

Development of the Impact Assessment of Offshore Wind Complexes on Biodiversity: Protocols, Analysis of Potential Areas and Environmental Restrictions for the Brazilian Coast

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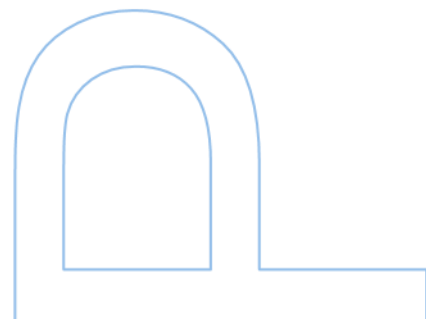
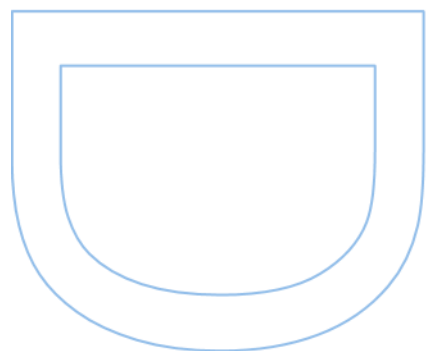
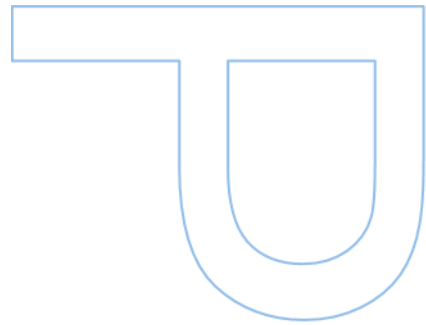
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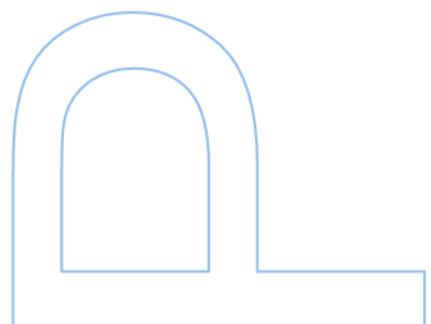
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Dedicated to the beloved daughters Clara and Laura.

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Resumo

O crescente desenvolvimento de parques eólicos offshore como fonte de energia limpa para mitigar as emissões de gases de efeito de estufa coloca desafios à gestão da biodiversidade, necessitando de avaliações estratégicas de impacto ambiental. Este estudo apresenta uma revisão quantitativa da cadeia dos impactos das usinas eólicas marinhas (UEMs) na biota, com enfoque na avifauna, e suas metodologias de diagnóstico e monitorização para contribuir para políticas energéticas sustentáveis no Brasil, informando os processos de tomada de decisão. A investigação salienta a importância de estudar todas as fases de desenvolvimento das UEMs e de estudos futuros para aprofundar a investigação dos seus impactos na biota marinha. Ainda, a modelagem de nicho ecológico (MNE) usando o algoritmo MaxEnt foi aplicada a sete espécies de albatrozes e petréis, cinco das quais enfrentam ameaças de extinção, para prever a aptidão de nicho dessas espécies e as diferenças nas distribuições sazonais. A MNE também foi utilizada para explorar a sobreposição de nicho de seis espécies ameaçadas de cetáceos marinhos com áreas de Unidades de Conservação, de pesca de emalhe e de UEMs na região sudeste e sul do Brasil. Além disso, a pesquisa identifica hotspots de biodiversidade compostos por aves marinhas, cetáceos e a tartaruga-verde (*Chelonia mydas*) nas Bacias Marinhas de Santos e Campos e propõe priorizações espaciais para orientar a expansão de áreas marinhas protegidas. Neste estudo, distinguiram-se duas áreas principais de hotspot de biodiversidade, uma na zona costeira até 12 milhas náuticas (mn) e a outra entre as faixas batimétricas de 200 a 1000 m de profundidade. Recomendamos evitar instalações de UEMs em zonas costeiras em até 12 mn da costa e incluir nos estudos de alternativas locais, pelo menos uma opção fora desse limiar. Além disso, salientamos a necessidade de um planejamento espacial marinho eficaz no Brasil para proteger a fauna marinha e os seus habitats face à expansão da exploração de energia eólica offshore. A integração da MNE e do índice de Riqueza em estudos de impacto ambiental é recomendada como uma ferramenta a ser utilizada para melhorar a conservação, o planejamento ambiental e a avaliação de impactos. Por fim, o estudo defende a realização de esforços para obter e disponibilizar informações abrangentes sobre a distribuição das espécies no espaço e no tempo, a fim de informar as estratégias de conservação e preservação das espécies.

Palavras-chave: áreas marinhas protegidas, aves marinhas, cetáceos, conservação da biodiversidade, energias sustentáveis, Modelação de Nicho Ecológico, parques eólicos offshore, revisão sistemática, tartaruga-verde, vertebrados marinhos.

Abstract

The increasing development of offshore wind farms (OWFs) as a clean energy source to combat greenhouse gas emissions poses challenges to biodiversity management, requiring strategic environmental impact assessments. This study presents a quantitative review of the chain of impacts of OWFs on biota, with a focus on avifauna, and their diagnostic and monitoring methodologies to contribute to sustainable energy policies in Brazil, informing decision-making processes. The research highlights the importance of studying all stages of development of OWFs and future studies to further investigate their impacts on marine biota. In addition, Ecological Niche Modelling (ENM) using the MaxEnt algorithm was applied to seven species of albatrosses and petrels, five of which face extinction threats, to predict species niche suitability and differences in seasonal distribution. ENM was also used to explore niche overlap of six threatened marine cetacean species with Marine Protected Areas, gillnet fisheries and OWF in the southeastern and southern regions of Brazil. In addition, the research identifies biodiversity hotspots of seabirds, cetaceans and the green turtle in the Santos and Campos Marine Basins and proposes spatial prioritizations to guide the expansion of marine protected areas. In this study, two main hotspot areas were distinguished, one in the coastal zone up to 12 nm and the other between the bathymetric ranges of 200 to 1000 m depth. We recommend avoiding OWF installations in coastal zones within 12 nm of the coast and including at least one option outside this threshold in studies of locational alternatives. Also, we emphasize the need for effective marine spatial planning in Brazil to protect marine fauna and their habitats in the face of expanding offshore wind energy exploitation. The integration of ENM and the Richness Index into environmental impact studies is recommended as a tool to improve conservation, environmental planning and impact assessment. Finally, the study advocates efforts to obtain and make available comprehensive information on the distribution of species in space and time, in order to inform species conservation and preservation strategies.

Keywords: biodiversity, conservation, cetaceans, Ecological Niche Modelling, green turtle, marine protected areas, marine vertebrates, offshore wind farms, seabirds, sustainable energy, systematic review.

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Figure 5.6. A: Map of areas of Offshore Wind Farms (OWFs) under planning, highlighting the Richness Index of selected vertebrates in these areas. Areas A, outlined by the dark blue line, correspond to RI = 0 species, areas B, outlined by the light blue line, to RI = 1 species. 85

List of Abbreviations

%	percent
°	degree
ACAP	Agreement on the Conservation of Albatrosses and Petrels
AG	<i>Ardenna gravis</i>
ANP	Agência Nacional do Petróleo
APA	Environmental Protection Area
AUC	Area Under the Curve
BI	Boyce Index
CBD	Convention on Biological Diversity
chl	chlorophyll-a
CR	Critically Endangered
D	Schoener's Niche Overlap Index
DE	<i>Diomedea exulans</i>
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
EN	Endangered
ENM	Ecological Niche Modeling
EPE	Brazilian Energy Research Company
FCUP	Faculty of Sciences of the University of Porto
FURG	Federal University of Rio Grande - FURG
g/m ³ /day	grams per cubic meter per day
GAM	Generalized Additive Models
GBIF	Global Biodiversity Information Facility

GLM	Generalized Linear Models
GLS	Global Location Sensor
GPS	Global Positioning System
GW	Gigawatt
GWEC	Global Wind Energy Council
IAIA	International Association for Impact Assessment
IBAMA	Brazilian Institute of the Environment and Renewable Natural Resources
ICMBio	Chico Mendes Institute for Biodiversity Conservation
IRENA	The International Renewable Energy Agency
IUCN	International Union for Conservation of Nature
km	kilometers
km ²	square kilometers
LAATM	Waterbirds and Sea Turtles Laboratory
lat	latitude
LC	Least Concern
lon	longitude
m	meters
mn	milhas náuticas
m/s	meters per second
MaxEnt	Maximum Entropy Software
mg/m ³	milligrams per cubic meter
MMA	Brazilian Ministry of Environment and Climate Change
MNE	Modelagem de Nicho Ecológico
MPA	Marine Protected Areas

MSP	Marine Spatial Planning
N	North
nm	nautical mile
NSI	Niche Suitability Index
NT	Near Threatened
OBIS	Ocean Biogeographic Information System
°C	degree Celsius
OWF, OWFs	Offshore Wind Farms
PA	<i>Procellaria aequinoctialis</i>
PBR	Potential Biological Removal
PC	<i>Procellaria conspicillata</i>
PEOs	Parques Eólicos Offshore
PETROBRAS	Petróleo Brasileiro S.A.
PI	<i>Pterodroma incerta</i>
PMC-BS	Santos Basin Cetacean Monitoring Project
PMP	Beach Monitoring Programs
PR	Paraná
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PSS	Practical Salinity Scale (sea surface salinity)
PTT	Platform Terminal Transmitters
PVA	Population Viability Analysis
REFAU	Wildlife refuge
RI	Richness Index
ROC	Receiver Operating Characteristic

RS	Rio Grande do Sul
S	South
SC	Santa Catarina
SDM	Species Distribution Models
sEEZ	Southern Exclusive Economic Zone
SIMBA	Aquatic Biota Monitoring System
SIMMAM	Support System for the Monitoring of Marine Mammals
SST	Sea Surface Temperature
TC	<i>Thalassarche chlororhynchos</i>
TM	<i>Thalassarche melanophris</i>
TSS	True Skill Statistic
UEMs	Usinas Eólicas Marinhas
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
UP	University of Porto
USA	United States of America
VI	Variable Importance
VIF	Variance Inflation Factor
VU	Vulnerable
W	West
WGS84	World Geodetic System 1984
μmol/m ³	micromole per cubic meter

CHAPTER I.

General Introduction

Accurately describing and understanding the processes that determine the distribution of organisms is a fundamental problem in biology, with important conservation and management implications. The overall distribution patterns of a population result from the combination of individual-specific movements, and interpreting these patterns is improved when considering both space and time (Forcada, 2018). The spatial and temporal distributions of species are key for evaluating species extinction risks and predicting future threats, such as climate change (Breiner et al., 2017). It is important to map species distributions and marine hotspot areas of sensitive species and habitats that could be impacted by anthropogenic activities (Borkenhagen et al., 2018; Pollock et al., 2021).

Effective *in situ* conservation requires the protection not only of organisms but also of the ecosystems that support them. Understanding which habitats are most frequently used, quantifying species richness and identifying the biotic and abiotic variables that influence these processes are critical components of current studies in ecology and conservation biology (Reeves, 2018; Martins et al., 2023). In marine environments, the distribution of vertebrates is typically categorized as coastal (estuarine or nearshore), neritic (on the continental shelf), or oceanic (pelagic, beyond the continental slope, in the open seas or oceans) (Forcada, 2018).

Brazil has one of the largest marine Exclusive Economic Zone (EEZ) in the world, spanning approximately 3.6 million km². It extends from the mouth of the Oiapoque River (04°N) to the mouth of the Chuí River (33°S) and from the limits of the municipalities of the coastal strip in the west to 200 nautical miles in the east, including the areas around Atol das Rocas, the archipelagos of Fernando de Noronha and São Pedro and São Paulo, and the islands of Trindade and Martin Vaz (Brasil, 1993) (Fig. 1.1).

The Brazilian EEZ has a great diversity of ecosystems that are of enormous relevance to the life cycle of many species and support various human activities. The region exhibits high biodiversity, with approximately 160 nationally threatened marine vertebrate species, many of which are endemic (Vilar & Joyeux, 2021). The continental shelf and slope of southeastern and southern Brazil are economically important regions for tourism, fishing, and the oil and gas industries (Di Tullio et al., 2016).

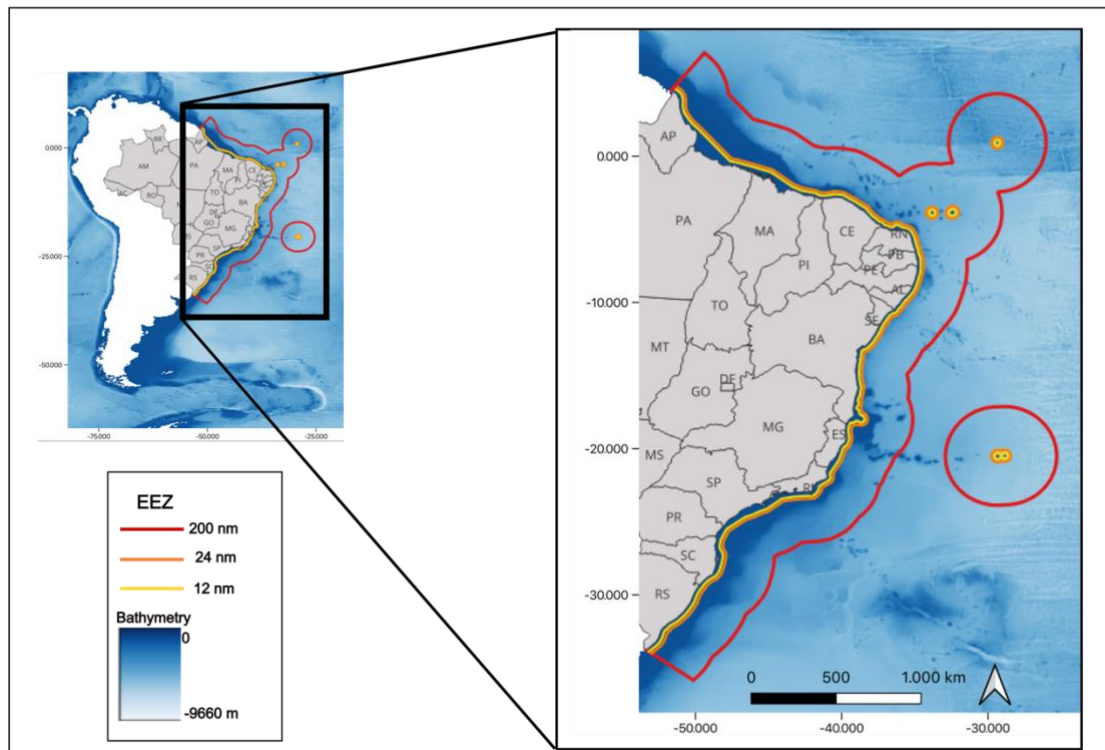


Figure 1.1. Delimitation of the Brazilian Exclusive Economic Zone, its limits of 12, 24 and 200 nautical miles (nm) and the bathymetry of the Atlantic Ocean.

Seabirds are among the most threatened of all groups of birds globally (Dias et al., 2019). As higher predators, seabirds play key roles in marine ecosystems, making their conservation critical (Grémillet et al., 2018). Understanding their distribution and habitat use is essential for avoiding and mitigating threats (Azuaje-Rodríguez et al., 2022). However, their high mobility presents challenges, especially because seabirds rely on multiple, often geographically distant ecosystems, all of which require some form of protection for successful conservation (Dunn et al., 2019).

Conducting surveys of seabirds at sea is logistically and financially challenging, often limiting their spatial and temporal coverage (Heinänen et al., 2017). For highly pelagic species, this is further complicated by the lack of an effective governance mechanism for areas beyond national jurisdictions and incomplete knowledge of their distribution throughout all life-history stages (Davies et al., 2021).

The order Procellariiformes (albatrosses, petrels and shearwaters) is a highly diverse group, with 45 species present in Brazilian waters (Pacheco et al., 2021). Procellariiforms undertake extensive migratory movements and long feeding trips covering thousands of

kilometres, rarely approaching land except for breeding. They have great longevity and reach sexual maturity late and produce only one egg per season which may occur at intervals of two or more years (Phillips et al., 2016; ICMBio, 2018). Albatrosses and petrels face a major mortality threat in fisheries and data on their distribution at sea are valuable for marine spatial planning (Tancell et al., 2016). Most of the species included in this study have elevated conservation concerns (IUCN, 2022; MMA, 2022) and/or are listed in the Agreement on the Conservation of Albatrosses and Petrels (ACAP, 2018) (Fig. 1.2).

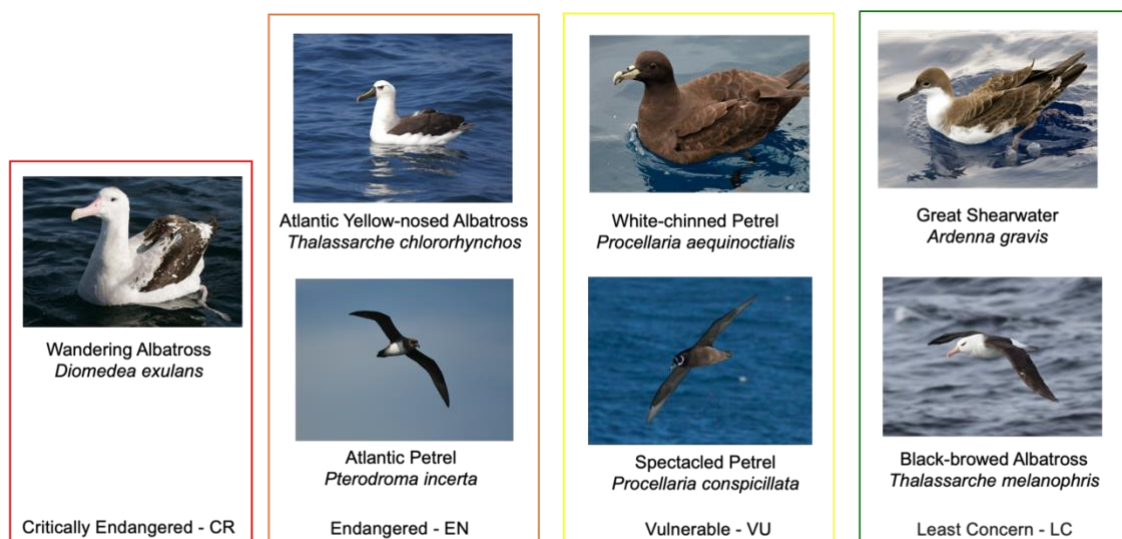


Figure 1.2 Threatened Procariiforms selected for ecological niche modelling and their degree of threat according to MMA (2022). The Wandering Albatross *Diomedea exulans*, the Atlantic Yellow-nosed Albatross *Thalassarche chlororhynchos*, the Atlantic Petrel *Pterodroma incerta*, the White-chinned Petrel *Procellaria aequinoctialis*, the Spectacled Petrel *Procellaria conspicillata*, the Great Shearwater *Ardenna gravis* and the Black-browed Albatross *Thalassarche melanophris*. (Adapted from Wikimedia Commons, pictures by Mark, J.; Quinn, L.; Bottai, H.; Jobin, T.; Dunens, E.; Gratwicke, B.; Coin, P., available at <https://commons.wikimedia.org/> accessed July 2023).

Fine-scale data on cetacean (order Cetartiodactyla) distribution patterns are limited because most of them are highly mobile and spend a substantial amount of time below sea surface, making detection and group size estimation inherently difficult (Redfern et al., 2006). Currently, there are 14 species from the suborder Mysticeti and 75 species from the suborder Odontoceti (Committee on Taxonomy, 2023). At least 46 species of cetacean have been registered off the Brazilian EEZ (Miranda et al., 2020), of which

seven are considered threatened and one is near threatened with extinction (MMA, 2022). With 38 recorded species, the southeastern and southern EEZ waters are among the richest worldwide, with about 83% of all cetacean species registered in Brazil (Martins et al., 2023). The Brazilian list of threatened species (MMA, 2022) includes eight marine cetaceans classified under some degree of threat” (Fig. 1. 3).

Cetaceans are a group of highly specialized animals with numerous adaptations for life in the water, performing essential ecosystem functions for the proper functioning of marine ecosystems, such as the regulation of trophic chains and nutrient cycling (Roman et al., 2014). Due to their long gestation periods, low birth rate, slow growth, and long life cycle, cetaceans exhibit low population growth rates, and increased mortality rates can cause rapid declines in populations that require long periods for recovery (Breen et al., 2017). Many species were intensively hunted until the last century, and most populations have not yet fully recovered, even with the suspension of large-scale commercial hunting (de Morais et al., 2017). Additionally, populations are being severely impacted in many parts of the world due to the expansion of human coastal and ocean activities, such as shipping, port developments, oil and gas exploration, and fishing activities, as well as pollution and contamination of the marine environment by industrial, agricultural and urban waste (Di Tullio et al., 2016; Marega-Imamura et al., 2020).

Brazilian Atlantic Ocean host five species of sea turtles, including the green turtle *Chelonia mydas* (Linnaeus, 1758), the loggerhead turtle *Caretta caretta* (Linnaeus, 1758), the hawksbill turtle *Eretmochelys imbricata* (Linnaeus, 1766), the olive turtle *Lepidochelys olivacea* (Eschscholtz, 1829) and the leatherback turtle *Dermochelys coriacea* (Vandelli, 1761) (Guedes et al., 2023). All five species are classified under threat categories on the IUCN Red List (IUCN, 2022), and only the green turtle is not included in the Brazilian list of threatened species (MMA, 2022) (Fig. 1.4).

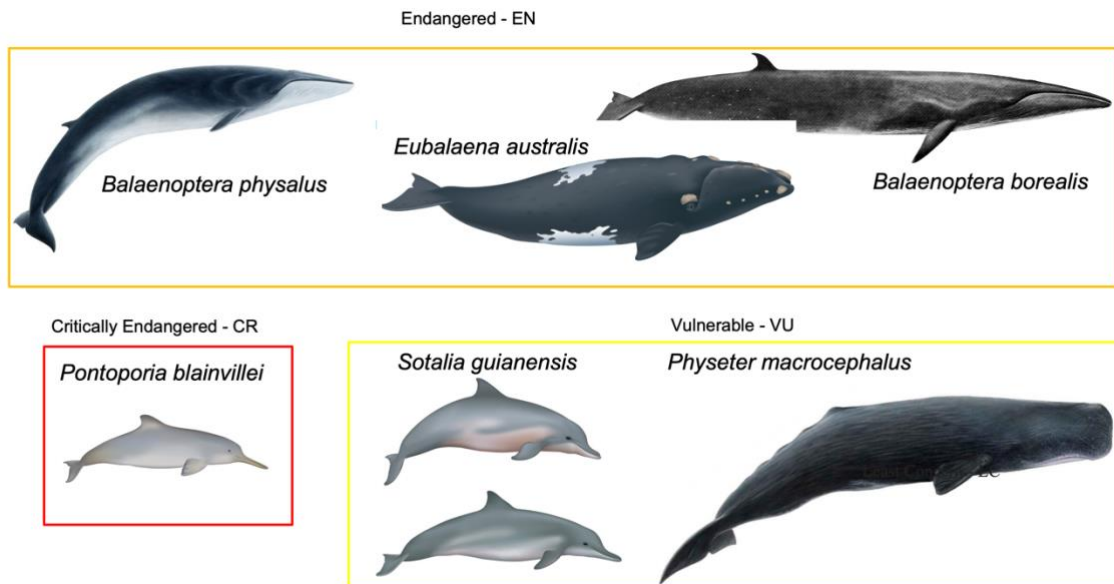


Figure 1.3. Threatened cetaceans selected for ecological niche modelling and their degree of threat according to MMA (2023). Fin whale *Balaenoptera physalus*, southern right whale *Eubalaena australis*, sei whale *Balaenoptera borealis*, Franciscana *Pontoporia blainvillei*, Guiana dolphin *Sotalia guianensis* and sperm whale *Physeter macrocephalus*. (Adapted from the American Cetacean Society, available at <https://www.acsonline.org/fact-sheets>, accessed June 2023).

Populations of loggerhead, olive ridley, and hawksbill turtles have shown significant increases in the abundance of nesting females, while the nesting populations of green and leatherback turtles have remained stable (Neves-Ferreira et al., 2023). Sea turtles nesting in Brazil primarily occur on beaches in the southeast and northeast regions and offshore islands, and the coastal waters of southern Brazil serve as important foraging and developmental habitats, particularly for loggerhead, green, and leatherback turtles (Bugoni et al., 2003; Almeida et al., 2011).

The green turtle has a long life cycle and is the most abundant species of marine turtle along the Brazilian coast. Their migrations in the South Atlantic Ocean can span 2,300 to 3,600 km between feeding and breeding sites (Agostinho et al., 2020). Their nesting areas in Brazil are almost exclusively on oceanic islands, mainly on Trindade Island (Bellini et al., 2013). Green turtles have neritic feeding grounds with possible seasonal migrations between summer and winter habitats. However, observing green turtles is challenging, except during the breeding season when females lay their eggs on nesting beaches (Baudouin et al., 2015). Since 2016 there are guidelines and restrictions for the installation of projects in areas and periods of sea turtle nesting (Sforza et al., 2017) (Fig. 1.4).

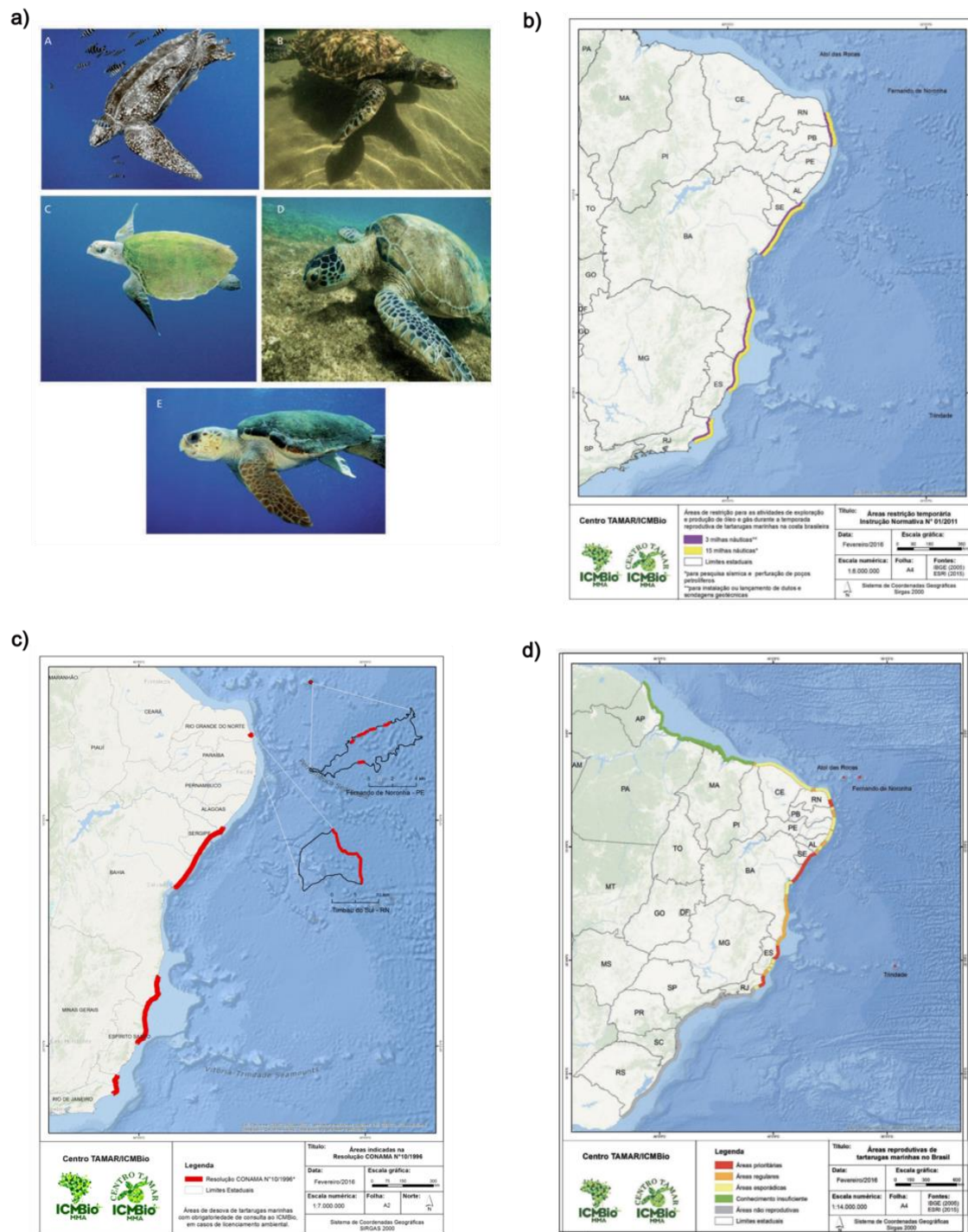


Figure 1. a) Sea turtles with occurrence in Brazil: A. the leatherback turtle *Dermochelys coriacea*; B. the hawksbill turtle *Eretmochelys imbricata*; C. the olive turtle *Lepidochelys olivacea*; D. the green turtle *Chelonia mydas* and E. the loggerhead turtle *Caretta caretta*; b) Areas of temporary restriction for marine seismic prospecting, drilling and pipeline installation activities; c) Map of priority areas for sea turtle breeding and d) Sea turtle breeding areas in Brazil (Adapted from Sforza et al., 2017).

Collecting data on marine animals at large spatial scales is challenging, and studies should aim to obtain critical data to support decision-making in biodiversity management (May et al., 2021). Computer modelling provides a useful tool for predicting species distributions as it is usually more cost-effective than extensive at-sea studies across the area of interest (Alexander et al., 2016). According to Santos et al. (2013), predictive modelling of distributions of species offers a potential solution to this challenge by combining occurrence data with environmental variables known to influence the presence of the studied species. Developing a model of the requirements of species based on the selected variables provides insights into their environmental tolerances and habitat preferences, i.e., their ecological niche (Anderson et al., 2003).

The concept of niche was first introduced in ecology by Grinnell (1924) who referred to the ecological or environmental niche as the geographical distribution of a species or population. Grinnell emphasized the importance of climatic variables in defining broad-scale features of distributions, while finer-scale habitat structure and biotic interactions determine the specific locations where organisms are found (Soberón & Nakamura, 2009). Later, Hutchinson (1957) defined the niche as a combination of conditions and resources that enable populations of a species to grow. He distinguished between variables that can be depleted by consumption and those that are conditions for existence, which he termed "scenopoetic". Hutchinson also introduced the concept of the fundamental or potential niche, which encompasses the various habitat characteristics that allow the presence of an organism. In contrast, the realized or effective niche considers not only the physical environment but also the presence of other species and their interactions that influence the occurrence of a particular organism (Hutchinson, 1978).

One approach to understanding the distribution of species at sea is to estimate their fundamental niches (Sillero, 2011). Areas that fulfill the requirements of the fundamental niche represent the potential distribution of a species (McClellan et al., 2014). The fundamental niche is defined as the "n-dimensional volume in the environmental space where a species can maintain a viable population and persist over time", and the realized niche is the portion of the fundamental niche that is constrained by species competition (Hutchinson, 1957).

Species distribution models (SDM) or ecological niche models (ENM) are numerical tools that integrate data on species occurrence or abundance with environmental information. They are used to gain insights into ecological and evolutionary processes and to predict species distributions across different time periods and landscapes, including terrestrial,

freshwater and marine environments (Elith & Leathwick, 2009; Elith et al., 2011). These predictions allow for the extrapolation of species distributions in space and time (Guisan & Thuiller, 2005; Stirling et al., 2016), and find applications in diverse environments (Mannocci et al., 2017). The increasing availability of niche modelling approaches, techniques, and toolkits helps to inform management and conservation strategies by identifying areas of potential conflict between human activities and marine organisms (Elith et al., 2011; Guisan et al., 2013; do Amaral et al., 2018; Renault-Braga et al., 2022).

Among the various algorithms used for spatial distribution modelling, Maximum Entropy (MaxEnt) stands out as a powerful tool. MaxEnt is a presence-only modelling method that predicts the fundamental niche and potential geographic distribution of species based on the principle of maximum entropy (Phillips et al., 2017) to estimate the areas with the highest suitability for species occurrence by relating environmental variables to species presence, aiming to achieve the maximum entropy distribution closest to the uniform distribution (Warren & Seifert, 2011; Roscioni et al., 2013; Warren et al., 2020). MaxEnt establishes a statistical relationship between predictor variables at occurrence points and 'background' points, producing suitability scores for each cell within a specified geographic region (Phillips et al., 2006; Phillips & Dudík, 2008; Warren et al., 2008). These predictions are then used to generate a map indicating the values of ecological niche suitability for each pixel cell (Khan et al., 2022). Understanding the role of habitat features in the distribution of marine vertebrates is crucial for evaluating the effectiveness of existing marine protected areas (MPA) and identifying areas of biological significance for conservation prioritization (Guisan & Thuiller, 2005).

Small sample sizes are often a common problem for modelling seabird, cetacean and turtles, due to limited occurrence data. This is mainly due to their wide-ranging and mobile characteristics, the rarity of some species, the challenges associated with field observations and the difficulty of accessing remote habitats where they live (Redfern et al., 2006; Derville et al., 2018). ENM, especially when using MaxEnt, proves to be a valuable tool for studying species with large ranges and limited sample sizes, as well as for datasets where absence or effort data are not available (Sahri et al., 2021).

