Using an integrated approach to design an effective marine protected area (MPA) for seabirds

Master Thesis Manuscript

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Abstract

The European Birds Directive aims to protect all European wild birds and their habitats, through measures such as Special Protection Areas. Seabirds face a unique set of threats which need to be given special consideration when managing their populations, such as prey depletion and bycatch mortality due to commercial fisheries. With the IUCN's new target of protecting 30% of marine habitats by 2030, the importance of well-planned marine protected areas (MPAs) as a conservation tool is recognized now more than ever.

We used a spatial conservation planning software, Zonation, to identify key areas for seabirds off the eastern Algarve coast (Portugal), with a focus on the rare and vulnerable Audouin's Gull (*Larus audouinii*) and the critically endangered Balearic Shearwater (*Puffinus mauretanicus*). We modelled the predicted distribution at sea of these two species and several others, and mapped the fishing effort of the important local small-scale fisheries. We combined these features in Zonation and tested multiple sets of parameters to identify areas of highest conservation value. The suggested new MPA is in the south-eastern corner of our study area. We hope that this project may serve as an introductory example for other researchers not yet familiar with Zonation.

Executive summary

The European Birds Directive aims to protect all European wild birds and their habitats, through measures such as Special Protection Areas. Seabirds face a unique set of threats which need to be given special consideration when managing their populations, such as prey depletion and bycatch mortality due to commercial fisheries. With the IUCN's new target of protecting 30% of marine habitats by 2030, the importance of well-planned marine protected areas (MPAs) as a conservation tool is recognized now more than ever.

The goal of this study was to identify key areas for seabirds off the eastern Algarve coast (Portugal), with a focus on the rare and vulnerable Audouin's Gull (*Larus audouinii*) and the critically endangered Balearic Shearwater (*Puffinus mauretanicus*). Seabird counts were conducted during 12 monthly at-sea ESAS surveys. This data, and environmental variables such as distance to land and bathymetry, were used to create Hurdle and Zero-inflated models that estimate density distribution of seabird species across our 2565 km^2 study area during different phenological periods. We also mapped local fishing effort based on questionnaire answers collected over a year.

The resulting raster maps were inputted into the spatial conservation planning software Zonation, which then assigns each cell of the study area grid a conservation value, and iteratively removes cells with the lowest value, until a final ranking is reached. We tested multiple feature combinations, definitions of conservation value, and sets of parameters, to identify areas of highest conservation value. The solution we settled on used the Additive Benefit Function (ABF) cell removal rule, and retained the top 20% fraction of the landscape.

Based on the location of these priority areas, we drew two versions of a potential new MPA, situated in the south-eastern corner of our study grid. One option is more compact, and the other is more costly but covers a larger portion of the top priority areas. We also suggest further additions and improvements to our analysis, and highlight an area outside of our proposed MPA boundaries that may be worth continuing to monitor. Despite the limitations and preliminary nature of our research, we hope that this project may serve as an introductory example for other researchers not yet familiar with Zonation.

INTRODUCTION

2021 marked the start of the United Nations' Decade of Ocean Science for Sustainable Development, putting a focus on the urgent global need for increased knowledge of our oceans and better marine spatial planning. Marine protected areas (MPAs) can play an essential role in achieving these goals, if designed and managed appropriately. In fact, their importance has been recognized by the scientific community, for example through promotion of the 30 x 30 objective: increasing the global coverage of land and oceans under protection to 30% by 2030[1]. This target was the third to be listed on the first draft of the UN Convention on Biological Diversity (CBD)'s post-2020 global biodiversity framework, presented and supported by many member states during the first installment of CBD COP15 (15th meeting of the Conference of the Parties), which took place in October 2021 in Kunming, China[2].

There is, however, controversy about the effectiveness of MPAs, regarding their design, size, location and management plans[1]. Some scientists argue that no-take marine reserves are by far the most effective, at least for fisheries recovery and potentially for ecosystem resilience on a larger scale[3]. There is also a growing emphasis on the need for larger, deep-water MPAs[1,4].

Nonetheless, coastlines are under high pressure and also need to be protected[4,5]. It is valuable but difficult to reach compromises when designating and managing new MPAs, particularly in coastal areas, where numerous stakeholders co-exist and there are overlapping ecosystem services, resource uses, and anthropogenic threats[4–6].

To tackle this problem, a "conservation prioritization" approach is useful. This involves combining spatially defined ecological data and factors such as connectivity, cost and uncertainty to identify areas where conservation action will be most efficient in reaching management goals. Spatial prioritization softwares such as Zonation and Marxan are convenient decision-supporting tools which use complex mathematical algorithms to identify priority areas[7–10]. Leathwick et al. (2008) noted that using Zonation to designate fishing MPAs delivered conservation benefits surpassing those of similar-sized areas, and at a lower cost to fishers[11]. McGowan et al. (2013) used spatial prioritization to point out that prime foraging habitat for seabirds was mostly left out of existing MPAs in central California[12]. These MPAs instead overlapped with sources of anthropogenic threats, rendering their value questionable.

Use of conservation prioritization tools is indeed particularly interesting when dealing with seabird conservation. Seabirds play an important role as some of the top predators in the ocean, and as a link between terrestrial and marine ecosystems. This also means they face a unique set of threats, both on-land and offshore: fisheries' accidental bycatch[13], predatory and invasive species[14], ingestion of plastic and other pollutants[15–17], artificial land-based lights which can attract or disorient birds and increase mortality[18] , and more.

Additionally, seabirds often are highly mobile, undertake long distance migration, separate their activities and life stages by different areas, and are sensitive to environmental changes[19,20]. This can be a challenge when trying to map their distribution and identify the most important areas to include in an MPA targeted at seabird conservation or SPA[21–23].

After 8 years of at-sea surveys, Pereira et al. (2018) incorporated data on seabird distribution and anthropogenic stressors into a multi-model ensemble forecasting approach, to identify several areas along the Portuguese coast that would benefit from the creation of new MPAs to complement the existing network[24]. Among these candidate areas, a section of the south-east coast, in the Algarve region, was selected for its particularly significant overlap between important seabird habitat use and fisheries.

Indeed, this costal shelf has occasional upwelling systems of cold, nutrient-rich water and overall high productivity[25]. Of all the Portuguese continental regions, the Algarve has the most fishers in proportion to its population[26]. In particular, the Ria Formosa flanking the cities of Tavira, Faro and Olhão is an intricate system of lagoons, wetlands and sandy islets which harbors rich habitat and species diversity. It is one of the most important fish nurseries in Portugal, host to a remarkable density of commercially important species, and is visited by a large number of migratory birds every year[27].

The location's ecological value is already acknowledged by several protected areas designations.

The Ria Formosa is a Special Protection Area (SPA) under the EU's Bird Directive as well as a Natural Park and a BirdLife Important Bird and biodiversity Area (IBA)[28]. There is also the Ria Formosa/Castro Marim Site of Community Importance under the EU Habitats Directive (SCI), which is also a Ramsar site and Natural reserve, and BirdLife has also identified a complementary marine IBA to this network (Figure 1).

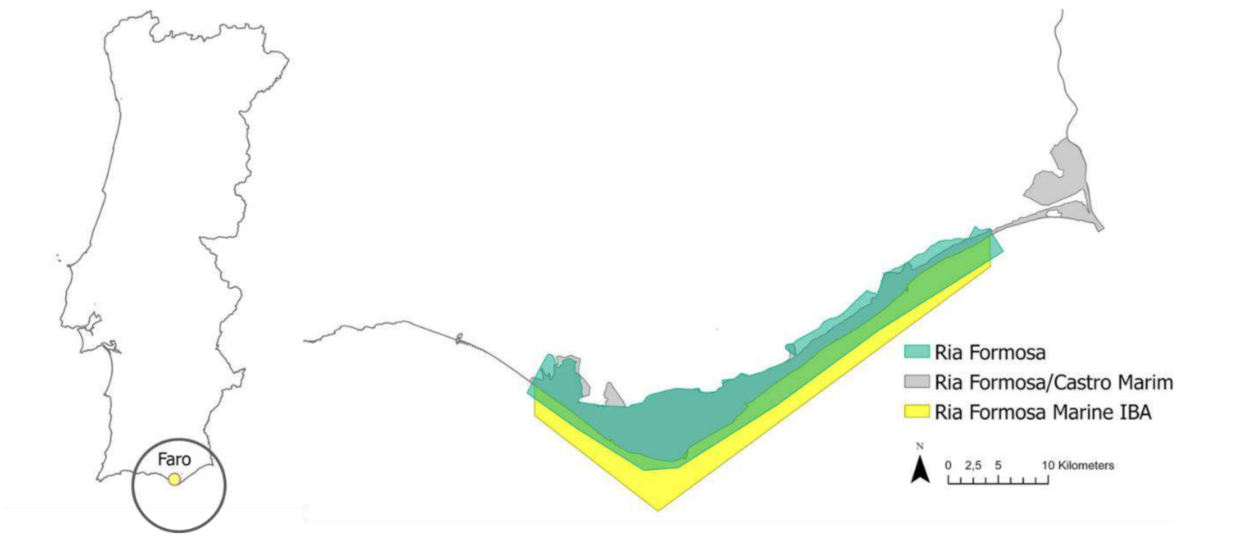


Figure 1: Existing network of recognized areas of conservation value in the south-eastern coast of Portugal.

Some of the criteria for these special designations include the presence of rare and threatened seabirds, and the prevalence of anthropogenic and environmental stressors. This includes, for example, human disturbance of nesting areas of Little terns and a rise in paretic syndrome in gulls due to *Clostridium botulinum* toxins[29,30].

Among the protected areas' targeted species, the Balearic Shearwater (*Puffinus mauretanicus*) stands out because of its status as the most critically endangered seabird in Europe[31]. It suffers from abnormally high adult mortality rates, mostly due to being particularly prone to accidental bycatch[32–34]. Balearic shearwaters breed almost exclusively in the Balearic Islands (Spain), but the highly productive Portuguese continental shelf is precious post- and pre-breeding habitat for them[35].

Another species to be given special attention to is the Audouin's gull (*Larus audouinii*), a rare species whose only breeding site in Portugal (and in the Atlantic) is Ilha Deserta (also known as Barreta Island)[36]. *L. audouinii* has only recently started breeding in Portugal, and since 60% of its global population is restricted to one colony in Spain, other colonies' protection is of upmost importance, so that they may act as buffers in case of catastrophical events[37]. Its overall conservation status is vulnerable, but because of its limited range in Portugal and the threats of habitat destruction and invasive mammal predation, it can be considered as locally endangered[38]. As a strict piscivore, unlike other generalist and opportunistic gulls, it may suffer more from competition with fisheries[37]. It can also be victim to kleptoparasitism and predation from other seabirds, notably the sympatric Yellow-legged gulls *Larus michahellis*[39].

There are already measures to mitigate threats on land, as for example increasing signage around valuable nesting habitat[29]. Additionally, LIFE Ilhas Barreira is a conservation project launched in 2020 and led by SPEA (Portuguese Society for the Study of Birds) which focuses on the habitat and biodiversity of the sandy islands separating the Ria Formosa and the ocean. Conservation actions include monitoring and removing invasive mammal and plant species, raising public awareness and limiting human disturbance. Some of its goals also include reducing the high bycatch mortality of the Balearic shearwater, and expanding the Ria Formosa SPEA boundaries[33,40]. Indeed, some local species such as *P. mauretanicus* and the Mediterranean gull *Larus melanocephalus* forage further from the coast that previously thought, which needs be reflected in protected areas[41,42]. Gomes et al. (2018) showed that southern Portugal had remarkably few conservation areas in proportion to its high marine biological value, and that deeper habitats were particularly under-represented[43].

The main aim of this thesis project was therefore to identify an optimal marine protected area that could complement the existing network. For this, we first had to predict seabird distribution and map fishing effort. We then used the conservation prioritization software Zonation to identify the most relevant areas for seabirds, while also taking into consideration the importance of small-scale fisheries in this region.

Beside this main objective, we hope that other groups that are also just getting started with the software and working on similar objectives may find the methods presented in this thesis to be a helpful starting point. Zonation has been applied in complex large-scale projects, often managed by big multidisciplinary teams[44–46]. However, it is a flexible tool that can also be used for smaller areas such ours (2565 km^2) and by non-academic teams, NGOs, etc., and this thesis could contribute to the body of literature documenting such uses.

METHODS

I) Study area and base grid

Since Zonation requires raster files as inputs, we needed a template for the rasterization of fishing effort and bird distribution. We used a polygon grid shapefile created by SPEA's marine department for coastal studies. Its coordinate system is WGS84 and its cell size is exactly 0.0416763139613325 decimal degrees, approaching 4x4km. Other at-sea survey studies of various scales have grids ranging from 1x1km, 2x2km, 6x6 km to 10x10 km[6,47,48], but we settled on 4x4km since it is a common grid size for SPEA projects and for environmental data rasters as well[49].

We imported the data from at-sea surveys into ArcGIS and displayed the geographical points. Some points from the very first month of the data collection campaign, in January 2020, were excluded since they were beyond the trajectory that was systematically used throughout the rest of the campaign. Based on the overall distribution of the sampling effort, we selected the MARPRO grid cells that would create the study area containing those points and serve as a template for the rest of the analyses (Figure 2).

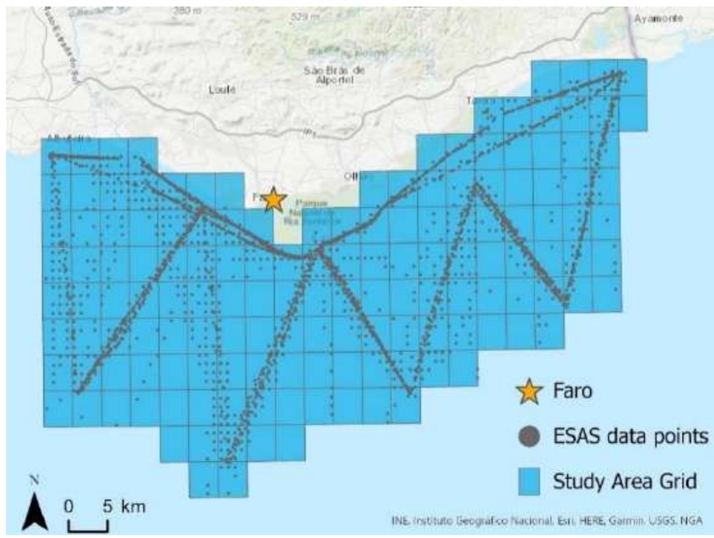


Figure 2: Data points from at-sea ESAS surveys and study area template grid.

II) Bird distribution

1. ESAS protocol

Data on seabird distribution and abundance has been collected from the study area in the context of LIFE Ilhas Barreira since January 2020, during monthly at-sea surveys. Some monthly surveys had to be cancelled due to the COVID-19 pandemic, however, between 2020 and 2021 we were able to obtain representative samples for all 12 months (January 2020, June to December 2020, February to May 2021). The methodology used is based on the ESAS (European Seabirds at Sea) protocol, derived from Tasker et al. (1984) recommendations[50,51]. This standardized approach and format makes it possible to share the collected information on the ESAS database, and compare results with those of other surveys, including from other countries in the same species' ranges.

Each census lasted 2 to 3 days, depending on daytime length. Data was collected by a minimum of two observers onboard a pleasure craft. The vessel sailed in a pre-defined zig-zagging transect along the coast line, from Albufeira to Villa Real de Santo António, up to 15 nautical miles from shore. Observers focused

on one side of the boat, which was chosen either at random or for best visibility conditions (depending on sun glare, sail position…). Attention was given to a 300m wide transect running parallel to ship course. The transect was divided into distance bands (A= 0-50 m, B= <50-100 m, C= <100-200 m, D =<200-300 m, E = >300 m), to later allow corrections for missed individuals at greater distances (Figure 3).
All birds on the water were identified, counted, and the distance band in which they were spotted in was recorded. Birds in flight, on the other hand, were only recorded using periodic snapshots, so as not to count the same individuals twice and over-estimate their density. The birds were only considered within transect if they were visible at the time of the snapshot. The snapshot interval is determined by vessel speed and the distance ahead of the vessel that is covered during the snapshot, as described by Johansen et al. (2015)[52]. At the typical cruising speed, we used 60 seconds intervals. For this project, only data on birds observed within the 300 m transect were used.
Recording of the observations was made using the CyberTracker software on an electronic tablet (https://www.cybertracker.org/). Besides making data entry easy, it also automatically recorded geographical coordinates every 5 minutes, and the calculated kilometers travelled and area surveyed during each 5-minute period. Individual count events were grouped by their corresponding 5-minute period and observation point coordinates.

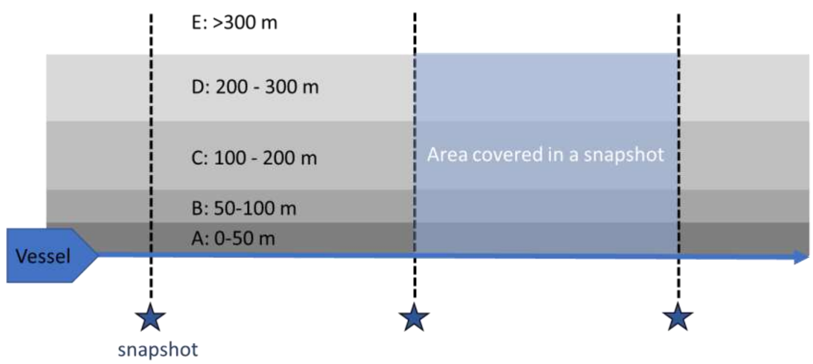


Figure 3: ESAS survey design

2. Correction for distance

We corrected the counts of birds on the water to account for their decreasing detectability with increasing distance from the vessel and prevent underestimation of their density[51]. Species were grouped in small, medium and large size categories. Using the {Distance} package in *R* (Miller et al., 2019, R Core Team 2021), we fitted the detection probability function to test the effect of distance on detectability of birds in different size groups (Appendix 1).
No effect of distance was apparent on detectability of large species.
For medium and small species, the detection function indicated a drop in detectability with distance. A correction factor x, as described by Pollock et al. (2000), was applied to their account for the proportion of birds that were not detected within the 300m transect area[54].

The correction factor for medium species was calculated using the following equation:
$x = \frac{(nA + nB) * 3}{nA + nB + nC + nD}$, where *nA* , *nB* , *nC* and *nD* is the total number of birds counted in each band (A - <50m, B - 51 to 100m, C - 101 to 200 and D - 201 to 300m), and 3 is the ratio between the total area of

bands A + B + C + D and the total area of bands A + B. This function assumes that detection within 100m from the vessel is perfect.
For small species, a decrease in detectability was noticeable starting from the 50-100m distance band, so the correction factor formula was corrected accordingly to $x = \frac{nA * 6}{nA + nB + nC + nD}$.
These correction factors were calculated and applied separately for birds that were counted in sea state 4 and above, and sea state 3 and below on the Beaufort scale.

3. Modelling of bird distribution

Once we obtained the corrected number of birds of each species for each observation point, we distributed the observation data to each grid cell of the study area, for each survey month. We transformed the resulting polygon grid dataframe to a points dataframe, to which we added columns for bathymetry and distance to land. SPEA provided a raster from which we extracted bathymetry, and shapefile of the Portuguese mainland with which we calculated distance to land using the {sf} package in R[55].

The next step was to model their density distribution in the study area. Close to 30 species of seabirds were recorded during the at-sea surveys, of which we selected a subset for density modelling based on abundance of observations and relevance to conservation objectives (Table 1; Appendix 2).
Yellow-legged gulls (*Larus michahellis*) and Lesser black-backed gulls (*Larus fuscus*) are abundant in the area and were modelled but ultimately removed from the spatial prioritization analysis since their conservation value is relatively low. In fact, there is debate about the benefits of culling *L. michahellis* to decrease their impact on breeding success and number of nesting pairs of *L. audouinii* in small and isolated colonies [56].

Common name	Scientific name	IUCN status	Local status	Weight
Balearic shearwater	*Puffinus mauretanicus*	CR, decreasing		5
Audouin's gull	*Larus audouinii*	VU	Increasing; small range	3.5
Cory's shearwater	*Puffinus borealis*	LC	VU, decreasing	3
Mediterranean gull	*Larus melanocephalus*	LC, decreasing		1.5
Northern gannet	*Morus bassanus*	LC, increasing		1
Great skua	*Catharacta skua*	LC		1
Little tern	*Sternula albifrons*	LC, decreasing	VU	3
Sandwich tern	*Thalasseus sandvicensis*	LC	NT	2
Razorbill	*Alca torda*	NT, decreasing		2.5

Table 1: Conservation status and weight given to biodiversity feature species and Species of Special Interest (SSI). CR = Critically Endangered, VU = Vulnerable, NT = Near Threatened, LC = Least Concerned.

