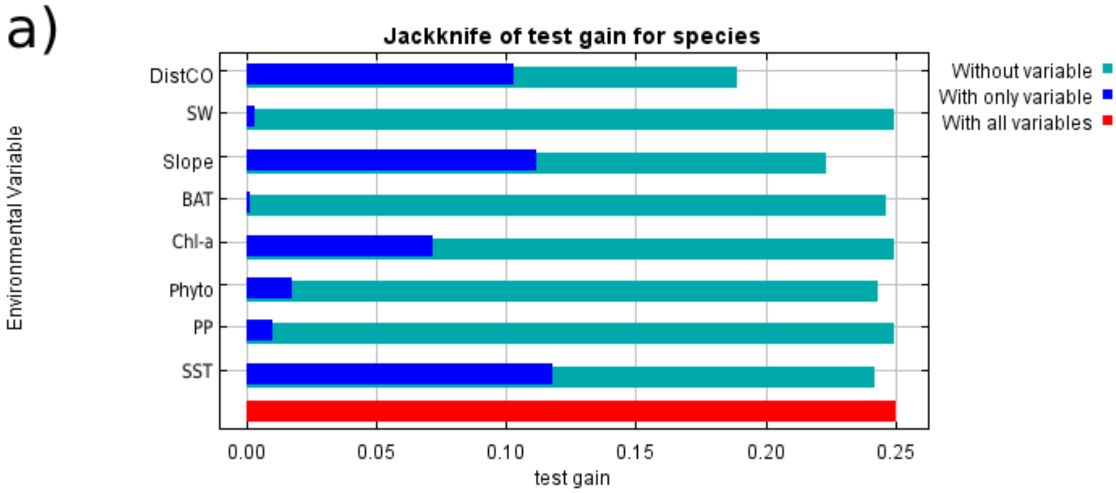


Figure S3. Pairwise correlation matrices between predictor variables by means of Spearman-rank correlation coefficient where higher values (towards 1/-1) indicate higher correlation rate. See section 2.3 Environmental data for abbreviations.

a)



b)

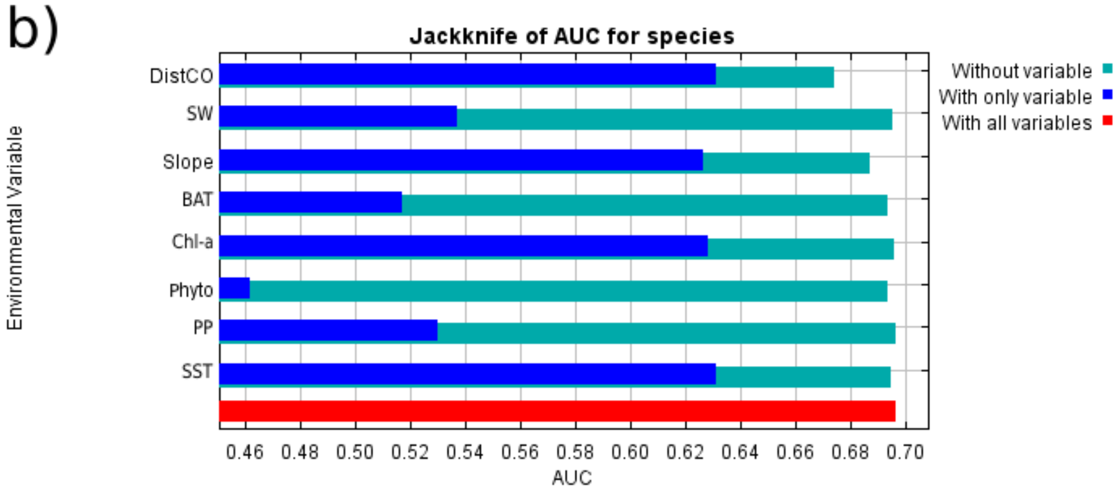
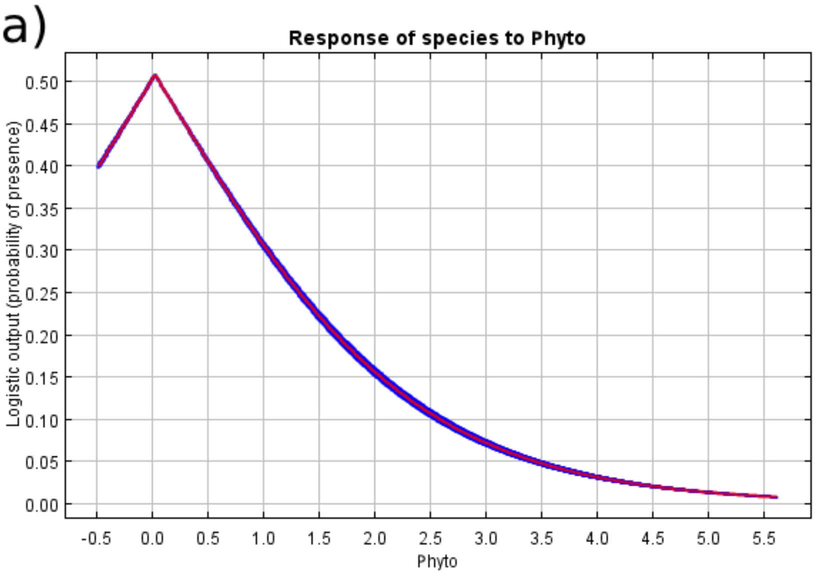