The main outcome of the models is the identification of suitable habitats, which can potentially lead to the creation of habitat suitability maps (Sillero, 2011). These predictions of suitability can then be used to generate a richness index (RI) that helps to identify biodiversity hotspots (Sahri et al., 2021). Biodiversity hotspots are geographic regions characterized by a high number of species (Tittensor et al., 2010). Hotspots are often considered areas that should receive increased protection (Ballance, 2018). Niche

modellings are valuable tools for identifying areas of high conservation value, demarcating future MPA, initiating conservation measures, and predicting the impact of anthropogenic activities on species distribution (Fivaz & Gonseth, 2014).

The conservation of biodiversity and the expansion of protected areas are key targets established by the Convention on Biological Diversity to prevent species extinction (CDB, 2022). To ensure effective biodiversity protection, it is necessary to identify hotspots where conservation efforts should be focused to mitigate population decline and biodiversity loss (Vilar et al., 2017). In Brazil, the extent of MPA has increased in recent years, covering 10% of the marine territory. However, their capacity to fulfil global conservation commitments remains uncertain (Pacheco et al., 2018; Steinke et al., 2018). Since collecting data at large spatial and temporal scales is challenging, studies should focus on critical data to support decision-making, and baseline and modelling data should address specific questions related to project monitoring and location characterization (May et al., 2019).

Spatial models can help decision-makers choose areas for development with the least impact on biodiversity and by preventing conflicts at the planning stage (May et al., 2021). These studies are often used for the process of Environmental Impact Assessment (EIA), a central tool to identify, predict, evaluate, and mitigate relevant effects of human activities on the environment (IAIA, 2009; Fonseca, 2023). A conceptual framework in EIA is the relation of cause, condition change and impact, often called an impact chain or an impact network (Sorensen & West, 1992). One of the expected products of large-scale EIA is also the generation of maps of high-risk areas, which could provide a valuable tool to locate sites where more survey efforts are needed to assess the impact on biodiversity (Catherine & Spray, 2009).

In 2023, a technical study was launched in Brazil for the implementation of a pilot maritime spatial planning project (MSP) in the southern region (SECIRM, 2023). Currently, the EIA is the only decision support tool for regulators to assess whether a proposed project can be accepted from an environmental point of view. To implement ecosystem-based management and MSP, it is crucial to employ integrative and spatialized tools capable of identifying local and global patterns of ecosystem modifications (Virtanen et al., 2020). Predicting the distribution of species is essential when planning the appropriate location of infrastructure developments to avoid and reduce their environmental impacts (Bennun et al., 2021).

The global need for changes in the energy matrix to meet the climate goals of the Paris Agreement has driven to the growth of wind power (UNFCCC, 2015). Brazil has committed to the United Nations Paris Agreement to strengthen a global response to climate change and address the global climate emergency by increasing the use of renewable energy resources (Brazil, 2022). Studies point to the existence of a technical offshore wind energy potential of about 700 GW in places as deep as 50 m (EPE, 2020).

In August 2023 there were 78 applications for OWF environmental licenses in Brazil, all of which are in planning stage or in the process of issuing Terms of Reference for the preparation of EIA (IBAMA, 2023). Impacts were anticipated to affect marine animals leading to changes in species distribution and abundance (Abramic et al., 2022). Placing OWF at higher-risk sites may result in approval delays, and increased development and operational efforts and costs (Bennun et al., 2021). Careful spatial planning of the construction site of wind farms has been identified as a key factor in mitigating the potential impact on wildlife (Larsen & Madsen, 2000; Punt et al., 2009). This is the ideal moment to structure marine spatial planning that involves the positive and negative impacts of this energy production on biodiversity.

1.1. Objectives

The aim of this work was to study seabirds, cetaceans and turtle distributions and biodiversity hotspots within the southwest Atlantic, in the area delimited by the marine Exclusive Economic Zone of Brazil and to identify areas for OWF development that decrease their potential impact in these animals.

The specific objectives were:

- A) Conduct a systematic review of the impacts of OWF on biota globally and to provide a comprehensive overview of the potential impacts on marine organisms, with focus on seabirds (Chapter II);
- B) Utilize ecological niche modelling to identify the spatial and temporal patterns in distribution by seven procellariiform species, and identify target species at risk of impacts of OWF in the Brazilian southern Economic Exclusive Zone (Chapter III);
- C) Assess the ecological niche of six threatened marine cetacean species and the overlap between the Brazilian Marine Protected Areas, fishing zones, and planned OWF in the Atlantic Ocean of South and Southeast Brazil (Chapter IV);

D) Predict the fundamental niche of 29 marine vertebrate species in the Santos and Campos Basins, evaluate biodiversity hotspots for ten cetaceans, six seabirds, and one turtle within depths ranging from 0 to 1000 m and assess the overlap between the hotspots and OWF areas (Chapter V).

CHAPTER II.

A systematic review of impacts of offshore wind farms on biodiversity and avifauna assessments

Abstract

The increasing number of offshore wind farm (OWF) projects aiming to contribute to the objective of reducing greenhouse gas emissions presents a challenge for biodiversity management to be addressed through strategic and targeted environmental impact assessments. We conducted a systematic review of scientific articles located on Web of Science and Scopus databases, covering January 2000 to December 2022, to obtain the most updated scientific findings concerning OWF and its impacts on biota. A total of 104 papers were in-depth read to systematize the data on the stage of development of OWF, environmental stressors, impacts, and receptors on biota. A quantitative review of the impact chain since the early project stage, stressors and impacts of OWF on biota. methodologies for diagnosing and monitoring impacted avifauna are presented to inform decision-making and contribute to the development of sustainable energy policies. Our results emphasize the importance of studies on all phases of OWF development on impacts on marine fauna but also further investigation in understudied topics such as impacts on macroinvertebrates, algae, plankton, zooplankton, and biofouling. Were systematized a total of 71 papers on the diagnosis of OWF impacts on birds. The main methodologies used for obtaining data on birds were boat-based surveys, indexes, and visual aerial surveys, analyzed mainly by modelling patterns of abundance and distribution, mapping directional analysis of flight paths and index of sensitivity or vulnerability. The abundance, distribution, and flight behaviour were the most frequent indicators of potential risk. More exhaustive and integrative assessments of both positive and negative impact indicators are needed for adequate planning and mitigation actions.

Keywords: Environmental Impact Assessment, impact chain, marine species, seabirds, sustainable energy.

2.1. Introduction

Offshore wind is a key renewable energy resource, whose technology contributes to the goal of reducing greenhouse gas emissions (UNFCCC, 2015), but can have complex environmental effects due to the large scale of some wind farms, the diversity of infrastructure technologies, and their location in potentially vulnerable environments (Willstead et al., 2017). Offshore wind farms (OWF) are increasing globally and require a comprehensive assessment of their potential impacts on marine biota. In 2022, the global cumulative offshore wind power capacity was 63 GW (IRENA, 2023), in which Europe is the largest market, summing 50.4% of global offshore wind installations.

It is thus necessary to understand the environmental baseline that will assist in monitoring methodologies and mitigation strategies, required to minimize the environmental impacts of the new technologies (Martínez et al., 2021). To better understand the OWF impacts, studies have been conducted over the years, resulting in a wealth of scientific literature on the subject (e.g., Philip-Jones and Fischer, 2013; Lüdeke, 2017). Impacts were anticipated to affect birds, benthos, and marine animals due to the introduction of new hard substrates, the movement of rotor blades, potential underwater noise, and the exclusion of fisheries, leading to displacement, changes in species distribution and abundance, and collision risk (Lindeboom et al., 2011; Degraer et al., 2013). Among the affected taxa, avifauna, including seabirds, shorebirds, and non-marine birds crossing the area during migration, are particularly susceptible to these impacts (Garthe and Hüppop, 2004; Furness et al., 2013; Schwemmer et al., 2023).

These studies are often used for the process of Environmental Impact Assessment (EIA), a crucial tool for evaluating the potential impacts of human activities on the environment. The EIA is a consenting (or permitting) process formalized through regulatory procedures to identify, predict, evaluate, and mitigate relevant effects of development proposals, assessing the future consequences of a present or proposed action (IAIA, 2009; Fonseca, 2023). A conceptual framework in EIA is the relation of cause, condition change and impact, often called an impact chain or an impact network (Sorensen and West, 1992). To synthesize and evaluate the existing research on the emerging and rapidly developing area of renewable energy, we present the results of a systematic review of the impacts of OWF on biota, globally. By analyzing and summarizing the findings of a range of studies, this review aims to provide a comprehensive overview of the potential effects of OWF on marine organisms and identify areas and topics where further research is needed. The precautionary approach regulators take in response to EIA uncertainties can delay the consenting process (Masden et al., 2015). Ultimately,

the goal is to inform decision-making and contribute to biodiversity preservation and to the development of sustainable offshore wind energy policies that consider both the benefits and potential consequences of this technology on the environment. Our study innovates in presenting a quantitative review of the chain of impacts of OWF on marine biota, as well as analyzing the effects of impacts and methodologies for diagnosing and monitoring impacted avifauna.

2.2. Methods

A systematic review of bibliographic databases was conducted to obtain the most updated scientific findings derived from scientific articles concerning OWF and its impacts on biota (Xiao and Watson, 2019; Pullin et al., 2022). The papers were located through searches on Web of Science (Clarivate, 2023) and Scopus (Elsevier, 2023) databases, covering January 2000 to December 2022. First, the following search string and conditions were used: "Offshore Wind" OR "Offshore Wind Farm*" AND "Environment* Impact Assessment" OR "Impact Assess*" and resulted in 2,690 initial records. The records were refined to show "Article or Review Article" and only "Open Access" articles in the categories of Web of Science "Ecology or Marine Freshwater Biology" OR "Environmental Sciences or Zoology" OR "Biodiversity Conservation" OR "Oceanography" OR "Fisheries" OR "Multidisciplinary Sciences" OR "Biology" OR "Evolutionary Biology" OR "Ornithology" OR "Water Resources" OR "Remote Sensing", and also in categories of Scopus limited to "Environmental Science", "Agricultural and Biological Sciences", "Earth and Planetary Sciences", "Energy", and "Biochemistry, Genetics and Molecular Biology", resulting in a total of 1,552 documents. The duplicated records excluded totaled 1,066 sources. The results were scrutinized again, to show results to the target words: "Cetac*" OR "Mammal*" OR "Seabird*" OR "Bird*" OR "Benth*" OR "Biofou*" OR "Fish" OR "Elasmo*" OR "Chondric*" OR "Coral*" OR "Turtle*" OR "Chelon*" OR "Species Distribution" OR "Population*" OR "*plank*" OR "*inverteb*" OR "algae*" with a total of 486 articles, removing redundancies from both databases.

We refined the search only for scientific papers written in English, that assessed the impacts caused by OWF on biota. We decided to focus on peer-reviewed articles because their availability and accessibility make them probably the first resource to be consulted by scientists conducting EIA research (Richardson et al., 2017). After reading each title, keywords and abstract to check the focus on the topic of assessing impacts on biota, we created a final database with 104 articles (Appendix S1). The articles selection workflow followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA Statement) (Moher et al., 2009; Page et al., 2021) (Fig. 2.1).

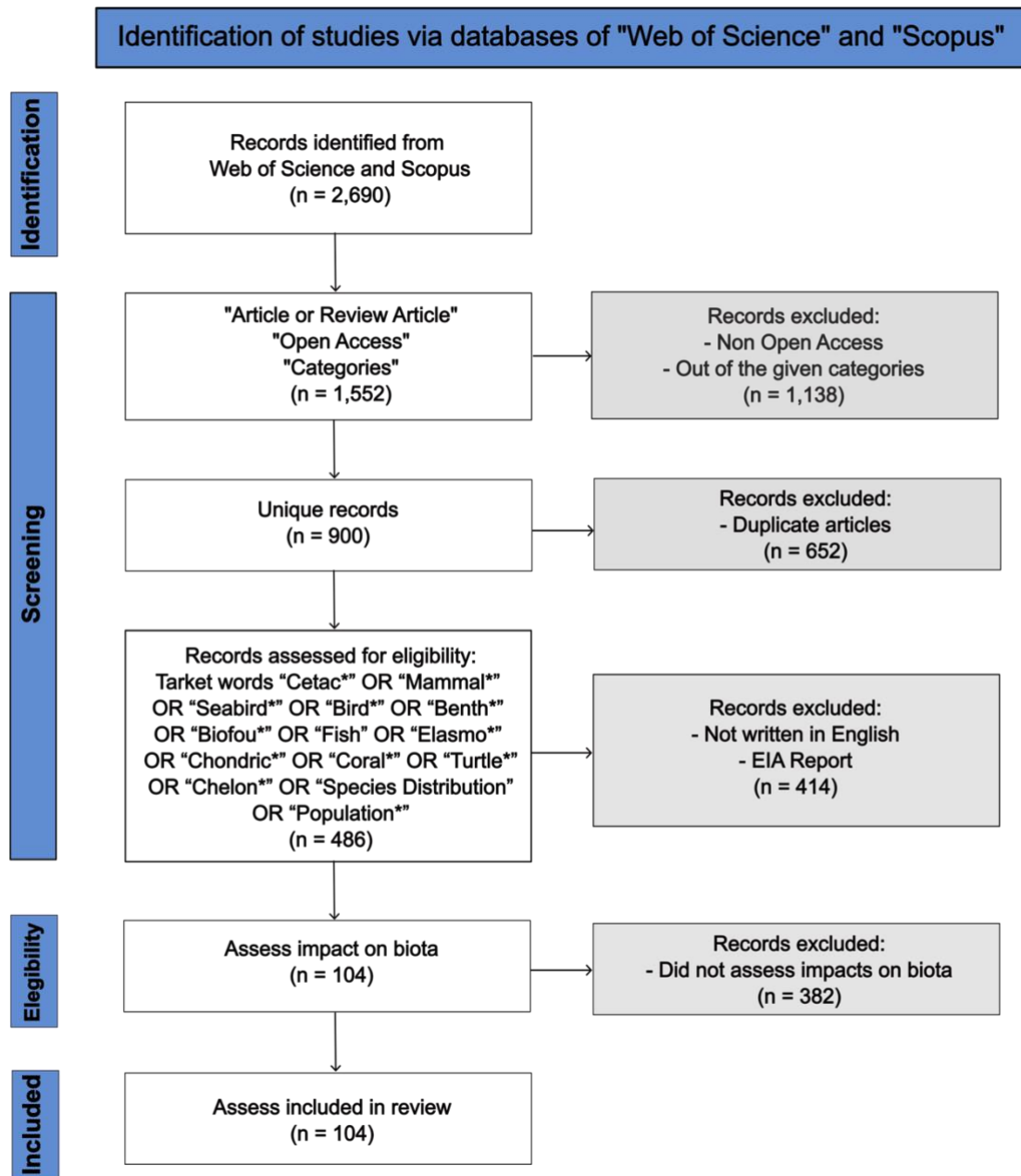


Figure 2.1. Workflow diagram for the systematic literature review of articles related to the biotic impacts of offshore wind farms, based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA Statement). White boxes show the inclusion criteria and the grey boxes the exclusion criteria.

The bibliometric analysis was conducted in “Bibliometrix” (Aria & Cuccurullo, 2017) in RStudio (RStudio Team, 2020) to highlight the annual increase in production and the progress of articles in terms of country scientific productivity.

The 104 selected articles were in-depth read to systematize the data on the stage of development of OWF, environmental stressors, impacts, and receptors on biota. If an article investigated more than one project phase, type of impact and/or receptors, all were considered and each one was analyzed separately. An orderly and systematic approach to cause and consequence relationships helped to identify all relevant impacts. The flows between the project stage, stressors, impact, and receptors were organized in Sankey diagrams with SankeyMATIC (Bogart, 2023) to represent the impact chain. Sankey diagrams are flow diagrams that use arrow width to depict flow rate useful for identifying the most significant contributors to a flow, such as the variables that are commonly studied when assessing the environmental impact of OWF.

According to Burkhard and Müller (2008), stressors (or drivers or aspects) are elements that interact with the environment and cause an impact. Impacts are the alteration of environmental quality resulting from the modification of natural processes by human action and are assessed by their direction (positive or negative), severity, intensity and/or duration (Boehlert and Gill, 2010).

Indicators are standard units that express the amount, size, level, or degree based on verifiable data and are essential to effectiveness assessment (Chen et al., 2023). An impact indicator represents a measure of an environmentally relevant phenomenon used to describe or assess environmental conditions or changes (Burkhard and Müller, 2008; Heink and Kowarik, 2010).

Receptors are ecosystem elements with the potential for some form of response to the stressor (Masden et al., 2010). We considered only biota as the receptor group in this study.

Also, was conducted a systematic review of the nature of impacts, data collection, analysis methodologies and key indicators used to relate the impacts of OWF to the biota group with the highest number of impact citations, i.e. avifauna.

2.3. Results

2.3.1. Bibliographic data

We obtained 104 articles (Appendix A, Table SM 2.1), analysed by Bibliometrix. The number of studies of environmental impacts on biota caused by OWF presented an annual growth rate of 10.8%. No articles were found from 2000 to 2001, with the highest amount of production between 2015 and 2017 (Fig. 2.2).

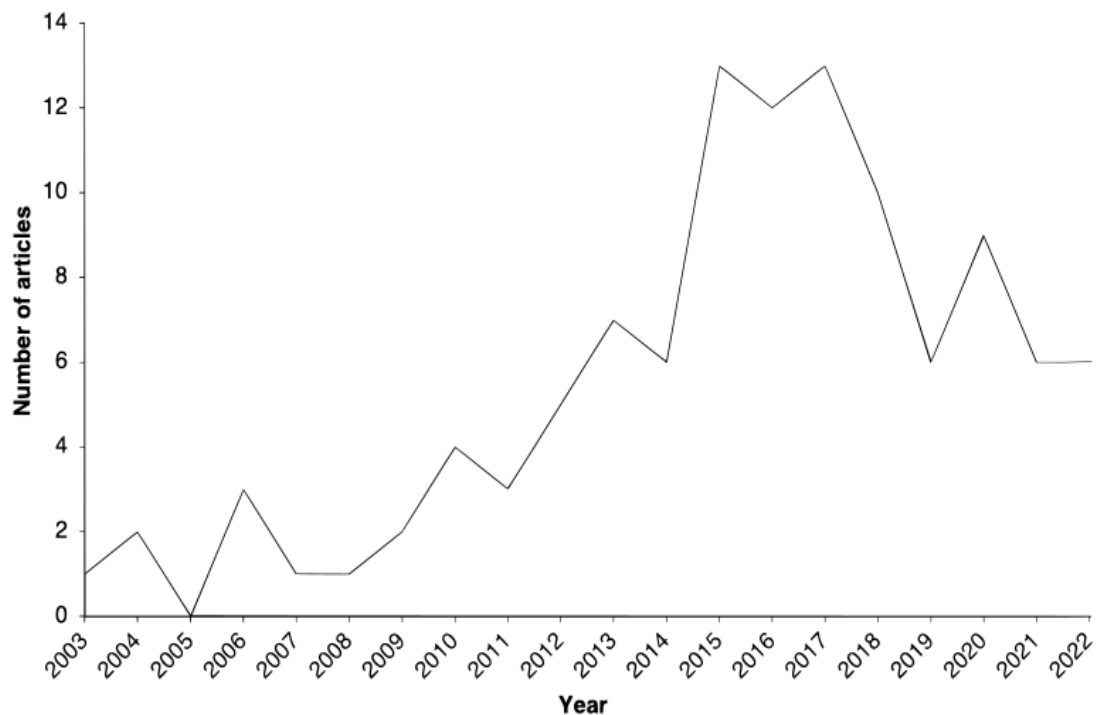


Figure 2.2. The number of peer-reviewed articles on offshore wind farms and impacts on biota published between 2003 and 2022 in Scopus and Web of Science database from the expanded Science Citation Index.

The countries with the highest frequency of participants in publications were the United Kingdom (UK) ($n = 100$), Germany ($n = 49$) and the United States of America (USA) ($n = 41$) (Fig. 2.3).

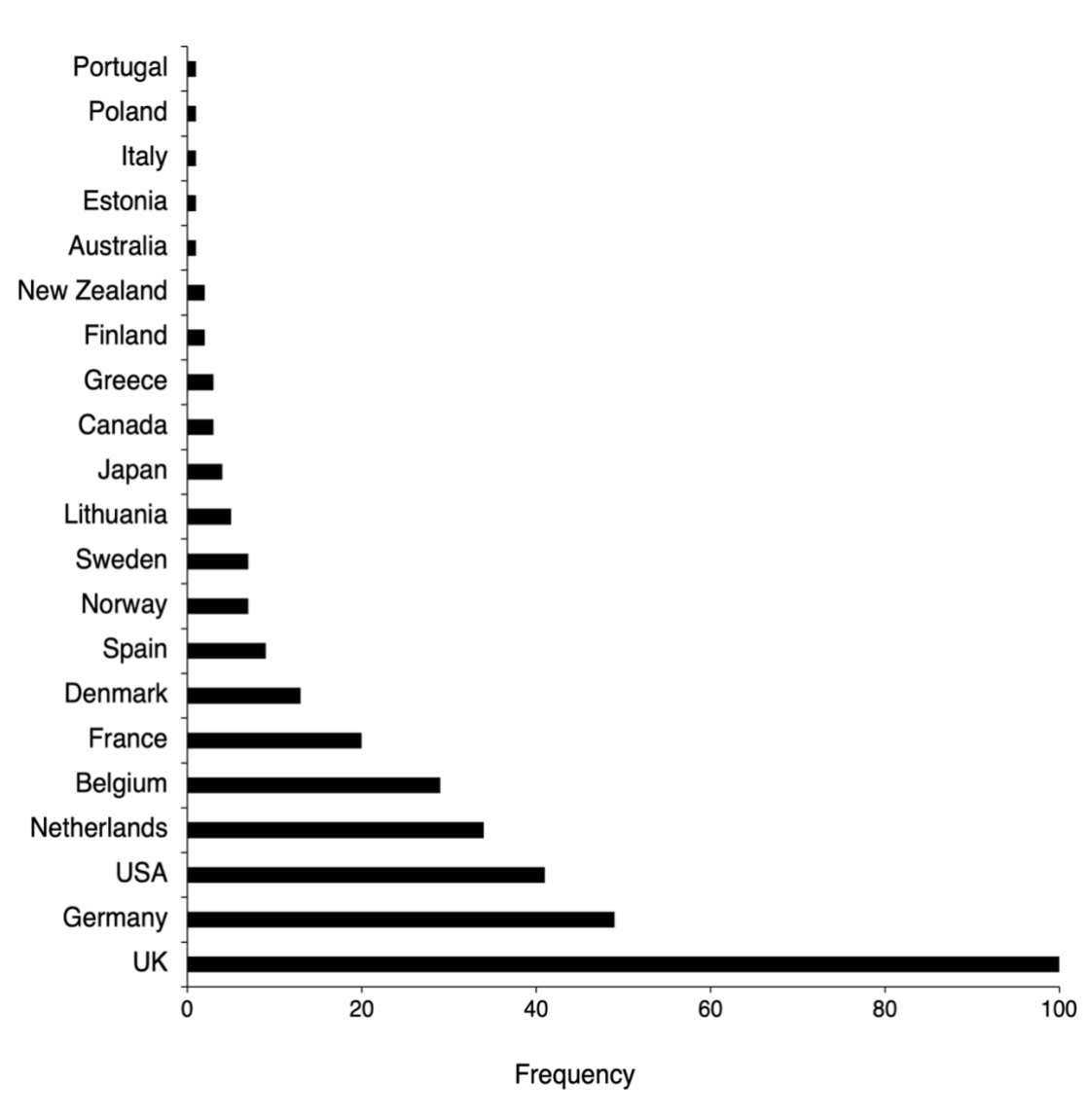


Figure 2.3. Frequency of scientific articles on offshore wind farms and biodiversity published by country of author affiliation, between 2003 and 2022.

2.3.2. Impact chain

From the analysis, it was possible to systematize the impact chain of OWF, represented in Figure 2.4. The operation phase had the highest number of mentions in articles ($n = 65$), followed by the planning phase, with 61 records. In the planning phase, studies include the analysis of the location of the enterprise and the status of biodiversity in the period before the impact. The impacts resulting from the decommissioning phase were not reported in any of the studies.

The five stressors identified were categorized as: a) wind turbine: which includes the effects caused by the tower, hub, nacelle, and blades; b) subsea installations: which include the foundations to support the wind turbines, such as gravity foundations, single piles, jackets or tripods, and also mooring lines, array cables and export cables; c) underwater noise: refers to the sounds generated by the construction, operation, and maintenance of OWF, including the installation and operation of wind turbines, and maintenance activities such as pile driving, cable laying, and vessel movements; d) vessel traffic: refers to the effects of increased marine vessel activity associated with the construction, operation, and maintenance of OWF; e) fishing exclusion: concerns to designated areas where fishing activities are restricted or prohibited. These zones are established to protect the safety of fishing vessels, workers, and equipment, and minimize potential impacts on the operation and maintenance of OWF.

The resulting stress factors mentioned in all phases were the wind turbines, subsea structures, and underwater noise. Vessel traffic ($n = 2$) and fishing exclusion zones ($n = 1$) were also identified, despite the low number of articles addressing these topics.

We identified six main impacts, grouped into: “displacement” which considers the fauna displacement from or attraction to the OWF areas at different geographic scales, studied in 38% of articles reviewed; “composition and abundance” refer to changes in the composition of communities and species abundance (23%); “collision”, which considered the impact of species colliding with turbine structures or vessels, resulting in increased mortality (19%); “trophic web”, related to food web effects caused by changes in prey abundance (9%); “hearing damage” that means temporary or permanent loss of hearing in marine mammals caused by underwater noise (1%), and “spatial prioritization” studies, which have entered the impact category, but it should be understood as the main strategy for preventing impacts because its main objective is to identify areas where they should be avoided (11%). The planning phase encompassed all the spatial prioritization studies and results obtained for the period prior to the construction of the OWF. The impacts related to “displacement”, “collision”, “composition and abundance” and “trophic web” were reported at studies to all stages, and “hearing damage” only in the construction phase.

The biotic receptors of these impacts were identified as birds (65%), benthos (15%), fish (8%) and marine mammals (5%). The lowest percentage of articles was related to studies of impacts on macroinvertebrates (3%), algae (1%), plankton (1%), zooplankton (1%), and biofouling (1%). The spatial prioritization studies presented results considered to be applied to all species (2%).

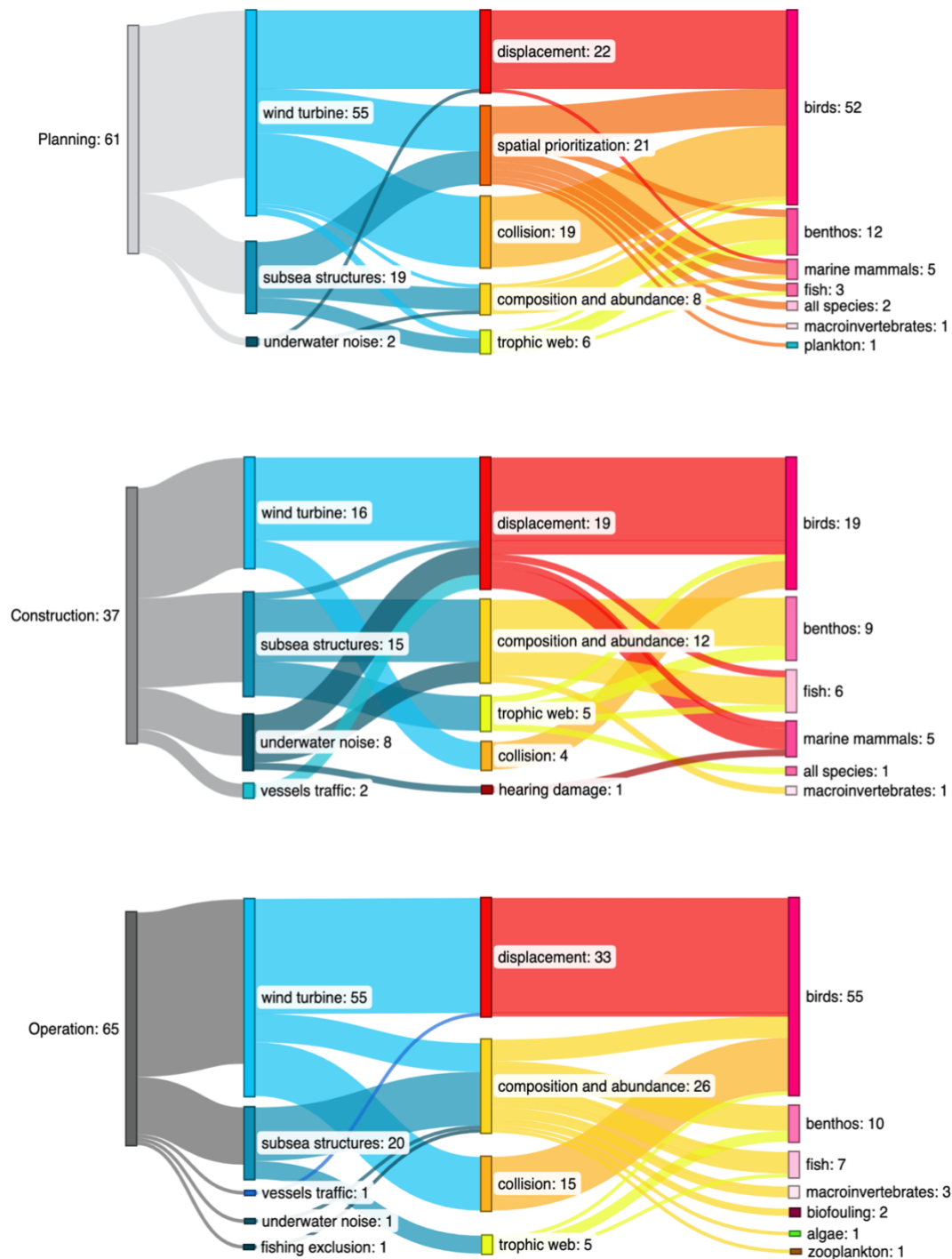


Figure 2.4. Sankey diagram representing the impact chain of offshore wind farms on marine biota. The combination of the number of articles in relation to the stage of the project, stressors, impact, and receptors are based on the bibliographic review. The width of the nodes and coloured lines is proportional to the flow quantity.

2.3.3. Impacts on birds

Birds were the group with the most citations on impacts in the studies with a total of 71 papers on the diagnosis of OWF impacts systematized. Were assessed the nature of impacts (whether positive or negative) on avifauna caused by OWF through a comprehensive review carried out (Fig. 2.5). The impact nature was assigned according to the opinions of authors and statements within each study, without any conservation value assessment. Mostly, the nature of the biotic impact was negative in 59% of responses of birds, unknown in 28%, neutral in 10%, and not relevant in 4%.

Methods of environmental impact assessment of OWF on birds were identified and described (Fig. 2.6). The most frequent methodologies for obtaining data were boat-based surveys (33%), aerial visual surveys (20%) and telemetry (20%). The most frequent methods of data analysis were the modelling of abundance and distribution patterns (58%), index of sensibility or vulnerability (24%) and spatialization of directional analysis of flight pathways (vertical or/and horizontal) (19%). The impact indicators identified were abundance or density (34%), distribution (31%), flight behaviour (28%) and demography (7%).

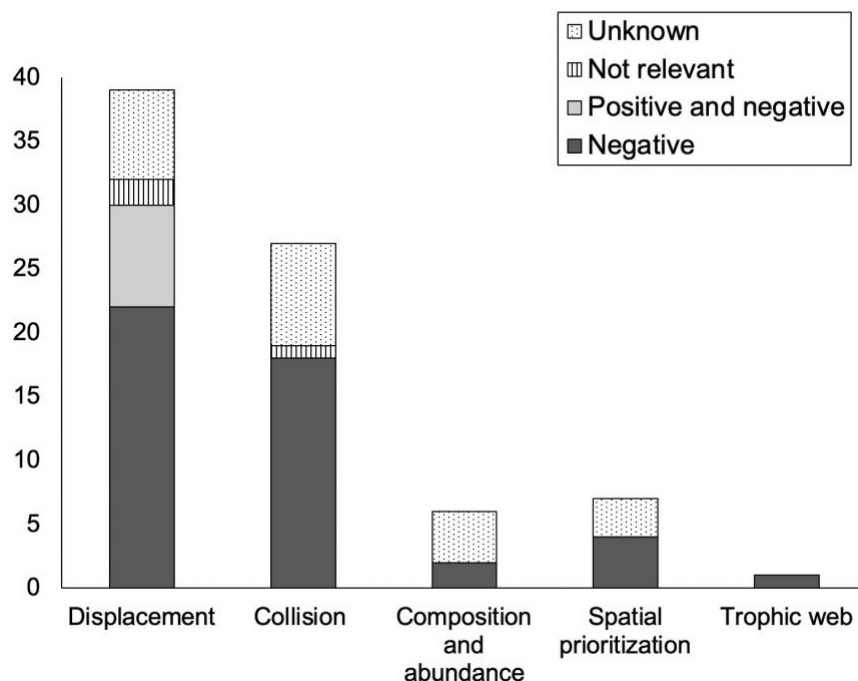


Figure 2.5. Impacts on birds of offshore wind farms in peer-reviewed studies included in the systematic review, from 2000 to 2022. Bars represent the number of biotic responses of birds detected by 71 articles reviewed according to the nature of effects.