We modelled seabird density and distribution using Hurdle and Zero-inflated models, similar to the approach taken by McGowan et al. (2013) and in another SPEA project[12,49].
Both Hurdle and Zero-inflated models are meant for count data with an excess of zeros and overdispersion. In our case, excess of zeros comes from continuously monitoring all species throughout the transects, and overdispersion comes from observations varying from a few solitary individuals to flocks of hundreds.

Hurdle models are two-part models that specify one process for zero counts and another process for positive counts. The first part of the model is typically a binomial (binary logistic regression) model. This part predicts the presence-absence of birds for an observation point. If the outcome indicates presence, then the second part of the model fits positive counts. The second part of the model is usually a zero-truncated Poisson or Negative Binomial model (HP or HNB).
Zero-inflated models are similar except they are a mixture distribution of the two components: binomial, and Poisson or Negative Binomial (ZIP or ZINB). Zero counts can be predicted by both parts of the models, and may represent "structural zeros" (true absence of birds) and "sampling" or "false" zeros (detection bias). ZINB & HNB are used when overdispersion is particularly high [57,58].

We used the {pscl} package available in *R* (R Core Team 2021) to test the fit of the four different model variations for each species[58]. Variables used in the modeling process were latitude, longitude, distance to land, bathymetry, and phenological period. Distance to land and bathymetry were previously found to be some of most important variables for predicting seabirds species distribution in Portugal[24,49]. Log(Area surveyed km^2) was used as an offset variable, as vessel speed was not perfectly consistent and therefore the area covered during each 5-minute observations grouping varied slightly. Timing of phenological periods (pre-breeding, breeding, post-breeding and wintering) for each species was based off of publications by Catry *et al.* (2010) and Meirinho et al. (2014) (Table 2)[36,59]. Periods with less than 10 observations were excluded from analysis and modelling (Appendix 3).
Two tern species (*Sternula albifrons* and *Thalasseus sandvicensis*) and Razorbills (*Alca torda*) could not be successfully modelled due to too few observations and were therefore included in the conservation prioritization process using a different approach, mentioned further (Section IV.4.i; Appendix 4).

Common name	Scientific name	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Balearic shearwater	*Puffinus mauretanicus*	Breeding	Breeding	Breeding	Breeding	Breeding	Breeding	Post-breeding	Wintering	Wintering	Pre-breeding	Pre-breeding	Breeding
Audouin's gull	*Larus audouinii*	Wintering	Pre-breeding	Breeding	Breeding	Breeding	Breeding	Breeding	Breeding	Breeding	Breeding	Post-breeding	Wintering
Cory's shearwater	*Puffinus borealis*	Wintering	Pre-breeding	Pre-breeding	Breeding	Breeding	Breeding	Breeding	Breeding	Breeding	Breeding	Post-breeding	Wintering
Mediterranean gull	*Larus melanocephalus*	Wintering	Pre-breeding	Pre-breeding	Breeding	Breeding	Post-breeding	Post-breeding	Post-breeding	Post-breeding	Post-breeding	Post-breeding	Wintering
Northern gannet	*Morus bassanus*	Pre-breeding	Pre-breeding	Breeding	Breeding	Breeding	Breeding	Breeding	Breeding	Post-breeding	Post-breeding	Wintering	Wintering
Great skua	*Catharacta skua*	Wintering	Wintering	Pre-breeding	Pre-breeding	Breeding	Breeding	Breeding	Breeding	Breeding	Post-breeding	Post-breeding	Wintering
Little tern	*Sternula albifrons*	Wintering	Wintering	Pre-breeding	Breeding	Breeding	Breeding	Breeding	Post-breeding	Wintering	Wintering	Wintering	Wintering
Sandwich tern	*Thalasseus sandvicensis*	Wintering	Wintering	Wintering	Pre-breeding	Breeding	Breeding	Breeding	Breeding	Post-breeding	Post-breeding	Wintering	Wintering
Razorbill	*Alca torda*	Wintering	Wintering	Pre-breeding	Pre-breeding	Breeding	Breeding	Breeding	Breeding	Post-breeding	Post-breeding	Wintering	Wintering

Table 2: Phenological periods of study species.

The models were at first run with all variables included. We then excluded variables with a *p*-value > 0.05 to produce several reduced models. However, based on Wilks' likelihood-ratio tests, none of the reduced models were a significantly better fit, and therefore all variables were maintained for all final models. For each species, the 4 model types (hurdle, hurdle with negative binomial regression, zero-inflated, zero-inflated with negative binomial regression) were compared using Akaike Information Criterion (AIC) values, log-likehood, hanging rootograms, and plots of observed densities overlayed on predicted density rasters generated by the models (Appendices 5 & 6)[60]. The model with the lowest AIC / highest log-likelihood values was not always chosen as final model; the interpretation of rootograms, residual plots and predicted density distribution maps sometimes led us to select a different model type.

The final models assigned a predicted abundance of birds for each 4x4 km grid cell (equivalent to density expressed in units of birds/16km^2), during phenological period with sufficient observations. For each species, we saved prediction grids in comma-separated-value format, from which we created rasters in ASCII format in R Studio using the {raster} package [61–63].

III) Fishing effort

1. Questionnaire data

Commercial fishers operating in the Algarve were given questionnaires by researchers from the University of Algarve/Centro de Ciências do Mar (UAlg/CCMAR) and SPEA employees. The questionnaire was sent several times throughout the year to collect information on fishing effort during the 3 months leading up to the questionnaire's answer date. The data represents fishing effort from December 2019 to November 2020. The form included the name of the fishing vessel, the number of days spent at sea per week, the number of hauls or casts per day, and the gear type used. The quasi-totality of entries indicated the use of either gill nets, trammel nets or purse seine nets. Fishers also named cities or landmarks to indicate the western and eastern limits of the fishing ground they used, and their minimum and maximum operating distance from shore. In total, 394 entries were received, although a few had to be excluded due to missing information.

2. Rasterization of fishing effort

From the questionnaire information, individual fishing zones could be defined as polygons with descriptions of the location of their NW, NE, SE and SW corners. We used ArcGIS Pro 2.7.1 with ESRI's World Topographic Map to find and assign coordinates in the WGS 1984 geographical system to these corners, as described by the fishers. A shapefile of the fishing zones polygons was generated from the corners coordinates in R Studio, and polygons were re-manipulated in ArcGIS to more accurately match the coastline. Fishing effort was joined to the shapefile's attribute table. *Total fishing effort* for each fishing zone was calculated using the following equation, with the reasoning that there are on average 12 weeks in each 3 months period: $Days\ at\ sea\ per\ week\ \times Number\ of\ hauls\ per\ day\ \times\ 12.$
Effort per km^2 was then calculated as $\frac{Total\ Effort}{Zone\ Area}$ for each polygon, to standardize effort across all fishing zones. Evidently, we had to assume that effort is evenly distributed across the fishing area.
We created subsets of the shapefile for each fishing gear and season combination. Using the *Spatial Join* tool, we extracted the sum of *Effort per km^2* of overlapping polygons to a point grid generated from the study area shapefile. Rasters were created from these point grids, with each cell value representing the total *Effort per km^2* for that cell, in that season and gear combination. The cell size was set to match the MARPRO and study area grids.

IV) Conservation prioritization

1. Choice of software

Several softwares are available for spatial conservation prioritization analysis. Two of the most commonly used ones are Zonation and Marxan and they differ in several ways. Marxan was developed specifically for marine environments, but its basic approach is to minimize cost while meeting pre-determined conservation targets and its analysis is based on stochastic optimization. Meanwhile, Zonation uses deterministic computation to maximize biodiversity benefits. It uses rasters rather than polygons as inputs, and can process not just absence/presence data but also density prediction [7]. Additionally, Zonation has more methods for including connectivity and population viability, and allows the user to simultaneously investigate and compare different levels of landscape protection [64]. Overall these differences result in Zonation having a higher return on conservation investment, on top of being deemed more user-friendly [7]. Therefore, we chose Zonation as our spatial conservation prioritization software. We relied on the extensive and detailed manual of the latest version of the software [65].

2. General process

Zonation starts with the full landscape, and attributes a conservation priority ranking value to each cell (between 1 and 0, 1 being highest priority) based on the biodiversity features it contains. With each round of the process, the Zonation meta-algorithm uses a cell removal rule and other parameters to determine which cell(s) represent the lowest marginal loss in terms of conservation value and representation of features, and removes them from the landscape.

The concepts of biodiversity loss and conservation value can be defined in different ways within Zonation. The two most commonly used cell removal rules are the additive benefit function formulation (ABF) and core-area zonation (CAZ). Put simply, ABF tends to prioritize areas with high species richness, while CAZ grants more value to areas with high occurrence of rare or otherwise important species[7].

After each iteration of the algorithm, the conservation value of each cell is recalculated and the process repeats until no cells are left. Zonation outputs then allow us to see which cells were retained the longest during the removal process, and therefore which cells represent the areas with highest conservation priority. Zonation can also show the remaining fraction of biodiversity features in the retained landscape after each cell removal round.

3. Running Zonation

i. Batch files

In order to be able to launch a Zonation run, a batch file is created. This file is written in a text editor software such as Notepad, and saved with a *.bat* extension. The batch file, also called project file, calls Zonation and indicates the path and names of the input and settings files, as well as an output path and a label that will be included in the different outputs' names. The batch file also specifies some parameters for uncertainty analysis, distribution smoothing, and dispersal kernel width, which were not used in this project and therefore dummy values were used.

A single project file can contain multiple lines, called instances, that can each specify a different set of inputs, setting files or output paths and be run simultaneously in Zonation.

Furthermore, batch files, features files and settings files can be edited directly from within the Zonation Graphical User Interface (GUI). However, during our experimentation with Zonation, we found that creating separate batch files for each combination of inputs and settings was useful for organizing and keeping track of the different variations and their outputs.

ii. Run settings file

This is a file written in a text editor and saved with a *.dat* extension, that describes settings for the Zonation run. If some settings that are required for a basic run are not specified, they will be assigned to their default.

Some of the settings that we specified during our runs were the cell removal rule (indicated by the line *cell removal = 1* for ABF, and *cell removal = 2* for CAZ) and the warp factor which was set to 1, meaning that for each iteration of the spatial analysis, once cell was removed at a time.

More settings were introduced step by step, such as edge removal (activated by writing the line *edge removal = 1*) which ensures that for each iteration, only cells at the external edges of the landscape can be removed, and therefore introduces some connectivity. Another connectivity setting that was tested was the Boundary Length Penalty (BLP), of which we attributed a 0.01 value (activated by writing the line *BLP = 0.01).* BLP limits the perimeter to area ratio of the priority landscape, therefore making it slightly more compact and cohesive. The value of 0.01 is standard in Zonation, but may be experimented with (Moilanen et al., 2014, section 5.1.2) [65,66].

We also gradually introduced optional input files, which we describe later in Section IV.4, by activating their use and specifying their path.

Although run setting files can be edited directly from within the Zonation Graphical User Interface (GUI), we created different setting files for each combination of parameters and optional files to keep a better track of the steps taken in our analysis.

iii. Biodiversity features list file and biodiversity feature map files

The biodiversity feature list file is a *.spp* file that is also created with Notepad. It indicates the path to the biodiversity feature map files, such as the seabird density distribution rasters.

All rasters listed in this file must have the same cell size and number of rows and columns, and include an extra row and column on either side filled with NA values in order for the project to run.

Despite its name, the biodiversity feature list file can actually include a wide variety of rasters related to the overall conservation value of the planning units, for example: ecosystem type, habitat suitability or degradation status, alternative land uses, pollutant absence/presence or concentration, and other threats and factors.

Each row of the feature list file contains a feature map's path in the sixth column, while previous columns specify various parameters, the first one being the weight of that feature, indicating its relative conservation value to the others. The next three columns are for dispersal kernel and Boundary Quality Penalty (BQP) connectivity parameters, which are not relevant for our project, and we therefore used a dummy value of 0. The fifth column, when using ABF, is the ABF exponent and controls how sensitive to habitat loss a feature is, but since we did not have precise information on this, we attributed all features a commonly found empirical value of 0.25, as suggested by the Zonation v.4 manual (Moilanen et al., 2014, p.107).

For the initial basic run, we inputted the bird density rasters as biodiversity features. The default weight for a feature is 1, but it may be increased to emphasize features of particular interest, such as endemic, rare or endangered species. There is no standard way of weighing features: complex calculations can be used, but subjective valuation is also common and valid, for example basing the weight of species on their IUCN conservation status [67,68]. We took the latter approach, weighing species based on their red list status, from a scale of 1 to 5 (Table 1). We divided the total weight of each species by the number of different phenological period layers it had, and assigned the resulting weight to each layer.

In later variations of the analysis, we also included fishing effort into the biodiversity feature list file. Fishing simultaneously represents a threat to seabirds, and an important socio-economic activity.
If fishing were to be strictly considered as a threat from which seabirds need to be protected, and the objectives of this project were to create an MPA which strongly restricts fishing activity, especially in areas with high abundance and diversity of seabirds, then fishing effort could have been treated as any other feature and given strong positive weights. This would have given cells with high fishing effort a higher priority ranking, and kept them longer in the cell removal process, so that the tentative MPA boundaries may overlap with currently significant fishing grounds.

Instead, the approach we have taken is to consider the presence of fishing as "competing land use", and to include it as an opportunity cost in the feature list file. Cost features are given negative weights, to decrease the priority ranking of the cells they occur in [44,46]. A cost layer can also be used as an optional raster file input. This can represent direct economic cost of implementing a protected area or restricting activities, or a proxy, such as overall fishing effort

However, incorporating fishing's opportunity cost into the feature list file gave us more flexibility, as weights can be manipulated. For instance, while we could not obtain precise location of bycatch incidents through the fishing effort questionnaires, we could still observe the number of reported incidents for each gear type. We standardized this by the total fishing effort for each gear and concluded that although the differences were subtle, trammel nets had the highest incidence of bycatch, followed by gill nets and finally purse seine nets (Table 3). By giving a smaller value to the negative weight to fishing gear with higher bycatch incidence, we still acknowledged their socio-economic importance by representing them as an opportunity cost, but conservation-wise, we were less "forgiving" by slightly reducing the likelihood of the cells containing that fishing activity to be excluded from the landscape early on than if it had a lower weight. Through experimenting with different species to fishing weight ratios, this method allows us to reach a compromise between giving high priority to sites that have high conservation value, and respecting socio-economic needs of stakeholders [69].

Gear type	Bycatch incidents	Total effort (hauls)	Seabird CPUE	Weight of feature
Gill	14	5502	0.25	-0.75
Purse seine	5	3564	0.14	-0.86
Trammel	22	7002	0.31	-0.69

Table 3: Summary of seabird bycatch and total effort reported by fishers in questionnaires, from December 2019 – November 2020, catch per unit effort (CPUE) of seabirds, and consequent weight of fishing features in the feature list file.

4. Optional files

i. SSI

The species mentioned earlier which had too few observations to be modelled across the study area were treated as "Special Species of Interest" (SSI), a means of incorporating point occurrence data into Zonation's conservation prioritization analysis.

SSI files were created for each of the 3 species: *S. albifrons, T. sandvicensis* and *A. torda*.

An SSI file is a text file that contains 3 columns: latitude, longitude, and count value for each observation location of that species. An SSI list file refers to the SSI files and indicates their respective weights. The option of using the SSI list file can then be activated in the settings file, by writing *use SSI = 1* , and the name and location of the SSI list file in the line below it.

ii. Group file

A group file is a simple *.txt* file containing 5 columns with integer values. This file allows features to be grouped together in various ways. The first column is for creating output groups. Zonation outputs mean, minimum, and maximum representation curves for each output group. This could be done manually from the standard representation curves, but creating groups in advance makes interpretation of results more efficient when the outcome for different features needs to be assessed separately. We grouped the different phenological periods for each species, and grouped all fishing effort together. Features to be grouped together are given the same integer in the first column of the group file. Each row in the group file represents a feature from the feature list file, so both files must contain the same number of rows and follow the same order. The other columns are for different grouping operations, which we did not use and therefore filled with -1 as a dummy value.

iii. Hierarchical Removal Mask file

A hierarchical removal mask is a raster which influences the priority rank of cells outside of feature maps, connectivity or other settings. Cells are attributed an integer value – the higher the value, the longer it will be kept in the cell removal process and vice versa. This can serve several purposes, one of which is to ensure that areas which are already protected or recognized for their conservation value are included in the top fraction of the landscape [44].

Since the northern edge of our study area overlaps with the Ria Formosa SPA (PTZPE0017), IBA (PT033) and Natural Park, as well as the Ria Formosa/Castro Marim SCI (PTCON0013), the Castro Marim Ramsar site and Natural reserve, and the Marine Ria Formosa IBA (PTM04), we wanted to test the effect of giving higher priority to the cells which overlapped with them[28].

Using ArcGIS and the shapefiles of the protected areas and our study area, we calculated the overlap in km^2 between the group of areas of recognized conservation value and each grid cell of our study area. This was converted to a raster where cells with <1% overlap were given a value of 0, cells with 1-50% overlap had a value of 1, and cells with >50% overlap had a value of 2 (Appendix 7). The use of the hierarchical removal mask was activated and its path specified in the run settings file.

5. Analysis variants

Zonation has a heuristic approach to conservation prioritization [44]. There are few strict rules or guidelines in the user manual and other documents produced by the creators of the software. They emphasize the need for every project manager or researcher to explore their own dataset and circumstances to decide which combination of features and parameters works best for their objective, while keeping in mind that there is no “perfect solution” [7,65].

We therefore conducted spatial prioritization analysis in incremental steps, adding components one at a time, and tested each step for both the ABF and CAZ cell removal rules. A summary list of the different combinations that were tested can be found in Appendix 8.

We started with only the species’ density distribution as biodiversity features, without fishing or other factors, as recommended by McGowan et al. (2013) and Moilanen et al. (2014).

We then experimented with a few different values for the Boundary Length Penalty (BLP), finally settling at 0.01, then included edge removal. The next step was to test the use of SSI in the analysis, with the original weight of the species at first (Table 1), then with 1/10th of those values to offset the high influence SSI files have.

In the next step, we incorporated fishing effort. We experimented with the relative weights of fishing effort in the analysis. We did this by testing different versions of the biodiversity feature file, in which the weights of bird distribution layers were kept as before, multiplied by a factor of 2, and multiplied by a factor of 4.

Finally, we added the hierarchical mask file, and also repeated the analysis with the different versions of the biodiversity files, as we did with fishing effort, to change the importance of the mask relative to the species’ density distribution.

RESULTS

I) Mapping of predicted bird abundance

1. Overall diversity and abundance

Over the 12 months of sampling, close to 30 different species were seen in-transect in the study area (Appendix 2). The most abundant species by far was the Northern gannet (*Morus bassanus*), followed by Cory's shearwater, Audouin's gull and the Yellow-legged gull. Northern gannets were present all year-round, as were Great skuas (Appendix 3). Observations of Cory's shearwater, Balearic shearwater and Audouin's gull were mostly limited to their breeding period. On the other hand, Mediterranean gulls were most abundant during their post-breeding and wintering period.
Little terns, Sandwich terns and Razorbills only had 21, 11 and 20 observed individuals respectively, throughout the entire study period, which is why they had to be excluded from our initial plan of modeling their distribution as well.
L. michahellis and other unidentified *Laridae sp.* were an abundant group, accounting for 1358 individuals in total. As for rare sightings, these included a few other shearwater species (Manx, Sooty and Great), tern species (Common and sooty), Black headed-gulls, Black-legged kittiwakes and Atlantic puffins.

2. Density distribution modelling

The prediction maps show that while for each species, while the density fluctuated, the distribution pattern itself tended to stay fairly consistent throughout the phenological periods.
There were, however, vast inter-species differences in both the distribution patterns and the scale of bird abundance. All of the abundance distribution maps and the summaries of predicted density values can be found in appendices 5 and 9, respectively.

As expected, some of the highest abundance predictions were made for the Northern gannet *(Morus bassanus)*, with peak numbers reaching over 80 individuals per grid cell, and average density ranging from 0.96 to 5.53 individuals per square kilometer (Appendix 6). Post breeding and wintering density predictions were very similar to one another, while pre-breeding abundance had the lowest estimates of all.