Figure S4. Results from the MaxEnt model Jackknife of a) regularized testing gain and b) AUC, Area Under the receiver-operating-characteristic Curve, for the environmental predictors of the model, where the contribution of each environmental predictor to the habitat suitability index prediction is estimated by the reduction of training gain after removing the variable (without variable vs. with all variables bars). See section 2.3 Environmental data for abbreviations.

a)



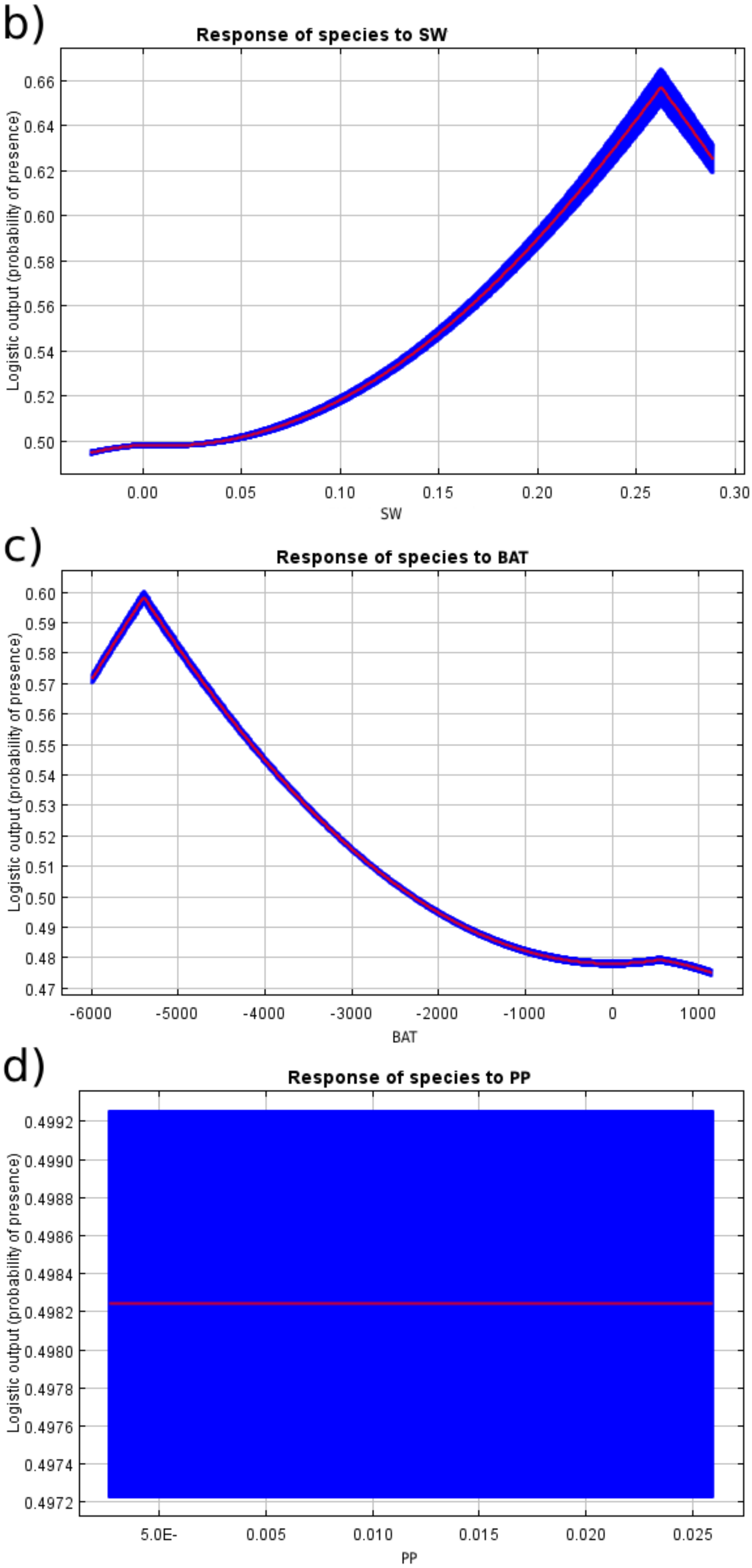


Figure S5. Response curves of the least important environmental variables showing in blue the 100 replicate responses and in red the averaged response of a) Phyto: phytoplankton concentration; b) SW: current velocity; c) BAT: bathymetry; d) PP: primary productivity. The values shown in all figures are averages over 100 replicate runs in Maxent.