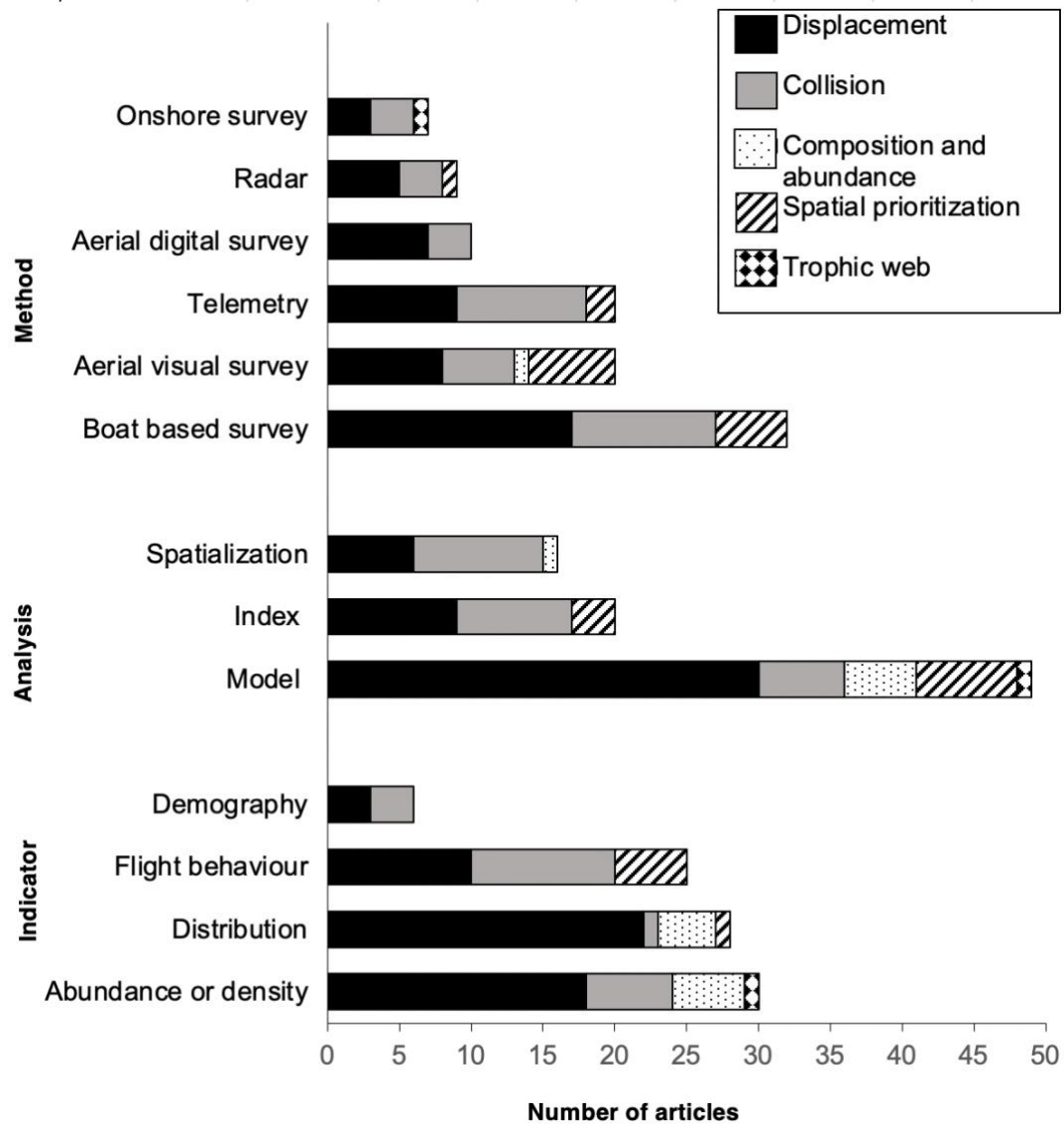


Figure 2.6. Methods used to obtain and analyze data and the indicators used for the impacts identified for avifauna in the systematic review of 71 published articles from 2000 to 2022.

2.4. Discussion

2.4.1. Bibliographic data

We covered the major impacts on marine biota reported in scientific sources over the last two decades on planning, construction, and operation stages of OWF and made further analyses of the most frequently addressed group, avifauna. The predominance of studies on birds probably reflects the perceived risk of collisions and displacements on this group by researchers, potentially derived from impacts already identified on birds in onshore wind farms.

The results indicated that the number of studies investigating the environmental impacts of OWF on biota has increased over the past 10 years. The number of publications in english peaked between 2015 and 2017, a trend consistent with the growth in the installed production capacity of OWFs, with a decline in the number of publications in 2019, which may be attributed to the disruptions caused by the COVID-19 pandemic, as reported by GWEC (2022).

The region with the highest frequency of publications was Europe (mainly UK and Germany), both leaders in offshore wind energy production, and then the USA, which is emerging as a key player in the field (GWEC, 2022; IRENA, 2023). Although China has contributed to 80% of new offshore installations (with approximately 17 GW) and has led the world in new OWF for the fourth year in a row in 2021 (GWEC, 2022), no published articles in english were found from this region. For Europe, where OWF operation is consolidated, there are a greater number of studies designed for EIA to all phases, identifying and quantifying impacts on biotic receptors. Despite this fact, no articles were found regarding the impact of decommissioning of structures, indicating a knowledge gap at a further stage when OWF structures expire their time-life period. After two decades of OWF operation being reached currently, decommissioning impacts should be a topic to receive attention in the near future. Also, there is a clear need to expand knowledge to less studied regions, including China and South America, where the offshore wind market is expected to grow exponentially (GWEC, 2022), but permit issuing is still at earlier stages, such as in Brazil (Lemos et al., 2023).

Our evaluation has, however, some limitations frequent in similar revisions, such as some relevant publications that lack search terms used, the exclusion of reports, books and other technical documents that are not in the databases used and the inclusion of only peer-reviewed scientific articles written in English (Amano et al., 2016). Since there is a chain of impacts, the resulting fluxes of the impact chain are influenced by the target taxa or level of biotic organization studied and may be expanded if increasingly specific impact categories and interactions assessed are adopted (Biasotto & Kindel, 2018).

2.4.2. Impact chain

The most frequent impact systematized to marine biota was “displacement” related to the presence of wind turbines and subsea structures, vessel traffic and underwater noise, with the largest number of studies relating to birds, but also some studies with fish and marine mammals. The effect of displacement is diverse and can span from complete avoidance to attraction to OWF areas (Dierschke et al., 2016; Heinänen et al., 2020;

Peschko et al., 2020a). By avoiding OWF, species can lose valuable habitats or must travel farther to reach suitable areas (Fox et al., 2006). On the other hand, OWF can also act as artificial habitats, attracting animals due to the potential foraging opportunities and/or rest platforms (Fox et al., 2006; Furness et al., 2013; Dierschke et al., 2016; Peschko et al., 2020a). The construction and maintenance of OWFs are further associated with a strong increase in shipping activities (Mendel et al., 2019). The impacts of vessel traffic on marine fauna are related to noise emissions, as well as visual attraction or disturbance (Burger et al., 2019).

Birds may avoid an OWF area (macro-avoidance) or only particular turbines or arrays (meso-avoidance) but may also perform micro-avoidance to prevent a collision with moving rotor blades (Garthe & Hüppop, 2004; Furness et al., 2013; Busch and Garthe, 2016). The behavioural reactions of marine mammals to the noise of pile driving related to “displacement” have revealed large-scale movement over distances ranging from 12 to 25 km (Haelters et al., 2015; Dähne et al., 2017). Despite this, empirical assessment of the impact of these activities on cetacean abundance and behaviour has been difficult to undertake, so there is a lack of large-scale data on distribution patterns and their responses to OWF remain poorly understood (Thompson et al., 2010). The impact of “displacement” on fish species is also poorly known. Rossington et al. (2013) proposed an individual-based model to predict the impacts on cod (*Gadus morhua*) from noise generated during a pile driving event. Both displacement and avoidance of OWF areas by fish are reported in response to noise exposure (Fewtrell & McCauley, 2012) and future studies should be directed at determining species-specific patterns.

The second most frequently mentioned biotic impact was “composition and abundance”, which refers to changes in the composition of communities and species abundance, mostly of benthic, algae, invertebrates, and fish. This impact is mainly related to the mechanical disturbance of the seabed, the creation of artificial reefs, the input of additional energy (e.g. sound) and the cessation of fisheries promoting the recovery and increase in the seabed biodiversity (Wilhelmsson & Malm, 2008; Dannheim et al., 2020; Hofstede et al., 2022), which could be a potentially positive effect of OWF installations.

Another important change to the benthic habitat results from the installation of the turbines, which reduce soft sediment availability and provide substantial hard substrate (Causon et al., 2022) and a significant increase in benthos biomass by enlarging habitats into the pelagic column (Janßen et al., 2015). However, scattered monitoring programs executed at arbitrary spatial scales mainly focus essentially on descriptive structural aspects of soft sediment and fouling communities (Dannheim et al., 2020). Only a limited

number of studies have analyzed OWF effects on the pelagic ecosystem, and even fewer include field measurements (Floeter et al., 2017). For successful micro-siting of turbines and cables avoiding sensitive habitats, more strategic and effective monitoring programs are urgently needed, with detailed baseline knowledge of the distribution and characteristics of benthic habitats, as well as the use of species models and distribution maps (Guarinello & Carey, 2022).

The studies reviewed investigated offshore bird abundance and composition since the planning stage to assess the variation in species-specific and community-level responses, showing dynamic and complex spatial patterns which are far from being understood (Groom et al., 2013; Goyert et al., 2016). The impacts on abundance were mostly analyzed through models on temporal fluctuations (Heinänen et al., 2017; Mercker et al., 2021; van Erp et al., 2021).

The impact of “collision” is related to the presence of wind turbines and subsea structures, with the largest number of studies relating to birds, and less on fish and marine mammals. Among marine species, seabirds have a high potential to be negatively affected by collision with such facilities (Mikami et al., 2022), with risk of injury or death due to encounters with turbines or rotor blades (Drewitt & Langston, 2006; Fox et al., 2006; Band, 2012). The direct impact of mortality due to collision is regularly modelled (Busch & Garthe, 2016). Collision risk models (CRM) make simplified assumptions about the movement and behaviour of seabirds at sea (Masden & Cook, 2016) and tend to assume a constant bird flux across the OWF, incorporating turbine parameters and aspects of bird flight characteristics and morphology (Band, 2012). These models also include a parameter relating to the proportion of birds which actively avoid the collision, the avoidance rate (AR), but that may not reflect reality (Kleyheeg-Hartman et al., 2018; Vanermen et al., 2020). With these models of collision is possible to identify sensitive areas of vulnerability of seabirds to OWF (Mikami et al., 2022). Major knowledge gaps persist on meso- and micro-scale avoidance, nocturnal bird behaviour and responses to meteorological circumstances (Vanermen et al., 2020). It is recommended to collect track data over several years to create an effective sensitivity map (Lane et al., 2020; Pollock et al., 2021; Mikami et al., 2022). The annual cycle stages of birds, roosting opportunities, distance to the colony, wind farm configuration, local habitat, as well as characteristics of species should also be considered when examining the impacts, as their vulnerability may vary throughout the year in different magnitudes of responses (Peschko et al., 2020a, 2020b; Vanermen et al., 2020).

Multiple perturbations interact to influence ecosystem functioning and stability, such as “trophic web” impacts caused by changes in prey abundance (Perrow et al., 2011), with studies focused mostly on the impact on benthos and fish. The reef effect (Raoux et al., 2018) and the fisheries exclusion zones can increase the diversity and abundance of fish making these areas valuable feeding grounds (Coates et al., 2016; Raoux et al., 2019), attracting mobile higher-level predators (Dannheim et al., 2020; Coolen et al., 2022; Hofstede et al., 2022). Conversely, the intensely noisy monopile installation was suggested to be responsible for the reduction in herring (*Clupea harengus*) abundance with a significant decline in the foraging success of little tern (*Sternula albifrons*) (Perrow et al., 2011), highlighting the importance of integrated community studies.

The production of underwater noise has the potential to cause “hearing damage” to acoustically sensitive species (Koschinski et al., 2003; Thompson et al., 2010; Dähne et al., 2017). For the planning stage, it is important to predict or simulate the distribution of marine mammals and sound propagation (Haelters et al., 2015). An effective tool to support assessments of the behaviour of marine mammals is the use of automated devices that remotely record the echolocation clicks of cetaceans (Thompson et al., 2010).

The main strategy for preventing impacts is “spatial prioritization”, in the early stages of planning to avoid conflicts between wildlife and OWF (Heinänen et al., 2020; Bennun et al., 2021). Improving access to a spatially explicit biodiversity database can help to avoid detrimental impacts on the most important sites, species and habitats (Underwood et al., 2018). Species distribution models can be used to provide a baseline context for impact assessment in areas planned for OWF, guiding siting and management decisions (Goodale & Milman, 2019; Friedland et al., 2021; Mercker et al., 2021), in space and time (Best & Halpin, 2019).

Nine taxa have been identified as impact receptors, whose monitoring should move from a species-oriented approach to an integrated and holistic management of the marine environment, considering cumulative impacts (Wilding et al., 2017). Emphasis in future studies should be given in assess the effects of OWF on understudied species, notably of the southern hemisphere, such as sea turtles, penguins, albatrosses, chondrichthyans, corals and pelagic species (Floeter et al., 2017).

2.4.3. Impacts on birds

Our analysis also analysed in detail the impacts of OWF on avifauna, being predominantly negative, with a substantial proportion of impacts classified as unknown.

While it is recognized that birds are affected by development of OWF, impacts on populations are still poorly understood (Green et al., 2016) and are difficult to assess due to inherent limitations of various monitoring techniques (van Erp et al., 2021).

2.4.3.1. Survey methods

Boat-based surveys are the predominant approach for data acquisition of birds, widely used for investigating density and estimating macro-avoidance rates (Thompson et al., 2010; Skov et al., 2018; Vanermen et al., 2020). However, it should be noted that boat-based transect surveys may introduce a disturbing effect on birds, leading to potential biases in data analyses (Vilela et al., 2021). Rangefinders are commonly employed during boat-based surveys to estimate flight heights of birds, known for their ease of operation and accuracy (Borkenhagen et al., 2018; Harwood et al., 2018) and their use should be encouraged.

Visual aerial surveys with line transects are valuable for studying widely distributed or remote bird species (Heinänen et al., 2017). High-altitude flights avoid bird disturbance, while providing detailed information on abundance and distribution (Buckland et al., 2012; Groom et al., 2013). However, they are time-consuming, expensive, and require qualified researchers for accurate surveys (Winiarski et al., 2014; Vilela et al., 2021). Aerial digital surveys also have been used to assess the effects of OWF displacements and ship traffic on the distribution and movements of birds (Burger et al., 2019; Heinänen et al., 2020; Vilela et al., 2021). However, digital aerial survey methods may face challenges due to image quality, variation in body size of species, and bird behaviour (Johnston & Cook, 2016). Buckland et al. (2012) compared abundance from digital and visual aerial surveys showing that the estimates from visual aerial surveys were significantly lower.

Telemetry technologies, including radio and acoustic signals, provided data on the movements and behaviour of individual birds in OWF areas (Cranmer et al., 2017; Johnston et al., 2022), contributing to understanding meso- and micro-scale avoidance, nocturnal bird behaviour and responses to meteorological conditions (Thaxter et al., 2015; Masden & Cook, 2016; Cook et al., 2018; Vanermen et al., 2020). Tracking devices with flight height and depth recorders enhance behavioural inferences (Borkenhagen et al., 2018; Johnston et al., 2022) and should be used in EIA, especially for identification of species at higher risk of collision.

Radar technology was utilized to measure bird density, altitudinal distribution, and monitor avian activity in adverse weather conditions and reduced visibility (Masden et

al., 2009, 2012; Plonczkier & Simms, 2012). Vertical radar data has been used to estimate collision rates, avoidance rates, and effects of OWF on bird populations (Fijn et al., 2015; Van Erp et al., 2021). These techniques work well for fixed areas where migrants commonly pass over, but they cannot readily provide species-specific information.

Unmanned aerial vehicles (drones) are used in recent studies of avifauna abundance and distribution allowing rapid surveys, access to remote locations and a precise scale of habitat use (Costagliola-Ray et al., 2022). Although this is a developing technology, the use of high-definition thermal cameras integrated on offshore platforms to detect bird micro- and meso-evasion and collision rates in three dimensions should be encouraged in EIA (Matzner, 2020).

2.4.3.2. Methods of analysis and indicators

The study's three main data analysis approaches were categorized as statistical models, spatialization and species sensitivity or vulnerability index. The impact indicators will be discussed with their generating analyses.

Statistical models, such as generalized additive mixed models (GAM) and generalized linear models (GLM), were used to predict spatial patterns of birds, to correlate species presence or abundance with habitat data, and to examine temporal trends in fecundity rates (Mendel et al., 2019; Peschko et al., 2020a, 2020b; van Erp et al., 2021; Horswill et al., 2022). Other models, such as kernel density estimation, were also employed (Soanes et al., 2013; Mikami et al., 2022). The studies referenced various applications of these models, including assessing habitat quality, analyzing the impact of OWF on habitat, and predicting collision probabilities for bird species. The models were also used to indicate abundance, a parameter essential to predict numbers determinant of population extinction risk (Ehrlén & Morris, 2015; Jørgensen & Fath, 2019).

In the spatialization category, studies focused on applying and refining spatial analysis methodologies, such as analyzing flight pathways and mapping species distributions, hotspot areas of sensitive species and habitats that are likely to be influenced by OWFs (Garthe et al., 2017; Borkenhagen et al., 2018; Pollock et al., 2021). Flight behaviour and distribution are the main indicators generated and considered mainly to determine collision and identify potential measures to reduce impacts (Masden et al., 2012). However, the extent to which seabird collision risk is influenced by turbines is currently poorly understood (Johnston et al., 2022). Three broad categories of distribution maps

are commonly recognized: single-species, community, and abiotic (or potential) habitat maps (Jørgensen & Fath, 2019).

The third category of analysis grouped the articles that used “indexes” composed of weighting parameters to define the significance of changes in ecological and management terms, such as Potential Biological Removal (PBR) (Busch & Garthe, 2016), Flux Collision Model (Kleyheeg-Hartman et al., 2018), and Population Viability Analysis (PVA) (Horswill et al., 2022). O’Brien et al. (2017) do not recommend PBR in an EIA context because these algorithms will depend on multiple assumptions about other population parameters that are not explicitly defined. The main indexes used for birds were used for scoring population collision and displacement vulnerability (Garthe & Hüppop, 2004; Furness et al., 2013; Brabant et al., 2015; Wade et al., 2016; Kelsey et al., 2018) or sensibility over space (Bradbury et al., 2014). However, the extent to which seabird collision risk is influenced by the attraction or displacement in relation with the turbines is currently poorly understood (Johnston et al., 2022) which requires further studies, aiming to obtain empirical data. These indices resulted mainly in the impact indicator “demography” to predict how vital rates are likely to be altered by OWF impacts (Cook & Robinson, 2017; Searle et al., 2019). Concerns about the potential collision risk to Sandwich terns (*Thalasseus sandvicensis*) has led to the refusal of environmental permit to one OWF in England (Broadbent & Nixon, 2019).

Knowledge regarding seabird behaviour may be improved through advances in aerial digital survey, telemetry, laser rangefinders, automated radar-tracking and infra-red thermal for collision detection, which may provide more accurate observations of flight height and movement patterns (Johnston et al., 2022). Research using a combination of these methods collects more comprehensive data on bird populations, behaviours and distribution patterns, considering the advantages and limitations of each approach. Finally, thresholds can vary between jurisdictions, hindering regional assessments for receptors that range beyond national boundaries (Lüdeke, 2017). Good practices in the EIA of OWFs highlight the need for standardization in monitoring and impact analysis procedures and strategic maritime spatial planning considering conservation areas and environmental sensitivity (Lüdeke, 2017).

2.5. Conclusion

We highlight in this review the need for further research, standardization, and strategic planning to ensure the sustainable development of OWF while minimizing its impacts on marine biota. The EIA could be a powerful tool to further development of innovative data

collection and analysis, such as incorporating remote sensing technologies and artificial intelligence for mining large data sets, including images and statistic models to detect and predict impacts, with long-term monitoring at the regional level. The impacts of displacement, particularly on seabirds, emphasize the potential threats posed by OWF. Mitigation actions for collision impacts on birds should be based on field surveys, with technology that allows assessment of flight in three dimensions to support modeling and index studies.

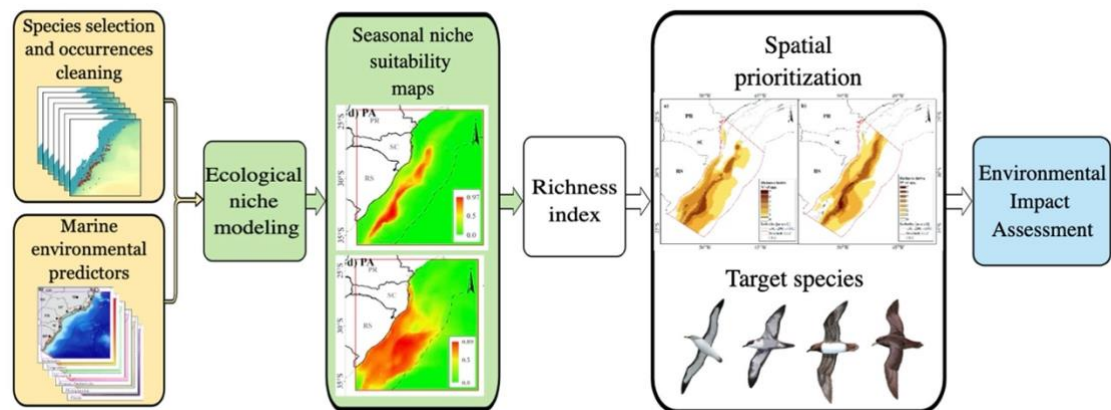
We also stress the importance of studies on all phases of OWF development, more comprehensive assessments of the positive and negative indicators of impacts and further investigation of impacts on macroinvertebrates, algae, plankton, zooplankton, and biofouling, including expansion of invasive species.

CHAPTER III.

Environmental assessment of proposed areas for offshore wind farms off southern Brazil based on ecological niche modelling and a species richness index for albatrosses and petrels

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Graphical abstract



Abstract

The increasing number of offshore wind farms (OWFs) proposed off the Brazilian coast is a biodiversity management challenge that needs to be addressed with strategic and targeted environmental impact assessments. The effects of OWFs on birds are much better studied in the northern than southern hemisphere. Knowledge of species distributions is key to developing effective conservation strategies. Ecological niche modeling can support strategic siting decisions and identify the target species for which mitigation of the impacts of OWFs may be required. We used the maximum entropy algorithm (MaxEnt) for modeling species niche suitability, incorporating environmental variables and presence-only data from tracking and at-sea surveys for seven albatrosses and petrels, of which five are threatened by extinction. We used the predicted niche suitability index (NSI) to calculate niche overlaps, assess distribution patterns and generate spatial prioritizations across seasons based on a species richness index (RI). Atlantic Yellow-nosed Albatross *Thalassarche chlororhynchos*, Atlantic Petrel *Pterodroma incerta*, and Great Shearwater *Ardenna gravis* were selected as target species for monitoring in Brazilian shallow waters (0–200 m depth) in the warm season, and Atlantic Yellow-nosed Albatross and White-chinned Petrel *Procellaria aequinoctialis* in the cold season. The RI was higher in waters between 200 m and 1000 m depth, a preferred area for OWFs with floating foundations. We advocate for the incorporation of niche models in environmental impact studies, as a tool for improving conservation, environmental planning, and impact assessment.

Keywords: Black-browed Albatross, Environmental impact assessment, Spatial planning, Spectacled Petrel, Target species, Wandering Albatross.

3.1. Introduction

Brazil has committed to the United Nations Paris Agreement to strengthen a global response to climate change and address global climate emergency by increasing the use of renewable energy resources (Brazil, 2022). On the one hand, offshore wind is a key renewable energy technology that contributes to the goal of reducing greenhouse gas emissions. On the other hand, wind energy development can have complex environmental impacts due to the large scale of some wind farms, their different infrastructure technologies, and their location in potentially vulnerable environments (Willsteed et al., 2018). No offshore wind farms (OWFs) are currently operating or under construction in Brazil, but several proposals are undergoing Environmental Impact Assessments (EIA). By October 2022, there were 66 EIAs for OWFs under advisement at the Brazilian environmental agency. These would add up to a 169 GW nameplate capacity, considering overlapping projects (IBAMA, 2022).

The EIA is a process, formalized through regulatory procedures, to evaluate and mitigate relevant effects of development proposals before major decisions and commitments (Senécal et al., 1999). Proper siting is the most important mechanism for reducing environmental impacts in the early planning stages (Bennun et al., 2021). Placing new OWFs at higher-risk sites may result in approval delays, and increased development and operational efforts and costs (Bennun et al., 2021). The potential of OWFs to mitigate climate change needs to be studied in more depth, by evaluating the positive and negative impacts of renewable energy alternatives using appropriate tools and methodologies to back the decision-making process (Bailey et al., 2014; Larsen, 2014). Best-practice principles require that EIA are practical and focused (Senécal et al., 1999). Thus, identifying habitats used by affected species is the first step in risk assessment and mitigation, which could involve limiting the construction and operation of turbines to locations and times of lower impact on biodiversity. This means selecting the safest turbine design, installing early warning systems to reduce the risk of collision, among other measures (Bennun et al., 2021; Maxwell et al., 2022). Substantial evidence of OWFs impacts, particularly on birds, include collisions (Masden & Cook, 2016), barrier or displacement effects which causes habitat loss and disruption of flight routes (Cook et al., 2018; Heinänen et al., 2020), change in breeding or feeding sites (Dierschke et al., 2016; Peschko et al., 2021), attraction (Rodríguez et al., 2019), and trophic cascades (Raoux et al., 2017; Pezy et al., 2020). However, few studies have analyzed the effects of OWFs on the pelagic ecosystem, and even fewer have involved targeted fieldwork (Abramic et al., 2022).

Seabird at sea surveys are logistically and financially challenging, often restricting their spatial and temporal coverage (Heinänen et al., 2017). The order Procellariiformes (albatrosses, petrels and shearwaters) is a highly diverse group, with 45 species present in Brazilian waters (Pacheco et al., 2021). Seabirds are among the most threatened of all groups of birds globally (Dias et al., 2019). Knowledge of their distribution and habitat use is key to avoiding and mitigating threats such as OWFs (Azuaje-Rodríguez et al., 2022).

Spatial models can help decision-makers choose areas for development with the lowest impact on biodiversity and improve the consenting process by preventing conflicts from the early planning stages (May et al., 2021). Computer modeling provides a useful tool for predicting species distributions since it is usually much cheaper than carrying out extensive at-sea studies across the area of interest (Alexander et al., 2016). One approach to understanding at-sea distributions is to estimate the fundamental niches of each species (Sillero, 2011). Areas that fulfil the fundamental niche requirements denote the potential distribution of the species (Merow et al., 2013; McClellan et al., 2014). Ecological niche modeling (ENM) provides detailed predictions of occupied areas and habitats by correlating presence with a suite of environmental predictors (Guisan & Thuiller, 2005; Stirling et al., 2016). Predictions generated by ENMs allow species distributions to be extrapolated across space and time, and can be used in a variety of environments (Mannocci et al., 2017). MaxEnt is a well-known modeling method used to predict the species niche and potential geographic distribution based on the principle of maximum entropy applied to presence-only data to estimate a set of functions that relate environmental variables and habitat suitability (Phillips & Dudík, 2008; Phillips et al., 2017; Warren et al., 2020).

This study provides a framework that can be used for mitigating of the potential impacts of OWFs off Brazil, using ENM as a tool for environmental assessment of seasonal changes in marine areas and habitats used by seabirds, and for identifying the target species that are most at risk and require monitoring. The fundamental niches of seven procellariiform species were analyzed in the austral warm and cold seasons, and used to generate a richness index (RI) for identifying the seasons and the areas with greater biodiversity. The analysis focused on the niche suitability of areas used by each species, and the spatial conflicts with OWFs sites. Including this analysis in the early planning process could minimize the potential impacts of OWFs on Brazilian marine biodiversity, a country that has no marine spatial planning approved.

3.2. Material and Methods

3.2.1. Study area

The ENM encompassed the region between 12°S and 40°S, and 60°W and 38°W, in the southwestern Atlantic Ocean. Spatial prioritization was evaluated between 25°S and 33°S, encompassing Brazil's southern Economic Exclusive Zone (sEEZ), which comprises the coasts of Paraná (PR), Santa Catarina (SC) and Rio Grande do Sul (RS) States (Fig. 3.1.).

We divided the area into four bathymetric zones for analysis, reflecting the technologies available for installing wind turbines. The shallowest bathymetric zone (0–50 m depth) comprises 48,247 km² of the sEEZ, with the greatest wind potential and least technical requirements for installing OWFs (Hernandez et al., 2021). Waters between 50 m and 200 m depth comprise the second largest zone of the sEEZ (101,711 km²). In this area, floating wind turbines are preferred. The other zones are located between 200 m and 1000 m depth, and between 1000 m and 6750 m depth, summing to 38,392 km² and 210,825 km², respectively. The installation of OWFs is not financially viable in depths greater than 200 m with existing technologies. The potential for harvesting offshore wind resources in the sEEZ is huge: at 10 m above sea level, wind speeds reach 5–9 m.s⁻¹ in January, and ~10 m.s⁻¹ in July (Pimenta et al., 2019; Tavares et al., 2020b). The sEEZ is also a highly productive region, supporting major commercial fish stocks and with predators occupying higher trophic positions. This area is located at the junction of the Malvinas Current, which transports cold sub-Antarctic waters northward, and the Brazil Current, which transports warm tropical waters south and then east, forming the western margin of the Subtropical Convergence (Odebrecht & Castello, 2001).

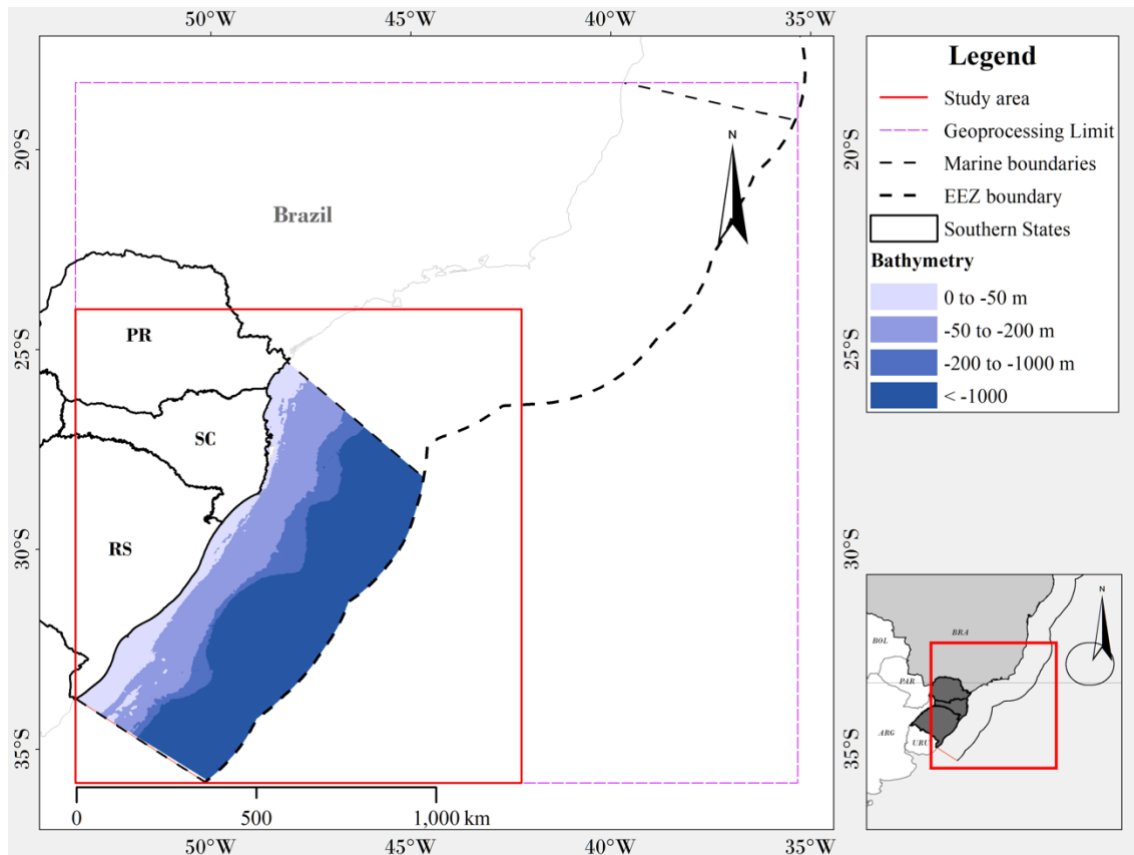


Figure 3.1. Map of the study area in the southwest Atlantic Ocean, indicating the four bathymetric zones included in this study. The area is part of the Brazilian Exclusive Economic Zone (EEZ). The southern Economic Exclusive Zone (sEEZ) includes the coasts of the States of Paraná (PR), Santa Catarina (SC) and Rio Grande do Sul (RS).