Throughout the year, the distribution pattern was characterized by two higher density zones, at western and eastern ends of the study area (Figure 4). The center portion had slightly elevated predicted density close to the coast, while the southern part of the study area, away from the shore, had lower values.

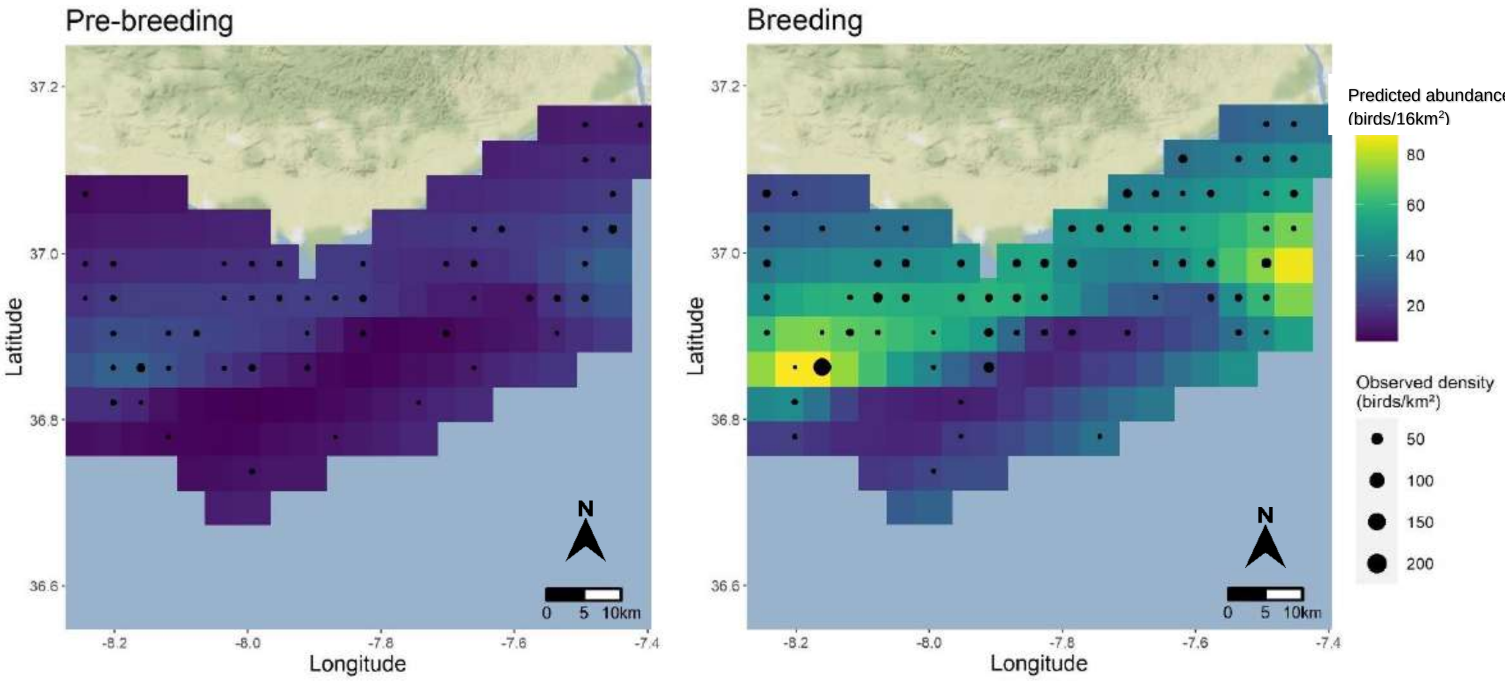


Figure 4: Predicted Northern gannet abundance maps for pre-breeding and breeding periods.

Similar to *M. bassanus,* the Great skua's pre-breeding and wintering density distribution were very similar to one another. Density was predicted to be higher during pre-breeding and breeding seasons, especially along the coastline.
The overall density of Mediterranean gulls was low throughout the area, but in the winter, there was a higher concentration of individuals in the center, away from the coastline.
The only phenological period with enough observations to model Cory's shearwater density distribution was the breeding phase, during which the species seemed to use the entire study area. However, the model we chose predicts higher densities near the southern edge of our grid, the furthest from the coastline.

Although Audouin's gull were not the most abundant species, they had some of the highest density prediction values, concentrated in a location slightly southwest of Deserta Island, where they form a colony every year (Figure 5).

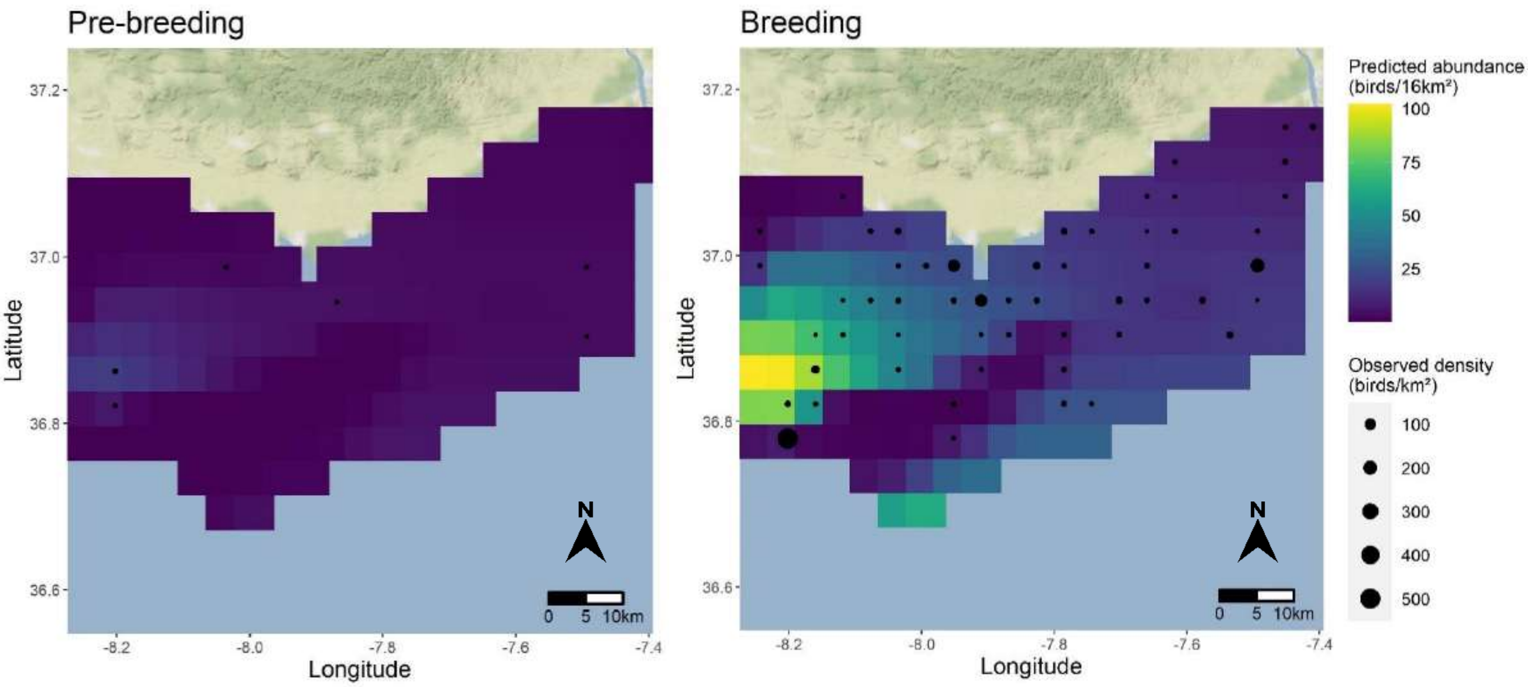


Figure 5: Predicted Audouin's gull abundance maps for pre-breeding and breeding periods.

Our other top species of interest, the Balearic shearwater, had its highest predicted density at the other end of the study area, on the eastern side (Fig. 6). Density was relatively low throughout the rest of the range, and was only slightly higher during the breeding season compared to the pre-breeding period.

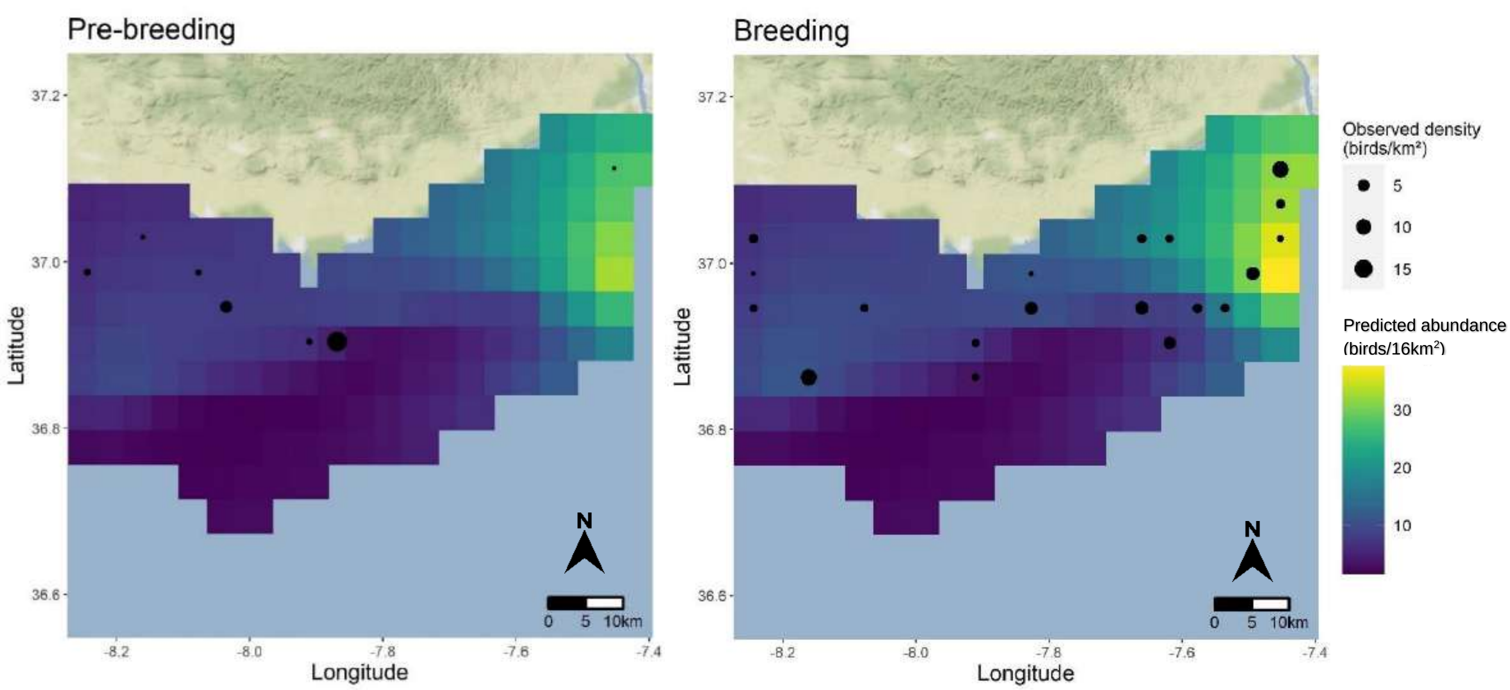
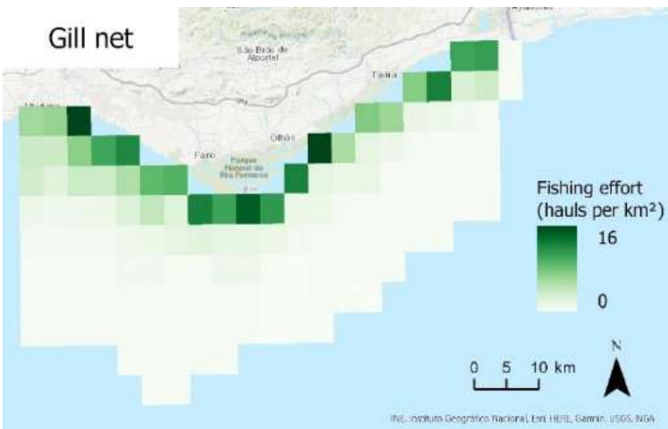


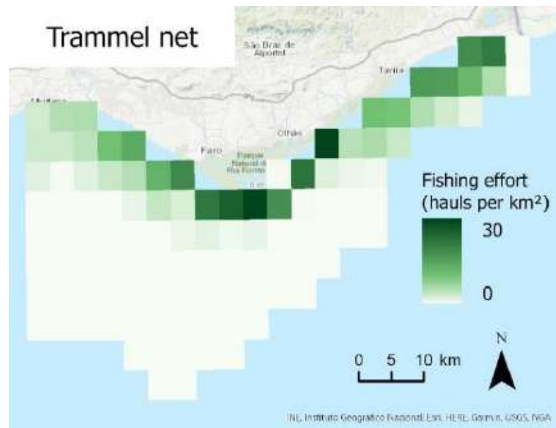
Figure 6: Predicted Balearic shearwater abundance maps for pre-breeding and breeding periods.

II) Mapping of fishing effort

Fishing range varied across seasons and gear type, but the overall fishing effort was predominantly concentrated near the coastline, with the exception of some of the grid cells directly adjacent to the shore, close to where the Ria Formosa SPA is located (Figure 7). Seasonal variations within each gear type can be seen in Appendix 10.

Trammel nets were not set as far offshore compared to the other gears, especially on the eastern half of the grid. Purse seine nets occupied the largest portion of the study area throughout the seasons, although the highest intensity effort was somewhat focused on the coast south of Faro. Meanwhile, gill net fishing effort was distributed slightly more evenly along the entire coastline.





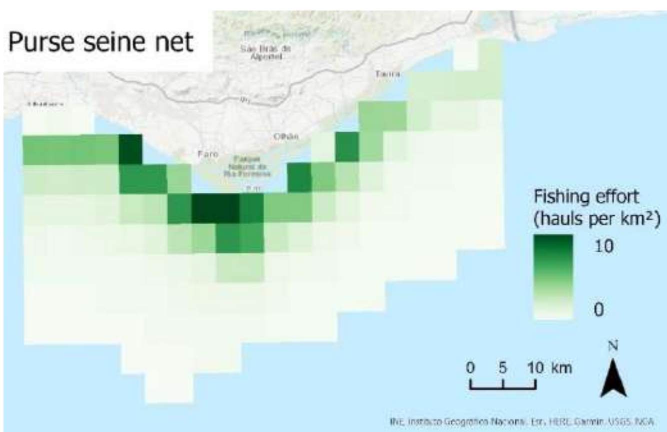


Figure 7: Fishing effort intensity within the study area, for each fishing gear type, measured in number of net hauls per km^2.
For each gear type only areas where there was recorded fishing activity are represented in the rasters, grid cells where there was no activity were left empty.

III) Spatial Conservation Prioritization analysis

We tested the different Zonation scenarios by combining different setting files, biodiversity feature files and batch files (Appendix 8). We inspected the outputs of each combination, adjusted parameters and eliminated some of the solutions based on the results.

As expected, we found that for both ABF and CAZ cell removal rules, using a BLP of 0.01 and edge removal gave us smoother, more homogenous maps of priority ranking, and were therefore kept throughout out all further analysis variants.

Including fishing effort rasters shifted a part of the top priority fraction to the cells nearest to shore, where no fishing effort occurred and therefore where no negative weight was applied.
We then increased the relative weight of the bird density distribution layers in contrast to the fishing effort rasters, leading the distribution of high conservation value cells to be re-distributed with less focus on the coastline, which fitted better our project's objectives.

At first, including the Special Species of Interest file strongly influenced the priority ranking, and resulted in more fragmented, patchy maps with some high priorities cells in the middle of otherwise low priority areas. (Figure 8). We then lowered the SSI weights, which caused the SSI's impact to drop and did not change the hierarchical cell ranking in a way that facilitated efficient priority area designation. Furthermore, the proportion of the SSI's remaining distribution dropped relatively early in the cell elimination process with this new solution (Figure 9). SSIs were therefore not maintained in further conservation prioritization processes

Similar to the SSI layer, the hierarchical mask had a strong influence on the priority ranking, also concentrating the majority of high priority cells to the northern edge, where there is overlap with existing conservation areas. This decreased the proportion of remaining biodiversity features relative to the proportion of protected landscape. The mask layer was therefore excluded from further analysis.

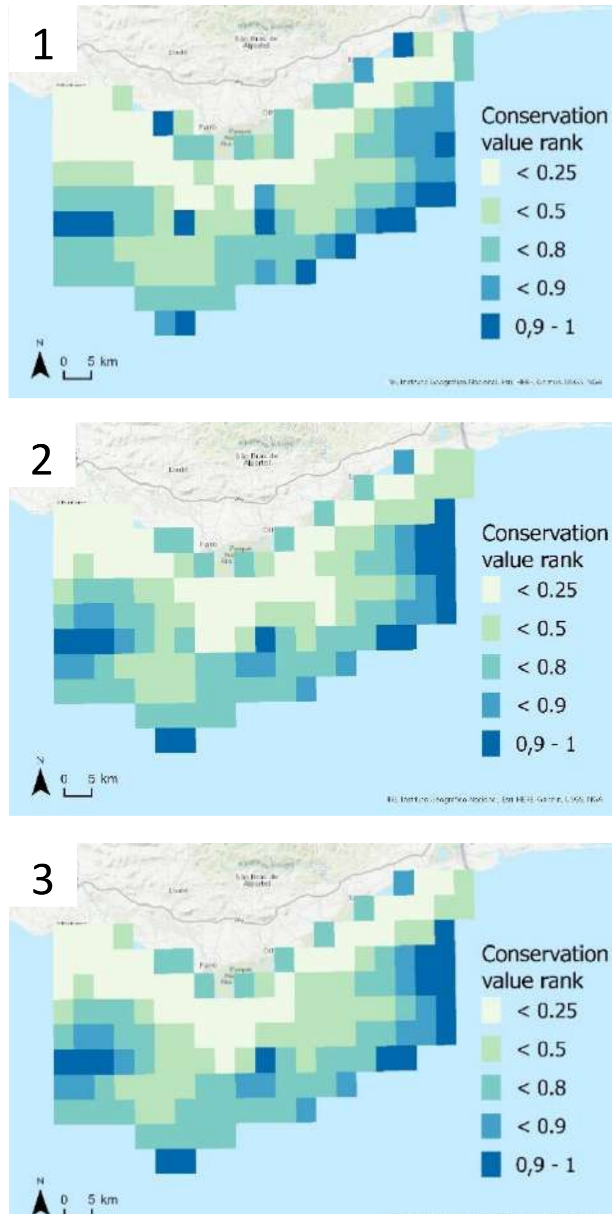


Figure 8: Different priority ranking results from 3 different scenarios using the CAZ cell removal rule. 1.Cell ranking including SSI at initial, full weight. 2.Cell ranking with SSI weights scaled down by a factor of 10. 3.Cell ranking without SSI input.

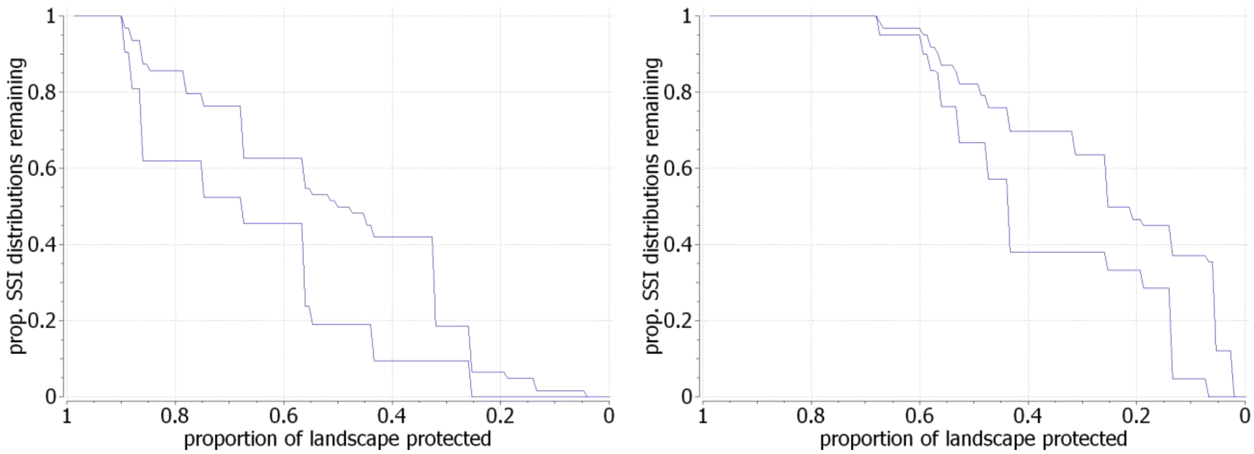


Figure 9: Proportion of remaining SSI distribution across range of protected landscape area. Left: SSI with standard basic weights (Scenario 1 from Fig.8). Right: SSI with lowered weights and increased distribution rasters weights (Scenario 2 from Fig. 8). Top line represents the average proportion for all SSI species and bottom line is the species with the lowest remaining distribution.