3.2.2. Species selection

Studies on birds and the impacts of OWFs have mostly been carried out in the northern hemisphere, and concluded that gulls (*Laridae*) and gannets *Morus* spp. are the most vulnerable to collision effects and avoidance behavior (Furness et al., 2013, Cook et al., 2018).

Presence records of coastal birds, shorebirds or seabirds off Brazil in public databases in Global Biodiversity Information Facility (GBIF) or Ocean Biogeographic Information System (OBIS) were too few for modeling of distributions. Gulls are scarce offshore, gannets are vagrants and there are no seaduck in Brazil (Pacheco et al., 2021), thus these groups were not included in our analyses. Furthermore, the minimum distance from shore recommended for OWFs installation in Brazilian waters is 18.5 km (IBAMA, 2019), which is why this study focused on pelagic seabird species, including several

procellariiform species that frequently use the sEEZ during the breeding or non-breeding seasons, and are either present in high numbers or are threatened by extinction (Table 1): Wandering Albatross *Diomedea exulans*, Atlantic Yellow-nosed Albatross *Thalassarche chlororhynchos*, Atlantic Petrel *Pterodroma incerta*, White-chinned Petrel *Procellaria aequinoctialis*, Spectacled Petrel *Procellaria conspicillata*, Black-browed Albatross *Thalassarche melanophris* and Great Shearwater *Ardenna gravis*.

Table 3.1. Procellariiform species included in ecological niche modeling in the southern Economic Exclusive Zone of Brazil, their threat status at global level (The International Union for Conservation of Nature [IUCN]) and national level (Brazilian Ministry of the Environment [MMA]), and whether listed by the Agreement on the Conservation of Albatrosses and Petrels (ACAP, 2018). CR: Critically Endangered; EN: Endangered; VU: Vulnerable; LC: Least Concern.

Species, author, and year	Common name	Species code	Degree of threat		ACAP
			IUCN	MMA	
<i>Diomedea exulans</i> Linnaeus, 1758	Wandering Albatross	DE	VU	CR	Yes
<i>Thalassarche chlororhynchos</i> (Gmelin, 1789)	Atlantic Yellow-nosed Albatross	TC	EN	EN	Yes
<i>Pterodroma incerta</i> (Schlegel, 1863)	Atlantic Petrel	PI	EN	EN	No
<i>Procellaria aequinoctialis</i> Linnaeus, 1758	White-chinned Petrel	PA	VU	VU	Yes
<i>Procellaria conspicillata</i> Gould, 1844	Spectacled Petrel	PC	VU	VU	Yes
<i>Thalassarche melanophris</i> (Temminck, 1828)	Black-browed Albatross	TM	LC	LC	Yes
<i>Ardenna gravis</i> (O'Reilly, 1818)	Great Shearwater	AG	LC	LC	No

3.2.3. Data sources

3.2.3.1. Seabird occurrence data

The locations of seabirds within the sEEZ were obtained from two robust sources of in situ data: (1) At-sea surveys between 2009 and 2015 in the Brazilian EEZ, with the data held in the Waterbirds and Sea Turtles Laboratory database at the Federal University of Rio Grande (LAATM/FURG). The sampling protocols are described in Neves et al. (2006b), Gianuca (2011), and Daudt et al. (2019). Instantaneous, continuous and follower methods were used, as we were interested in presence data only; (2) Tracking of seabirds from BirdLife International (2021), mostly from deployments of satellite

transmitters (Platform Terminal Transmitters - PTTs), GPS loggers and geolocators (Global Location Sensor or GLS loggers). We used occurrence data from 2003 to 2020 in the analyses. Deployment and other details are provided in Phillips et al. (2006), Bugoni et al. (2009), Mackley et al. (2011), Froy et al. (2015), Clay et al. (2018), Ronconi et al. (2018), and Frankish et al. (2020a). For further information on the at-sea survey and tracking datasets, see Supplementary Material 3.1. Occurrences were divided into warm (October to March) and cold (April to September) austral seasons. Analysis and selection of occurrence data, including scrutiny, filtering, and cleaning of duplicate records (Hijmans & Elith, 2019) were conducted in ArcGIS 10.6 software.

3.2.3.2. Marine environmental data

Key environmental parameters that characterize habitats and at-sea distribution of seabirds were based on bibliographic sources (Ainley et al., 2012; Bosch et al., 2018). In ENMs, these parameters include environmental variables that indicate habitat suitability and are statistically independent (Elith et al., 2011). Initially, we considered long-term averages (2000–2014) of eight spatial variables: sea surface chlorophyll (mg/m^3); sea surface carbon phytoplankton biomass ($\mu\text{mol}/\text{m}^3$); sea surface primary production ($\text{g}/\text{m}^3/\text{day}$); sea surface salinity (Practical Salinity Scale (PSS)) and sea surface temperature ($^{\circ}\text{C}$) obtained from Bio-ORACLE v.2.1 (Assis et al., 2017); mean wind speed (m/s) at 10 m above the sea level raster file obtained with the 'rWind' v.1.1.7 package (Fernández-López & Schliep, 2019) in RStudio software (RStudio Team, 2020) from a time series of monthly averages using data from the Copernicus Marine Service (2021); bathymetry (m), and distance from coast (m) obtained from Sbrocco & Barber (2013). The raster files for each variable were converted to a WGS84 coordinate system with a spatial resolution of ~ 9.2 km using RStudio.

Highly collinear variables were identified using Variance Inflation Factors (VIF) within the 'sdm' package (Naimi & Araújo, 2016; Harisena et al., 2021). Sea surface chlorophyll (mg/m^3) and sea surface carbon phytoplankton biomass ($\mu\text{mol}/\text{m}^3$) were excluded due to high collinearity ($\text{VIF} > 10$) with sea surface primary production ($\text{g}/\text{m}^3/\text{day}$).

3.2.3.3. Ecological niche modeling

Data were analysed using MaxEnt v.3.4.1 (Phillips et al., 2017) in the 'sdm' package in RStudio to generate ENMs represented by the seasonal niche suitability index (NSI) for the seven seabird taxa. The dataset was presence-only, and 10,000 background points were randomly sampled throughout the study area (Elith et al., 2020; Sillero et al., 2021) to reduce spatial bias associated with the patchiness of sampling effort and to adjust

models (Phillips et al., 2009). The presence data were randomly split into 30% and 70% for model testing and calibration, respectively, and a 10-fold cross-validation procedure was used to estimate predictive performance on held-out folds (Elith et al., 2011; Merow et al., 2013). Habitat suitability was mapped using the average of the ten cross-validations (Peterson et al., 2011a), to produce the final raster files for the NSI. Scores for habitat suitability vary from 0 (unsuitable habitat) to 1 (highly suitable habitat).

We evaluated the predicted habitat suitability using the area under the Receiver Operating Curve (ROC), known as the Area Under the Curve (AUC) (Fielding and Bell, 1997), the True Skill Statistic (TSS) (Allouche et al., 2006), and the Boyce Index (BI) (Hirzel et al., 2006). AUC and TSS were calculated using the 'sdm' package and the BI was calculated using the 'ecospat' package (di Cola et al., 2017) in RStudio. Model predictive performances based on AUC values were classified as follows: 0.6–0.7 = poor; 0.7–0.8 = average; 0.8–0.9 = good; and > 0.9 = excellent (Araújo & Guisan, 2006). The accuracy classification scores according to TSS were: < 0.2 = no predictive ability; 0.2–0.4 = poor; 0.4–0.6 = fair; 0.6–0.8 = good and > 0.8 excellent (Allouche et al., 2006). Even though the first two metrics are widely used in ENM, the BI is the most appropriate metric for presence-only models (Pearce & Boyce, 2006). It is a continuous index that varies between -1 and $+1$, where positive values indicate that the model predictions are consistent with the distribution of presences in the evaluated dataset (Hirzel et al., 2006; Scales et al., 2016).

We used Variable Importance (VI) to assess the importance of a particular predictor variable compared to other variables within the same model. VI values range from 0 to 1; higher values indicate more influence on the model and greater explanatory power independent of the other predictors, whereas a value close to zero indicates little independent explanatory power (Thuiller et al., 2009).

3.2.3.4. Niche overlap

We quantified the overlap in species ENM through the Schoener's niche overlap index (D) (Schoener, 1970; Warren et al., 2008), calculated with the 'ENMtools' package in RStudio and applied to pairs of models (Fourcade et al., 2014; Warren et al., 2021). The D index provides an ecological interpretation of niche similarities, ranging from 0 (no overlap) to 1 (all grid cells are occupied by both species), and was used to analyse the species' seasonal patterns. In our study, values of $D \geq 0.65$ were considered high and indicative of significant niche overlap.

3.2.3.5. Spatial prioritization and target species

The spatial prioritization described above identifies areas in which conservation may be relevant according to a conservation value index (Araújo et al., 2019), but does not indicate how many species are present in each site at the same time (Tobes et al., 2016). We used niche suitability maps for warm and cold seasons to generate the RI, which ranged from 0 to 7, i.e., the minimum to the maximum number of species in the same raster cell (Stephenson et al., 2020; Sahri et al., 2021). The RI was based on the sum of the NSI values of all seven seabird species. We used ArcGIS 10.6 software to convert the NSI continuous values into Boolean layers, such that $NSI < 0.7$ was converted to 0, and $NSI \geq 0.7$ was converted into 1 (Pineda & Lobo, 2009; Calabrese et al., 2014). The target areas for each species were selected with the high-suitability niche layers summed using the Sum Overlay Tool in ArcGIS 10.6.

The script for the analyses performed in RStudio is presented in Supplementary Material 3.2.

3.3. Results

3.3.1. Seabird's distributions

Based on the at-sea survey and tracking data, Atlantic Yellow-nosed Albatross and Atlantic Petrel were more common in the study area during the warm season, while the opposite was found for Wandering Albatross, White-chinned Petrel, Spectacled Petrel, and Great Shearwater (Table 3.2.). Data for Black-browed Albatrosses were from at-sea surveys, while those for Wandering Albatrosses were obtained from tracking studies, because the species is difficult to distinguish from Tristan Albatross *Diomedea dabbenena* at sea.

3.3.2. Ecological niche modeling

All ENMs performed better than the random models. Based on the AUC, TSS, and BI, the predictive performance ranged from good to excellent in terms of discrimination power; AUC scores were > 0.90 , and TSS scores were > 0.70 , with good agreement among metrics. All BI values were higher than 0.9 and corresponded well with the presence locations and the model results (Table 3.2.).

Table 3.2 Ecological niche modeling in the warm and cold season for procellariiform species in the Brazil's southern Economic Exclusive Zone. Number of presence points included in models divided into warm (October to March) and cold (April to September) austral seasons. Predictive performance of the models: area under the curve (AUC), true skill statistic (TSS), and Boyce Index (BI). Species codes as in Table 1.

Species code	Presence warm	Presence cold	AUC warm	AUC cold	TSS warm	TSS cold	Boyce Index warm	Boyce Index cold
DE	140	258	0.95	0.96	0.76	0.83	0.95	0.95
TC	1 971	261	0.95	0.94	0.81	0.81	0.98	0.94
PI	791	149	0.91	0.97	0.72	0.85	0.99	0.96
PA	212	814	0.98	0.95	0.88	0.82	0.98	0.99
PC	617	1 436	0.98	0.97	0.89	0.87	0.99	0.99
TM	217	247	0.98	0.98	0.94	0.92	0.98	0.98
AG	227	846	0.91	0.92	0.71	0.72	0.97	0.99

For each species and season, the models produced useful predictions for mapping. Variation in NSI between the warm and cold seasons is shown in Figs. 3.2. and 3.3. Results indicate that the sEEZ is an important area for all albatross and petrel species considered here, with areas with NSI >0.7 in both seasons.

We calculated VI values for each predictor and model (Supplementary Material 3.3.). Overall, warm-season distributions were best predicted by bathymetry (VI 0.25–0.65), distance to coast (VI 0.17–0.42), and wind speed (VI 0.03–0.42), while sea surface temperature and bathymetry (both VI 0.21–0.63) best described cold-season distributions. Salinity had the lowest independent explanatory power in the models (VI = 0.01–0.04 in the warm season and 0–0.25 in the cold season).

The niche overlap index (*D*) ranged from 0.36 to 0.91 (Table 3.3.). Overlaps between cold and warm seasons were high for Wandering Albatross (0.79), Atlantic Yellow-nosed Albatross (0.80), Great Shearwater (0.82), and Black-browed Albatross (0.91), suggesting the use of similar habitat areas in both seasons. A lower overlap for the Atlantic Petrel (0.61), White-chinned Petrel (0.54) and Spectacled Petrel (0.55), indicates a greater seasonal change in habitat use and distribution.

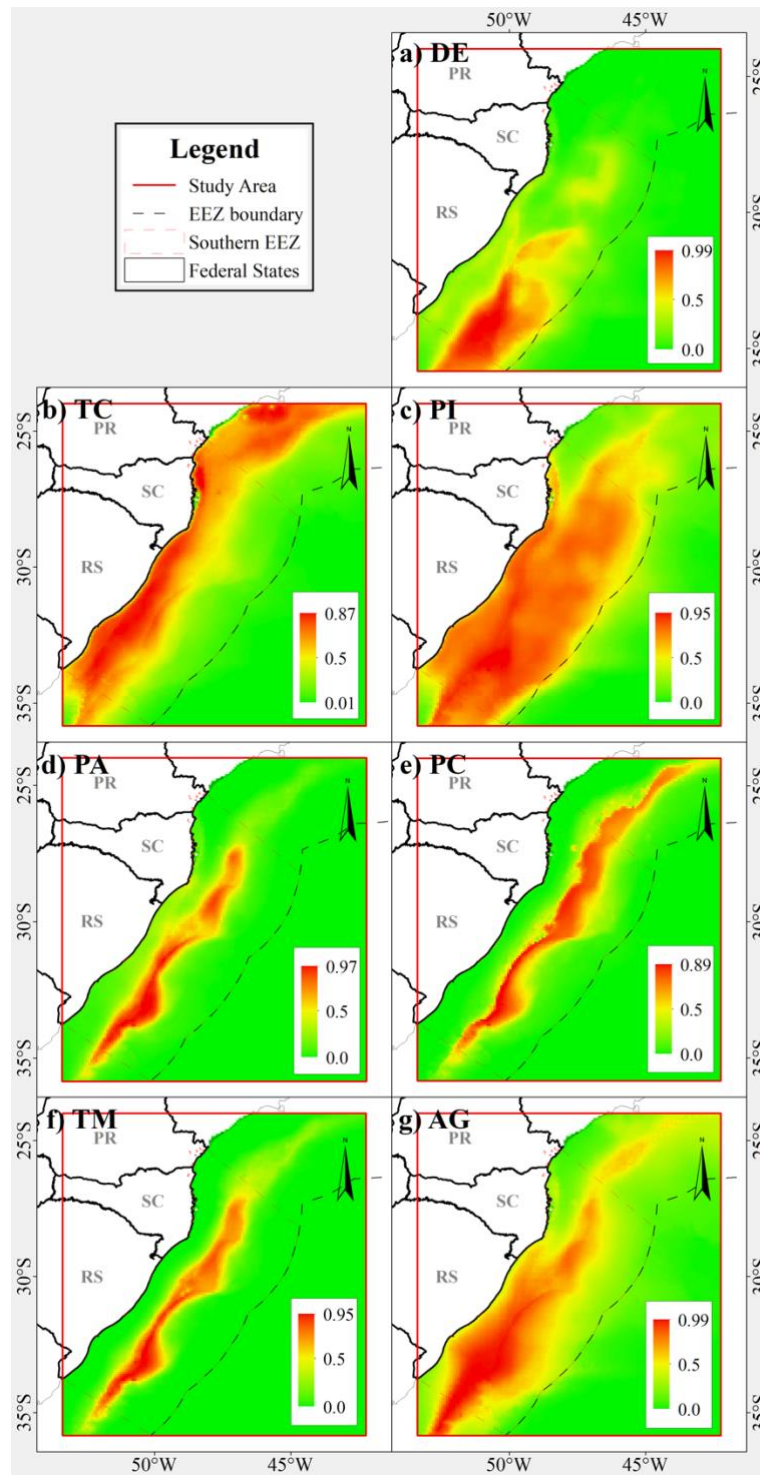


Figure 3.2. Spatial predictions from ecological niche modelling of procellariiform species in Brazil's southern Economic Exclusive Zone, in the warm season (October–March), displayed as niche suitability index (NSI) scaled from 0 to 1, and mapped to a) DE - Wandering Albatross, b) TC - Atlantic Yellow-nosed Albatross, c) PI - Atlantic Petrel, d) PA - White-chinned Petrel, e) PC - Spectacled Petrel, f) TM - Black-browed Albatross and g) AG - Great Shearwater. PR: State of Paraná, SC: State of Santa Catarina and RS: State of Rio Grande do Sul.

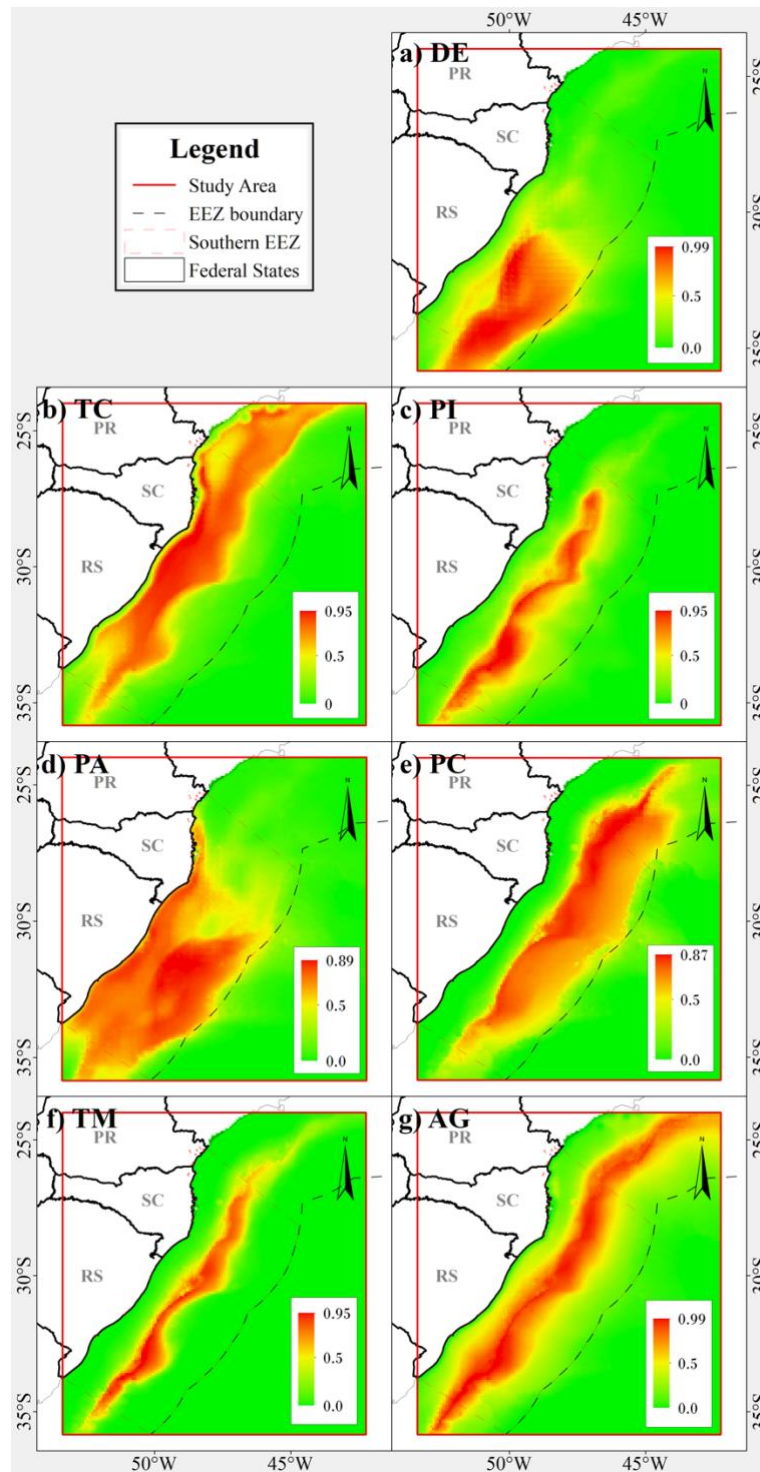


Figure 3.3. Spatial predictions from ecological niche modeling of procellariiform species in Brazil's southern Economic Exclusive Zone, in the cold season (April–September), displayed as niche suitability index (NSI) scaled from 0 to 1, and mapped to a) DE - Wandering Albatross, b) TC - Atlantic Yellow-nosed Albatross, c) PI - Atlantic Petrel, d) PA - White-chinned Petrel, e) PC - Spectacled Petrel, f) TM - Black-browed Albatross and g) AG - Great Shearwater. PR: State of Paraná, SC: State of Santa Catarina and RS: State of Rio Grande do Sul.

The Atlantic Petrel showed the greatest niche overlap with other species in both seasons, particularly during the warm season when most of the sEEZ area was suitable. The results of all seasonal ENMs, presented as $NSI > 0.5$ – 0.7 and > 0.71 – 1 , are in Supplementary Material 3.4.

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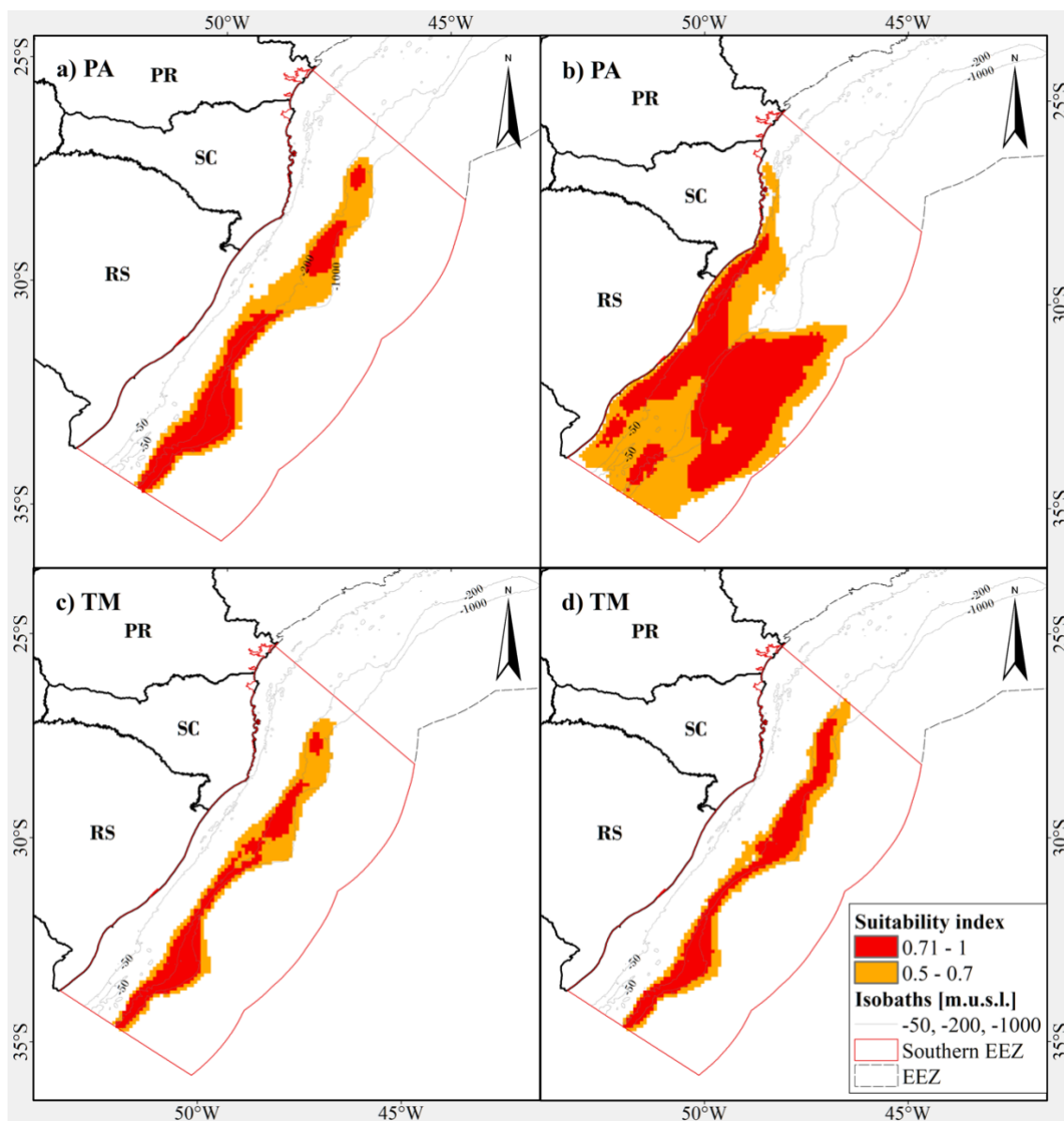


Figure 3.4. Seasonal maps of ecological niche modeling of PA - Spectacled Petrel and TM - Black-browed Albatross, displayed as niche suitability index (NSI) >0.5 to 0.7 and 0.71 to 1, to a) warm season (October–March) and b) cold season (April–September). PR: State of Paraná, SC: State of Santa Catarina and RS: State of Rio Grande do Sul.

3.3.3. Spatial prioritization and target species

Spatial prioritization by season and using the chosen approach ($NSI > 0.7$), showed that about half of the areas in the sEEZ had low suitability for the studied species and the highest RI (five to seven predicted species) was in waters from 200 m to 1000 m depth, corresponding to the outer continental shelf and shelf-break in both seasons. (Fig. 3.5.).

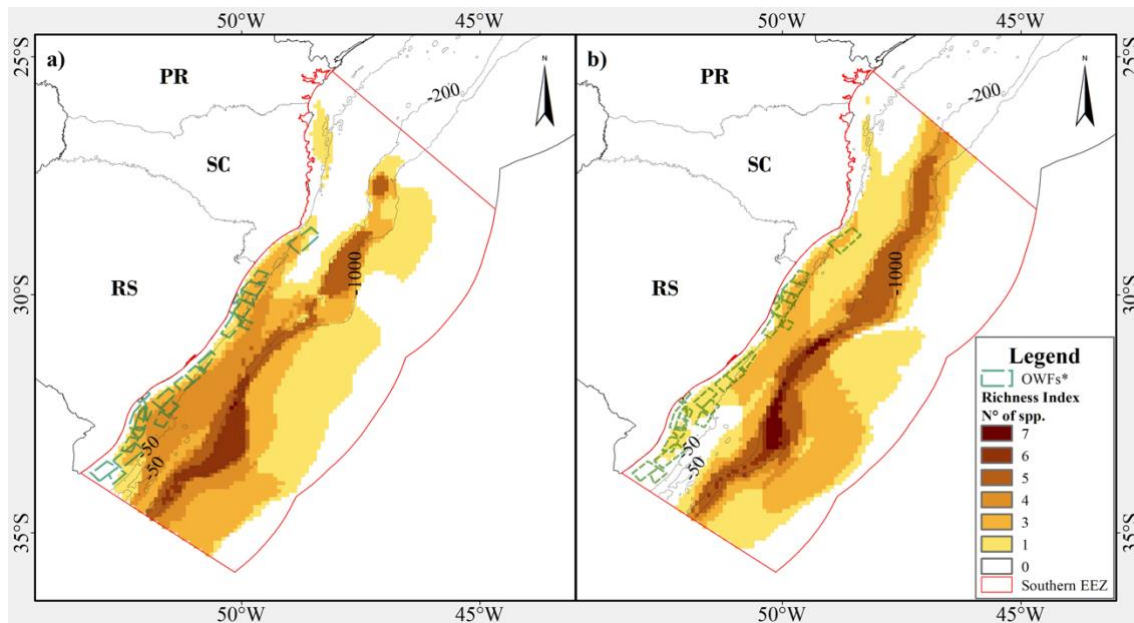


Figure 3.5. Richness index (RI) of procellariiform species in the warm (October-March) and the cold (April-September) seasons in Brazil's southern Economic Exclusive Zone. Darker colours show hotspots of seabird richness per cell. PR: State of Paraná, SC: State of Santa Catarina and RS: State of Rio Grande do Sul. *Polygons represent the offshore wind farms (OWFs) with environmental licensing processes in the initial scoping phase.

Between 0 and 50 m depth, the maximum RI included three species (Atlantic Yellow-nosed Albatross, Atlantic Petrel, and Great Shearwater) in the warm season, over a maximum extent of 5112 km² (10.3%). In the cold season, the RI reduces to two species (Atlantic Yellow-nosed Albatross and White-chinned Petrel), over a 3062 km² area (6.2%). Most of the area evaluated – 21,879 km² and 32,286 km² (44.1% and 65.3%) – had RI = 0 species in the warm and cold seasons, respectively.

The species composition in waters of 0–50 m and 50–200 m depth was the same (Atlantic Yellow-nosed Albatross, Atlantic Petrel and Great Shearwater). These three species occurred in a smaller percentage of this area in the warm season, whereas at

least two species were present in about 70% of the area in the cold season. Waters from 200 m to 1000 m depth were the hotspot in terms of species occurrence. In the cold season, the entire area was suitable for at least one species, and 7.7% for all species according to the RI. About 38% of the area was predicted to hold at least five species. In the warm season, around 42% of this area would contain five to seven species. The largest area within the sEEZ is the depth zone from 1000 m to 6750 m. Despite its size, this zone was suitable for fewer species: in the cold season, no species was predicted to occur in 47.2% of the area, and two species (Wandering Albatross and Spectacled Petrel) in 40% of the area. Even in the warm season, a maximum of six species was predicted to occur in a very small portion (1.4%) of the area.

The results of spatial prioritization with RI mapped for $NSI > 0.5$ and > 0.8 are shown in the Supplementary Material 3.5., and the RI results by percentage of areas and bathymetric zones are shown in Supplementary Material 3.6.

3.4. Discussion

The models we generated are spatially explicit, applicable to a wide range of taxa at various spatial scales, and relatively quick and cheap for assessing potential population-level impacts of different processes and threats (Bennun et al., 2021). Identifying key ecological requirements and species distribution in the oceans is crucial for effective species conservation and mitigation of risks associated with OWFs and other developments (Vignali et al., 2021). We predicted the key pelagic habitats for the seven species of procellariiform during the austral warm and cold seasons through NSI and RI. The ENM also improved our understanding of seasonal changes in habitat use of these highly mobile species (Oppel et al., 2012; Azuaje-Rodríguez et al., 2022). We emphasize that the good and the excellent predictive performances of our models reflect the quality of the complementary sampling methodologies (at-sea surveys and seabirds tracking).

Spatial analyses indicated that OWFs construction in areas between 0 and 50 m depth present the least risk to albatrosses and petrels, based on the low RI. Additionally, there are sites where all species had low niche suitability ($NSI < 0.7$) in the coastal areas of SC and PR. Atlantic Yellow-nosed Albatross, Atlantic Petrel, White-chinned Petrel, and Great Shearwater were identified as the most important target species for impact monitoring, requiring greater attention due to their higher NSI in neritic waters (0 to ~200 m depth). Their NSI varied seasonally, with higher NSI (> 0.7) areas for the Atlantic Yellow-nosed Albatross and the White-chinned Petrel in the cold season, and Atlantic Yellow-nosed Albatross, Atlantic Petrel and Great Shearwater in the warm season.

Based on $RI = 07$, the greatest potential conflict between seabirds and OWFs occurs in waters between with 200 m and 1000 m deep, given that this area was highly suitable for all species. This also makes it an area of great relevance for seabird conservation (Tancell et al., 2016; Dias et al., 2017). Current technology limits the installation of offshore wind turbines with fixed-bottom foundations in shallow waters (up to 60 m depth), which is fortunate according to our results that showed that this region has the lowest suitability for albatrosses and petrels. However, it is likely that in the near future, technical advances will allow for floating (and higher) structures to be installed in deeper waters, which will increase impacts in areas used by multiple seabird species, particularly in terms of the risks of collision or displacement.

In the sEEZ, some species are present during their non-breeding period, and others during the breeding season on long feeding trips, after which they return to incubate eggs or feed chicks at Tristan da Cunha, the Falkland Islands or South Georgia (Tancell et al., 2016; Dias et al., 2017). Our study documented clear seasonal changes in the pattern of use of the sEEZ, where the Wandering, Atlantic Yellow-nosed and Black-browed Albatrosses were present over deep waters throughout the year, since albatrosses spend their non-breeding season exploiting the high productivity areas over the shelf break and around the Subtropical Convergence Zone (Wakefield et al., 2011; Clay et al., 2018).

Our results also showed that the Atlantic Yellow-nosed Albatross was particularly common in shallow waters and should be featured in early efforts to mitigate the risk from OWFs during all seasons, given the high suitability for this species throughout the year. The sEEZ is an important feeding area for post-breeding individuals from the Tristan da Cunha and Gough archipelagos during the austral summer, which feed in the sEEZ predominantly in the cold season (Tavares et al., 2020a). The Black-browed Albatross showed greater niche suitability in the upper continental slope (waters from 200 m to 1000 m depth). Some of the population from South Georgia spend their nonbreeding season at the Patagonian Shelf, and use the sEEZ (Phillips et al., 2005). Black-browed Albatrosses breeding in the Falkland Islands remain close to the Patagonian shelf all year-round (Paz et al., 2021), displaying a nonbreeding range that largely overlaps with the foraging areas used during the breeding season (Ponchon et al., 2019). Juvenile and immature Black-browed Albatross use areas such as the sEEZ during mid-autumn and winter (Bugoni et al., 2008; Bugoni & Furness, 2009).