To summarize, on top of omitting SSIs and the hierarchical removal mask, we decided that our final solution would include edge removal, a BLP value of 0.01, fishing effort, and bird density rasters with their weights split by phenological period and multiplied by a factor of 4.

We then had to choose the cell removal rule and the top cell rank portion to be used for designating a potential protected area. We made these decisions based on the main outputs of Zonation: the priority rank maps, and the plots of remaining biodiversity feature proportion depending on the retained landscape fraction (Figures 10 & 11). These plots can be customized to include lines for specific features or groups, for the feature with the lowest or highest remaining proportion etc.

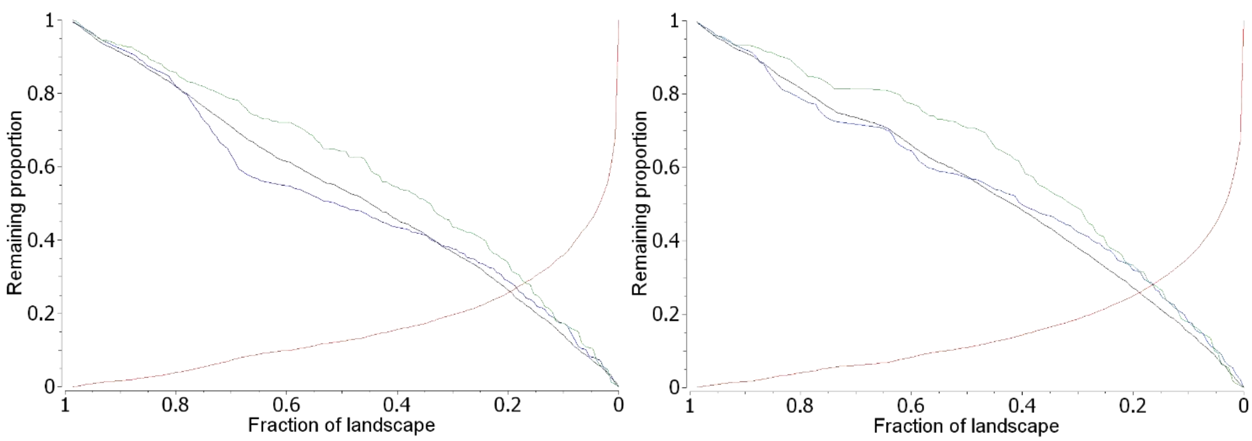


Figure 10: Remaining proportion of biodiversity features depending on the landscape fraction retained as a priority area, as calculated with the CAZ (left) and ABF (right) cell removal rules.
Blue curve: remaining proportion of P. mauretanicus. Green: remaining proportion of L. audouinii. Black: mean remaining proportion of all biodiversity features. Red: estimated average species extinction risk.

The fraction allocated to conservation may vary greatly from project to project, usually from 2 to 20%, depending on the goals and unique local circumstances[66,67].

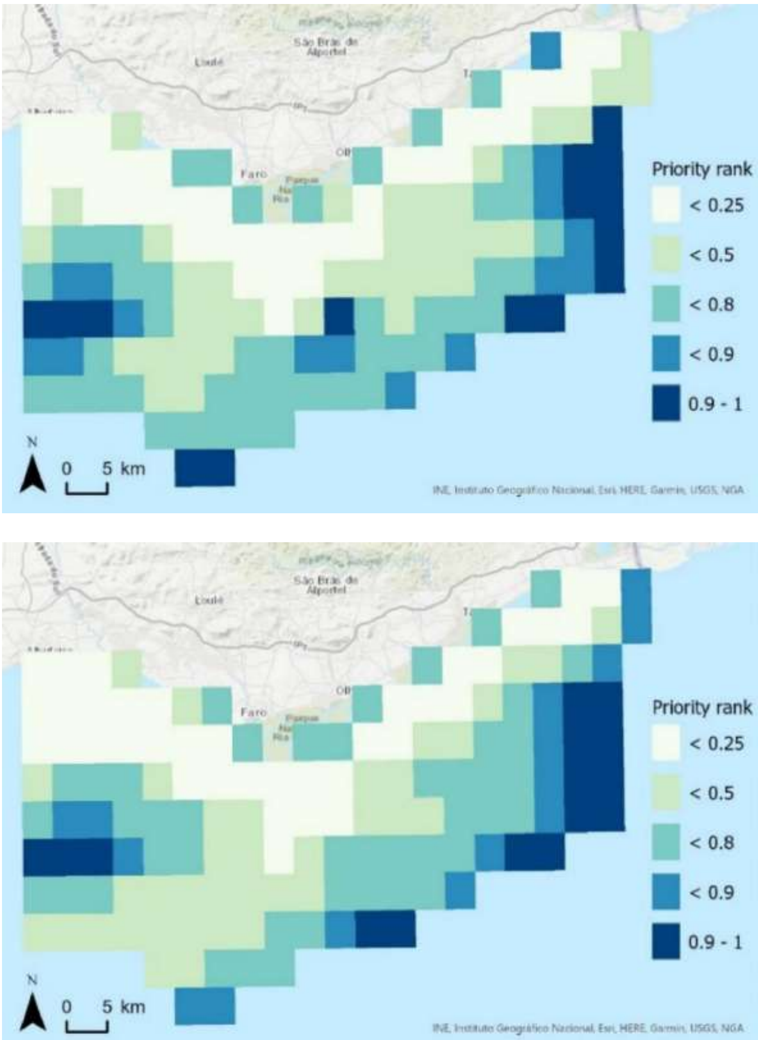


Figure 11: Priority rank map of the study area using the CAZ (top) and ABF (bottom) cell removal rules. Cells are attributed a rank value ranging from 0 to 1 by the Zonation meta-algorithm, with 1 being the highest rank.

We decided to start the conservation area outlining process using the top 20% cells. We used the highest end of the typical range because the higher priority areas are fragmented, and therefore the final retained fraction of the landscape would have to be decreased in the selection process (all top 20% would not be able to be included in the outline of our proposed new conservation area).

Starting the outlining process with a smaller top fraction would have increased fragmentation and the difficulty of creating a compact, cohesive conservation area (Fig. 11). Furthermore, studies with more conservative retained landscape fractions typically cover a much greater area than ours, where 20% of the surface is more likely to represent a difficult and costly area to implement conservation regulations [66,70].

Additionally, the average extinction risk of biodiversity features, as estimated by Zonation from the species-area relation with a default z parameter value of 0.25, increases drastically for fractions of landscape retained smaller than 0.2 (Figure 10, red curve).

During the Zonation variations testing process, depending on the combination of biodiversity features, settings and parameters, the cell removal rule yielding better results varied between CAZ and ABF. For the final solution however, we chose to base ourselves on the top 20% cells retained by the Additive Benefit Function (ABF) removal rule.

Differences between the two priority ranking distributions were subtle, but the solution provided by ABF had a more compact priority area on the eastern end of the study grid (Figure 12). Additionally, although unlike CAZ, ABF favors total species richness over rarity, we found that within our project ABF retained slightly higher proportions of Audouin’s gull and Balearic shearwater, our main species of interest, throughout the cell elimination process (Figure 10).

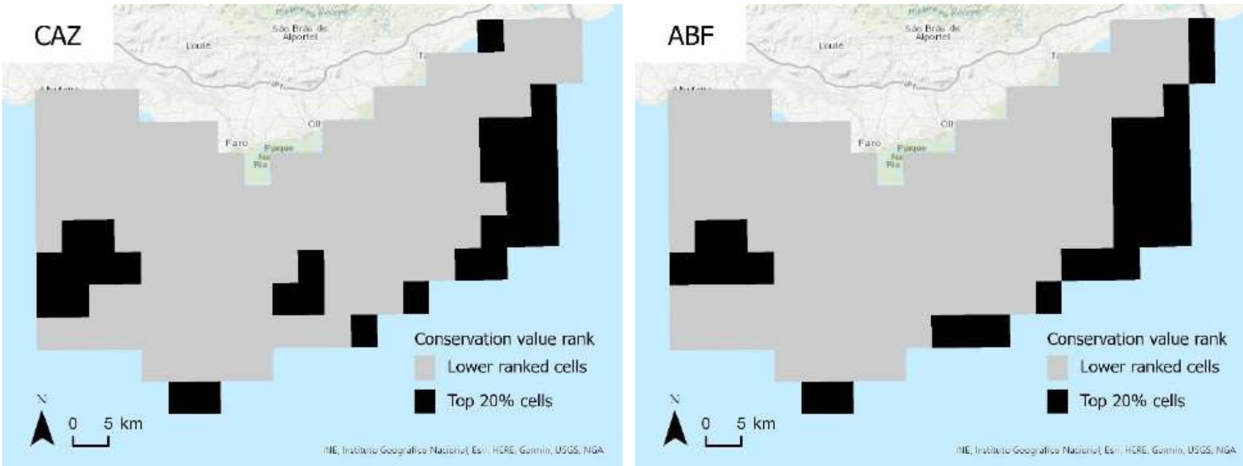


Figure 12: Areas with conservation values in the top 20% range, according to CAZ and ABF cell removal rules.

Using ABF and the previously mentioned final set of parameters, and based on the distribution of the resulting priority cell ranking, we thus came to propose the following area to be used as a conservation site (Figure 13):

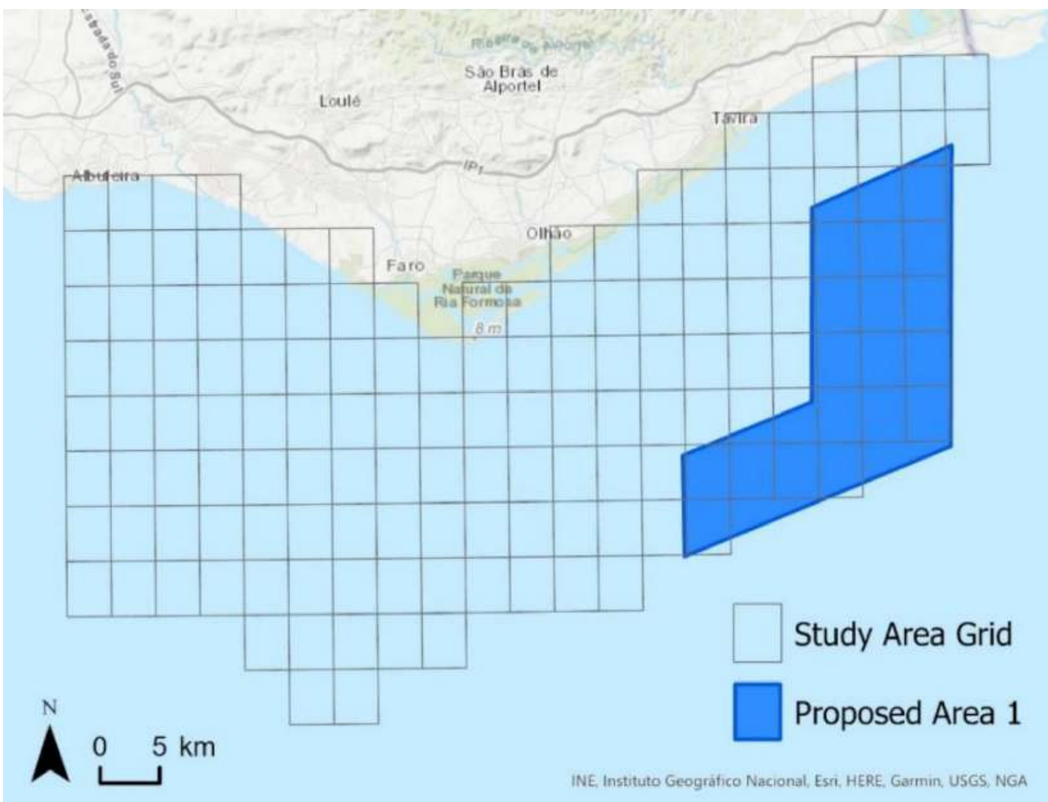


Figure 13: Proposed area for a new conservation site for seabirds off the coast of southeastern Portugal.

The site has an area of 385 km^2 and a 100 km perimeter (boundary to area ratio = 0.26). It is located on the eastern part of our grid, close to the Portugal-Spain border, and covers 15% of the 2565 km^2 study area.

An alternative design covers more of the top 20% cells identified by Zonation, along the southeastern edge of the study grid (Figure 12, Figure 14). This area is larger (535 km^2), covering around 20% of the study grid. It has a higher boundary to area ratio of 0.24. These two characteristics make this suggested alternative potentially more costly to monitor and to enforce conservation regulations within its limits.

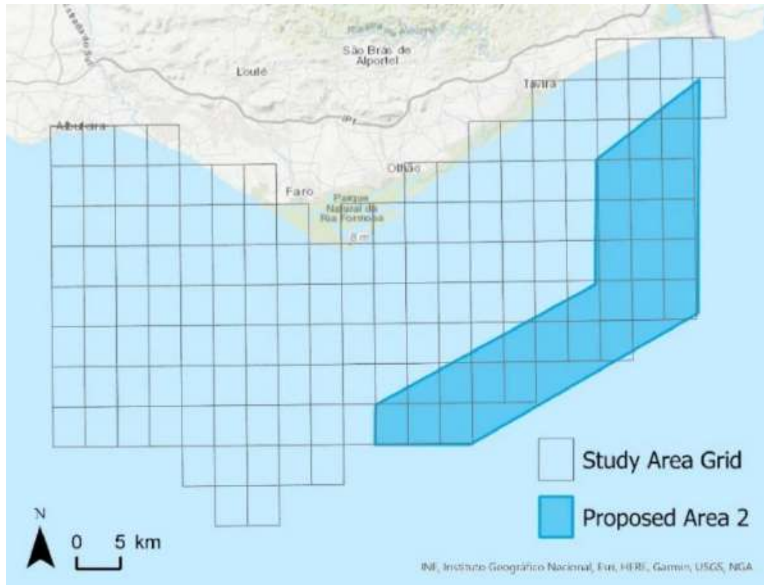


Figure 14: Alternative proposed area for a new conservation site for seabirds off the coast of southeastern Portugal.

Finally, one more area to consider is the cluster of high priority conservation cells near the western edge of the grid, which were included in the top 20% fraction of the landscape in both of the solutions made using ABF and CAZ. This cluster was not included in the final proposed conservation areas due to fragmentation and because it was smaller than the other main cluster of high priority cells. However, this area has high Audouin's gull density during the breeding period (Figure 5) and it may therefore be worthwhile to further investigate this zone.

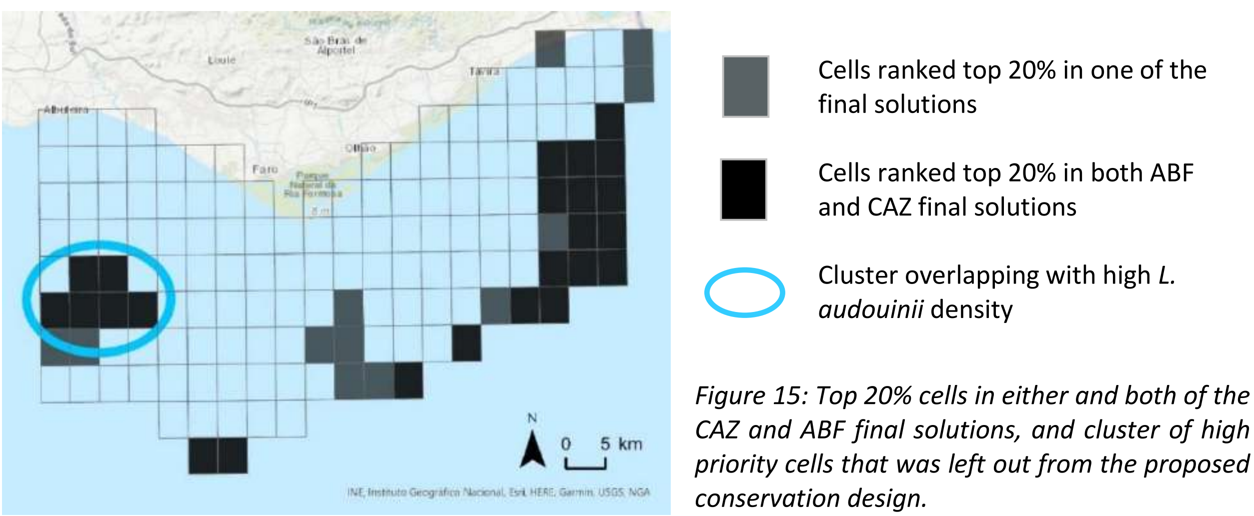


Figure 15: Top 20% cells in either and both of the CAZ and ABF final solutions, and cluster of high priority cells that was left out from the proposed conservation design.

DISCUSSION

Main findings

Our at-sea observations over the course of 12 months and subsequent modelling efforts revealed the variations in density and distribution of local seabirds across species and phenological periods. The density of Audouin's gulls was highest during the breeding season, which was expected since each year these gulls form a large breeding colony on Deserta Island that slightly overlaps with a northern section of our study area. The highest predicted densities for Audouin's gull were not in the immediate vicinity of Deserta island, but rather in the western part. Perhaps this is an attractive foraging location, as is suggested by the abundance of some other species (Northern gannet, Cory's shearwater, Appendix 5).
Meanwhile, our other main species of interest, the Balearic shearwater, had highest predicted densities in the eastern part of the study area. Its abundance was lower than some other species, but its predicted distribution pattern had a big influence on the conservation prioritization's outcome, since it had the highest weight of all biodiversity features due to its critically endangered status.

As for fishing effort, there were seasonal and gear-specific variations in distribution, but it was overall concentrated in cells which were close to the coast but not in direct contact with the shore line and the existing conservation areas of Ria Formosa. The biggest impact of incorporating fishing effort as a negatively weighted feature in the conservation prioritization process was therefore to lower the value of those coast-adjacent areas, as is evident in the detailed priority-rank maps of Figure 11.
The ABF cell removal rule provided us with better results than CAZ by a small margin. Had we included more species than the six which were modelled here, we may have chosen CAZ, as ABF tends to highlight areas with high species richness, including those of least concern, potentially to the detriment of our two main species of interest and other rare species.
The SSI and hierarchical mask layers had a strong influence on the priority ranking, resulting in fragmented maps and loss of conservation value. This is partially because of our relatively low number of biodiversity features. Additionally, the outcome of using the hierarchical map was to be expected: it puts a strong bias on the areas close to the coastline, where the IBA, SPA and SCI are found. This decreases conservation value because the predicted bird densities there are not the highest for most species, and because these cells are disconnected from other high priority areas. Furthermore, these conservation areas were not necessarily created for the species we used in this study. For example, one of their targets are Little terns, which we did not have enough observations of to include in the analysis. Nonetheless, while we did not find reason to connect this zone to a new conservation site, the fact that even without the hierarchical mask, final solutions placed these cells in the top half of priority ranking is an acknowledgement of these existing sites' value.

We reached the conclusion that the most representative and promising area was found at the eastern end of the study grid and along part of the southern edge (Figure 14). Our suggested design for a new protected area is relatively compact and conservative, but depending on the cost that the Portuguese government and other stakeholders are willing to accept, an alternative outline for a larger, more comprehensive area could be proposed as well (Figure 15).
The distribution of a few high priority cells along the southern edge of the grid hints at the possibility that if the study area had extended further offshore, we would have found a larger cluster of high conservation value cells there. Finally, we wanted to highlight a location at the western end of the grid that was left out from these two suggestions, but may be an area of high conservation value for Audouin's gull in particular.

Limitations and future research

Oppel et al. (2012) found that modelling seabird abundance or density is difficult, unlike occurrence probability, which can be best predicted with an ensemble approach[71]. Indeed, our models could be improved and built upon in several ways.