The South American continental shelf break is an important foraging area exploited by the Atlantic Petrel year-round (Neves et al., 2006a; Pastor-Prieto et al., 2019). Our

seasonal predictions indicated a larger area of highly suitable habitat ($NSI > 0.7$) in the warm season to be occupied by adults which spend the non-breeding period (end of December to mid-April) off the coast of northern Argentina, Uruguay and southern Brazil. The lower winter NSI of the area coincides with the period when this species breeds at Gough Island (Ramos et al., 2017; Pastor-Prieto et al., 2019).

Our results indicated a clear niche segregation between the congeneric White-chinned Petrel and Spectacled Petrel. According to the NSI, the White-chinned Petrel makes extensive use of highly productive coastal waters. These are avoided by the Spectacled Petrel, who prefers the shelf break and the deep offshore mesotrophic or oligotrophic waters further north (Bugoni et al., 2009). Also, the White-chinned Petrel has an extensive foraging range that reduces competition with other procellariiform species (Phillips et al., 2006). During the cold months, this species occupies extensive shallow waters (0–50 m depth). These patterns agree with the information about the influx into sEEZ of nonbreeding adults and juveniles from the population breeding in South Georgia in April and May, the start of the cold season and the non-breeding period (Phillips et al., 2006; Frankish et al., 2020a). Similarly, our analyses show that the sEEZ is used by post-breeding Spectacled Petrels from Inaccessible Island (Bugoni et al., 2009). However, non-breeding birds are more common in shallower waters (< 1000 m depth) during the summer, when fewer White-chinned Petrels are present (Reid et al., 2014).

The NSI for the Great Shearwater confirmed its presence in the sEEZ throughout the year, with a larger suitable area in the warm season (Neves et al., 2006a; Ronconi et al., 2018). Although this species performs a trans-equatorial migration, a huge population breeds at Tristan da Cunha and Gough Islands in the austral summer (Schoombie et al., 2018); as such, their predicted high occurrence in the sEEZ will consist of breeding individuals on long foraging trips during the warm season and staging individuals before or after the migration, in the cold season (Ronconi et al., 2018; Carvalho et al., 2022).

VI calculations showed the relevance of interactions between abiotic factors, including bathymetry and SST, for most species niche predictions. Both factors are known to be important drivers of distribution patterns of some Procellariiformes (Paz et al., 2021; Azuaje-Rodríguez et al., 2022). As described above, the continental shelf and shelf-break were clearly of high suitability for the studied species in terms of bathymetric zones. In general, SST is linked to global patterns of marine biodiversity (Tittensor et al., 2010). Wind was also an important influence on several species' habitat use (Wandering and Black-browed Albatrosses, White-chinned and Atlantic Petrels), which agrees with studies of tracked movements of albatrosses and petrels (e.g. Wakefield et al., 2009;

Clay et al., 2020; Frankish et al., 2020b). Furthermore, flight height and flight behaviour are key factors in determining collision risk with turbines (Maxwell et al., 2022). Unfortunately, we were unable to find information on flight heights for our study species in the southern hemisphere, which could inform the selection of safe blade-tip heights above sea level. Data on flight heights of seabird species that use the sEEZ are therefore urgently required for improving OWFs risk assessments.

Our results also underline the importance of considering the dynamic nature of pelagic habitats when developing management plans and conservation initiatives to protect highly mobile animals such as seabirds. The future installation of OWFs in the sEEZ offers the opportunity for comparing the distribution (through tracking and at-sea surveys) of seabirds before, during, and after construction, by applying a before-after-control-impact monitoring program (Vanermen et al., 2015). A Brazilian biodiversity database compiling data from existing EIAs would allow a more strategic approach to risk assessment to be adopted. Indeed, such a database is a requirement under Brazilian legislation (ICMBio, 2014), but is yet to be implemented.

For the modeling area, no records of the Black-browed Albatross were obtained from tracking, nor records of the Wandering Albatross from on-board censuses. Thus, the *in situ* sampling methodologies should be complemented for better quality in EIA results. MaxEnt was appropriate for modeling the habitat suitability of these highly mobile species, and for predicting habitat use and distribution in non-sampled areas (Oppel et al., 2012; Tobeña et al., 2016; Smith et al., 2020). ENM can be used in EIA to predict the effects of future environmental changes and also in data-deficient years (Guisan & Zimmermann, 2000). However, these models should not be focused solely on initial planning, and do not replace *in situ* surveys for generating data for more robust models that should be used in developing environmental management strategies during the installation, operation and decommissioning of infrastructures. ENM and RI should be focused on local conditions, with campaigns and sampling scales appropriate to the particular threat or impact. Species presence, absence and abundance data can improve the overall prediction of the models (Araújo & New, 2007; Scales et al., 2016), and should be obtained as early as the EIA submission stage. To date, little attention has been paid to the possible impacts of OWFs on South Atlantic species (Rodríguez et al., 2019). Despite limitations and biases inherent to all niche modeling approaches, we are confident that ENM and the use of a RI can improve environmental planning by providing much-needed information on seasonal changes in the distributions and niches of sensitive species.

3.5. Conclusions

This study underlines the value of using ENM and a RI as integral parts of the process of biodiversity conservation, supporting strategic environmental assessments and spatial planning. These methods can be used to examine ecological patterns, identify target species, and select periods and areas where risks are highest, so that more attention is given to developing proper mitigation of biodiversity impacts. Furthermore, the RI can be used to identify key marine areas for different species or communities, assess the potential environmental impacts of other activities, and ensure that seabird surveys take place in appropriate areas (optimising the use of resources allocated to monitoring). The ENM and the RI results serve also as a baseline for studying changes in habitat of seabirds during the monitoring phase, specifically, for studies of displacement and the probability of collision with wind turbines.

Good practices in the EIA of OWFs stress the need for standardization in monitoring and impact analysis, and should ensure strategic marine spatial planning that focuses in particular on areas of high conservation value and environmental sensitivity (Lüdeke, 2017). The large number of proposed OWFs in the Brazilian EEZ represents a management challenge that needs to be met with early environmental planning and assessment. This study showed that OWFs in the shallowest areas of the sEEZ will require specific programs to avoid, mitigate or compensate impacts on the Atlantic Yellow-nosed Albatross, the Atlantic Petrel and the Great Shearwater in the warm season, and the Atlantic Yellow-nosed Albatross and the White-chinned Petrel in the cold season. In contrast, ENM showed that the predicted richness of procellariiform species is higher in waters between 200 m and 1000 m deep. As such, the predicted overlap of vulnerable seabirds with OWFs with fixed foundations on the sea bed is lower than a future scenario involving floating foundation technology operating in deeper waters.

The methods proposed in this work are not yet part of the EIA scoping practices for OWFs in Brazil (IBAMA, 2019). Given the multiplicity of insights derived from this study, we believe that ENMs and RI are a desired addition to the EIA toolbox for sites with little biodiversity data availability and no spatial planning. They provide a scientific basis on which to develop biodiversity conservation criteria, informing licensing processes and mitigation.

CHAPTER IV.

Ecological niche and hotspots of threatened marine cetaceans in southeastern and southern regions of Brazil: Implications for conservation and marine spatial planning

Abstract

In the southwest Atlantic Ocean, the Brazilian Exclusive Economic Zone (EEZ) is known for its high biodiversity, including approximately 160 nationally threatened marine vertebrate species. This region plays a crucial role in several economic sectors. However, these activities, especially fishing, represent direct threats to marine fauna. Offshore wind energy is emerging as a key player in the transition to clean renewable sources but could result in additional impacts for neritic environments. To achieve effective marine spatial planning (MSP) in Brazil, decision support tools are needed to assess the ecological processes and biological features influencing species distribution. This study aimed to characterize the ecological niches and conservation needs of the eight marine cetaceans classified under some degree of threat in the Brazilian list of threatened species. Using MaxEnt we identify areas of high niche suitability in the in water of southeastern and southern regions of Brazil, for the fin whale *Balaenoptera physalus*, sei whale *Balaenoptera borealis*, the southern right whale *Eubalaena australis*, the sperm whale *Physeter macrocephalus*, the Guiana dolphin *Sotalia guianensis*, and the Franciscana *Pontoporia blainvillei*. Our results highlighted the importance of environmental variables in determining the distribution of cetacean species, with bathymetry, distance from the coast, primary productivity and sea surface temperature being key factors. Spatial prioritization showed that the largest area of richness hotspots was between 23.5°S and 28°S in waters from 200 m to 1000 m depth, to the fin, the sei and the sperm whales. The coastal zones are important for the Franciscana and the Guiana dolphin, which are restricted to shallow coastal waters, and for the southern right whale with a preference for coastal waters with high primary productivity and cooler waters. The Franciscana and the southern right whale have overlapping areas with planned offshore wind farms (OWF), emphasizing the need for conservation measures to mitigate the potential impacts. Additionally, gillnet fisheries poses a significant threat, particularly to the Guiana dolphin, the Franciscana, and the southern right whale. Although Brazil has designated protected areas, their distribution is unbalanced, and the ability of the current system to protect threatened marine mammals remains unclear.

Only the hotspots of the southern right whale and the Franciscana have a small overlap with conservation areas, which supports the need to prioritize the remaining hotspot regions as targets for threatened species conservation efforts. Also, further research is required to better understand the conservation needs of threatened cetacean, such as Lahille's bottlenose dolphin *Tursiops gephyreus*, and the blue whale *Baleanoptera musculus*, which were not analyzed due to the low number of systematized records.

Keywords: marine spatial planning, protected areas, species distribution models, threatened cetaceans.

4.1. Introduction

Brazil has one of the largest marine Exclusive Economic Zone (EEZ) in the world (about 3.6 million km²), a region of high biodiversity with about 160 nationally threatened marine vertebrate species, many of which are endemic (Vilar & Joyeux, 2021). The continental shelf and slope of southeastern and southern Brazil is an economically important region for tourism, fishing, and the oil and gas industries (Di Tullio et al., 2016). One impact with a direct threat to marine fauna is that of fishing and bycatch (Lucas & Berggren, 2022). The impact on fauna of bycatch caused by commercial fishing is substantial and greater than the pressures on stocks from climate change, habitat degradation, pollution and ocean acidification (McKechnie et al., 2020; Senko et al., 2022).

It is expected that offshore wind energy will play a key role in the energy transition towards clean renewable sources. Future impacts of offshore wind farms (OWFs) planned for the Brazilian coast must be foreseen, representing a challenge in marine spatial planning (MSP) (Abramic et al., 2022). The expansion of offshore renewable energy includes potential impacts on cetacean populations (Thompson et al., 2010) related mostly to abundance and behavioural reactions to pile driving, seismic surveys and noise of construction activities (Haelters et al., 2015; Dähne et al., 2017). Despite this, we found no references to these potential impacts for biological groups occurring in the South Atlantic or off the coast of Brazil in the review carried out in Chapter II. The existence of endangered species in the area to be analyzed for environmental permits results in specific legal procedures in Brazil (ICMBio & IBAMA, 2014) that may lead to the non-issuance of permits or changes in the initially proposed project.

Decision support tools also can help regulators to determine whether a proposed project can be legally accepted. One of the main stages of MSP is to map the spatial distribution

of ecological processes and biological features (Sahri et al., 2021). Accurately describing and understanding the processes that determine the distribution of organisms is a fundamental problem in ecology, with important conservation and management implications. It is important to map species distributions and marine hotspot areas of sensitive species and habitats that are likely to be impacted by fishing and OWF (Borkenhagen et al., 2018; Pollock et al., 2021).

Collecting data on such large spatial and temporal scales in the marine environment is challenging. Thus, it is crucial that studies focus on data that is critical to support decision making and the baseline and modelling data must be directed to respond to specific questions related to the requirements for monitoring and characterizing the location of the project (May et al., 2019). Quantifying species richness and identifying the variables with most influence on this process are critical components of current studies in ecology and conservation biology (Martins et al., 2023). Fine-scale data on cetacean distribution patterns are limited, and even less is known about the extent to which these species may respond to impacts because most cetaceans are highly mobile and spend a substantial amount of time below the surface, making detection and group size estimation inherently difficult (Redfern et al., 2006). These facts seriously limit our understanding of whether and how current fisheries and the future expansion of marine renewables present a major threat to cetaceans.

At least 46 species of cetacean have been registered off the EEZ (Miranda et al., 2020). With 38 recorded species, the southeastern and southern EEZ waters are among the richest worldwide, with about 83% of all cetacean species registered in Brazil (Martins et al., 2023). The Brazilian list of threatened species (MMA, 2022a) presents eight marine cetaceans classified under some degree of threat. The Franciscana *Pontoporia blainvillei* (Gervais & d'Orbigny, 1844) is listed as "Critically Endangered" together with the blue whale *Balaenoptera musculus* (Linnaeus, 1758). The fin whale *Balaenoptera physalus* (Linnaeus, 1758), the sei whale *Balaenoptera borealis* Lesson, 1828, the southern right whale *Eubalaena australis* (Desmoulins, 1822) and the Lahille's bottlenose dolphin *Tursiops gephyreus* Lahille, 1908, are listed as "Endangered". The Guiana dolphin *Sotalia guianensis* (Van Bénédén, 1864) and the sperm whale *Physeter macrocephalus* Linnaeus, 1758, are listed as "Vulnerable". The IUCN Red List of Threatened Species classifies the blue and sei whales as "Endangered", the Franciscana, the fin whale, the sperm whale and the Lahille's bottlenose dolphin as "Vulnerable", the Guiana dolphin as "Near Threatened" and the southern right whale as "Least Concern" (IUCN, 2022).

Niche modelling approaches, techniques and toolkits available are being increasingly used to provide basic information to determine management and conservation strategies (do Amaral et al., 2018; Renault-Braga et al., 2022) identifying areas of potential conflict between human activities and marine organisms in space and time (Elith et al., 2011; Guisan et al., 2013). Ecological niche models have been widely used in studies on the distribution of cetaceans (Barragán-Barrera et al., 2019; Correia et al., 2021).

One of the powerful modelling tools used by numerous studies for cetacean species worldwide is Maximum Entropy (MaxEnt) a presence-only modelling method used to predict the fundamental niche of species and potential geographic distribution. It is a presence-only modelling method used to predict the fundamental niche of species and potential geographic distribution (Phillips et al., 2017). Based on the principle of maximum entropy MaxEnt estimates a set of functions that relate environmental variables and habitat suitability (Warren et al., 2020). MaxEnt is a tool useful for studies of species with large ranges and small sample sizes, and for datasets for which absence or effort data are not available and it is particularly useful for managers and decision-makers (Sahri et al., 2021).

Brazil has more than 5.7 million km² of marine area under national jurisdiction. The Atlantic Ocean under legal protection in Brazil has 190 protected areas, covering 26.5% of its area (MMA, 2022b), but their distribution is still unbalanced in terms of protection objectives, use and management categories (Endo et al., 2019). Species richness hotspots are geographic regions where the number of species is high (Tittensor et al., 2010), therefore the identification and mapping of these areas is fundamental for the planning of actions to protect endangered species. Cetacean hotspots have already been suggested to be indicative of regions that deserve greater protection (Ballance, 2018). In Brazil, after the whaling moratorium, the threat to conservation of cetaceans includes entanglements in fishing gear and collisions with ships (Danilewicz et al., 2017; Pinheiro et al., 2019; Ribeiro-Campos et al., 2021). Despite reaching in 2018 the total area required by the Convention on Biological Diversity (CDB, 2022), the ability of the current MPA system to represent threatened vertebrates remains poorly understood.

Our goal in the current study was to represent the fundamental ecological niche of six threatened marine cetacean species in Brazilians' southern and southeastern areas, and project it onto a niche suitability map, to identify the cetacean hotspots using a Richness Index (RI), to assess the overlap of the fundamental niche areas with Brazilian Marine Protected Areas, fishing and planned OWF. We hope that our results can contribute to

the evaluation of Brazilian Marine Protected Areas, fishing zones, and planned OWF in the Atlantic Ocean of South and Southeast Brazil.

4.2. Methods

4.2.1. Area of study

The study area was delimited as the Southwest of the South Atlantic Ocean (12°S and 37°S, and 54°W and 33°W) and includes the Brazilian waters of south and southeast regions. The southeast region includes the coast of the states of Espírito Santo (ES), Rio de Janeiro (RJ) and São Paulo (SP) and the south region includes the coast of the states of Paraná (PR), Santa Catarina (SC) and Rio Grande do Sul (RS) (Fig. 4.1). These are the two Brazilian regions with the most populous urban centres, with great socioeconomic importance and energy demand (Tavares et al., 2020).

These two regions are also characterized by different dominant hydrographic dynamics. The oceanic currents in the southeastern are influenced by the tropical waters of the Brazil Current, which transports warm tropical waters from the north to the south, with high-salinity and oligotrophic waters (Campos et al., 2000). The southern region is highly productive, supporting major commercial fish stocks and with predators occupying higher trophic positions. This area is located at the junction of the Malvinas Current, which transports cold sub-Antarctic waters northward, and the Brazil Current, which transports warm tropical waters south and then east, forming the western margin of the Subtropical Convergence (Odebrecht & Castello, 2001). These upwelling events influence the productivity in offshore waters by enhancing the concentration of inorganic nutrients, chlorophyll-a and density of zooplankton (Di Tullio et al., 2016).

4.2.2. Cetacean occurrence data

Data on the occurrence of cetacean species in the Brazilian Atlantic Ocean are few, especially for endangered species with low population density, making all stages of environmental assessment difficult. We obtained occurrences data of cetacean (Fig. 4.1) from monitoring programs required by the federal environmental agency of Brazil (IBAMA), for the environmental licensing process of oil production and transport, available at PETROBRAS (2023) and recorded with telemetry, boat-based, visual aerial and acoustic surveys in the period between 2015 to 2022. In addition, these data were complemented with occurrences obtained from the Global Biodiversity Information Facility (GBIF, 2023) with records from 2000 to 2022, the Ocean Biodiversity Information System (OBIS, 2023), with records from 2005 to 2021 and the Support System for the

Monitoring of Marine Mammals (SIMMAM) of the University of Vale do Itajaí (Cabral & Barreto, 2022) with data from 1983 to 2022.

We adopted the Brazilian list of threatened species which follows the methodology proposed by the IUCN but with annual assessments of local fauna (ICMBio, 2023a). The eight cetacean species with a higher degree of threat initially selected were: the Franciscana, the blue whale, the fin whale, the sei whale, the southern right whale, the Lahille's bottlenose dolphin, the Guiana dolphin, and the sperm whale. Only species with ≥ 10 occurrences were included in ENM (Sahri et al., 2021). Therefore, the Lahille's bottlenose dolphin and the blue whale were not included in the niche analysis.

To reduce autocorrelation bias from clustered occurrence, data was reduced with a 10 km radius buffer around each presence record (Aiello-Lammens et al., 2015) with the "spThin function" in Wallace v.2.0.5 (Kass et al., 2018).

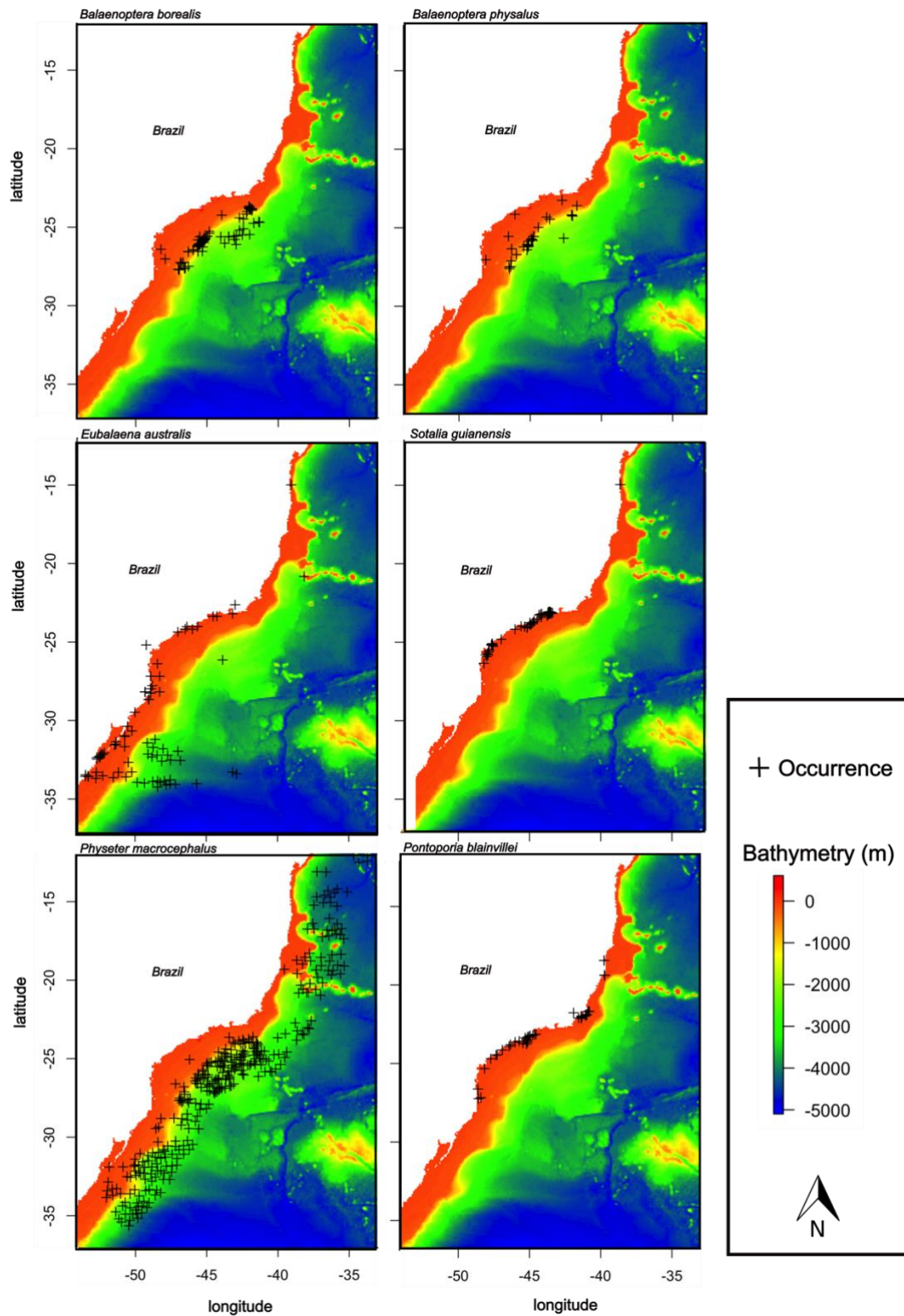


Figure 4.1. Study area and distribution of raw data occurrences of six threatened cetaceans used in the ecological niche modelling and bathymetry in the Atlantic Ocean of South and Southeast Brazil.

4.2.3. Marine environmental data

Habitat features such as bathymetry and productivity are key factors to determine patterns of cetacean distribution (Di Tullio et al., 2016). We initially considered eight spatial variables, based on their reported influence on the occurrence of marine cetacean: sea surface chlorophyll (mg/m^3); sea surface carbon phytoplankton biomass ($\mu\text{mol}/\text{m}^3$); sea surface primary production ($\text{g}/\text{m}^3/\text{day}$); wind speed (m/s); sea surface salinity (PSS); sea surface temperature ($^{\circ}\text{C}$); bathymetry (m) and distance from coast (m) (Redfern et al., 2006; Sahri et al., 2021). Most were available as raster files from Bio-ORACLE v.2.1, with averages from 2000 to 2014 (Assis et al., 2017) converted to a WGS84 coordinate system with a spatial resolution of 5 arcmin (~ 9.2 km) using RStudio. The bathymetry and distance from the coast were obtained from Sbrocco and Barber, (2013). Mean wind speed at 10 m above the sea level was obtained with the 'rWind' v.1.1.7 package (Fernández-López & Schliep, 2019), from a time series of monthly averages from 2010 to 2014 using data from Copernicus Marine Service (2021).

Highly collinear variables were identified using Pearson's correlation coefficient and Variance Inflation Factors (VIF) within the 'sdm' package (Naimi et al., 2014; Harisena et al., 2021). Sea surface chlorophyll (mg/m^3) and sea surface carbon phytoplankton biomass ($\mu\text{mol}/\text{m}^3$) were excluded due to high collinearity with sea surface primary production ($\text{g}/\text{m}^3/\text{day}$). Values used in model predictions were the means of sea surface primary production ($\text{g}/\text{m}^3/\text{day}$), wind speed (m/s), sea surface salinity (PSS), sea surface temperature (SST) ($^{\circ}\text{C}$), bathymetry (m) and distance from the coast (m).

4.2.4. Ecological niche modelling

Ecological niche modeling is a potentially powerful tool for understanding the ecological processes and distribution of cetaceans (Redfern et al., 2006). To generate ENMs our presence-only datasets were analysed using MaxEnt v.3.4.1 (Phillips et al., 2017) in the 'sdm' package, represented by the niche suitability index (NSI). Scores for habitat suitability vary from 0 (unsuitable habitat) to 1 (highly suitable habitat). To address sampling bias, we used a spatial thinning algorithm to select points 10 km apart, in Wallace software (Kass et al., 2018). We also generated 10,000 background points (Phillips et al., 2009) randomly sampled throughout the study area (Elith et al., 2020; Zurell et al., 2020; Sillero & Barbosa, 2021). The data were randomly split into 30% and 70% for model testing and calibration, respectively, and a 10-fold cross-validation procedure was used to estimate predictive performance on held-out folds (Guisan et al., 2006; Merow et al., 2013). Habitat suitability was mapped using the mean of the ten

cross-validations (Peterson et al., 2011a) to produce the final raster files for the NSI, a tool previously used to identify hotspots for several vertebrate groups, including marine mammals (Renault-Braga et al., 2022).

The predictive habitat suitability from the MaxEnt models was evaluated using the area under the Receiver Operating Curve (ROC), known as the area under the curve (AUC) (Fielding & Bell, 1997; Araújo & Guisan, 2006) and the True Skill Statistic (TSS) (Allouche et al., 2006). AUC and TSS were calculated using the 'sdm' package in RStudio. Model predictive performances based on AUC values were classified as follows: 0.6–0.7 = poor; 0.7–0.8 = average; 0.8–0.9 = good; and >0.9 = excellent. The accuracy classification scores according to TSS were: <0.2 = no predictive ability; 0.2–0.4 = poor; 0.4–0.6 = fair; 0.6–0.8 = good and >0.8 excellent (Landis & Koch, 1977; Allouche et al., 2006).

Variable Importance (VI) was used to assess the importance of a particular predictor variable compared to other variables within the same model. VI values range from 0 to 1; higher values indicate more influence on the model and greater explanatory power independent of the other predictors, whereas a value close to zero indicates little independent explanatory power (Thuiller et al., 2009).

Response curves were obtained by model varying only one variable while maintaining all other variables constant where the x-axis represents the range of values of the environmental variable, and the y-axis gives the probability of occurrence on a scale from 0 (low probability) to 1 (high probability) (Elith et al., 2011).

4.2.5. Spatial Analysis

The MaxEnt NSI raster files were imported into QGIS (2023) software. Areas with high habitat suitability ($NSI \geq 0.6$) were considered for the analysis of hotspots for the target species (Ranù et al., 2022) and converted into the Boolean category 1, and pixel values equal to 0 were considered null and were removed (Pineda & Lobo, 2009; Calabrese et al., 2014). We used NSI to generate a richness index (RI), which ranges from 0 to 6, i.e., the minimum to the maximum number of species in the same raster cell (Stephenson et al., 2020; Sahri et al., 2021). Afterwards, areas with high habitat suitability of the target species have been overlapped to map and quantify the biodiversity hotspot, an area with higher biodiversity (Ranù et al., 2022). The RI does not indicate how many species are present in each site at the same time (Tobena et al., 2016), but can identify areas in which conservation may be relevant according to a conservation value index (Araújo et al., 2019).

We obtained Marine Protected Areas (MPA) shapefiles from the official Brazilian protected areas database (ICMBio, 2023b), to which a 5 km radius was applied, considered as the buffer of influence of the MPA. The shapefiles of OWF with processes submitted to environmental licencing by 24 March 2023, were obtained from IBAMA (2023). The shapefile with kernel density data from bottom gillnets and diversified gillnets fishing was obtained from the Brazilian Program for the Satellite Tracking of Fishing Vessels (MAPA, 2023). The areas of overlap of high habitat suitability of each species with the MPA, OWF and fishing areas were calculated to assess the areas with the most risk of impacts on cetaceans.

4.3. Results

4.3.1. Ecological niche modelling

At-sea records of eight species of cetacean were obtained from multiple databases and the final thinned occurrences used in ENM are presented in Table 4.1. All ENMs produced useful predictions for mapping. Based on the AUC and TSS results the predictive performance ranged from good to excellent in terms of discrimination power. The AUC scores were >0.89, and the TSS scores were >0.78, with good agreement among metrics (Table 4.1).

Tabel 4.1. Ecological niche modelling of cetacean species in the Atlantic Ocean of South and Southeast Brazil. Number of presence points included in models and predictive performance of modellings: area under the curve (AUC), true skill statistic (TSS).

Taxon	Common name	Scientific name	Number of occurrences	AUC	TSS
Family Balaenopteridae					
	sei whale	<i>Balaenoptera borealis</i>	93	0.96	0.85
	fin whale	<i>Balaenoptera physalus</i>	31	0.97	0.94
Family Balaenidae					
	southern right whale	<i>Eubalaena australis</i>	87	0.92	0.80
Family Physeteridae					
	sperm whale	<i>Physeter macrocephalus</i>	327	0.89	0.78
Family Pontoporiidae					
	Franciscana	<i>Pontoporia blainvillei</i>	36	0.96	0.92
Family Delphinidae					
	Guiana dolphin	<i>Sotalia guianensis</i>	408	0.98	0.96

For each species, the models produced useful predictions for mapping. Results indicate that the Brazilian waters of south and southeast regions are an important for the threatened species of cetaceans considered here, with areas with NSI >0.6 near the coastal area and in the bathymetry from 200 to 1000 m depth (Figs. 4.2. and 4.3).

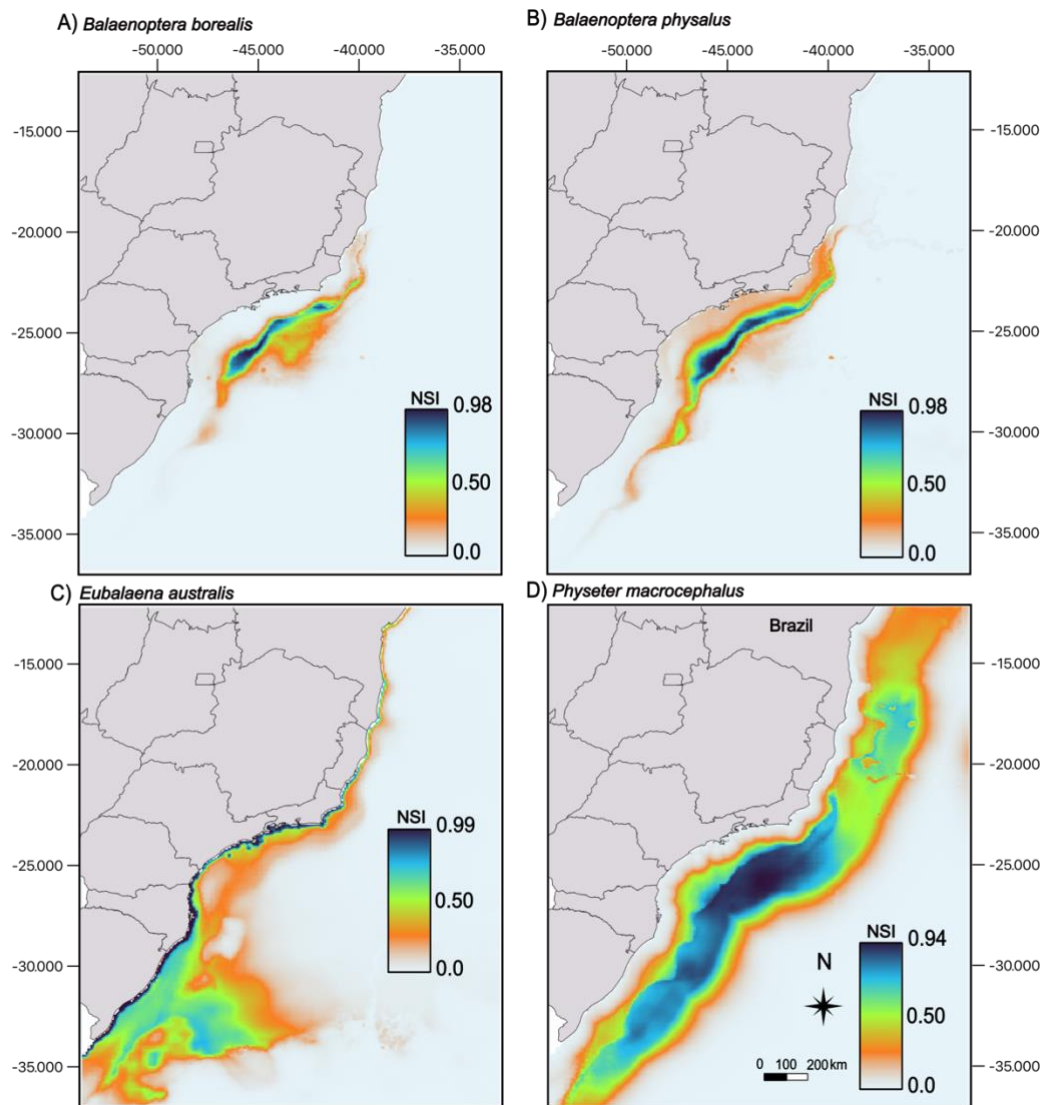


Figure 4.2. Spatial predictions from ecological niche modelling of cetacean species in the Atlantic Ocean of South and Southeast Brazil, displayed as niche suitability index (NSI) scaled from 0 to 1, and mapped to a) *Balaenoptera borealis*, b) *Balaenoptera physalus*, c) *Eubalaena australis*, d) *Physeter macrocephalus*.

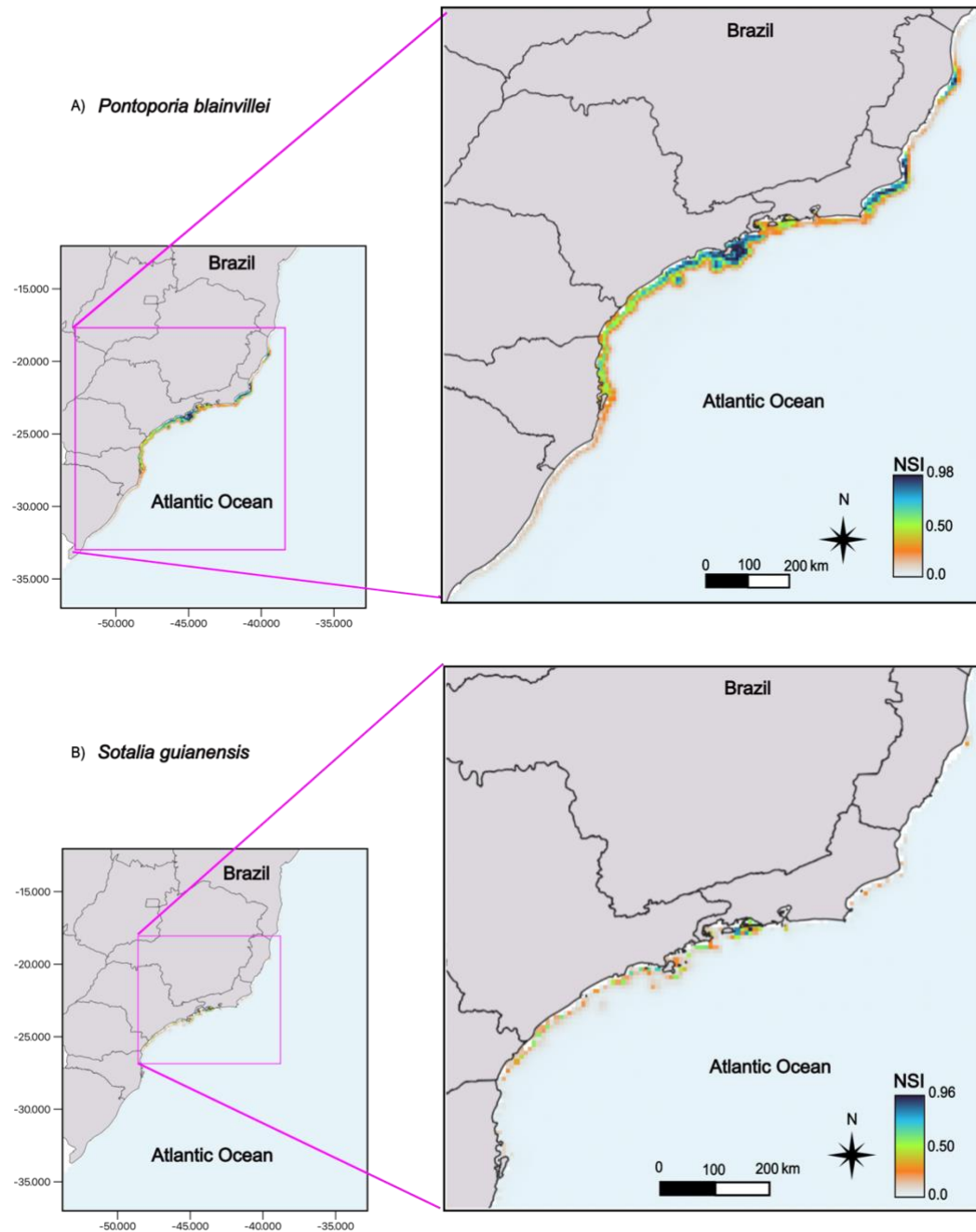


Figure 4.3. Spatial predictions from ecological niche modeling of cetacean species in the southeastern and southern regions of Brazil, displayed as niche suitability index (NSI) scaled from 0 to 1, and mapped to a) *Pontoporia blainvillei*, b) *Sotalia guianensis*.

The results of Variable Importance showed the relevance of interactions between abiotic and each species, including bathymetry, distance of shore, primary production and SST, for most species niche predictions (Fig. 4.4).

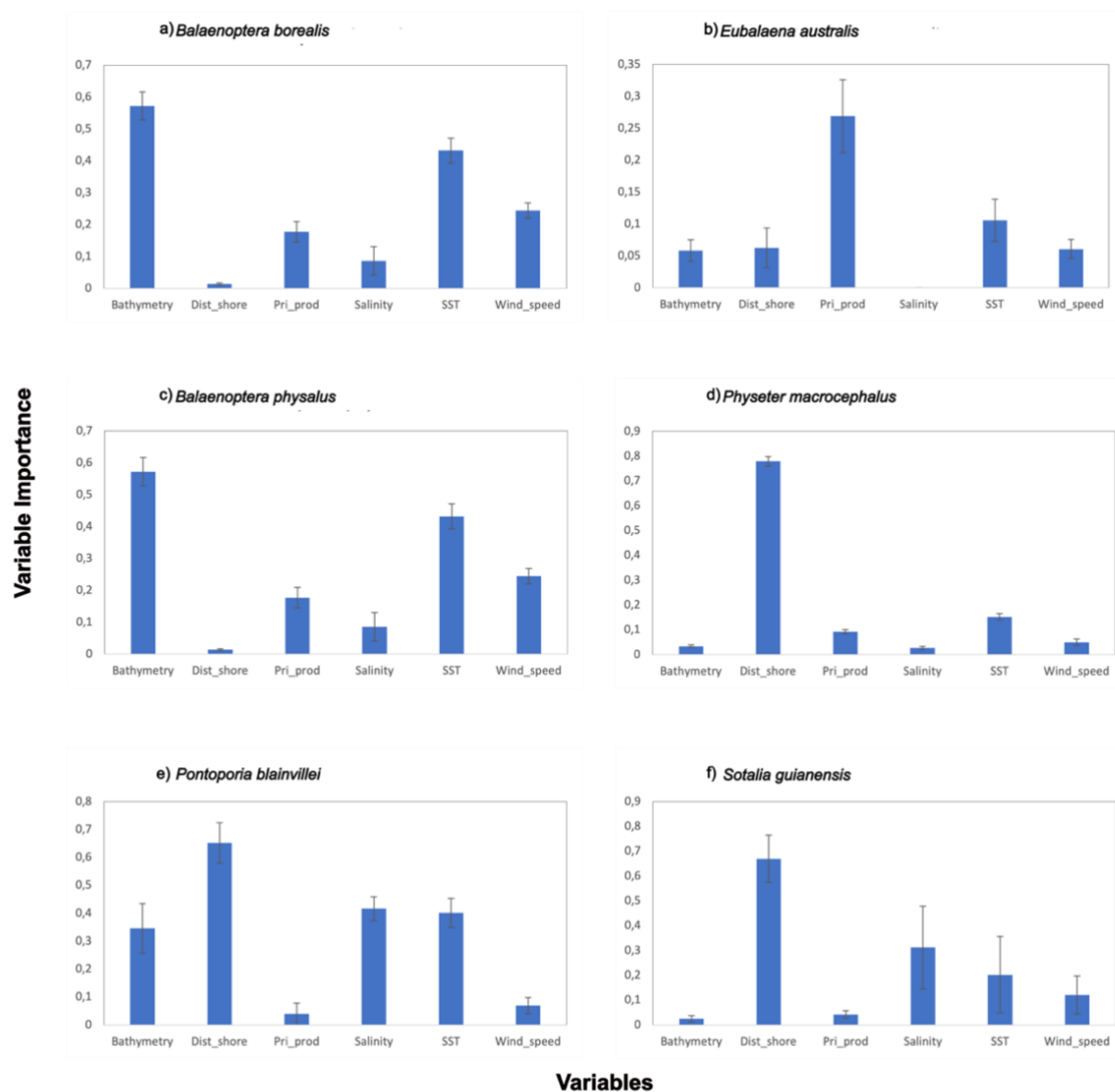


Figure 4.4. Variable Importance values for Ecological Niche Modellings of cetaceans in the Atlantic Ocean of South and Southeast Brazil. Variable Importance for Bathymetry (m); Distance from the Nearest Shore (m); Sea Surface Primary Production (g/m³/day); Sea Surface Salinity (PSS); Sea Surface Temperature (°C) and Wind speed (m/s).

The response curves used to show the relationship between the probability of occurrence for a species and each of the environmental variables used in modelling are in Fig. 4.5. For the sei and fin whales the main variable responsible for the occurrences was the bathymetry. The response curves to the southern right whale show that the probability of occurrence of this species follows an optimum curve for the annual primary production with a high probability in shallow water areas, but the other variables also contribute to the differentiation of the probabilities of occurrence, except for salinity. On the other hand, salinity was determinant for the distribution of the occurrences of the sperm whale. Distance from shore was the variable that contributed most to the highest probability number of occurrences in shallow waters for the Franciscana and mean ocean temperature was the variable related to the highest number of occurrences of the Guiana dolphin (Fig. 4.5.).

4.3.2. Spatial Analysis

Spatial prioritization using the chosen approach ($NSI \geq 0.6$), showed that the highest area of RI (three predicted species) was between 23.5°S and 28°S in waters from 200 m to 1000 m depth, corresponding to 37,306 km² of the outer continental shelf and shelf-break (Fig. 4.6). In this area, there is no OWF installation foreseen or technology available so far. In this pelagic region there are no MPA and there is overlap of suitable area for species with fishing areas in the southern region of the hotspot, between 26.5°S and 29°S.

The coastal zone presents only 101 km² of areas with higher richness ($RI = 3$) near the protected area of Alcatrazes Archipelago Wildlife Refuge (24°S and 45°W). The region between 21.5°S and 23°S is the largest (12,713 km²) hotspot area ($RI = 2$) near the coast, with the larger overlap with OWFs areas and the least overlap with gillnet fishing areas. A small coastal hotspot is found on the north coast of Santa Catarina, near 26.5°S and 48° W.

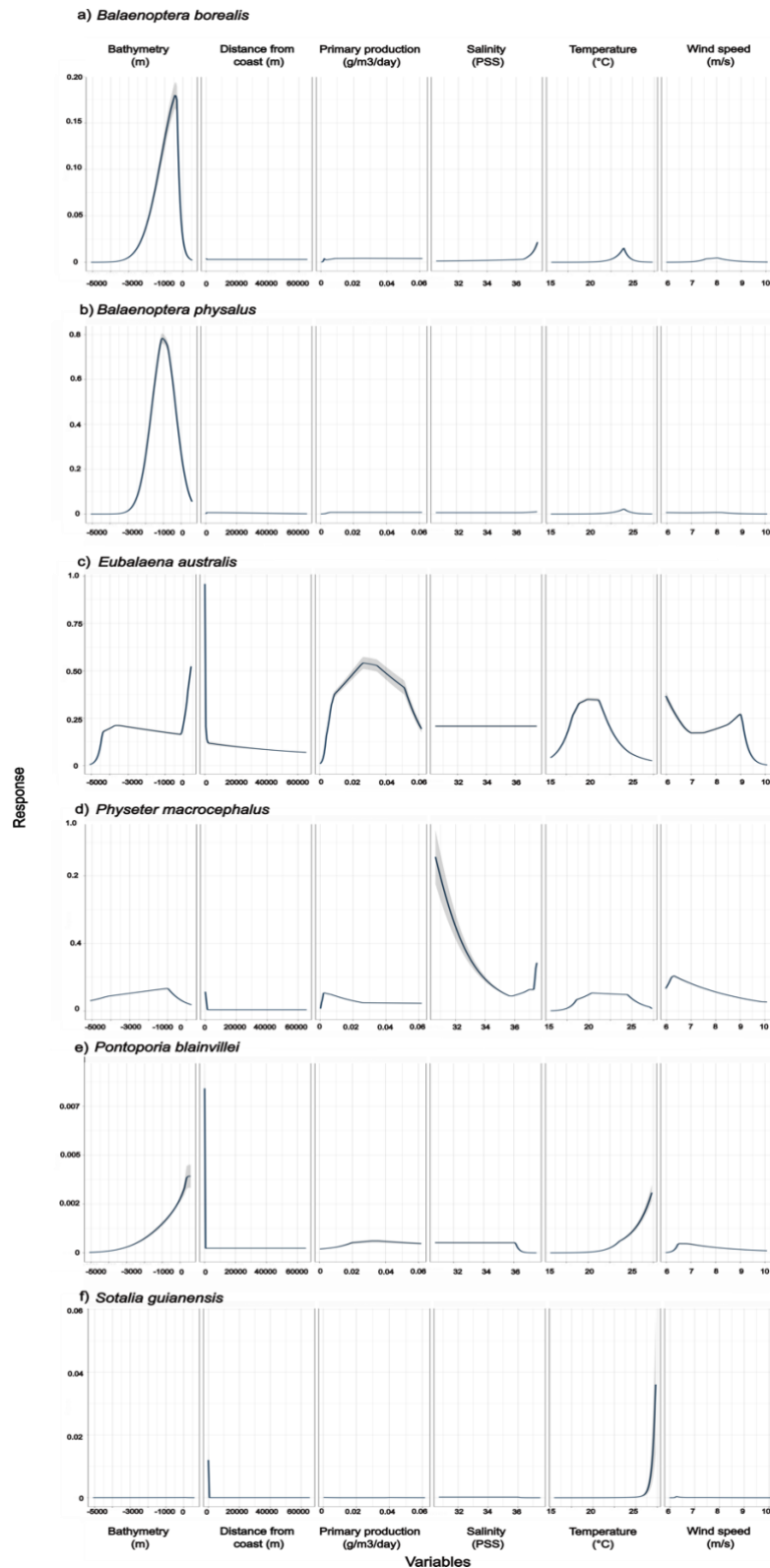


Figure 4.5. Response curves between the probability of occurrence for a species and each of the environmental variables used in niche suitability modelling in MaxEnt to *Balaenoptera borealis*, *Balaenoptera physalus*, *Eubalaena australis*, *Physeter macrocephalus*, *Pontoporia blainvillei* and *Sotalia guianensis*.

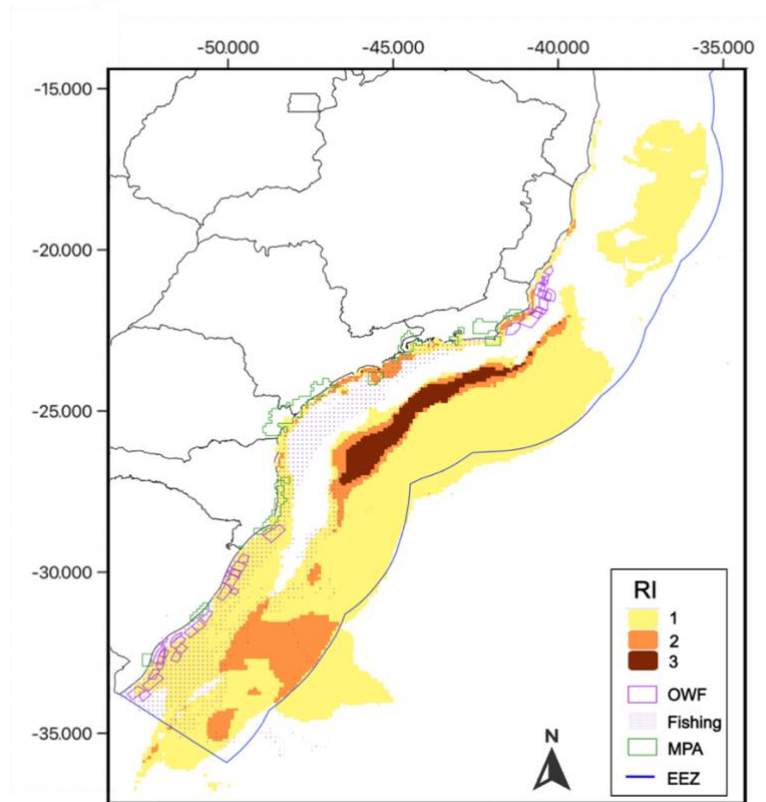


Figure 4.6. Richness index (RI) of cetacean species in the south and southeast Brazilian Economic Exclusive Zone (EEZ). Darker colours show hotspots of cetaceans. OWF: offshore wind farms. MAP: Marine Protected Areas.

Only the southern right whale and the Franciscana showed overlapping areas with MPA and OWF. The percentage of overlap between areas of high southern right whale habitat suitability and MPAs was 4.0% and with OWF zones was 8.0%. The Franciscana showed a higher overlap with MPA (9.1%) than with OWF (3.7%). All species presented areas of overlapping with gillnet fisheries, being the coastal species the most affected, with 75.3% of the area of Guiana dolphins, 57.3% of the area of Franciscanas and 47.3% of southern right whales (Table 4.2.).

Tabel 4.2. Areas with high habitat suitability per species and areas of overlap with Marine Protection Areas (MPA), offshore wind farms (OWF) and gillnet fishing areas in the Atlantic Ocean of South and Southeast Brazil.

Species	High suitability (km ²)	Overlap with MPA (km ²)	Overlap with OWF (km ²)	Overlap with fishing (km ²)
<i>Balaenoptera borealis</i>	31,108	0	0	2,009
<i>Balaenoptera physalus</i>	50,725	0	0	5,616
<i>Eubalaena australis</i>	178,684	7,219	14,241	84,430
<i>Physeter macrocephalus</i>	435,839	0	0	32,069
<i>Pontoporia blainvillei</i>	13,511	1,232	502	7,738
<i>Sotalia guianensis</i>	550	0	0	414

4.4. Discussion

Our results of spatial analyses of the fundamental ecological niche of six species of threatened marine cetaceans in Brazil presented good and excellent predictive performances allowing to assess the most important regions for protection of these species. The result of the hotspot analysis through the RI of threatened cetacean species showed two main areas of biodiversity. The first region corresponds to the coastal areas up to 50 m depth and the second to the southeastern areas in the 200 m to 1000 m isobath, corresponding to the outer continental shelf and the shelf break. Overall, the niche suitability maps described by our models agree with the sightings and potential distribution zones described previously (e.g. do Amaral et al., 2018; Renault-Braga et al., 2018; Weir et al., 2020; Lobo et al., 2021; Renault-Braga et al., 2022).

Coastal zones presented hotspot areas for the Franciscana, the Guiana dolphin and southern right whale. Distance from shore was the variable that contributed most to the highest number of occurrences in shallow water for the Franciscana, followed by bathymetry and SST. The Franciscana is primarily restricted to coastal waters, on an average of 50 km from the coast and up to 35 m deep with individuals rarely recorded beyond 50 m isobaths (Prado et al., 2013; do Amaral et al., 2018). Due to their coastal and estuarine habits, Franciscanas are subject to extensive fisheries bycatch, as well as from habitat loss and degradation and are the most threatened dolphins in the southwestern Atlantic (Cunha et al., 2014; Pinheiro et al., 2019). Franciscana density decreases with distance from the coast, although the rate and degree of the decrease vary according to the width of the continental shelf (Cunha et al., 2014).

The SST was the variable that explained better the occurrences of Guiana dolphin, followed by the distance from the coast. The Guiana dolphin is often found in shallow

waters and coastal regions, but also occurs up to 70 km from the coast (Lobo et al., 2021) with a preference for waters around islands and channels (Ribeiro-Campos et al., 2021) in a more restricted distribution to these regions (Teixeira et al., 2023). This species feed in areas of highly productive coastal muddy shallows, found at and near the mouths of estuaries (Giacomo et al., 2021). The coastal habit and site fidelity make these dolphins vulnerable to human activities, such as fishing, boat traffic, oil exploration, and urban development (Ribeiro-Campos et al., 2021).

The southern coast also presented important areas of hotspot of southern right whales. These areas are preferred for mother-calf pairs by the advantage of protecting the calves from waves, wind and predation since these areas are usually shallow and thus limit predator attack (Danilewicz et al., 2009; Danilewicz et al., 2017; Renault-Braga et al., 2022). The results of response curves to southern right whale showed that the probability of occurrence of this species follows an optimum curve for the primary productivity, with a high probability in shallow water areas. Also, our data suggest that SST around 20°C is limiting for southern right whale distributions due to their preference for cold waters (Purdon et al., 2020).

Our results point out that the southern right whale, Franciscana and Guiana dolphins should be the target of preservation measures for the potential impacts caused by OWF, since there are areas of overlap with these threatened species. The impact of the OWF in the coastal hotspot areas of these species may accelerate the decline of the populations due to habitat loss or displacement caused by noise and vessel traffic (Culloch et al., 2016; Dähne et al., 2017). We recommend avoiding impacts from installing OWF during reproductive periods of southern right whale. Previous data showed that cetacean species richness peaks from August to September months, with the occurrence of migratory species moving towards productive areas (Prado et al., 2022). The coastal area of the southern states (RS and SC) is of great wind potential and used as a migratory passage area and an important part of the breeding ground of southern right whales (Danilewicz et al., 2017; Renault-Braga et al., 2018, 2022). The higher occurrence of the southern right whales between Florianópolis (27.7°S) and Torres (29.4°S) may be related to the philopatry to the breeding grounds (Renault-Braga et al., 2022), to which we suggest studies on a regional scale to better evaluate these sites.

The second most important hotspot area resulting from our modeling was found in the southeastern waters, between 200 m and 1000 m depth and we suggest that future

Brazilian marine spatial planning prioritize this region in terms of conservation. Cetacean species richness is expected to increase with proximity to the shelf and slope break due to subsurface processes that increase productivity (Piola et al., 2000; Di Tullio et al., 2016). The main variable responsible for explaining the occurrences of the sei whale and the fin whale was bathymetry. The bathymetry also showed the suitability for occurrences of the sperm whale in the 1000 m depth range. The breeding, feeding and migration areas of the sei whales remain poorly documented worldwide, but they are usually observed in deeper waters, far from shore, and may not return to the same areas for long periods (Andriolo et al., 2010). Bathymetry was also the most important variable related to distribution of fin whales in Canada (Schleimer et al., 2019), in the Mediterranean Sea (Pennino et al., 2017) and in the northeast Atlantic of Iceland (Víkingsson et al., 2015). In Brazil, sperm whales are the most frequent species in south and southeast areas, sighted only in offshore waters, at depths over 1000 m in both seasons (Andriolo et al., 2010; Di Tullio et al., 2016).

All species studied presented areas of overlapping with gillnet fisheries, being the Guiana dolphins, Franciscanas and southern right whales the most affected. Pelagic gillnet fleets are known to be a cause of considerable mortality of marine mammals, relatively less known and more difficult to control than other fleets operating in more coastal areas (Marigo & Giffoni, 2010). In the case of the southern right whale, collisions with fishing boats and even entanglement in fishing nets have been described, resulting in reduced foraging and debilitation due to tissue damage (Zappes et al., 2013). The removal of top predators can also affect the trophic chain, leading to the collapse or restructuring of food chains (Lucas & Berggren, 2022). Due to their small home ranges, the Guiana dolphins are particularly vulnerable to local anthropogenic activities and habitat loss and are highly vulnerable to the effects of incidental capture in fishing nets (Conversani et al., 2021). These characteristics imply a strong need for regionalized management plans to reduce negative impacts and maintain the ecological functionality of the species (de Moura et al., 2021).

The operational phase of an OWF could impact positively biodiversity due to a fishery “reserve effect” due to the exclusion of shipping for safety reasons (Bergström et al., 2014; Coates et al., 2016; Bennun et al., 2021). As a measure to mitigate the impacts of fishing it is also recommended to use sensory deterrent devices to try to reduce bycatch and maintain the quantity and quality of fish catches (Lucas & Berggren, 2022).

4.5. Conclusion

The use of species distribution models provides valuable support for making management decisions, detecting target areas for conservation of biodiversity or mitigation of impacts, and applying effective conservation measures in the context of marine spatial planning. The results of RI can provide important information of hotspots for marine biodiversity conservation and management planning, allowing for the identification of currently unprotected cetacean habitats in Marine Protected Areas network. Models can be used to explore empirical associations between distributions and the physical and biological features of the study area when little is known about the ecology of a species (Redfern et al., 2006).

Our results also identify the areas of greatest anthropogenic impact by gillnet fishing and OWF and can be used to reduce or avoid these threats firstly through spatial prioritization, contributing to the long-term preservation of cetacean populations and their habitats.

We emphasize the importance of coastal areas and the continental slope break region for the diversity of cetaceans found in the southern and southeastern Brazilian Atlantic Ocean, providing information on the distribution and richness of threatened species. Also, intensified research efforts are needed to increase our knowledge and understanding of conservation needs, especially in pelagic environments of mysticetes (Marega-Imamura et al., 2020) and threatened species with low numbers of occurrence in Brazil such as the Lahille's bottlenose dolphin and the blue whale.

CHAPTER V. Improving spatial planning of offshore wind farms through ecological niche modelling of cetaceans, seabirds, and chelonians in Southeast Brazil.

Abstract

The global shift towards renewable energy sources, driven by the climate goals of the Paris Agreement, has led to ambitious plans for installation of offshore wind farms (OWFs) in the Brazilian sea. The potential impacts of OWFs on biodiversity must be considered in environmental impact assessments. Actually, the main threats to marine biodiversity of these regions are offshore oil and gas exploration, in addition to fisheries and the absence of marine spatial planning (MSP) to prevent the reduction of spatial conflicts. We seek to contribute to effective MSP and conservation efforts by assessing which species and areas will require more attention in the environmental impact assessment of OWF. Employing ecological niche models (ENM) using the maximum entropy algorithm MaxEnt we predict the fundamental niche of 29 marine vertebrate species, including cetaceans, seabirds, and the green turtle *Chelonia mydas*, in the Santos and Campos Marine Basins down to the 1000 m bathymetry. Two main hotspot areas were distinguished, one in the coastal zone up to 12 nm and the other in the shelfbreak, from 200 to 1000 m deep. Niche suitability results in coastal waters (~12 nm) of the southeast predicted the occurrence of ten cetacean species, in addition to the Atlantic yellow-nosed albatross *Thalassarche chlororhynchos* and the green turtle. These species should be considered as target for OWF environmental assessment and programs. A higher richness is observed in the central portion of the Santos basin, in the region between 12 nm and the shoreline. Our study contributes to filling some knowledge gaps, identifying biodiversity hotspots, guiding the expansion of MPA and contributing to marine spatial planning to ensure effective protection of biodiversity. ENM proved to be powerful tools to assess areas and species that require special attention in the environmental impact assessment of OWF.

Keywords: Atlantic Ocean, biodiversity, coastal zone, impact avoidance, marine protected areas, pelagic zone.

5.1. Introduction

The conservation of biodiversity and the expansion of protected areas are key targets set by the Convention on Biological Diversity to prevent further extinction of species (CDB, 2022). To ensure an effective representation of biodiversity, it is necessary to identify areas where conservation efforts should be focused to mitigate population decline and biodiversity loss (Vilar & Joyeux, 2021). In Brazil, the total extent of marine protected areas (MPA) has increased in recent years, reaching 10% of marine territory, but their capacity to fulfil global conservation commitments remains uncertain (Pacheco et al., 2018; Steinke et al., 2018). To be ecologically efficient the MPAs need to meet four criteria: adequacy, connectivity, representativity and replication (Kullberg et al., 2015; CDB, 2022). The design of MPA networks should cover different connected and complementary areas. Unfortunately, historically protected areas have been designated in low-income regions, leading to insufficient protection of ecologically important areas for conservation (Farashi & Alizadeh-Noughani, 2019).

Suitable habitats for the species should be considered when selecting protected areas in future (Farashi & Alizadeh-Noughani, 2019). A geographic conservation approach may include a wide variety of species with different ecological characteristics in a given area (Lucifora et al., 2011). To face international conservation agreements information on the gaps in biodiversity protection at scales appropriate to support decision-making is key in the management of marine ecosystems.

Based on a dataset containing marine vertebrate species with the highest trophic level, this study revealed previously undocumented gaps in biodiversity protection and can help guide the expansion of MPA. In addition, there is an urgent need to expand the coverage of MPA to improve ecological representation and prevent further biodiversity losses (CBD, 2022). Brazil agreed in 2022 at the CBD Conference of the Parties to increase the marine areas covered with some form of protection to 30%. The ecoregions of the Brazilian southeastern marine areas concentrate many threatened, species that are unprotected or poorly protected, presenting critical regions for the conservation of multiple taxonomic groups heavily affected by fishing (Magris et al., 2020; Vilar et al., 2020; Vilar & Joyeux, 2021). Under-represented deep-sea ecosystems are clearly neglected and need to be included in MPAs, through coordinated scientific engagement (Almada & Bernardino, 2017).

Despite the percentage of coverage, the current MPA are unequally distributed among Brazilian marine biogeographic provinces and are more concentrated at the edges of the

contiguous coastal zone (24 nm). The dimensions of anthropogenic impacts on marine animals and their habitats are still poorly understood, reinforcing the need for an integrated and vigilant marine spatial planning, as well as a governmental commitment to respond adequately to mitigate economic, social and biological impacts (Magris et al., 2020; Vilar et al., 2020; Vilar & Joyeux, 2021).

The historical record of oil and gas exploration in the Southwest Atlantic Ocean, mainly in areas shallower than 200 m depth, and the lack of basin-wide management for the offshore industry are threats to biodiversity (Almada & Bernardino, 2017). The global need for changes in the energy matrix to meet the climate goals of the Paris Agreement has driven the growth of wind power (UNFCCC, 2015). The installation of wind farms in the Brazilian sea will be a reality in the coming years. Studies point to the existence of a technical offshore wind energy potential of about 700 GW in places as deep as 50 m (EPE, 2020). The impact of developments on biodiversity is a critical aspect to be considered in environmental impact assessment (EIA) (Meynell, 2005).

By July 2023 there were 78 applications for OWF environmental licenses in Brazil, all of which are in the planning stage or in the process of issuing Terms of Reference for the preparation of the Environmental Impact Assessment (EIA) (IBAMA, 2023). This is the ideal moment to structure marine spatial planning that involves the positive and negative impacts of this energy production. The consideration of both economic and ecological spatial effects is essential in planning the location of OWF, considering trade-offs between revenues, costs, and species conservation (Punt et al., 2009). These developments are expected to affect marine animals leading to changes in species distribution and abundance (Abramic et al., 2022). Among the affected taxa, avifauna and marine mammals are particularly susceptible to impacts of OWF, and thus have received most attention from studies globally (see Chapter II).

To implement ecosystem-based management and marine spatial planning, it is crucial to employ integrative and spatialized tools capable of identifying local and global patterns of ecosystem modifications and localized changes resulting from OWF (Nogues et al., 2022). A proper evaluation of ecologically important areas requires extensive data and suitable analytical tools (Virtanen et al., 2018). Despite two centuries of sampling biodiversity around the globe, occurrence data for most known marine species are scarce, and taxonomic, temporal, and geographical biases abound, a situation called the Wallacean shortfall (Bini et al., 2006; Herkt et al., 2017).

Ecological Niche Models (ENM) are valuable tools for identifying areas of high conservation value, demarcating future MPAs, initiating conservation measures, and predicting the impacts of OWF on the distribution of species. Modelling species distributions using environmental variables allows a comprehensive understanding of potential niches and supports conservation planning (Fivaz & Gonseth, 2014). One of the expected products of large-scale impact assessments is also the generation of maps of high-risk areas, which could provide a crucial tool to locate sites where wind farms cannot be planned or sites where more survey efforts are needed to assess the impact (Catherine & Spray, 2009). The maximum entropy algorithm (MaxEnt) is an important statistical technique for predictive modelling of species distributions from occurrence records and environmental data (Phillips et al., 2017). The predictions are used to generate a map with values of ecological niche suitability in given pixel cells (Khan et al., 2022). Spatial distributions are one aspect of species ecology used in assessing conservation status (Mason et al., 2021). Understanding the role that habitat features play in the distribution of marine vertebrates is a crucial step in assessing the suitability of existing MPA and identifying areas of biological importance to spatial prioritization for conservation (Guisan & Thuiller, 2005). Predictions are then used to produce a richness index (RI) used to identify biodiversity hotspots.