The static variables we used (bathymetry, distance to land, latitude and longitude, and phenological period) were found to be significant for most of our study species in other projects[49,72]. Previous studies also point out that using fluctuating environmental variables as explanatory variables can be difficult, since it varies based on the species and phenological period, and there are time lags[22,47,72]. Nevertheless, many studies with similar objectives incorporate fluctuating environmental covariates; we suggest enriching the models by including chlorophyll-*a* concentration, perhaps wind strength and direction, and sea-surface temperature[6,22,73]. Ideally, there would also be a long-term, multi-year monitoring plan implemented, because interannual variations in the marine environment may be in turn reflected in seabird distribution [23,68].

Additionally, some species' sample sizes were barely over our threshold of 10 observations within a phenological period, which likely affected the fit of their distribution models. However, SPEA's monthly ESAS surveys were still ongoing while this project was being finalized. The sightings from those additional months may help enrich the datasets of the rarer species.

On top of the continuation of the ESAS surveys, in January 2022, SPEA and the University of Coimbra are planning on placing approximately 110 data-logger GPS devices on Yellow-legged gulls, Little terns and Audouin's gulls nesting on Deserta Island in the Ria Formosa. This could provide us with more information on Little terns' distribution, for which we did not collect enough observations to model its density.

Tracking of individual seabirds has been used in previous SPEA projects, for example when selecting Marine IBAs[73]. Other studies have also shown that individual tracking data can complement distribution estimation from at-sea census data, especially for movement at sea and for small or isolated colonies, for birds which are active at night, and whose juveniles are difficultly distinguished from other species', all of which is the case for *L. audouinii* in the Ria Formosa[42,48,74–78]. This study may therefore give us insights on the foraging behavior behind our predicted distribution pattern of Audouin's gull, or could even shift the pattern itself, for example with higher densities close to Deserta.

Meier et al. (2015) were able to show using bio-loggers that *Puffinus mauretanicus* employed consistent foraging areas and commuting corridors in their breeding grounds in the northwestern Mediterranean, and that those strongly overlapped with existing Spanish SPAs. This is a hopeful sign that Portuguese MPAs could contribute to the regional conservation network and protect Balearic shearwaters during their pre and post-nuptial migration[36].

The work in Zonation that was conducted during this thesis could also be built upon by adding other data layers, for example Automatic Identification System (AIS) data on fishing effort. We conducted this project solely with fishing effort from questionnaires since most of the local fishing fleet consists of boats under 12 m that are not legally required to be equipped with an AIS[26,80]. However, information about larger fishing vessels would be valuable, and is potentially more efficient, since the format of our fishing effort questionnaires made it a time-consuming task to convert the information into rasters. Questionnaire data may also be subjective, imprecise or incomplete.

AIS data could also be used to track traffic from other types of vessels such as cargo ships and tourism-associated pleasure crafts, which may represent a nuisance to birds, an increase in probability of oil spills, and overall, another layer of complexity in marine spatial planning [81].

Monitoring cost could also be added as a layer, measured, for instance, as distance to Olhão, the city hosting the regional branch of the Institute for Nature Conservation and Forests (ICNF), the public authority responsible for enforcing conservation policies.
More generally speaking, Zonation tools, settings and outputs could be further explored. Because Zonation can be customized to very specific aspects of a project, it can be difficult to determine which parts of a case study's methodology can be transferred to other studies, and papers tend to omit details [82]. The software creators have a few recommendations for different management needs, but they mostly emphasize the need for every project manager or researcher to explore their own dataset and decide which combination of features and parameters works best for their objective, while keeping in mind that there is no "perfect solution" [7,65].

On a broader scale, this project could be turned into a collaboration with other research groups working with other taxa, for a more integrated approach to conservation prioritization[83]. They could, for example, provide data on sea turtles, cetaceans, pelagic and demersal fish, as the southern coast has been identified by Gomes et al. (2018) as an important area for each of these groups[43]. That being said, by being relatively easy to observe, and sensitive to environmental factors and threats, seabirds make good bio-indicators and proxies for more elusive species [20,84].

Implications for conservation action and fisheries-seabirds interactions

The relationship between the local fishing activity and the seabird populations is a complex one. For the Balearic shearwater especially, its high adult mortality is attributed to bycatch, but its breeding success is also positively influenced by fisheries discards availability [85]. The bycatch rate by itself is already beyond sustainable limits for this species, but the potential limits or bans on discards implemented in some European countries may further compromise the species' viability, even if it could have generally positive effect on fish stocks and marine ecosystems [86]. Audouin's gulls may be in direct competition for small pelagic with purse seine fisheries and are threatened by prey depletion, but they also benefit from being able to capture live fish gathered by the nets at night [39,87]
Therefore, even if the proposed conservation areas do not overlap the bulk of the fishing effort, turning them into no-take or no-go zones will not likely be feasible nor beneficial, not only because of potential tension with fishers, but also because it might influence the distribution and abundance of the birds themselves [39,76].

Some of the main conservation actions that could be taken are therefore related to monitoring and limiting bycatch of seabirds. For example, with financial support from the community and the government, vessels could switch from gill nets to fish traps, which have roughly the same catch per unit effort but are less of a bycatch risk[83]. Remote Electronic Monitoring (REM) system, which can record GPS location and footage of fishing activity, bycatch etc., are becoming suited for smaller vessels, which could help monitoring the local fisheries[83]. Implementing specialized spatio-temporal closures, modifying fishing gear, increasing net visibility and/or depth are also options that need to be further investigated [13,83]. SPEA has been working with fishers in the Berlengas Archipelago, off of Peniche on the Portuguese west coast, to better quantify bycatch and to come up with cost-efficient, easy to implement methods to repel birds, as part of the MedAves Pesca project [88,89]. A promising solution is the installation of a raptor-shaped kite onboard vessels to scare other birds away, and the results of this study could be applied to this region as well.

Finally, it goes without saying that this spatial conservation prioritization analysis is the first of many steps towards the implementation of a new MPA. The proposed areas for conservation will be reviewed and discussed with the Portuguese government, and the final design and conservation policies of the MPA should be agreed upon with the local community and stakeholders, since their acceptance of it will directly affect its effectiveness [83,90]. On the long-term, the MPA design and location might have to be re-assessed if the effects of climate change cause shifts in seabird ranges and density, which will have to be monitored closely, especially for the Balearic shearwater in which this phenomenon has already been observed [91,92].

CONCLUSION

The aims of this project were to predict seabird density and distribution at sea, map local fishing effort, and use the conservation prioritization tool Zonation to identify, based on these features, which area of the southeastern cost of Portugal would be a suitable candidate for a new MPA aimed at protecting the seabird community from at-sea threats.

We have suggested two MPA outlines based on an area with high conservation value in the south-eastern part of our study area. We have identified an additional priority area for one of our species of interest in particular, and brought up some of the shortcomings and potential future directions this research could take.

This was the very first step towards the designation and implementation of a new MPA, and while there are many more phases to come, we believe that this study could be an example of a starting point for similar small to medium scale projects. Although Zonation can indeed be applied to very large datasets and complex computations, it is also accessible to users without prior knowledge in the field of conservation prioritization.

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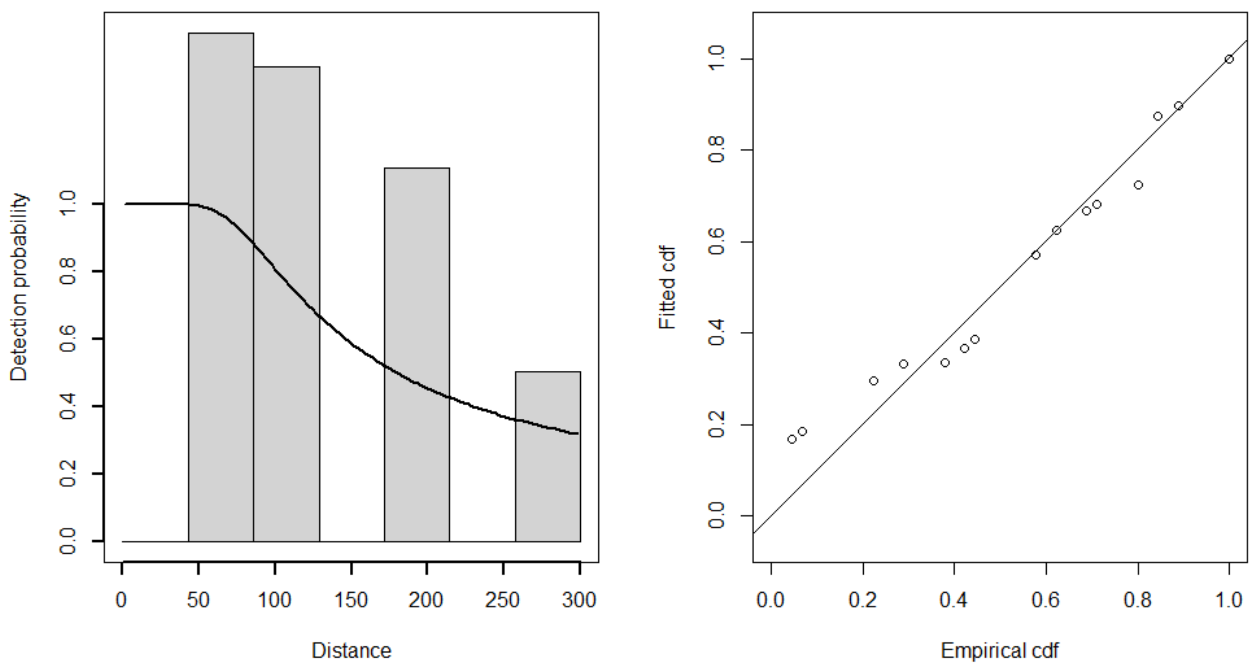
APPENDIX

APPENDIX 1: Detection probability function and goodness of fit tests.

A. Small-sized species

Left: Bird detection probability as a function of distance (m) perpendicular to the vessel.
Right: quantile-quantile (Q-Q) plot demonstrating goodness of fit of the density probability function.



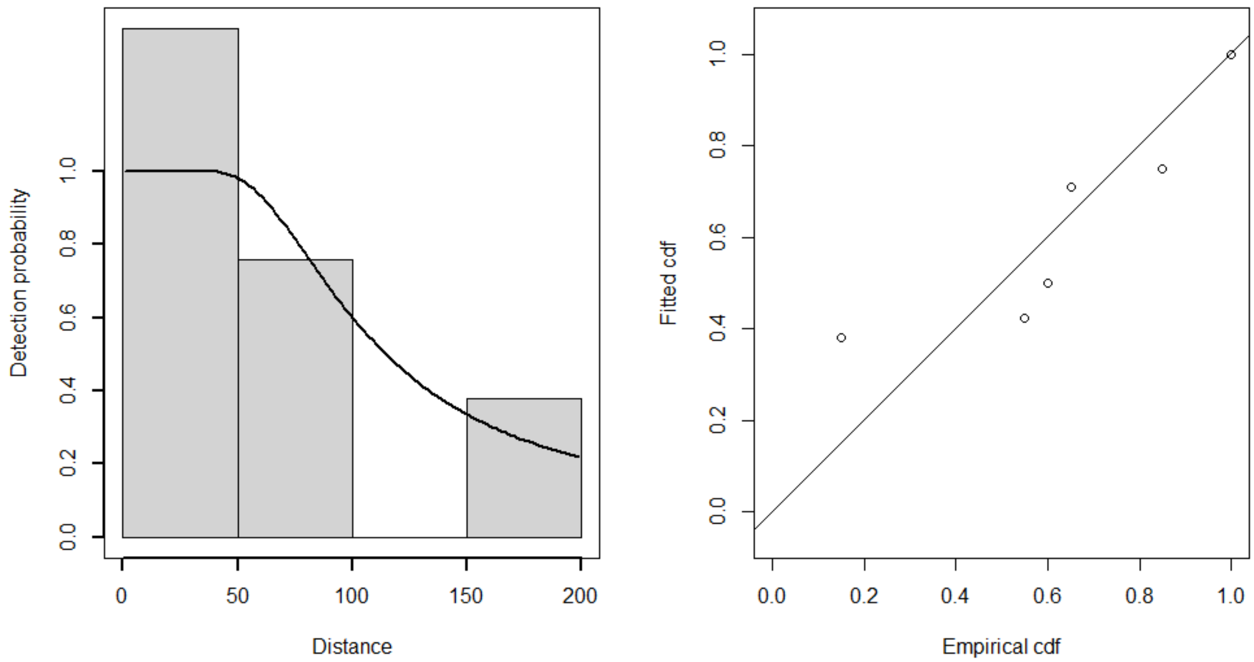
Chi-square goodness of fit test:

Distance (m)	[0,50]	(50,100]	(100,150]	(150,200]
Observed	11	6	7	3
Expected	7.90	6.39	3.57	2.13
Chi-square	1.21	0.02	3.57	0.25

Distance sampling Cramer-von Mises test (unweighted):
Test statistic = 0.48 p-value = 0.04

B. Medium- sized species

Left: Bird detection probability as a function of distance (m) perpendicular to the vessel.
Right: quantile-quantile (Q-Q) plot demonstrating goodness of fit of the density probability function.



Chi-square goodness of fit test:

Distance (m)	[0,42.9]	(42.9,85.7]	(85.7,129]	(129,171]	(171,214]	(214,257]	(257,300]
Observed	0	15	14	0	11	0	5
Expected	9.94	9.55	7.69	5.87	4.68	3.90	3.36
Chi-square	9.94	3.11	5.19	5.87	8.52	3.90	0.80

Distance sampling Cramer-von Mises test (unweighted):
Test statistic = 0.33 p-value = 0.11

APPENDIX 2

EURING codes corresponding to species that were recorded within transect, and the total of observed individuals, over the course of the 12 months of at-sea census.

The species we focused on in this project are highlighted in gray. In the darker shade are the main species, for which we created density distribution models. The species highlighted in light gray are those for which we did not have enough observations to develop models, and instead regarded them as Special Species of Interest (SSI).

Note: EURING is the coordinating organization for European bird ringing schemes. The codes it attributes to individual species are widely used in monitoring and research projects.

EURING Code	Scientific Name	Common name	# Individuals (in transect)
360	*Calonectris diomedea*	Cory's shearwater	716
400	*Ardenna gravis*	Great shearwater	10
430	*Ardenna grisea*	Sooty shearwater	42
460	*Puffinus puffinus*	Manx shearwater	7
462	*Puffinus mauretanicus*	Balearic shearwater	85
500	*Oceanites oceanicus*	Wilson's storm petrel	3
520	*Hydrobates pelagicus*	European storm petrel	315
580	*Hydrobates castro*	Band-rumped storm petrel	33
710	*Morus bassanus*	Northern gannet	1853
720	*Phalacrocorax carbo*	Great cormorant	108
1220	*Ardea cinerea*	Grey heron	2
2130	*Melanitta nigra*	Common scoter	37
5690	*Catharacta skua*	Great skua	247
5750	*Larus melanocephalus*	Mediterranean gull	110
5820	*Larus ridibundus*	Black-headed gull	8
5880	*Larus audouinii*	Audouin's gull	683
5910	*Larus fuscus*	Lesser black-backed gull	78
5928	*Larus michahellis*	Yellow-legged gull	616
6008	*Laridae sp.*		742
6020	*Rissa tridactyla*	Black-legged kittiwake	5
6110	*Thalasseus sandvicensis*	Sandwich tern	21
6150	*Sterna hirundo*	Common tern	8
6230	*Onychoprion fuscatus*	Sooty tern	1
6240	*Sternula albifrons*	Little tern	11
6270	*Chlidonias niger*	Black tern	9
6289	*Chlidonias sp.*		3
6360	*Alca torda*	Razorbill	20
6540	*Fratercula arctica*	Atlantic puffin	15
9920	*Hirundo rustica*	Barn swallow	1

APPENDIX 3

Number of observed individuals observed for each species of interest throughout their respective phenological periods. See Appendix 2 for species EURING code.

EURING code / Month	360	462	710	5690	5750	5880	6110	6240	6360
1	0	67	229	75	69	1	6	0	5
2	0				4	20			
3			996	49		662		0	15
4	716				0		0	11	
5				91			12		0
6					37				
7		0							
8		1						0	
9			319				3		0
10		17		32					
11	0		309			0			
12									
Total	**716**	**85**	**1853**	**247**	**110**	**685**	**21**	**11**	**20**

Pre-breeding

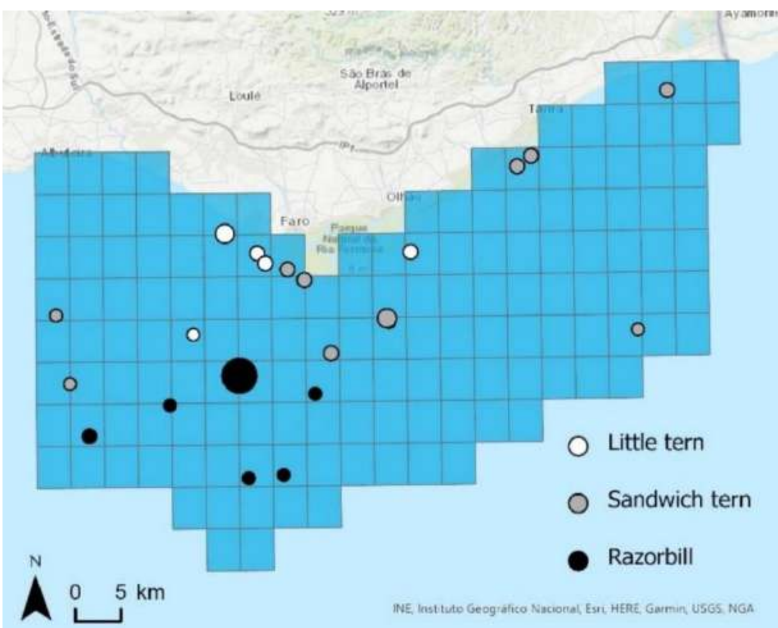
Breeding

Post-breeding

Wintering

APPENDIX 4

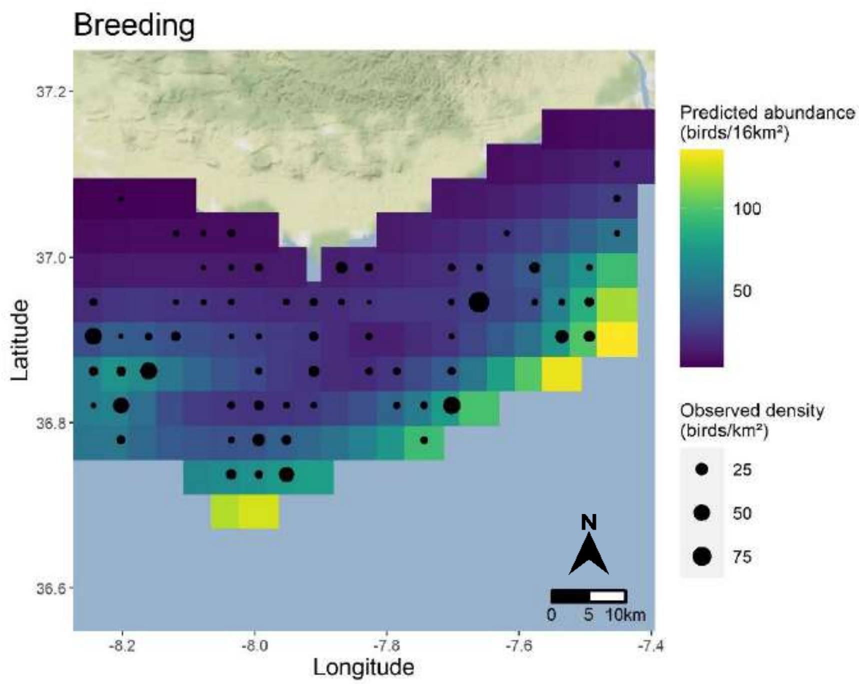
Distribution of Special Species of Interest. Symbol size is proportionate to the number of sighted individuals at the observation point (N_{max} = 14).