This study aims to predict the fundamental niche of 29 marine vertebrate species in two marine ecoregions in Brazil, the Santos and Campos Basins. In addition, we intend to evaluate the areas with high habitat suitability per species obtained by niche modelling of ten cetaceans, six seabirds and one turtle in areas from 0 to 1000 m depth and evaluate their hotspots in coastal areas. We also seek to contribute to effective marine spatial planning and conservation efforts by assessing which areas will require more attention in the environmental impact assessment of OWF.

5.2. Methodology

5.2.1. Study area

Niche modeling areas were carried out in the southeast Brazilian marine region, between 17°S and 34°S, and 55°W and 34°W. The analyses of hotspots of biodiversity were delimited only for the coastal zone of up to 1000 m depth in the Campos (~39,330 km²) and Santos (~167,231 km²) marine basins (Fig. 5.1).

The Campos Basin is located on the southwestern margin of the South Atlantic, between latitudes 21° and 23°S, extending from the state of Espírito Santo to the northern coast of the state of Rio de Janeiro (Viana et al., 1998; Sousa et al., 2006). More than 70% of

this basin is at water depths greater than 200 m, and it is under the influence of three boundary currents: the Brazil Current, the Intermediate Western Boundary Current and the Deep Western Boundary Current (Silveira et al., 2000).

The Santos Basin is the largest Brazilian offshore sedimentary basin with approximately 350,000 km² of the southeastern-southern Brazilian coast (between 23° and 28°S), bordered to the north by the Campos Basin, and to the south by the Pelotas Basin (28.55°S and 48.47°W) (Souza & Sgarbi, 2019). Most of Brazil's oil production comes from the Campos (23%) and Santos (76%) Basins, with a total production of ~170,476,243 m³ in 2022 (ANP, 2023).

The dynamics and the water mass structure in the northern region of Campos and Santos Basins are influenced by open ocean intrusions caused by the frequent meandering of the Brazil Current (BC) with intense coastal upwelling. While these warm, salty Subtropical Shelf Water extends primarily north, from the south the relatively cold Subantarctic Shelf Water form a low-salinity tongue that extends northward over the shelf penetrating farther north in winter than in summer, dominated by the Rio de la Plata (50S) and the Patos (32°S) outflows. An intense difference in temperature, salinity, and nutrient separates these water masses in a relatively narrow frontal zone referred to as the Subtropical Shelf Front (Piola et al., 2000). This encounter influences the productivity of offshore waters by increasing the concentration of organic and inorganic nutrients (Campos et al., 2000; Di Tullio et al., 2016).

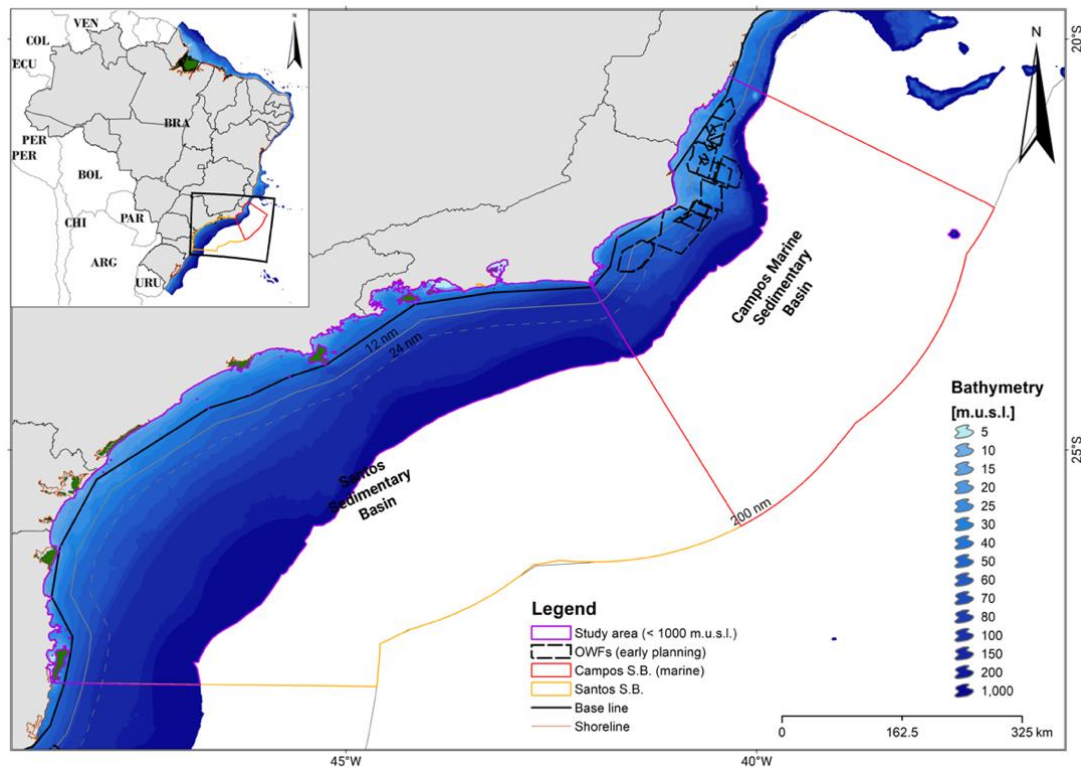


Figure 5.1. Location of the study area in the Southwest Atlantic Ocean, Brazil, and the bathymetric ranges up to 1000 m depth. The red line represents the limit of the Campos Basin. The orange line represents the Santos Basin. The Ecological Niche Modelling was performed in the Atlantic Ocean between 17°S and 34°S, and 55°W and 34°W. The purple line represents the boundary of the hotspot of biodiversity analysis area. Offshore wind farms in early planning are represented as black-stippled areas.

5.2.2. Ecological Niche Modelling

Georeferenced occurrence data of marine mammals and chelonians were initially obtained from Global Biodiversity Information Facility (GBIF, 2023) and the Ocean Biodiversity Information System (OBIS, 2023). We search all species with a minimum of ten occurrences in the study area, required for fundamental niche modelling (Sahri et al., 2021). Due to the low number of records of species present in these databases, the occurrences were complemented with records obtained in the Beach Monitoring Programs (PMP), the Santos Basin Cetacean Monitoring Project (PMC-BS) and the Aquatic Biota Monitoring System (SIMBA), required by the Brazilian environmental licensing of offshore oil and gas (PETROBRAS, 2023). Thus, the records of occurrences of 22 marine cetaceans and one chelonian were systematized for the niche distribution analyses. Occurrences data were reduced with a 10 km radius buffer around each presence record to reduce autocorrelation bias from clustered data (Aiello-Lammens et al., 2015) with the “spThin function” in Wallace v.2.0.5 (Kass et al., 2018).

Five species of sea turtles occur in Brazil: the green turtle *Chelonia mydas* (Linnaeus, 1758), the loggerhead turtle *Caretta caretta* (Linnaeus, 1758), the hawksbill turtle *Eretmochelys imbricata* (Linnaeus, 1766), the olive turtle *Lepidochelys olivacea* (Eschscholtz, 1829) and the leatherback turtle *Dermochelys coriacea* (Vandelli, 1761). Despite this, there were few occurrences of turtles available at sea, most of the records are in beach areas where they nest or are found stranded, an area beyond the scope of this study. The green turtle was the only species that showed a minimum number of occurrences ($n > 10$) for the fundamental niche modelling ($n = 35$).

We obtained georeferenced occurrence data for 22 cetacean species that were used in niche modeling. From these, the species with the highest suitability in coastal areas were selected for the biodiversity hotspot and overlap analyses with the OWF (Table 5.1).

The niche modelling of seabirds followed the methodology presented in Chapter II. The species with suitability for the study area initially selected were the Atlantic yellow-nosed albatross *Thalassarche chlororhynchos*, the Atlantic petrel *Pterodroma incerta*, the white-chinned petrel *Procellaria aequinoctialis*, the spectacled petrel *Procellaria conspicillata*, the black-browed albatross *Thalassarche melanophris* and the great shearwater *Ardenna gravis*. To obtain the hotspot zone, a single map averaging the suitability by species was generated in ArcGIS 10.6. with the data of NSI presented in Chapter III.

5.2.3. Marine environmental data

We considered six spatial variables, based on their reported influence on occurrence of marine species: sea surface primary production ($\text{g/m}^3/\text{day}$); wind speed (m/s); sea surface salinity (PSS); sea surface temperature ($^{\circ}\text{C}$); bathymetry (m) and distance from coast (m) (Putra & Mustika, 2021; Arslan et al., 2023; Martins et al., 2023). The treatment and analysis of environmental variables used follow those described in Chapter IV, section 4.3.

5.2.4. Niche Suitability

To generate ENM our datasets were analyzed using MaxEnt v.3.4.1 (Phillips et al., 2017) in the 'sdm' package as described in Chapter IV. Model predictive performances were based on AUC values classified as follows: 0.6 – 0.7 = poor; 0.7 – 0.8 = average; 0.8 – 0.9 = good; and > 0.9 = excellent. The accuracy classification scores according to TSS were: < 0.2 = no predictive ability; 0.2 – 0.4 = poor; 0.4 – 0.6 = fair; 0.6 – 0.8 = good and > 0.8 excellent (Landis & Koch, 1977; Allouche et al., 2006).

5.2.5. Hotspot

The continuous maps of habitat suitability provided by MaxEnt were imported into ArcGIS software. Areas with high habitat suitability ($NSI \geq 0.6$) were selected for the target species (Ranù et al., 2022) and converted into the Boolean category 1, and pixel values equal to 0 were considered null and were removed (Sahri et al., 2021). We used NSI to generate a richness index (RI) and identify areas in which conservation may be relevant according to this conservation value index (Araújo et al., 2019). Species richness for each cell was obtained by summing the number of species occurring in each cell (Lucifora et al., 2011). The RI ranges from the minimum to the maximum number of species overlapped in the same raster cell (Stephenson et al., 2020), but does not indicate the absolute richness (Sahri et al., 2021). In this study, 17 species are the theoretical maximum richness to be found (Stephenson et al., 2020). The RI maps were then used to evaluate the areas of high species diversity, considered hotspots (Davies et al., 2021) in the Campos and Santos Basins, as well as the overlap between hotspot habitats and OWFs areas (Farashi & Alizadeh-Noughani, 2019).

5.3. Results

The MaxEnt model performed presented excellent discriminant power for most species modelled (Table 5.1), except for short-finned pilot whale and orca which had the prediction considered good. Based on the TSS scores, the accuracy of modelling was considered excellent, with only three species reaching the score good. When the 29 species were assessed, the distribution of areas with the highest relative species richness shows a large spatial variation. Therefore, we identified and mapped the 17 marine species with the highest suitability in coastal environments up to 1000 m depth to perform the spatial analyses of hotspots (Figs. 5.2 and 5.3). Species of cetaceans with ranges predicted to occur primarily in coastal waters (~12 nautic miles) included Bryde's whale, Franciscana, common, Guiana, rough-toothed, Atlantic spotted and common bottlenose dolphins and false killer whale. The orca also shows high suitability in coastal areas near the Marabaia sandbank (23°S, 44°W). The Atlantic yellow-nosed albatross and the green turtle also had a high niche prediction in the hotspot assessment areas.

The Variable Importance differed between the modelling results for each of the species selected for the hotspot assessment (Fig. 5.4). The most important variables for niche suitability across all modelling were bathymetry, distance of shore and sea surface temperature (SST). The Variable Importance for seabird niche prediction was analyzed in Chapter III.

Table 5. 1 Family, common name, scientific name, number of thinned occurrences and predictive performance of modelling represented by the area under the curve (AUC), true skill statistic (TSS) of 23 marine vertebrate species in the Campos and Santos Basins.

Family	Common name	Scientific name	Total thinned occurrences (10 km)	AUC	TSS
Balaenopteridae					
	common minke whale	<i>Balaenoptera acutorostrata</i> Lacépède, 1804	56	0.92	0.81
	sei whale	<i>Balaenoptera borealis</i> Lesson, 1828	94	0.96	0.85
	Bryde's whale*	<i>Balaenoptera edeni</i> Anderson, 1879	107	0.97	0.91
	Antarctic minke whale	<i>Balaenoptera bonaerensis</i> Burmeister, 1867	30	0.93	0.86
	fin whale	<i>Balaenoptera physalus</i> (Linnaeus, 1758)	31	0.95	0.89
	humpback whale	<i>Megaptera novaeangliae</i> (Borowski, 1781)	457	0.92	0.76
Physeteridae					
	sperm whale	<i>Physeter macrocephalus</i> Linnaeus, 1758	128	0.94	0.87
Pontoporiidae					
	Franciscana*	<i>Pontoporia blainvillei</i> (Gervais & d'Orbigny, 1844)	22	0.98	0.98
Delphinidae					
	common dolphin*	<i>Delphinus delphis</i> Linnaeus, 1758	16	0.92	0.90
	pygmy killer whale	<i>Feresa attenuata</i> Gray, 1874	21	0.94	0.91
	short-finned pilot whale*	<i>Globicephala macrorhynchus</i> Gray, 1846	17	0.87	0.81
	Risso's dolphin	<i>Grampus griseus</i> (Cuvier, 1812)	131	0.97	0.91
	killer whale or orca*	<i>Orcinus orca</i> (Linnaeus, 1758)	44	0.89	0.78
	melon-headed whale	<i>Peponocephala electra</i> (Owen, 1846)	18	0.96	0.93
	false killer whale*	<i>Pseudorca crassidens</i> (Owen, 1846)	22	0.90	0.85
	Guiana dolphin*	<i>Sotalia guianensis</i> (Van Bénédén, 1864)	28	0.98	0.96
	rough-toothed dolphin*	<i>Steno bredanensis</i> (Cuvier, 1828)	46	0.94	0.88
	panropical spotted dolphin	<i>Stenella attenuata</i> (Gray, 1846)	79	0.95	0.86
	Clymene dolphin	<i>Stenella clymene</i> (Gray, 1850)	37	0.94	0.87
	Atlantic spotted dolphin*	<i>Stenella frontalis</i> (Cuvier, 1829)	235	0.95	0.85
	spinner dolphin	<i>Stenella longirostris</i> (Gray, 1828)	85	0.97	0.90
	common bottlenose dolphin*	<i>Tursiops truncatus</i> (Montagu, 1821)	184	0.93	0.79
Cheloniidae					
	green turtle*	<i>Chelonia mydas</i> (Linnaeus, 1758)	35	0.97	0.96

* Species selected for the hotspots analyses.

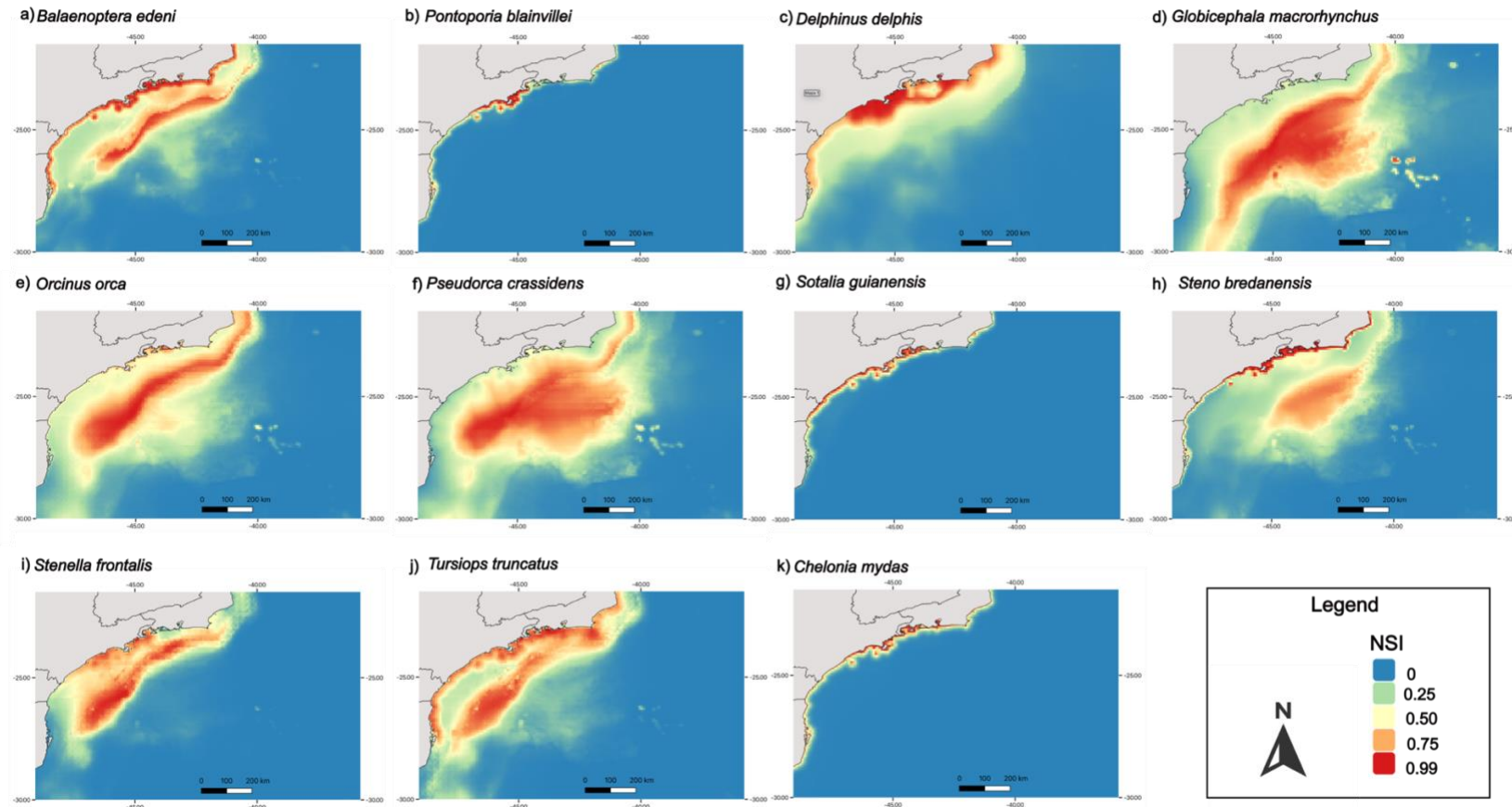


Figure 5.2. Ecological Niche Modelling represented by Niche Suitability Index of a) the Bryde's whale (*Balaenoptera edeni*), b) the Franciscana (*Pontoporia blainvillei*), c) the common dolphin (*Delphinus delphis*), d) the short-finned pilot whale (*Globicephala macrorhynchus*), e) the orca (*Orcinus orca*), f) the false killer whale (*Pseudorca crassidens*), g) the Guiana dolphin (*Sotalia guianensis*), h) the rough-toothed dolphin (*Steno bredanensis*), i) the Atlantic spotted dolphin (*Stenella frontalis*), j) the common bottlenose dolphin (*Tursiops truncatus*) and k) green turtle (*Chelonia mydas*), in the Campos and Santos Basins, southeastern Brazil, southwestern Atlantic Ocean.

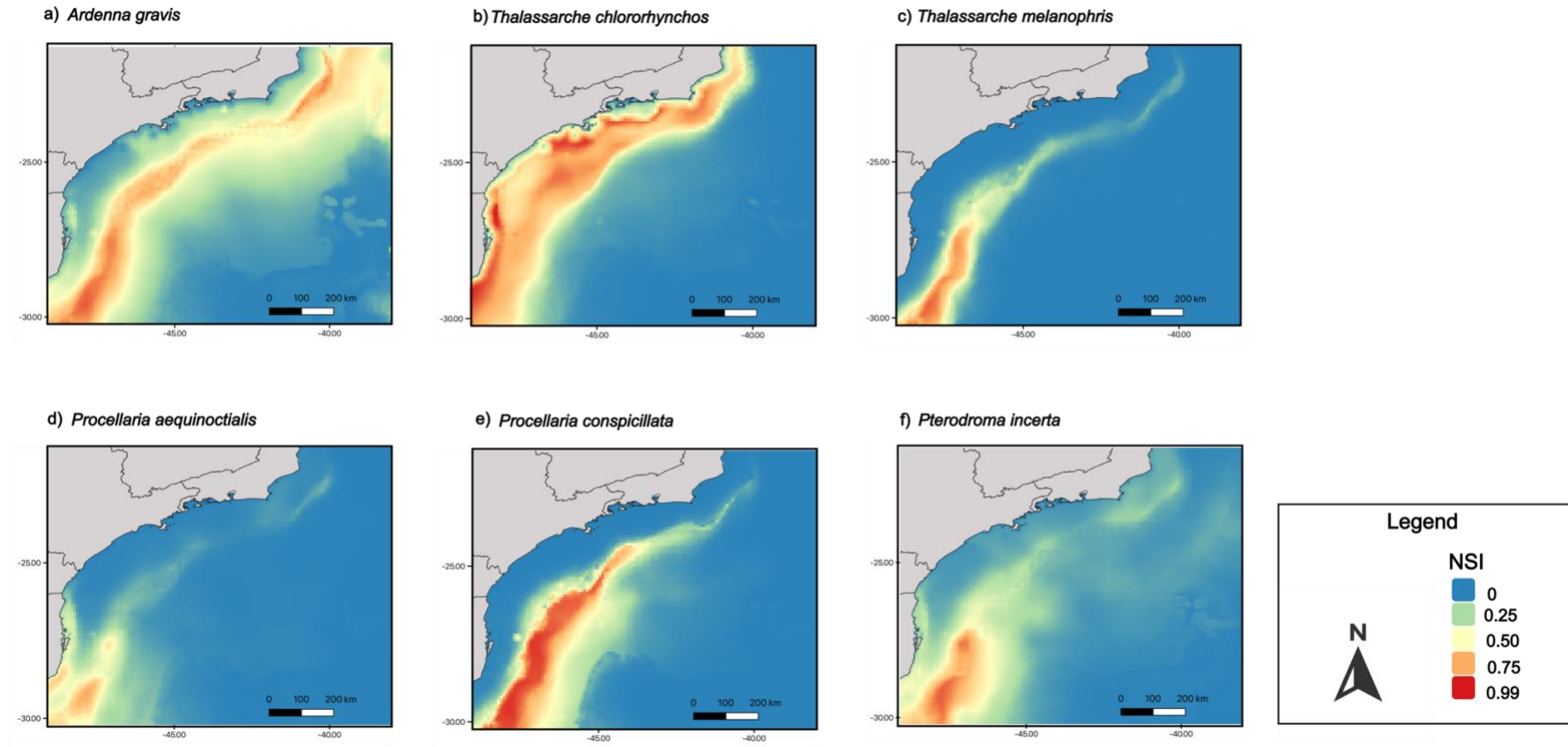


Figure 5.3. Ecological Niche Modelling represented by Niche Suitability Index of the a) great shearwater (*Ardenna gravis*), b) the Atlantic yellow-nosed albatross (*Thalassarche chlororhynchos*), c) black-browed albatross (*Thalassarche melanophris*), d) Atlantic petrel (*Procellaria aequinoctialis*), e) white-chinned petrel (*Procellaria conspicillata*), and f) the Atlantic petrel (*Pterodroma incerta*), in the Campos and Santos Basins, southeastern Brazil, southwestern Atlantic Ocean.

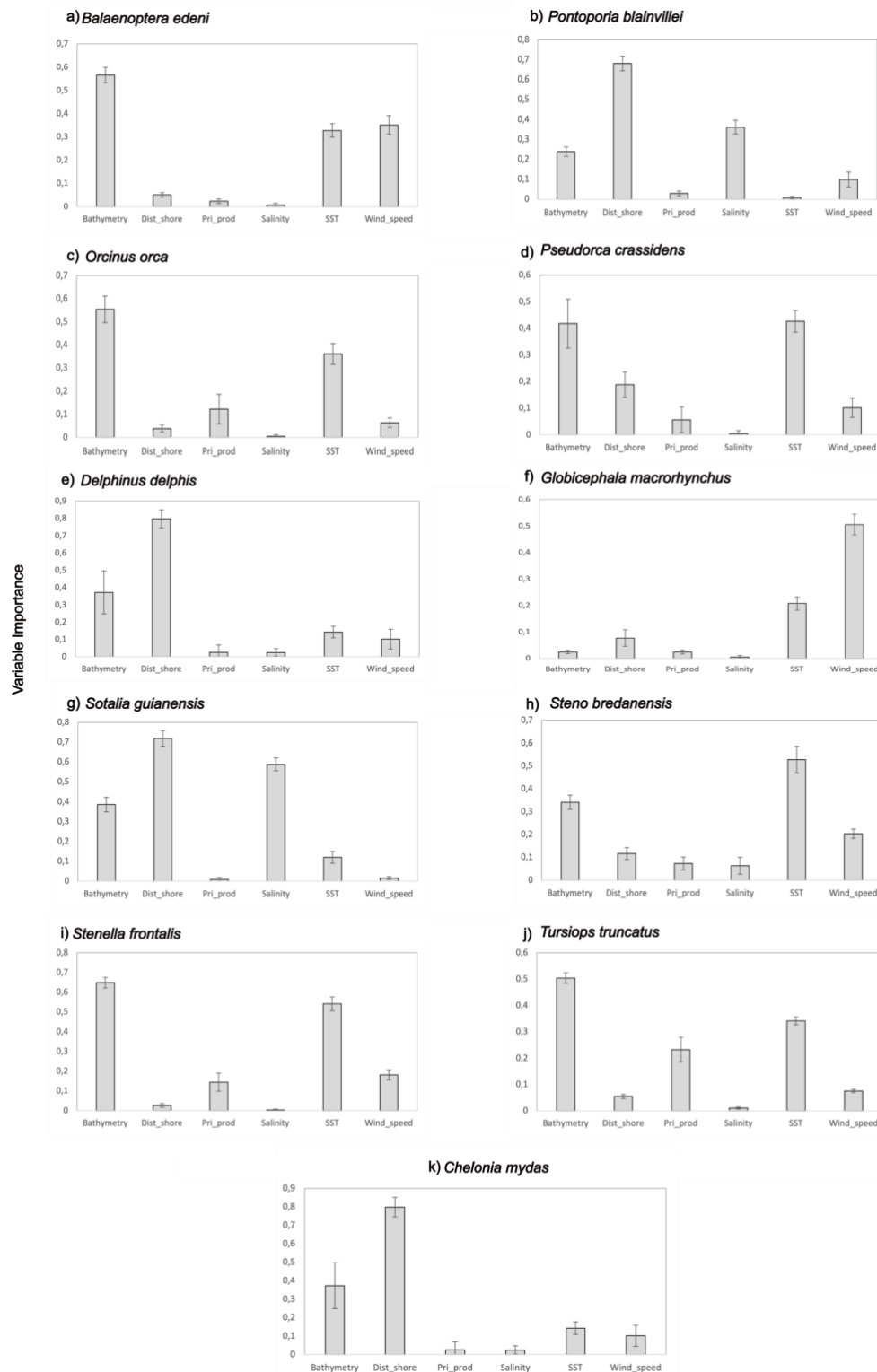


Figure 5.4. Variable Importance for Bathymetry (m); Distance from the nearest shore (m); Sea Surface Primary Production (g/m³/day); Sea Surface Salinity (PSS); Sea Surface Temperature (°C) and Wind speed (m/s) used to modelling the niche for: a) the Bryde's whale (*Balaenoptera edeni*), b) the Franciscana (*Pontoporia blainvillei*), c) the orca (*Orcinus orca*), d) the false killer whale (*Pseudorca crassidens*), e) the common dolphin (*Delphinus delphis*), f) the short-finned pilot whale (*Globicephala macrorhynchus*), g) the Guiana dolphin (*Sotalia guianensis*), h) the rough-toothed dolphin (*Steno bredanensis*), i) the Atlantic spotted dolphin (*Stenella frontalis*), j) the common bottlenose dolphin (*Tursiops truncatus*) and k) green turtle (*Chelonia mydas*).

The RI varied from 0 to 10 in the range up to 1000 m depth, the minimum to the maximum number of species overlapped in the same raster cell (Fig. 5.5). Two main hotspot areas were distinguished, one in the coastal zone up to 12 nm and the other in the bathymetry from 200 to 1000 m depth. In the Campos Basin the maximum RI found was seven species, which is less than that found in the Santos Basin (RI = 10). Proportionally, the Santos basin holds more and has larger areas with high habitat suitability to the studied coastal marine species, although it also presents a large area with low richness (~19,612 km²), in the south and from 12 nautical miles toward offshore waters.

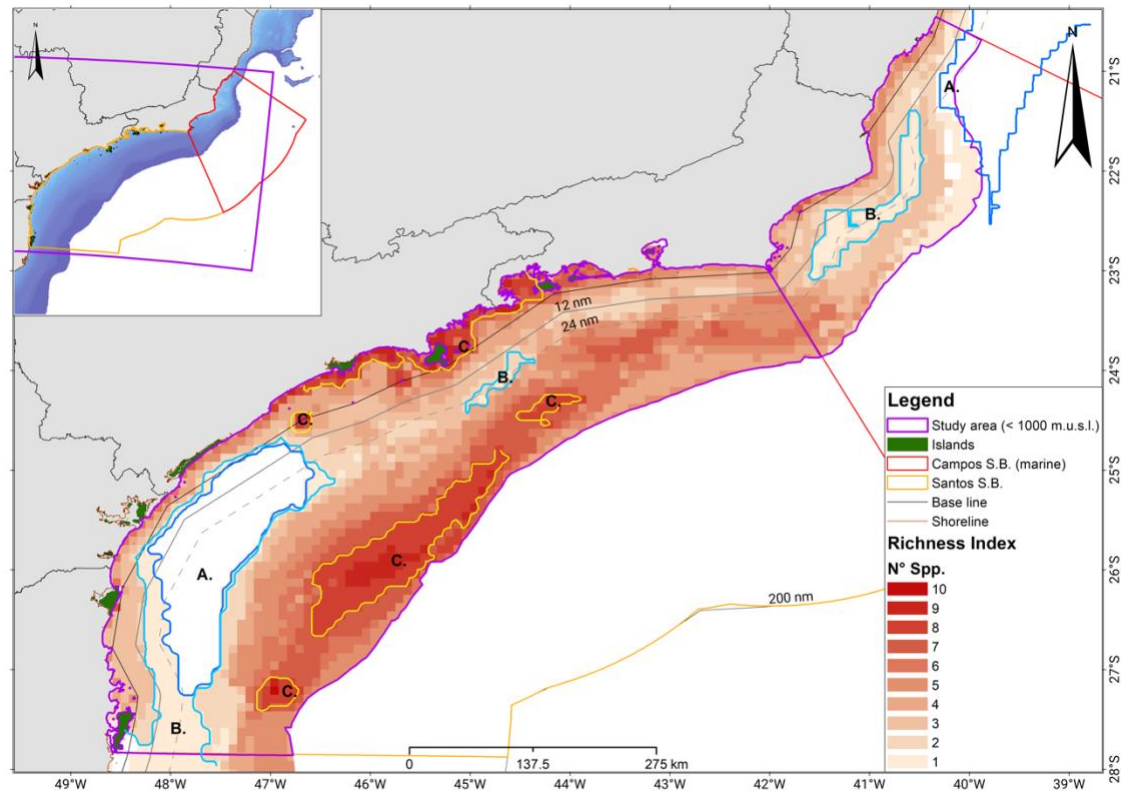


Figure 5.5. Hotspots of Biodiversity identified in the Campos and Santos Basins, Southwest Atlantic Ocean, Brazil. Areas A, outlined by the dark blue line, correspond to RI = 0 species, areas B, outlined by the light blue line, to RI = 1 species, and areas C, outlined by the yellow line to the hotspots with RI $\geq$ 8.

The Campos Basin concentrates all existing offshore wind proposals in the southeast Brazilian ocean and no proposals exist yet for the Santos Basin. The biodiversity hotspot areas overlaid with OWF areas are detailed in Fig. 5.6. A higher richness (RI = 6) is observed in the central portion of the basin, in the region between 12 nm and the shoreline.

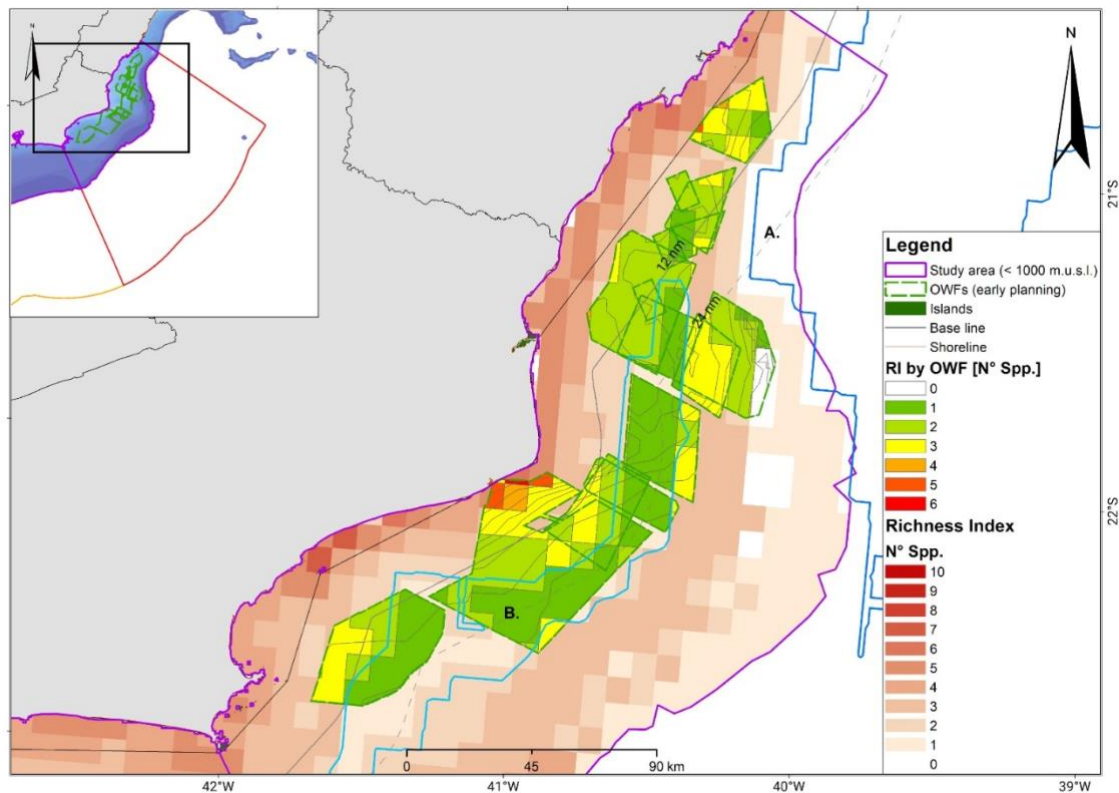


Figure 5.6. A: Map of areas of Offshore Wind Farms (OWFs) under planning, highlighting the Richness Index of selected vertebrates in these areas. Areas A, outlined by the dark blue line, correspond to RI = 0 species, areas B, outlined by the light blue line, to RI = 1 species.