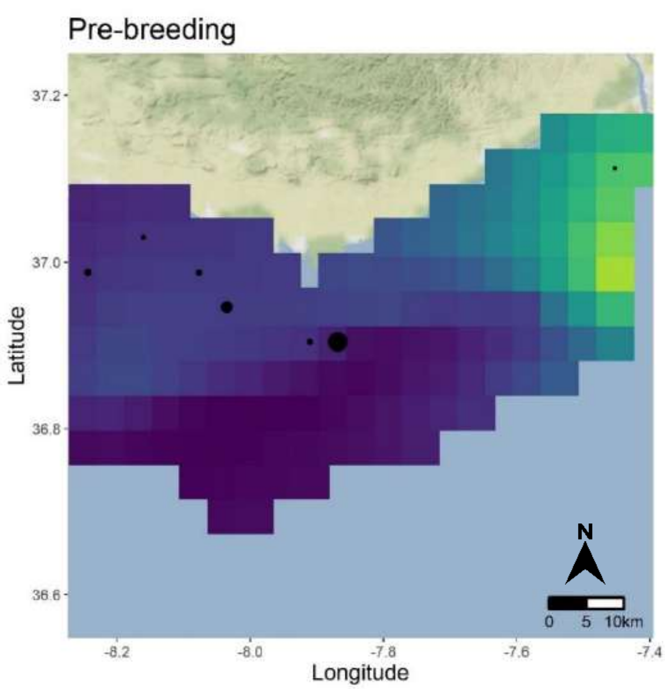
APPENDIX 5

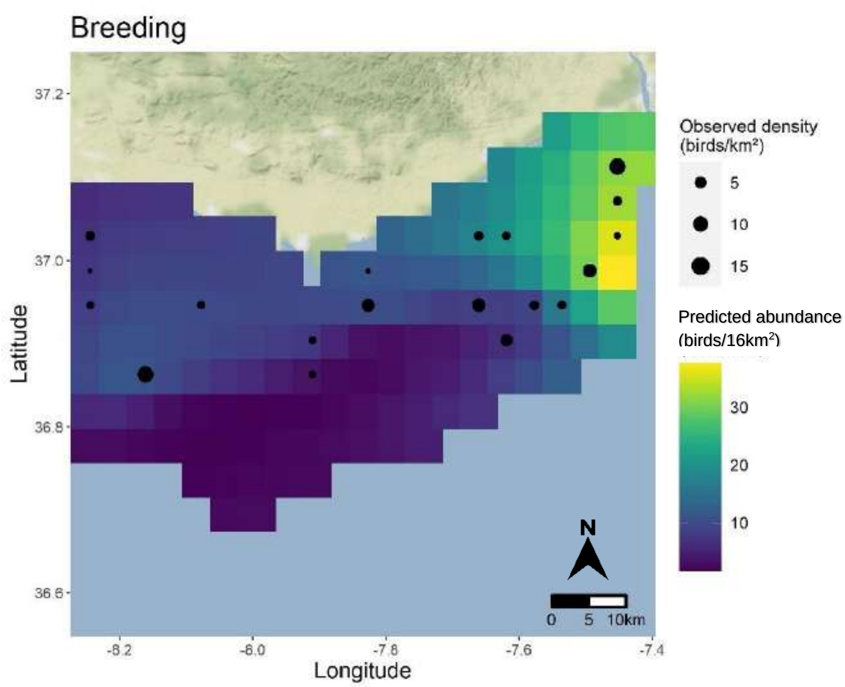
Density distribution maps of seabird species in our study area during different phenological periods. Black points represent observed density (birds/km^2), based on at-sea counts, and cell color represents the predicted abundance of individuals within each 4x4 km cell, as determined by our models.

Cory's shearwater



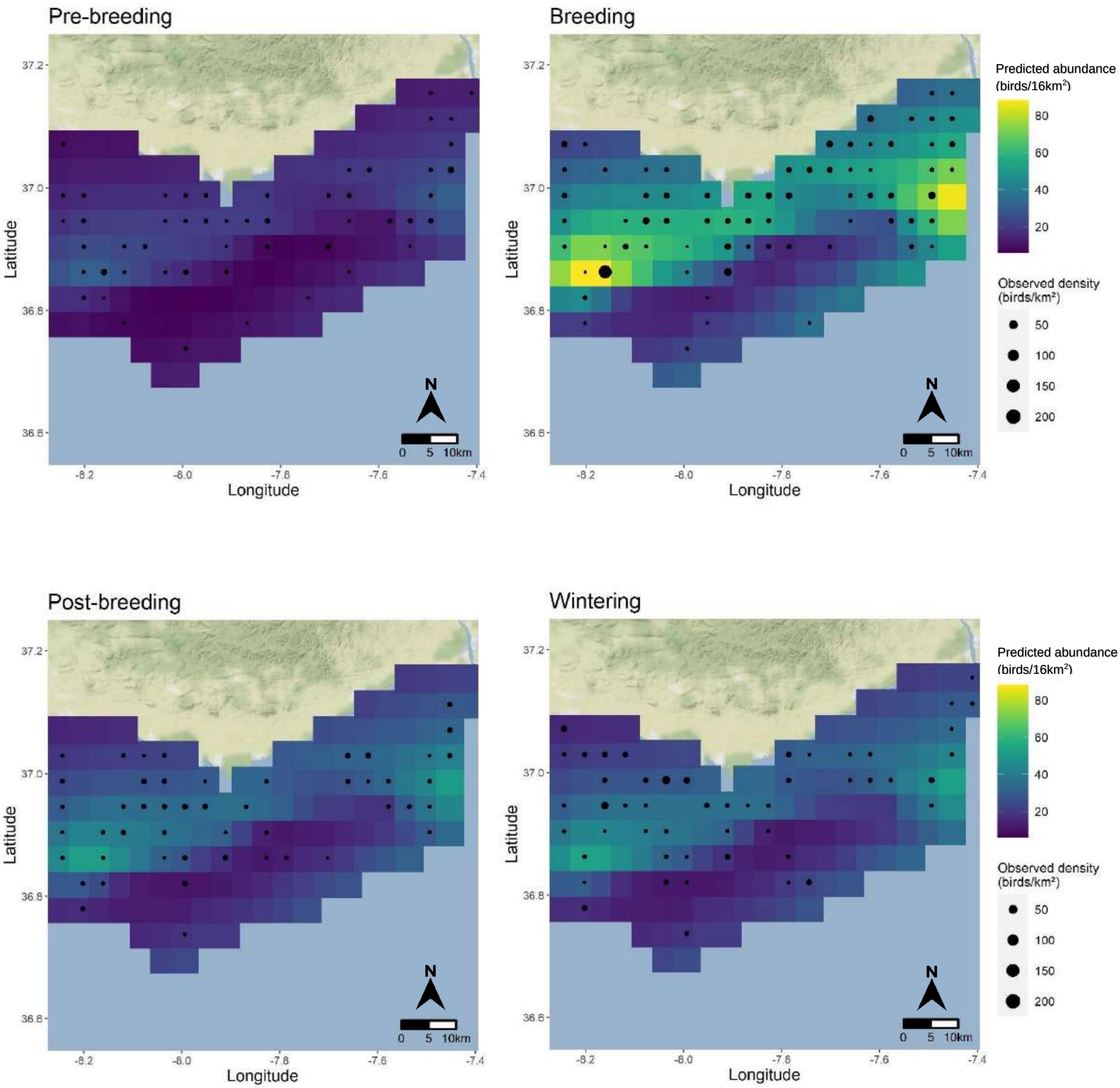
Balearic shearwater



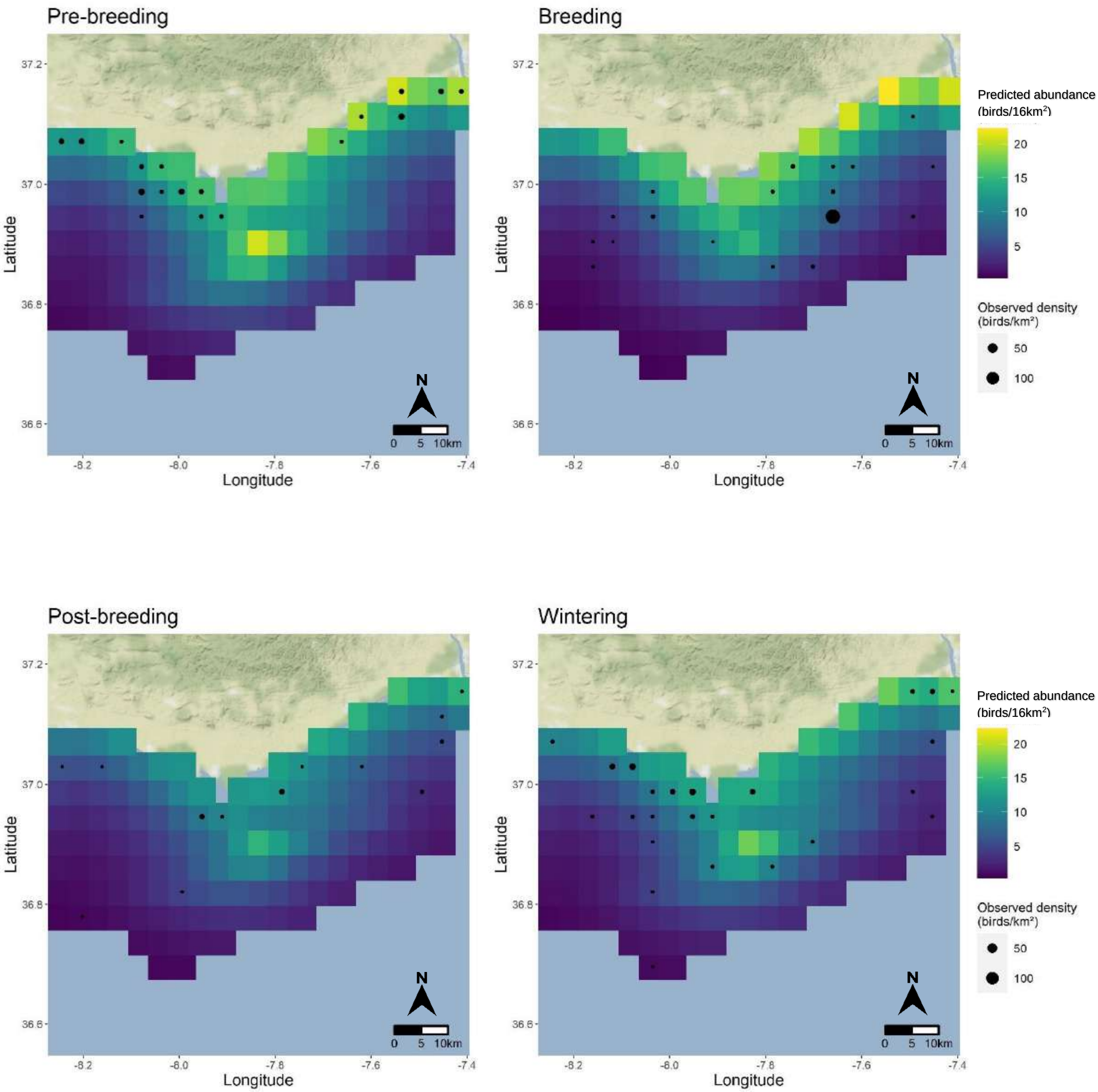


Northern gannet

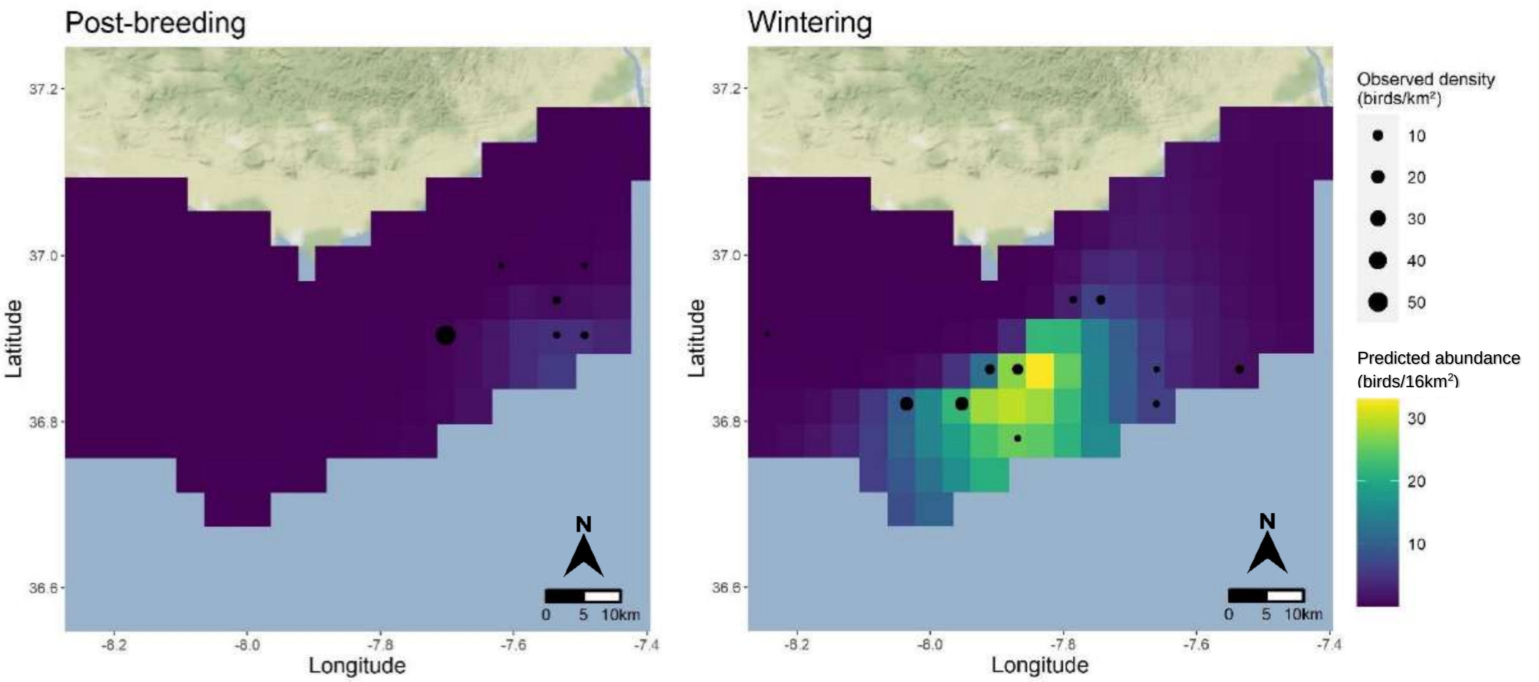
z



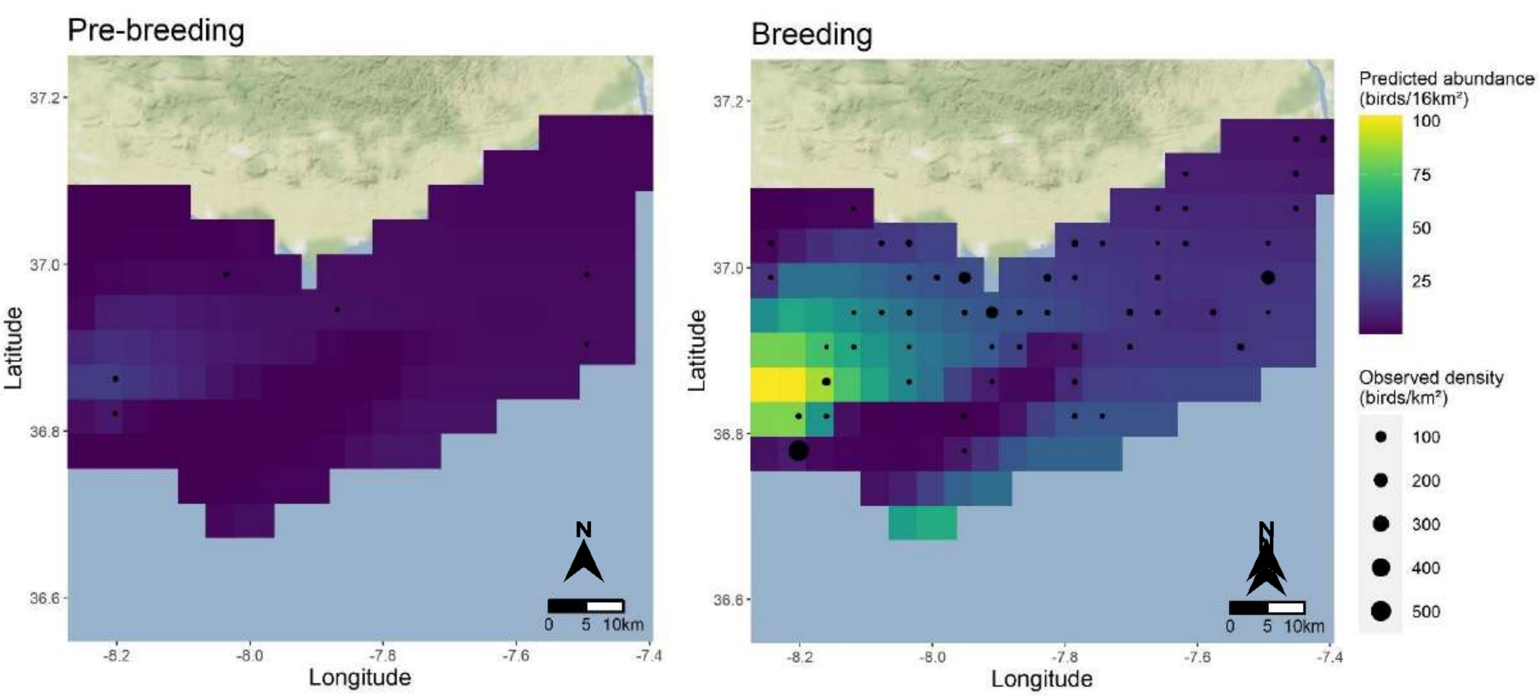
Great skua


Pre-breeding
Breeding
Post-breeding
Wintering
Latitude
Longitude
37.2
37.0
36.8
36.6
-8.2
-8.0
-7.8
-7.6
-7.4
N
0 5 10km
Predicted abundance (birds/16km²)
20
15
10
5
Observed density (birds/km²)
50
100

Mediterranean gull



Audouin's gull



APPENDIX 6: Seabird density distribution modeling

A. Density distribution models goodness-of-fit results for each species. Left to right: degrees of freedom, Akaike Information Criterion, log-likelihood, and estimated number of zeros in the predicted values. In bold are the models that were selected for the final predicted density raster of each species.

Cory's shearwater

Model type	df	AIC	log-L	Est. 0s
hurdle.neg	**11**	**1106.93**	**-542.47**	**403**
zip.neg	11	1112.45	-545.23	407
hurdle	10	2359.43	-1169.72	403
zip	10	2413.08	-1196.54	397
		Observed 0s:		403

Northern gannet

Model type	df	AIC	log-L	Est. 0s
hurdle.neg	**17**	**2886.82**	**-1426.41**	**585**
zip.neg	17	2917.11	-1441.56	597
hurdle	16	4973.38	-2470.69	585
zip	16	5021.21	-2494.61	571
		Observed 0s:		585

Balearic Shearwater

Model type	df	AIC	log-L	Est. 0s
zip.neg	13	434.67	-204.34	688
hurdle.neg	13	436.94	-205.47	688
hurdle	**12**	**473.15**	**-224.58**	**688**
zip	12	503.69	-239.84	686
		Observed 0s:		688

Great skua

Model type	df	AIC	log-L	Est. 0s
hurdle.neg	**17**	**1001.98**	**-483.99**	**846**
zip.neg	17	1012.76	-489.38	849
hurdle	16	1238.14	-603.07	846
zip	16	1251.59	-609.79	842
		Observed 0s:		846

Audouin's gull

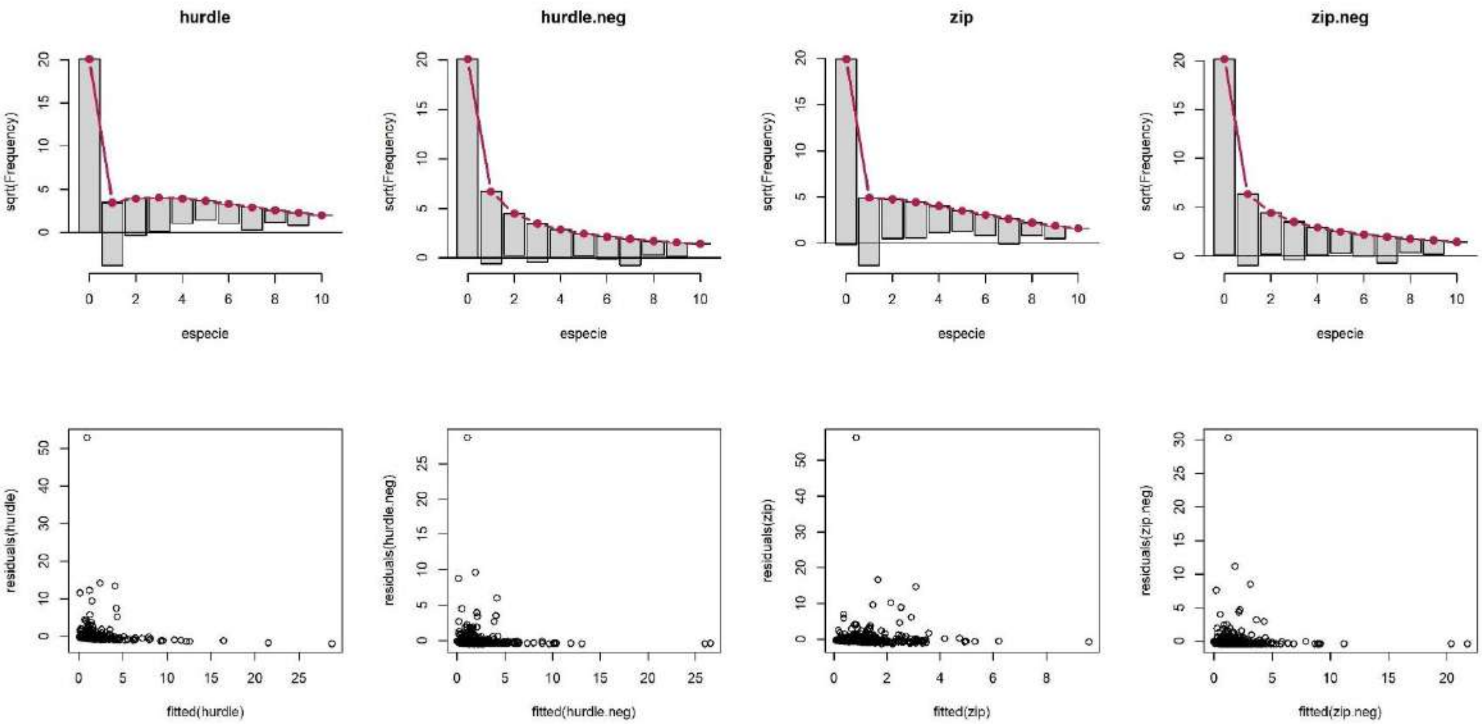
Model type	df	AIC	log-L	Est. 0s
hurdle.neg	13	1052.82	-513.41	576
zip.neg	**13**	**1063.57**	**-518.78**	**579**
hurdle	12	3115.3	-1545.65	576
zip	12	3155.23	-1565.62	573
		Observed 0s:		576

Mediterranean gull

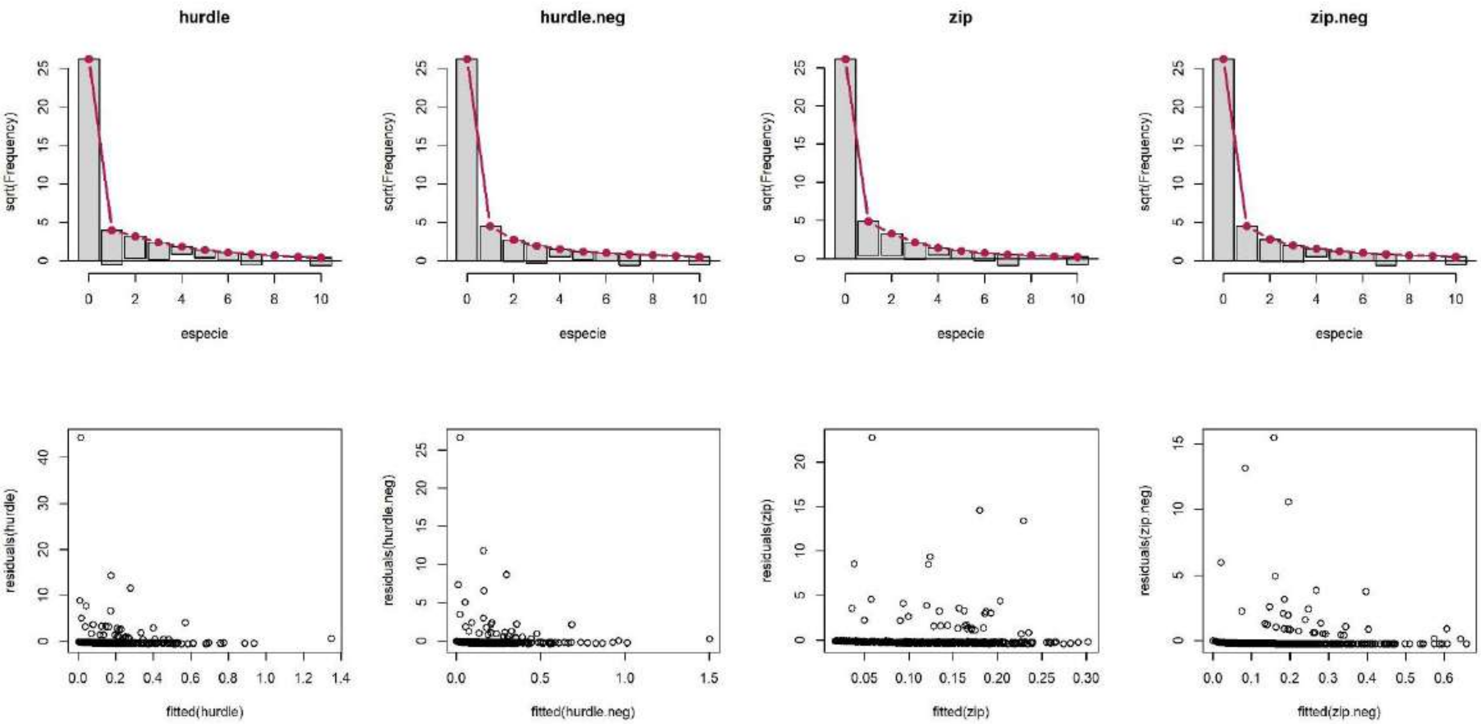
Model type	df	AIC	log-L	Est. 0s
zip.neg	**13**	**210.94**	**-92.47**	**452**
hurdle	12	222.86	-99.43	453
hurdle.neg	13	226.4	-100.2	453
zip	12	231.77	-103.88	453
		Observed 0s:		453

B. Rootograms and residual plots of each tested density distribution model for each species. The hanging rootograms' x-axis values are bird count bins (truncated at 10). On the y-axis are the frequency's square root. The histograms are for the observed frequencies and hang from the red line which represents the predicted frequencies. The models' fit can thus be assessed by comparison of the histograms' position with the horizontal axis. Bins for which the histogram bar dips below the x-axis have been underfitted, and vice-versa for bins where the histogram bar does not reach 0. On the scatter plots, the residuals of each model (y-axis) are compared with the predicted values (x-axis).

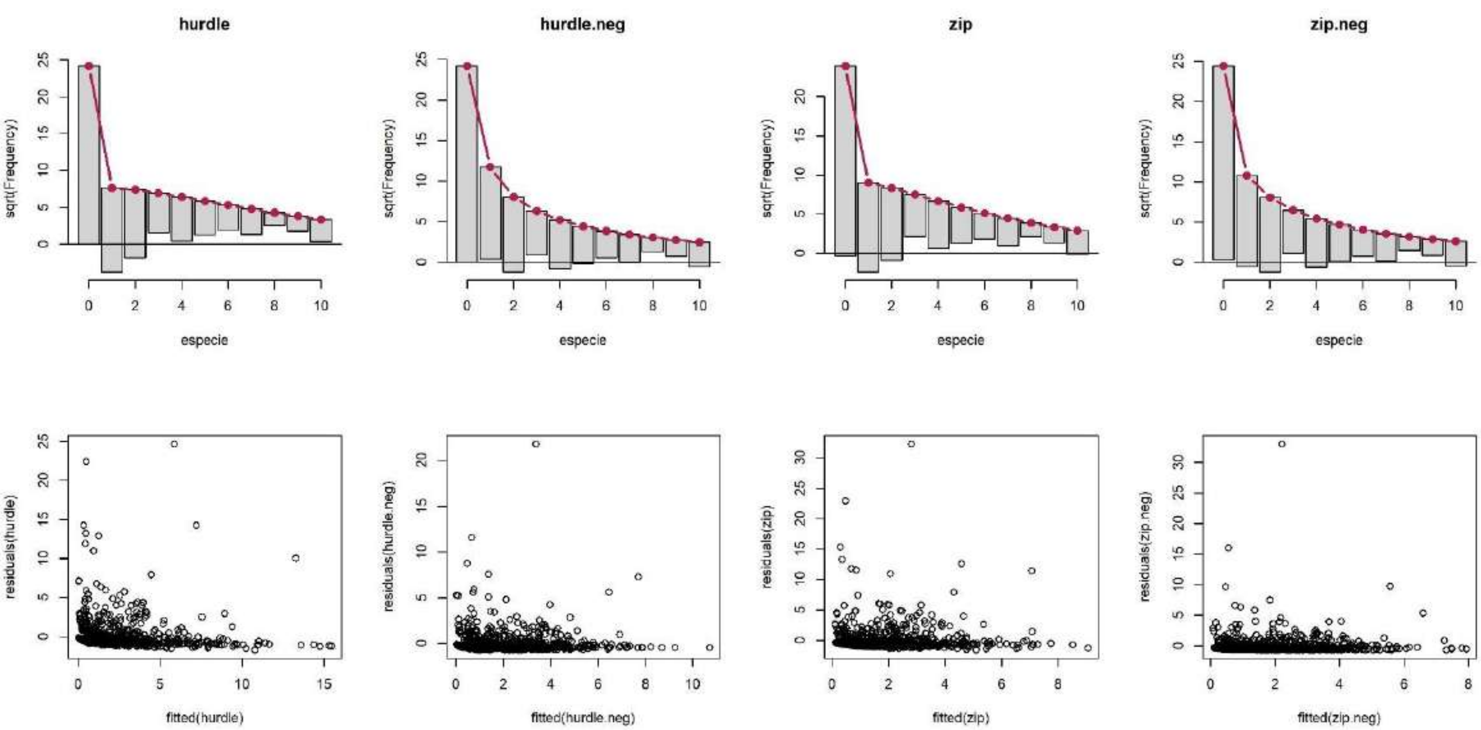
Cory's shearwater:



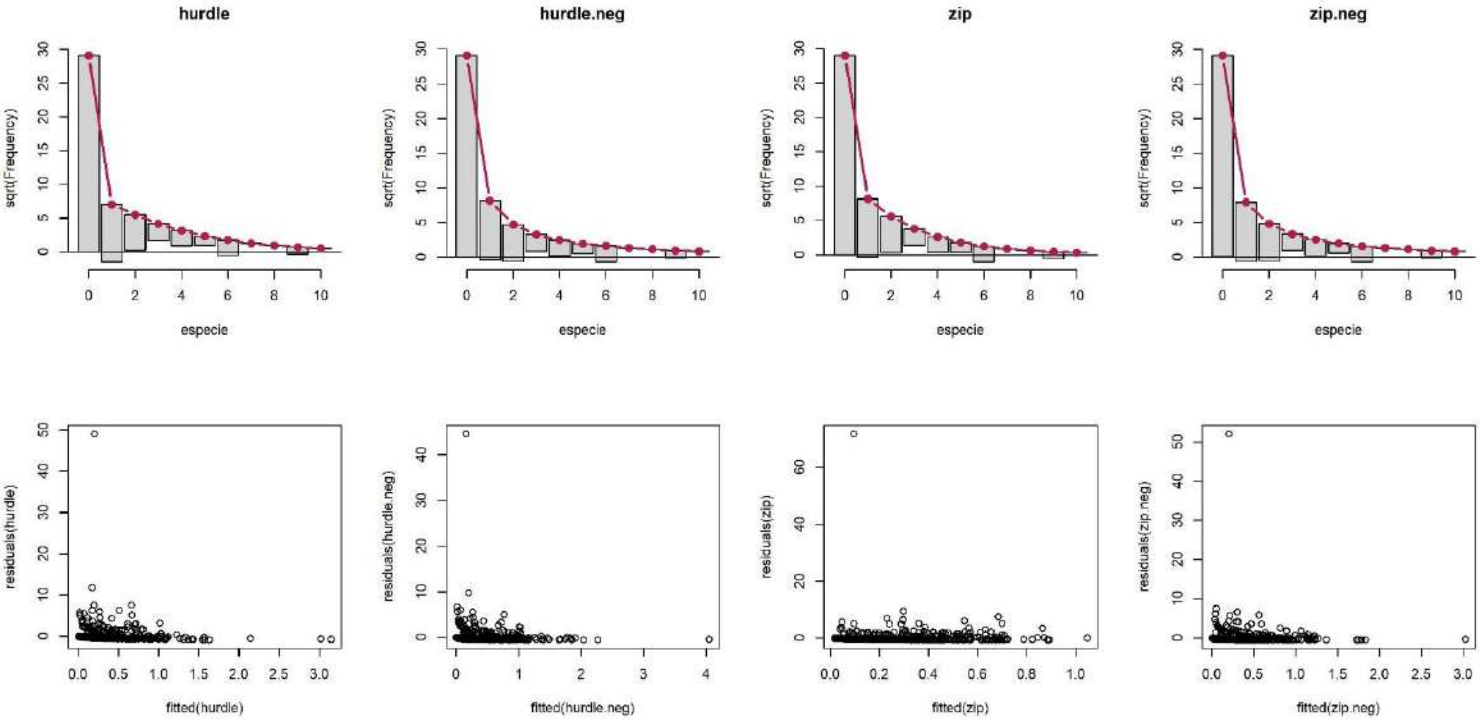
Balearic shearwater:



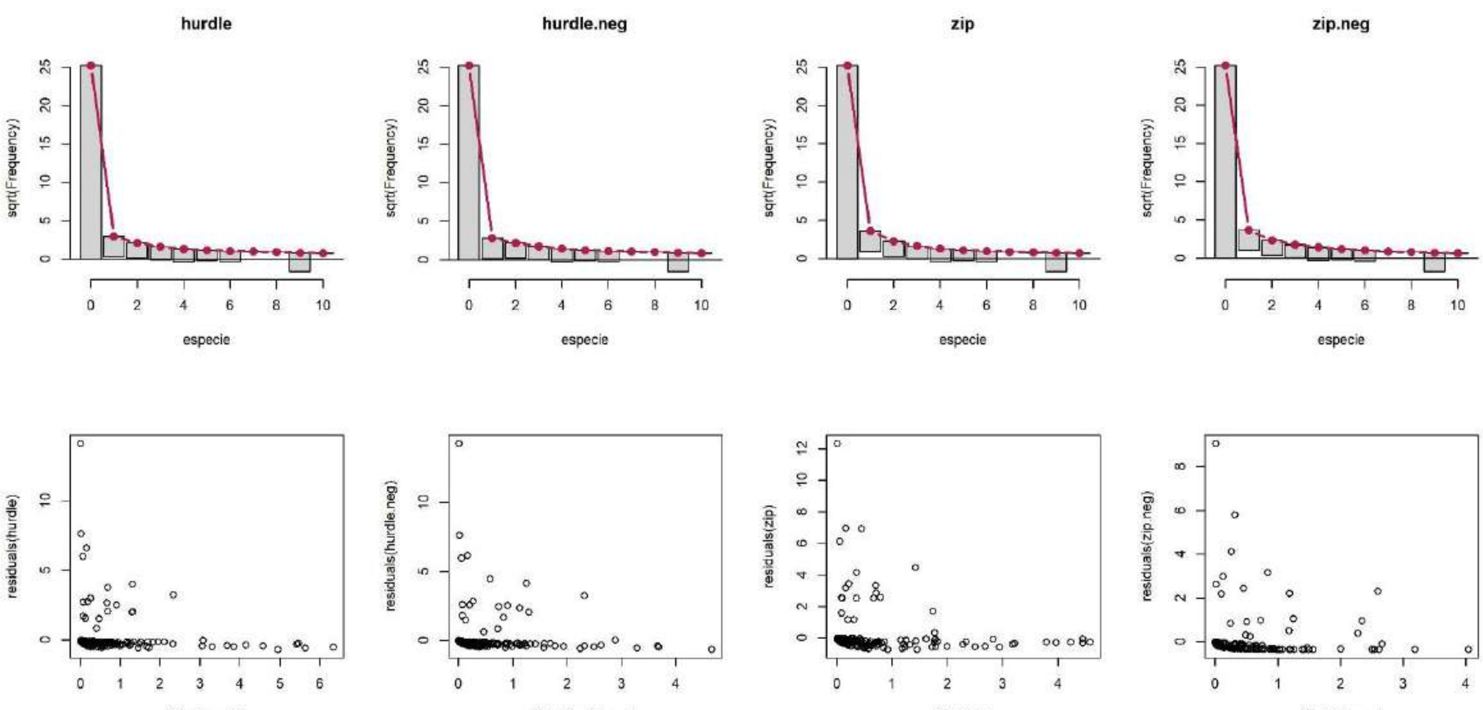
Northern gannet:



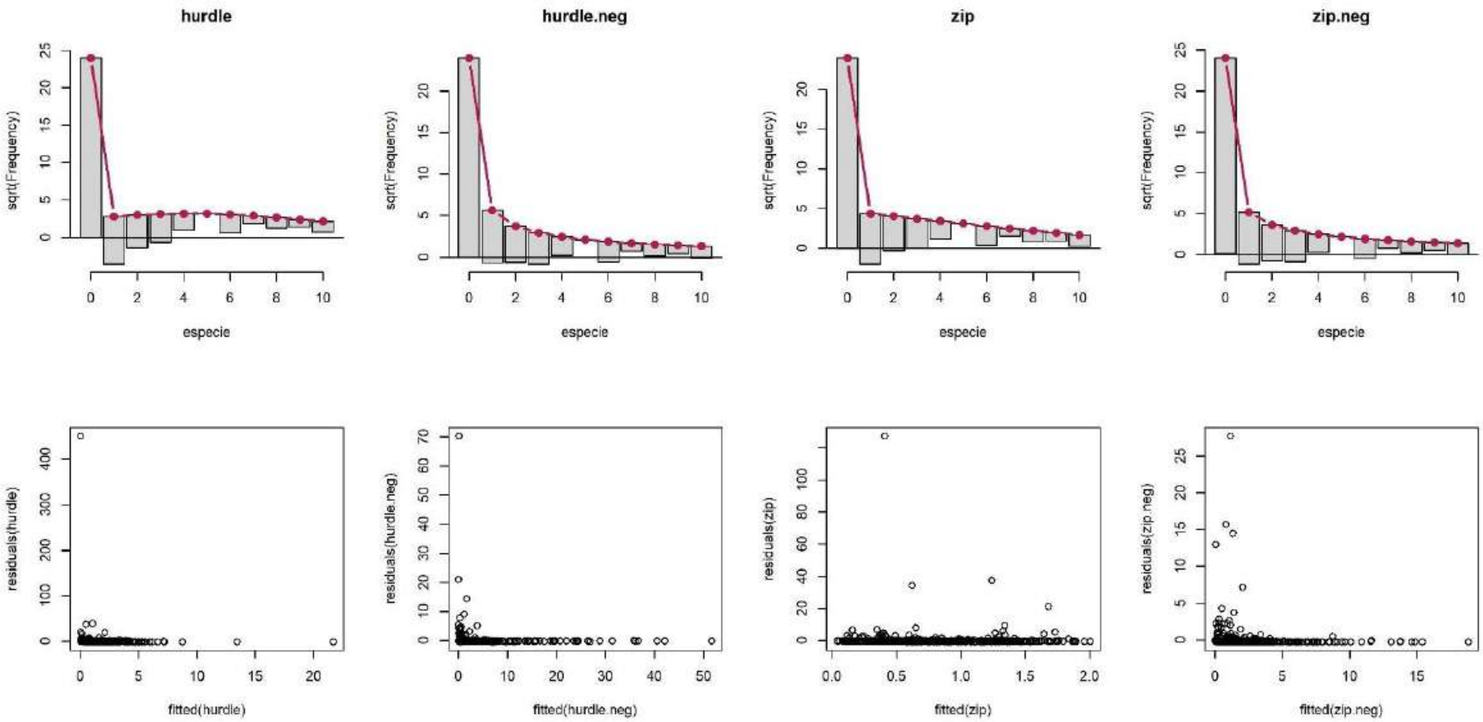
Great skua:



Mediterranean gull:

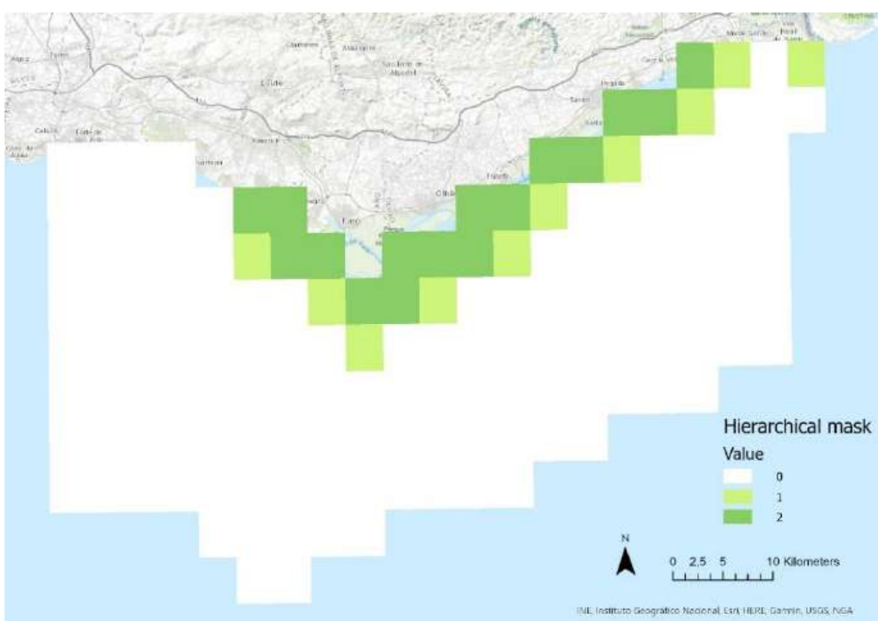


Audouin's gull:



APPENDIX 7

Hierarchical mask based on overlap of existing conservation areas (both protected and unprotected) with study area grid cells. Values of 0 mean there is no overlap, 1 means there is a 1-50% grid cell area overlap, and 2 means there is >50% overlap.



APPENDIX 8

Settings and biodiversity features used in the different variations of the Zonation runs that were tested. This set of variants was tested for both ABF and CAZ cell removal rules, for a total of 40 possible scenarios.

Variant	BLP	Split weight*	Edge removal	SSIs**	Fishing rasters	Mask
1	0					
2	0.1					
3	0.01					
4						
5						
6						
7				full weight		
8				full weight		
9				/ 10		
10				/ 10		
11				/ 10		
12						
13						
14		x 2				
15		x 2		/ 10		
16		x 4				
17		x 4		/ 10		
18						
19		x 2				
20		x 4				

The Boundary Length Penalty (BLP) value was set at 0.01 for the third and all subsequent iterations.

* We tested different settings for the weights of bird density distribution rasters. Initially, the weight for each raster was the value we determined based on the species' IUCN conservation status (see Main Text, Table 1). In later iterations, we split each species' overall weight according to the number of different rasters (phenological periods) we obtained for it. This way, each species retained its originally determined weight and importance regardless of whether it was fond throughout the year or only seasonally.

** Special species of interest were originally introduced via the SSI file with each species' weight set at the value determined by their IUCN conservation status (see Main Text, Table 1). However, because of the relatively low number of biological features included in the project, the influence of SSIs can be disproportionately large. We tried other iterations where the initial weight of each SSI was scaled down by 1/10.

APPENDIX 9: Summary of observed and model-predicted seabird densities in the study area.

Cory's shearwater

Period	Obs. density (Birds/km^2) Mean ± SD (min-max)	Pred. density (Birds/km^2) Mean ± SD (min-max)
Breeding	2.03 ± 7.77 (0 - 94.69)	2.28 ± 1.77 (0.22 - 8.46)

Balearic shearwater

Period	Obs. density (Birds/km^2) Mean ± SD (min-max)	Pred. density (Birds/km^2) Mean ± SD (min-max)
Pre-breeding	0.2 ± 1.67 (0 - 18.75)	0.51 ± 0.31 (0.12 - 1.52)
Breeding	0.11 ± 0.81 (0 - 14.62)	0.35 ± 0.22 (0.07 - 1.04)

Northern gannet

Period	Obs. density (Birds/km^2) Mean ± SD (min-max)	Pred. density (Birds/km^2) Mean ± SD (min-max)
Pre-breeding	1.16 ± 2.19 (0 - 18.04)	0.96 ± 0.36 (0.37 - 1.94)
Breeding	1.96 ± 8.91 (0 - 150.46)	2.53 ± 1.1 (0.8 - 5.51)
Post-breeding	1.93 ± 2.9 (0 - 13.33)	1.61 ± 0.59 (0.66 - 3.25)
Wintering	1.87 ± 3.5 (0 - 23.26)	1.66 ± 0.61 (0.69 - 3.35)

Great skua

Period	Obs. density (Birds/km^2) Mean ± SD (min-max)	Pred. density (Birds/km^2) Mean ± SD (min-max)
Pre-breeding	0.56 ± 1.88 (0 - 12.82)	0.51 ± 0.33 (0.05 - 1.3)
Breeding	0.18 ± 1.94 (0 - 37.88)	0.44 ± 0.35 (0.02 - 1.39)
Post-breeding	0.22 ± 0.81 (0 - 7.27)	0.37 ± 0.24 (0.03 - 0.96)
Wintering	0.32 ± 1.08 (0 - 9.16)	0.43 ± 0.27 (0.04 - 1.09)

Mediterranean gull

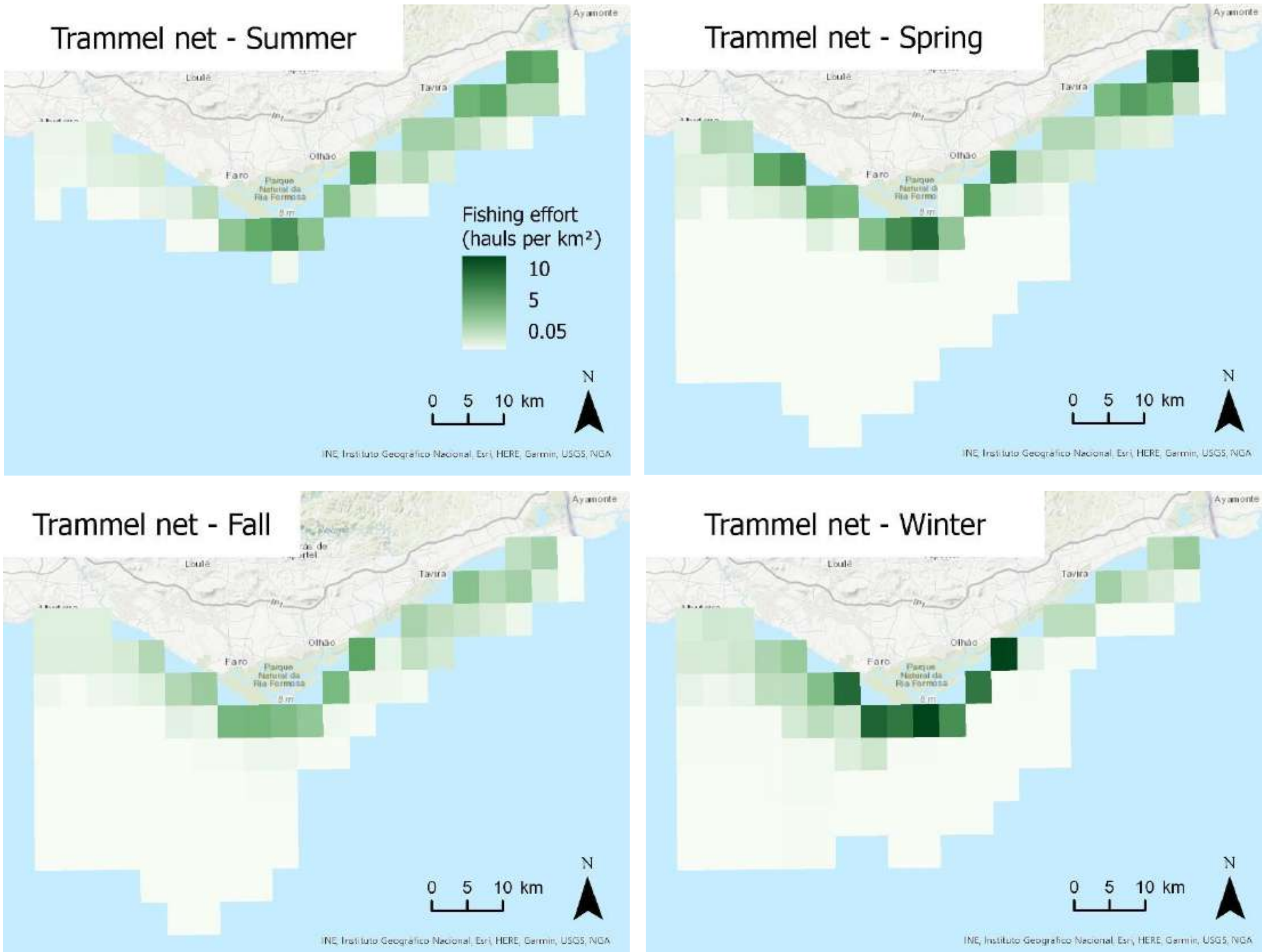
Period	Obs. density (Birds/km^2) Mean ± SD (min-max)	Pred. density (Birds/km^2) Mean ± SD (min-max)
Post-breeding	0.2 ± 2.82 (0 - 53.66)	0.02 + 0.06 (0 - 0.34)
Wintering	0.79 ± 3.08 (0 - 19.23)	0.31 + 0.5 (0 - 2.06)

Audouin's gull

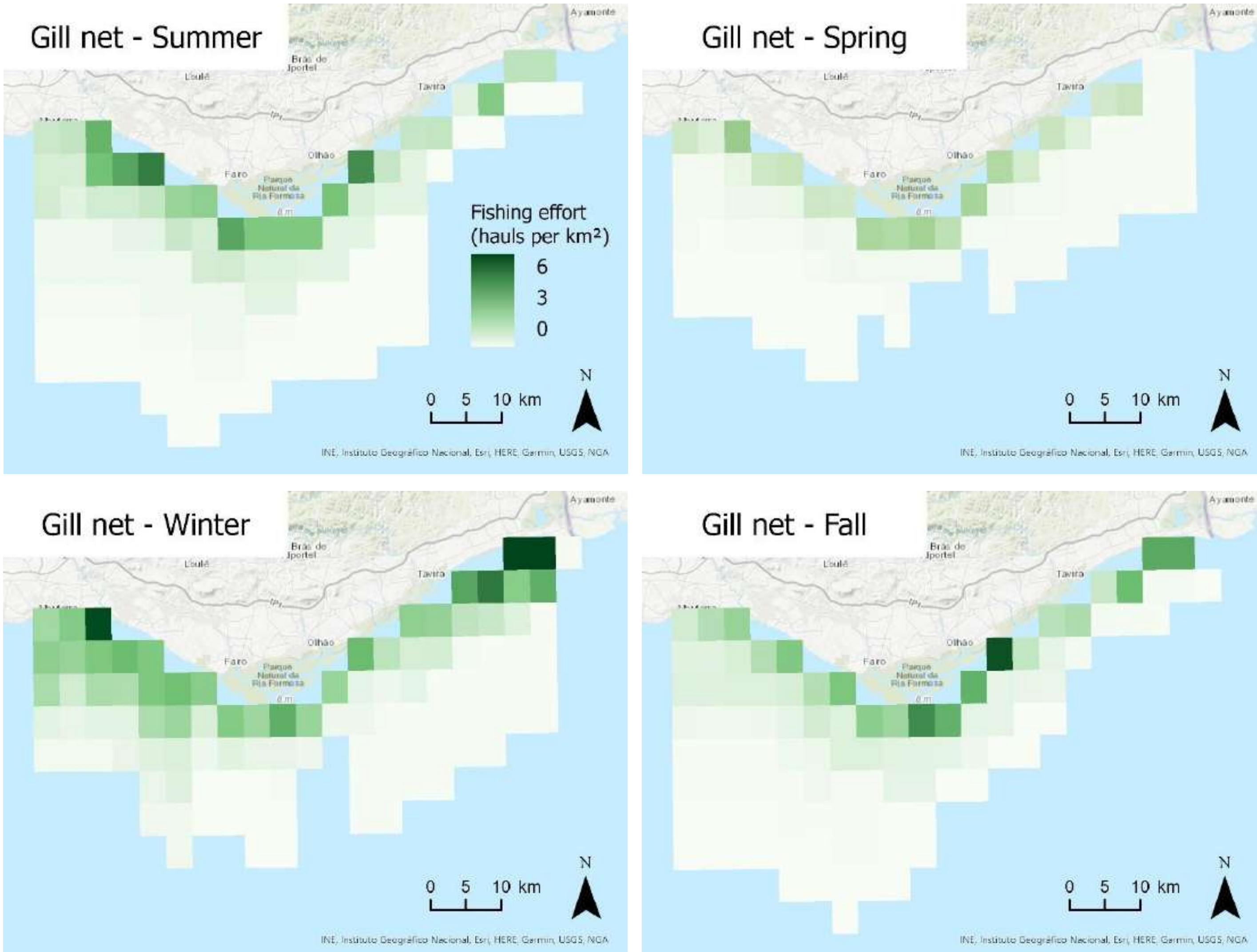
Period	Obs. density (Birds/km^2) Mean ± SD (min-max)	Pred. density (Birds/km^2) Mean ± SD (min-max)
Pre-breeding	0.26 ± 0.94 (0 - 5.79)	0.19 ± 0.21 (0 - 1.13)
Breeding	1.85 ± 23.29 (0 - 556.92)	1.45 ± 1.35 (0.01 - 6.38)

APPENDIX 10: Fishing effort intensity in the study area, measured in net hauls per km², and separated by gear type and season.

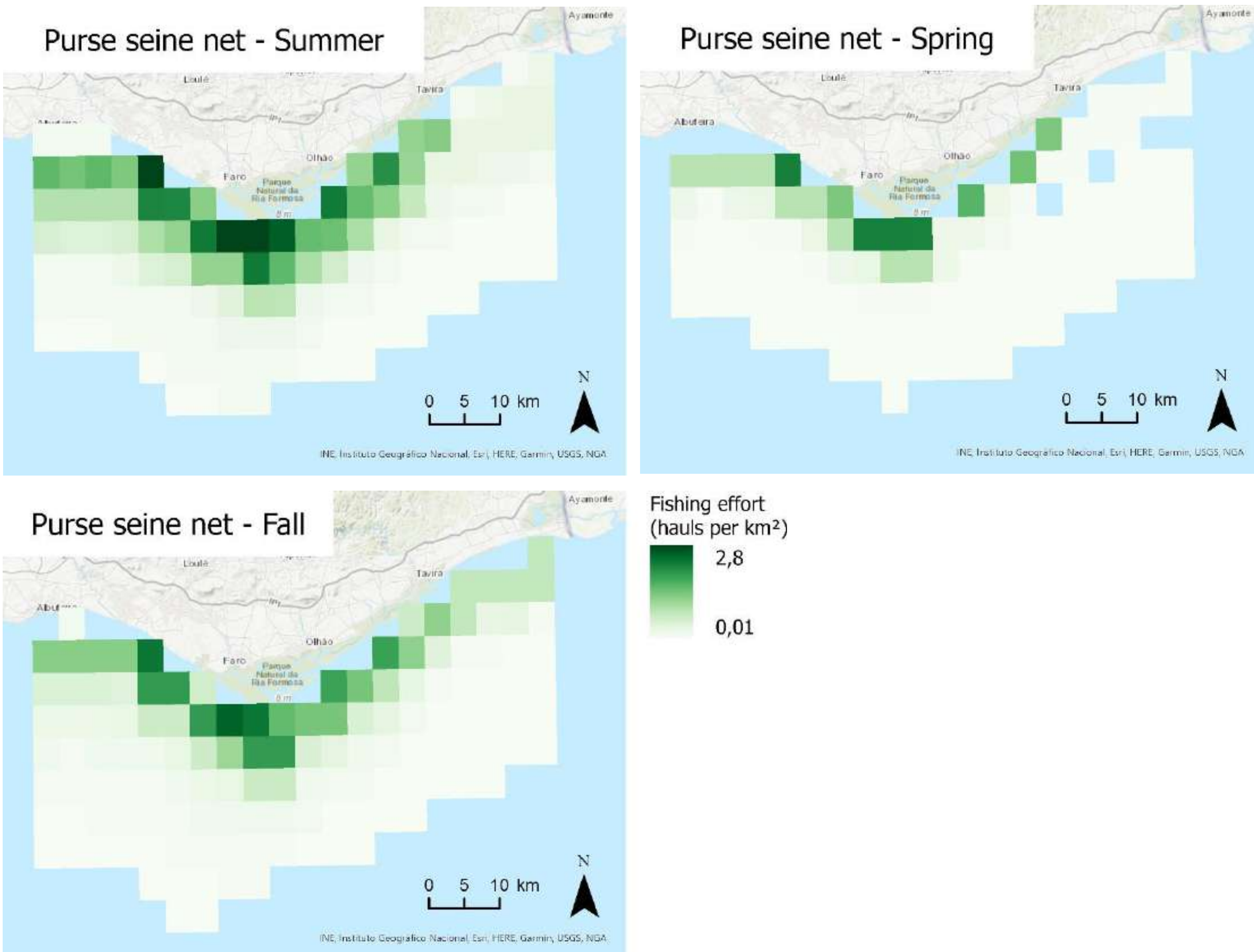
A.



B.


Gill net - Summer
Gill net - Spring
Gill net - Winter
Gill net - Fall
Fishing effort
(hauls per km²)
6
3
0
0 5 10 km
N
Ayamonte
Brás de Jportel
Loulé
Tavira
Olhão
Faro
Parque Natural da Ria Formosa
INE, Instituto Geográfico Nacional, Esri, HERE, Garmin, USGS, NGA

c.


Purse seine net - Summer
Purse seine net - Spring
Purse seine net - Fall
Fishing effort
(hauls per km²)
2,8
0,01
0 5 10 km
N
Ayamonte
Loulé
Tavira
Albufeira
Olhão
Faro
Parque Natural da Ria Formosa
INE, Instituto Geográfico Nacional, Esri, HERE, Garmin, USGS, NGA

List of supplementary materials and raw data

ESAS Data

- *BD_ESAS_2020_a_05-2021_IlhasBarreira.xlsx*: original data from at-sea surveys, including month and year, latitude and longitude of observation point, distance travelled and area surveyed, species and number of sighted individuals, distance range, behavior, sea condition and more *(source: SPEA)*
  Transformed
  - *ESAS_DistCorrected_Bat+DLand.csv:* modified ESAS data, with corrected number of birds for each species, as well as distance to land and bathymetry for each observation point
  - *Prediction Grids:* csv files for each species, containing predicted abundance in each grid cell at each relevant phenological period
  - *PRED_RASTERS:* density distribution rasters (ascii format) of each species and phenological period combination

Fishing effort

- *BD_LIFEIB_esforço de pesca e bycatch de aves.ods :* original, untranslated questionnaire data (source: SPEA & UAlg/CCMAR)
  Transformed
  - *FishingZones_CornerCoords_Effort.xlsx*: spreadsheet with one questionnaire entry per line, date, vessel name, gear type, min and max operating distances, western and eastern limits of fishing area, xy coordinates of each polygon corner, total number of hauls in the season, and number of bycatch incidents.
  - *Fishing_Polygons*: multi- polygon shapefile with all fishing areas described in questionnaire data, and total fishing effort in number of hauls
  - *Fishing_Rasters*: effort density distribution rasters for all season/gear type combinations

Bathymetry Raster

Shapefiles

- *Castro Marim :* Castro Marim SCI polygon (source : Natura 2000 network)
- *Ria Formosa :* Ria Formosa SPA polygon (source : Natura 2000 network)
- *Marine IBA :* Ria Formosa PTM04 IBA polygon (source : SPEA)
- *Portugal borders :* Portugal mainland polygon (source : SPEA)
  Transformed
  - *Study area grid :* Study area multi-polygon shapefile with 149 objects (grid cells), extracted from “Grid MARPRO coastal 4x4km” (source: SPEA)
  - *ESASpts* : ESAS observation point shapefile, coordinates extracted from original census dataset (source: SPEA)

Zonation

- *Run_files:* Folder containing all project batch files, inputs (setting files, biodiversity features lists) and outputs