5.4. Discussion

We found data to perform niche modelling for 22 cetacean species, which corresponds to 92% of the richness found in the study region (Martins et al., 2023), but only enough data to model the green turtle, which did not allow assessment of the other three chelonians species that occur in the southeast region. The data we provide is derived from extensive global species datasets that are freely available. Our study seems to be the first to simultaneously assess cetacean, seabird and chelonian hotspots areas to guide conservation strategies and marine spatial planning on the southeast coast of Brazil. All ENM modelled with MaxEnt had sufficient discriminatory capacity and were robust enough to serve as useful estimates of geographical ranges of species (Herkt et al., 2017).

A limitation detected was that data were not sufficient for seasonal analysis, due to the small number of occurrences and we assume that species do not show temporal

variation. This may bias the models for those species that have a strong seasonal influence (Tobeaña et al., 2016). MaxEnt modelling using only presence data is in line with other presence-background and presence-absence methods for predicting species distribution (Fiedler et al., 2018). The use of modelling techniques based on presence alone, without the need for observed absence or sampling effort data, can extend our ability to conduct spatially explicit risk assessments for marine vertebrates, as frequently such data is obtained opportunistically or during no systematic surveys (Fiedler et al., 2018).

Our study confirms the importance of bathymetry and distance of shore in explaining the niche suitability of most species in the Campos and Santos Basins. Bathymetry plays a significant role in cetacean habitat preference, reflecting species-specific depth preferences related to behavior, physiological limitations, and foraging (Putra & Mustika, 2021).

The two main hotspot areas identified and mapped in this study were the coastal zone up to 12 nm and in the bathymetric areas from 200 to 1000 m depth, both understood as critical habitats across multiple species. The preferred habitats of many dolphin species are coastal water characterized by shallow bathymetry, proximity to freshwater, and association with intertidal channels, coastal inlets, creeks, estuaries, river mouths and other oceanographic features that affect prey occurrence (Bouchet et al., 2021). The offshore hotspot area is characterized by shelf break upwellings that take place along continental slope and the seasonal movements of Brazil and Malvinas Currents, altering water compositions and enhancing densities of autotrophic communities of upper layers (Piola et al., 2000; Di Tullio et al., 2016). Whales and seabird species richness also is expected to increase near the shelf break and slope, because of subsurface processes that increase productivity in this region (Martins et al., 2023). The Santos basin appears to be an important area to keep free of OWF development as it has the highest nearshore diversity and lower wind speed resource (Pimenta et al., 2019).

Niche suitability results for the green turtle revealed higher values for coastal areas. Despite the excellent accuracy of the modelling, this result may present the bias of sampling only part of the population structure, since this species changes from pelagic and carnivorous habits to a predominantly herbivorous diet near the coast, especially by the juveniles or early adults (Lima et al., 2021). Although these foraging grounds are important areas for the turtles, further investigations are necessary to fill knowledge gaps and ensure the long-term sustainability of green sea turtles in Brazil (Neves-Ferreira et al., 2023). Due to the restricted number of occurrences and lack of data on pelagic areas,

we suggest that OWF environmental feasibility studies present telemetry data to remedy these sampling bias problems. The results of these studies should also be used to evaluate the possible barrier effect of offshore structures on the access of animals to coastal and pelagic areas. With respect to OWF, risk to turtle species is less well-studied than for marine mammals, birds and fish (see Chapter II). Studies should be directed towards understanding the possible impacts of underwater noise, luminosity, electromagnetic field emitted by underwater cables, and attraction to newly created habitats (Bennun et al. 2021). Conservation efforts and their outcome resulted in the species being removed from the Brazilian threatened list in 2022 (MMA, 2022), but the green turtle maintains its global endangered status by IUCN (2022).

The Franciscana, the common and the Guiana dolphins showed higher niche suitability only in the coastal waters up to 12 nm. We strongly recommend that no OWF structures be installed in the high suitability areas of Franciscana, a species listed as “Critically Endangered” by extinction (MMA, 2022) and restricted to shallow coastal waters within an average distance of 50 km from the coast and up to 35 m depth, with rare records beyond 50 m isobaths (Prado et al., 2013; Cunha et al., 2014; do Amaral et al., 2018). The common dolphin data is limited in our study region (Lima et al., 2021) requiring further primary data collection for a better understanding of the impact of anthropogenic activities on this species. The Guiana dolphin is the most common cetacean species found within nearshore area of Brazil and considered to be the resident species with the highest population decline recorded (do Amaral et al., 2015; Santos et al., 2019; Figueiredo et al., 2020).

The remaining cetacean studied showed areas of higher suitability both in coastal and pelagic zones between 200 and 1000 m depth. Therefore, studies on the dynamics of fauna corridors between these two seascapes are needed to ensure the least impact on the main routes used by the species and to contemplate seasonal behaviour analysis. The orca showed high suitability in coastal areas near the Marabaia sandbank (23°S, 44°W) but its largest high suitability area occurs on the continental shelf break. In southeastern Brazil orcas are observed in coastal and temperate waters, especially in areas of high productivity between November and February, but no information was available on their local abundance, movements, and distribution (Santos et al., 2019). Our ecological niche modelling indicates a broad high suitability area of the false killer orca, with higher suitability in the southern portion of the Santos basin, higher at depths of around 500 m. The false killer orca is known to prefer both oceanic and protective

bays areas with productive waters in a depth range of 38 m to 4,331 m (Putra & Mustika, 2021).

The rough-toothed, the Atlantic spotted and the common bottlenose dolphins showed higher niche suitability in coastal areas but the slope break zone also showed niche importance. The rough-toothed dolphin is all year sighted only in the coastal waters of southeastern Brazil, with a possible site fidelity in coastal waters between Cabo Frio and Rio de Janeiro cities, but also exists the need to better understand the home range of this species (Santos et al., 2019). The Atlantic spotted dolphin is a small delphinid that prefers near-shore habitat during coastal upwelling events (Santos et al., 2019, Putra & Mustika, 2021). The common bottlenose dolphin is one of the most frequently sighted species in the study areas, widely distributed along the Brazilian coast and also in the continental shelf break, up to the slope (Lima et al., 2021; Maricato et al., 2022).

In our study, the Bryde's whale (*B. edeni*), the fin whale (*B. physallus*) and the sei whale (*B. borealis*) (see Chapter IV) have distinct distribution areas, with Bryde's whale showing the highest suitability in near-shore areas. The Bryde's whale showed higher suitability in areas close to the coast and near the slope (~500 m depth). It is a widely distributed species (or species complex) found in tropical and temperate waters, feeding on schooling pelagic fishes and performing seasonal migrations (Fiedler et al., 2018). Taxonomic uncertainties in modelling the distribution of this species are challenging, but studying its ecological niche through modelling approaches could provide valuable information on niche separation if distinct environmental preferences exist between different taxonomic groups (Fiedler et al., 2018).

The short-finned pilot whale was the species that showed the lowest suitability in coastal areas, probably because it is a deep-diving odontocete found in tropical and sub-tropical regions that primarily forage on deep-water and shows consistency in habitat use relative to the shelf break (Stepanuk et al., 2018; Putra & Mustika, 2021).

The Atlantic yellow-nosed albatross was the most suitable seabird analyzed near the southeast coast and should certainly be included in efforts to mitigate the risk of OWF impacts in all seasons (Lemos et al., 2023), as discussed in Chapter III. Despite the importance of seabirds and their association with oceanographic and meteorological characteristics, efforts to assess their abundance and distribution in the Santos Basin region, both coastal and pelagic, remain scarce (Valls et al., 2023).

This study has demonstrated that the area currently proposed for OWF overlaps with 19% of the area of marine species hotspots in Campos Basin. Many important areas that

lie outside it could be targeted for protection in environmental compensation measures for impacts and/or preservation by the creation of MPAs. In marine ecosystems, direct exploitation of organisms (mainly fishing) is the biggest impact on biodiversity, followed by changes in the use of the sea due to direct/indirect human activities (Virtanen et al., 2018; IPBES, 2019).

We suggest that more data be obtained in future studies to assess the use of different areas for breeding and foraging at small and large temporal and spatial scales. Through future baseline population size sampling with standardized effort, our approach can be extended by modelling the effect of OWF impacts on abundance and density of marine fauna, through a highly desirable Before-After Control Impact (BACI) approach. Data deficiency remains a pervasive obstacle to wildlife management and conservation worldwide, especially in tropical marine environments, where reports of inconspicuous or unusual taxa are typically scarce and of lower quality due to cryptic animal behaviour, the unequal sampling effort, as well as the technical difficulties associated with surveying remote and extensive seascapes (Bouchet et al., 2021).

5.5. Conclusions

The biodiversity hotspot maps generated in this study can not only help minimize the impacts of wind energy but also assist in planning areas for other economic activities, such as fishing, marine mining and oil exploration. Our approach and analytical procedure can be easily replicated elsewhere, even with limited records of species presence. The results presented in this study provide valuable support for the strategic creation and strengthening of existing MPAs, to improve their individual and collective effectiveness in conserving global biodiversity (Le Saout et al., 2013). It is crucial to create MPAs in biodiversity-rich pelagic environments, which are currently not covered by Brazilian legislation, and to enforce the protection of key hotspot areas in neritic zones required for OWFs implementation.

To minimize future impacts on identified biodiversity hotspots, we recommend avoiding OWF installations in coastal areas up to at least 12 nautical miles (nm) from the coast. Therefore, environmental impact assessments of OWFs in Brazil should include at least one alternative location option outside the 12 nautical mile threshold. Integrating impact avoidance strategies into spatial planning, and utilizing local-level information, is crucial for safeguarding biodiversity from anthropogenic impacts (Phalan et al., 2018).

For the installation stage of OWFs it is important to observe construction-free periods during crucial breeding, migrating, or growth periods of marine fauna to mitigate potential

disturbances (Sabadini et al., 2020). Finally, impact assessments should provide answers to the effect of cumulative barrier impacts of multiple wind farms on migratory path, cumulative habitat loss from displacement or behavioural interference, the cumulative underwater noise impacts and increased potential for vessel strikes due to the installation/construction of multiple projects (Bennun et al. 2021).

CHAPTER VI

Conclusions

We successfully achieved our objectives of gaining a comprehensive understanding of the distribution of seabirds, cetaceans and sea turtles, as well as identifying biodiversity hotspots within the southwest Atlantic Ocean, in the area delimited by the marine Exclusive Economic Zone of Brazil. Data on the occurrence of species in the Brazilian Atlantic Ocean are few and not systematized for public use. Despite this, the models we generated are spatially explicit, applicable to a wide range of taxa and spatial scales, and relatively quick and cheap for assessing potential population-level impacts of different processes and threats. It could also identify target species for conservation, monitoring or more in depth studies focused on mitigating potential impacts of offshore windfarms. The most widely used conservation feature in conservation planning is the geographical distribution of multiple species, as species distributions are often best known compared to other biodiversity facets (Domisch et al., 2019).

One of the major challenges for conservation planners is to overcome the Wallacean shortfall, that is, to know the full geographical distribution of species (Domisch et al., 2019). The main tool used to produce such range-wide species distribution data species are ecological niche modelling (ENM) (Guisan & Thuiller, 2005). Modellers often have to collate existing data rather than obtain expensive survey-based samples (Valavi et al., 2022). MaxEnt modelling (Phillips & Dudík, 2008; Phillips et al., 2017) using only presence data is considered to be on par with other presence-absence methods for predicting species distribution, among the best-performing models (Fiedler et al., 2018; Valavi et al., 2022).

The niche suitability predictions obtained helped to generate a richness index (RI) used in the identification of biodiversity hotspots. Hotspots can be interpreted as sites with intense biological activity and high species richness that have aggregated from favourable oceanographic and biological features often considered areas that should receive greater protection (Palacios et al., 2006; Tittensor et al., 2010; Sahri et al., 2021). The main outcome of the predictions generated by the models was the identification and mapping of suitable habitats (Sillero, 2011).

Two main hotspot areas had been distinguished in this study, one in the coastal zone down to 12 nm and the other in the bathymetric strips from 200 to 1000 m depth. We

emphasize the importance of coastal areas for the diversity of cetaceans found in the southern and southeastern Brazilian Atlantic Ocean. Our results show that the predicted marine vertebrates occurring mainly in the southeast coastal hotspot zone (~12 nm) included Bryde's whale *Balaenoptera edeni*, Franciscana *Pontoporia blainvillei*, common dolphin *Delphinus delphis*, Guiana dolphin *Sotalia guianensis*, Atlantic spotted dolphin *Stenella frontalis*, common bottlenose dolphin *Tursiops truncatus*, rough-toothed dolphin *Steno bredanensis*, southern right whale *Eubalaena australis*, green turtle *Chelonia mydas*, and Atlantic yellow-nosed albatross *Thalassarche chlororhynchos*.

The cetacean and seabird species richness are expected to increase in the vicinity of the shelf break and slope because of the interaction and incomplete mixing between the different water masses produce the oceanographic fronts, regions that have a high biological diversity due to enhanced local productivity. Cold currents from the polar regions, such as the Malvinas Current, reach the southern coast of Brazil, providing a great diversity of organisms and a high biomass of food resources for these top predators (Di Tullio et al., 2016; Martins et al., 2023; Valls et al., 2023). There is an important oceanographic front formed by the difference between shelf and continental slope waters in the western South Atlantic region. The mean location of this front is closely associated with the 200 m isobath, which corresponds to the interface between the colder, lower salinity waters of the shelf and the warmer, saltier waters of the Brazil Current (BC) (Pereira et al., 2009). The pelagic zone located has proven to be a hotspot for wandering albatross *Diomedea exulans*, Atlantic yellow-nosed albatross *Thalassarche chlororhynchos*, Atlantic petrel *Pterodroma incerta*, White-chinned Petrel *Procellaria aequinoctialis*, Spectacled Petrel *Procellaria conspicillata*, Black-browed Albatross *Thalassarche melanophris*, Great Shearwater *Ardenna gravis*, Bryde's whale *Balaenoptera edeni*, sei whale *Balaenoptera borealis*, fin whale *Balaenoptera physalus*, sperm whale *Physeter macrocephalus*, short-finned pilot whale *Globicephala macrorhynchus*, orca *Orcinus orca*, false killer whale *Pseudorca crassidens*, rough-toothed dolphin *Steno bredanensis* and common bottlenose dolphin *Tursiops truncatus*.

The increasing number of offshore wind farms (OWFs) proposed off the Brazilian coast is a biodiversity management challenge that needs to be addressed with strategic and targeted environmental impact assessments. Despite the benefits of renewable sources, several studies reveal environmental impacts of renewable energy projects, which vary in type and intensity according to the technology used, geographic location, ecological resources, among other factors (Bennun, et al., 2021; Degraer et al., 2021 and Chapter II). To determine the environmental changes and significance of impacts of major

infrastructure projects, including OWFs, normally requires an Environmental Impact Assessments (EIA) (Causon et al., 2022). Ecosystem survey and monitoring are an integral part of the EIA study and mainly involve collection of baseline data on various biotic and abiotic parameters (Adhikari et al., 2019). A full assessment of potential impacts on protected wildlife populations is required in the EIA to obtain consent for certain activities (Horswill et al., 2022). We emphasize that the quality of the biodiversity data on which these assessments are based is critical to avoid or mitigate the negative impacts of development (Dias et al., 2022). Good practices in the EIA also highlight the need for standardization in monitoring and impact analysis procedures and strategic maritime spatial planning that considers conservation areas and environmental sensitivity (Lüdeke, 2017).

Improving access to spatially explicit biodiversity database can help to develop management options to avoid detrimental impacts on the most important sites, species and habitats (Underwood et al., 2018). Species distribution models can be used to provide a baseline context for impact assessment in areas planned for OWF, guiding siting and management decisions (Best & Halpin, 2019; Goodale & Milman, 2019; Mercker et al., 2021). Further industry engagement and better spatial planning and management of the marine basins (Almada & Bernardino, 2017).

The main strategy for preventing impacts is “spatial prioritization”, in the early stage of planning to avoid conflicts between wildlife and OWF (Heinänen et al., 2020; Bennun, et al., 2021). Prioritization exercises are valuable tools to structure a balance between conservation measures and sustainable ocean management. In the last decades, many efforts have been made to develop science-based methodologies to select priority areas for biodiversity conservation (Vu et al., 2022). In Brazilian EEZ’s shallow waters (0 to 200 m depth) in the warm season, the niche modelling results indicated the Atlantic yellow-nosed albatross, the Atlantic petrel and the great shearwater as target species for monitoring impacts of OWF. The Atlantic yellow-nosed albatross and the white-chinned petrel were the target species of the cold season. The Franciscana and the southern right whale had overlapping areas with planned OWF, emphasizing the need for conservation measures to mitigate the potential impacts. Prediction maps of previous studies have shown that along the southern Brazilian coastline the high suitability areas for mother-calf pairs of the southern right whale were more coastal than those for unaccompanied adults (Renault-Braga et al., 2022). These species certainly will require specific programs to avoid, mitigate or compensate impacts such as collision and displacement. Coastal zones are important for the Franciscana and the Guiana dolphins,

which are restricted to shallow coastal waters, and for the southern right whale with a preference for coastal waters with high primary production and cold waters.

All the threatened cetacean species analyzed in this study had areas of high suitability overlapping with gillnet fishing, being the Guiana dolphin, the Franciscana and the southern right whale the most affected. Fisheries are one of the most widespread threats to marine ecosystems (IPBES, 2019) and are responsible for the decline of many populations of marine fauna through direct competition, deliberate capture for food and bycatch (Bugoni et al., 2008; Grémillet et al., 2018; Stepanuk et al., 2018). The decline of turtle populations is also associated with human activities on their habitat, such as incidental capture through the use of different fishing gears and pollution by solid waste, which can hinder female access to the spawning site (compromising reproductive success) and climate change, due to the role of temperature in determining the sex of embryos (Ribeiro-Silva et al., 2011; Monteiro et al., 2016; Sforza et al., 2017; Bastos et al., 2022).

Our results showed that some pelagic areas are important for the conservation of procellariiforms and cetaceans but remain uncovered in the legally protected areas in Brazil. So, it is crucial to create MPAs in biodiversity-rich pelagic environments. The results presented in this study provide valuable support for the strategic creation and strengthening of existing MPAs, to improve their individual and collective effectiveness in conserving global biodiversity (Le Saout et al., 2013). Although Brazil has designated protected areas, their distribution is unbalanced, and the ability of the current system to protect threatened marine mammals remains unclear. Understanding how marine fauna overlaps and interacts with threats in space is crucial for its conservation (Carneiro et al., 2020). Biodiversity conservation and the expansion of protected areas are critical targets to prevent species extinction, as highlighted by the Convention on Biological Diversity (CDB, 2022). Priority areas for biodiversity conservation are identified at the regional to a global scale, by using criteria such as species richness, rarity, endemism, representativeness, and complementarity to drive the conservation effort (Vu et al., 2022).

Only the high suitability areas of southern right whale and Franciscana have a small overlap with conservation areas, which supports the need to prioritize the remaining hotspot regions as targets for threatened species conservation efforts. Also, further research is required to better understand the conservation needed by threatened cetaceans, such as Lahille's bottlenose dolphin and the blue whale. The analysis of the seasonal distribution of procellariiforms demonstrates the importance of considering in

conservation strategies the different use areas of animals that have habitats in distant areas. The south Brazilian shelf is an important area for juveniles, immatures and non-breeding adults. Ignoring the distributions of birds at different life stages leads to biased estimates and can misdirect management and conservation efforts (Carneiro et al., 2020).

This study highlights the importance of using ENM and a Richness Index (RI) in understanding species distribution patterns as integral parts of the process of biodiversity conservation, supporting strategic environmental assessments and spatial planning. The modelling prediction can be useful to examine ecological patterns, identify target species, and select periods and areas where risks are highest so that more attention is given to developing proper mitigation of impacts on biodiversity (Best & Halpin, 2019).

Our study also reveals the valuable insights that ecological niche assessment through modelling approaches can offer, contributing to the clarification of taxonomic uncertainties (Fiedler et al., 2018). We found distinct distribution areas for Bryde's whales, fin whales and sei whales, with Bryde's whales showing the highest niche segregation and suitability in coastal areas. In addition, we observed a clear niche segregation between the congeneric white-chinned petrel and spectacled petrel. The white-chinned petrel makes extensive use of highly productive coastal waters (Phillips et al., 2006) and the spectacled petrel has greater niche suitability in the shelf break waters further north (Bugoni et al., 2009).

Given the multiplicity of insights derived from this study, we are confident that ENMs and RI are desired additions to the EIA toolbox for sites with limited biodiversity data availability, to provide a scientific basis on which to develop biodiversity conservation criteria, informing licensing processes and mitigation measures.

6.1. Recommendations and future studies

The results obtained by the predictions with MaxEnt can be used for future projection based on predicted environmental changes and to help assess the impacts of proposed changes on possible niche shifts.

We suggest that ENM should be useful in EIA studies to guide biodiversity survey, identify potential habitats that might be threatened, and delineating conservation areas (Adhikari et al., 2019). We advocate for the incorporation of niche models in EIA, as a tool for improving environmental planning, impact assessment and conservation. Our

study demonstrates that integrating ENM and RI in the EIA can enhance its effectiveness through an improved understanding of the distribution areas of marine vertebrates. ENM facilitates the interpolation of the potential distribution of species in areas that have not been fully studied, generating a result in the form of a predictive map, which can be validated through sampling in field (Peterson et al., 2011b; Adhikari et al., 2019).

We also recommend ENM and RI to be applied to other marine fauna, with different threats or other spatial scales to gain a more complete understanding of multispecies risk zones and periods (Carneiro et al., 2020). Research related to a more local investigation should seek to gather inventory information on natural species in the region and their respective patterns of distribution in space and time (Stirling et al., 2016; Mannocci et al., 2017; Best & Halpin, 2019).

We advise avoiding OWF installations in coastal areas up to at least 12 nautical miles (nm) from the coast and include at least one alternative location option outside the 12 nautical mile threshold. The OWF environmental feasibility study assessments should present telemetry data and address the possible barrier effect of offshore structures on animal access to coastal and pelagic areas.

Also, intensified research efforts are needed to increase our knowledge and understanding of conservation needs, especially in pelagic environments and about threatened species with low numbers of occurrence in Brazil.

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Attachments

A. Supporting information of Chapter II

Table SM 2. 1. The 104 selected articles in-depth read to systematize the data on the stage of development of OWF, environmental stressors, impacts, and receptors on biota.

Authors	Title	Year	DOI
Causon P.D., Jude S., Gill A.B., Leinster P.	Critical evaluation of ecosystem changes from an offshore wind farm: producing natural capital asset and risk registers	2022	10.1016/j.envsci.2022.07.003
Mikami K., Kazama K., Kazama M.T., Watanuki Y.	Mapping the collision risk between two gull species and offshore wind turbines: Modelling and validation	2022	10.1016/j.jenvma.n.2022.115220
Coolen J.W.P., Vanaverbeke J., Dannheim J., Garcia C., Birchenough S.N.R., Krone R., Beermann J.	Generalized changes of benthic communities after construction of wind farms in the southern North Sea	2022	10.1016/j.jenvma.n.2022.115173
ter Hofstede R., Driessen F.M.F., Elzinga P.J., Van Koningsveld M., Schutter M.	Offshore wind farms contribute to epibenthic biodiversity in the North Sea	2022	10.1016/j.seares.2022.102229
Guarinello M.L., Carey D.A.	Multi-modal Approach for Benthic Impact Assessments in Moraine Habitats: a Case Study at the Block Island Wind Farm	2022	10.1007/s12237-020-00818-w
Wilber D.H., Brown L., Griffin M., Decelles G.R., Carey D.A.	Demersal fish and invertebrate catches relative to construction and operation of North America's first offshore wind farm	2022	10.1093/icesjms/fac051
Horswill C., Miller J.A.O., Wood M.J.	Impact assessments of wind farms on seabird populations that overlook existing drivers of demographic change should be treated with caution	2022	10.1111/csp2.12644
Kok A.C.M., Bruil L., Berges B., Sakinan S., Debusschere E., Reubens J., de Haan D., Norro A., Slabbekoorn H.	An echosounder view on the potential effects of impulsive noise pollution on pelagic fish around windfarms in the North Sea	2021	10.1016/j.envpol.2021.118063
Mercker M., Dierschke V., Camphuysen K., Kreutle A., Markones N., Vanermen N., Garthe S.	An indicator for assessing the status of marine-bird habitats affected by multiple human activities: A novel statistical approach	2021	10.1016/j.ecolind.2021.108036
van Erp J.A., van Loon E.E., Camphuysen K.J., Shamoun-Baranes J.	Temporal patterns in offshore bird abundance during the breeding season at the Dutch North Sea coast	2021	10.1007/s00227-021-03954-4
Pollock C.J., Lane J.V., Buckingham L., Garthe S., Jeavons R., Furness R.W., Hamer K.C.	Risks to different populations and age classes of gannets from impacts of offshore wind farms in the southern North Sea	2021	10.1016/j.marenvres.2021.105457

Vilela R., Burger C., Diederichs A., Bachl F.E., Szostek L., Freund A., Braasch A., Bellebaum J., Beckers B., Piper W., Nehls G.	Use of an INLA Latent Gaussian Modeling Approach to Assess Bird Population Changes Due to the Development of Offshore Wind Farms	2021	10.3389/fmars.2021.701332
Pezy J.-P., Dauvin J.-C.	Wide coverage but few quantitative data: Coarse sediments in the English Channel	2021	10.1016/j.ecolind.2020.107010
Lane J.V., Jeavons R., Deakin Z., Sherley R.B., Pollock C.J., Wanless R.J., Hamer K.C.	Vulnerability of northern gannets to offshore wind farms; seasonal and sex-specific collision risk and demographic consequences	2020	10.1016/j.marenvres.2020.105196
Peschko V., Mendel B., Müller S., Markones N., Mercker M., Garthe S.	Effects of offshore windfarms on seabird abundance: Strong effects in spring and in the breeding season	2020	10.1016/j.marenvres.2020.105157
Stenhouse I.J., Berlin A.M., Gilbert A.T., Goodale M.W., Gray C.E., Montevecchi W.A., Savoy L., Spiegel C.S.	Assessing the exposure of three diving bird species to offshore wind areas on the U.S. Atlantic Outer Continental Shelf using satellite telemetry	2020	10.1111/ddi.13168
Heinänen S., Žydelis R., Kleinschmidt B., Dorsch M., Burger C., Morkūnas J., Quillfeldt P., Nehls G.	Satellite telemetry and digital aerial surveys show strong displacement of red-throated divers (<i>Gavia stellata</i>) from offshore wind farms	2020	10.1016/j.marenvres.2020.104989
Peschko V., Mercker M., Garthe S.	Telemetry reveals strong effects of offshore wind farms on behaviour and habitat use of common guillemots (<i>Uria aalge</i>) during the breeding season	2020	10.1007/s00227-020-03735-5
Goodale M.W., Milman A.	Assessing Cumulative Exposure of Northern Gannets to Offshore Wind Farms	2020	10.1002/wsb.1087
Dannheim J., Bergström L., Birchenough S.N.R., Brzana R., Boon A.R., Coolen J.W.P., Dauvin J.-C., De Mesel I., Derweduwen J., Gill A.B., Hutchison Z.L., Jackson A.C., Janas U., Martin G., Raoux A., Reubens J., Rostin L., Vanaverbeke J., Wilding T.A., Wilhelmsson D., S.	Benthic effects of offshore renewables: Identification of knowledge gaps and urgently needed research	2020	10.1093/icesjms/fsz018
Matzner S., Warfel T., Hull R.	ThermalTracker-3D: A thermal stereo vision system for quantifying bird and bat activity at offshore wind energy sites	2020	10.1016/j.ecoinf.2020.101069
Vanermen N., Courtens W., Daelemans R., Lens L., Müller W., Van De Walle M., Verstraete H., Stienen E.W.M.	Attracted to the outside: A meso-scale response pattern of lesser black-backed gulls at an offshore wind farm revealed by GPS telemetry	2020	10.1093/icesjms/fsz199
Burger C., Schubert A., Heinänen S., Dorsch M., Kleinschmidt B., Žydelis R., Morkūnas J., Quillfeldt P., Nehls G.	A novel approach for assessing effects of ship traffic on distributions and movements of seabirds	2019	10.1016/j.jenvman.2019.109511
Best B.D., Halpin P.N.	Minimizing wildlife impacts for offshore wind energy development: Winning tradeoffs for seabirds in space and cetaceans in time	2019	10.1371/journal.pone.0215722

Goodale M.W., Milman A.	Assessing the cumulative exposure of wildlife to offshore wind energy development	2019	10.1016/j.jenvma n.2019.01.022
Mendel B., Schwemmer P., Peschko V., Müller S., Schwemmer H., Mercker M., Garthe S.	Operational offshore wind farms and associated ship traffic cause profound changes in distribution patterns of Loons (<i>Gavia</i> spp.)	2019	10.1016/j.jenvma n.2018.10.053
Raoux A., Lassalle G., Pezy J.-P., Tecchio S., Safi G., Ernande B., Mazé C., Loc'h F.L., Lequesne J., Girardin V., Dauvin J.-C., Niquil N.	Measuring sensitivity of two OSPAR indicators for a coastal food web model under offshore wind farm construction	2019	10.1016/j.ecolind. 2018.07.014
Harwood A.J.P., Perrow M.R., Berridge R.J.	Use of an optical rangefinder to assess the reliability of seabird flight heights from boat-based surveyors: implications for collision risk at offshore wind farms	2018	10.1111/jofo.122 69
Kelsey E.C., Felis J.J., Czapanskiy M., Pereksta D.M., Adams J.	Collision and displacement vulnerability to offshore wind energy infrastructure among marine birds of the Pacific Outer Continental Shelf	2018	10.1016/j.jenvma n.2018.08.051
Kleyheeg-Hartman J.C., Krijgsveld K.L., Collier M.P., Poot M.J.M., Boon A.R., Troost T.A., Dirksen S.	Predicting bird collisions with wind turbines: Comparison of the new empirical Flux Collision Model with the SOSS Band model	2018	10.1016/j.ecolmo del.2018.06.025
Busch M., Garthe S.	Looking at the bigger picture: The importance of considering annual cycles in impact assessments illustrated in a migratory seabird species	2018	10.1093/icesjms/f sx170
Raoux A., Dambacher J.M., Pezy J.-P., Mazé C., Dauvin J.-C., Niquil N.	Assessing cumulative socio-ecological impacts of offshore wind farm development in the Bay of Seine (English Channel)	2018	10.1016/j.marpol. 2017.12.007
Thaxter C.B., Ross-Smith V.H., Bouten W., Masden E.A., Clark N.A., Conway G.J., Barber L., Clewley G.D., Burton N.H.K.	Dodging the blades: New insights into three-dimensional space use of offshore wind farms by lesser black-backed gulls <i>Larus fuscus</i>	2018	10.3354/meps12 415
Borkenhagen K., Corman A.-M., Garthe S.	Estimating flight heights of seabirds using optical rangefinders and GPS data loggers: a methodological comparison	2018	10.1007/s00227- 017-3273-z
May R., Åström J., Hamre, Dahl E.L.	Do birds in flight respond to (ultra)violet lighting?	2017	10.1186/s40657- 017-0092-3
Vallejo G.C., Grellier K., Nelson E.J., McGregor R.M., Canning S.J., Caryl F.M., McLean N.	Responses of two marine top predators to an offshore wind farm	2017	10.1002/ECE3.33 89
O'Brien S.H., Cook A.S.C.P., Robinson R.A.	Implicit assumptions underlying simple harvest models of marine bird populations can mislead environmental management decisions	2017	10.1016/j.jenvma n.2017.06.037
Horswill C., O'Brien S.H., Robinson R.A.	Density dependence and marine bird populations: are wind farm assessments precautionary?	2017	10.1111/1365- 2664.12841

Dähne M., Tougaard J., Carstensen J., Rose A., Nabe-Nielsen J.	Bubble curtains attenuate noise from offshore wind farm construction and reduce temporary habitat loss for harbour porpoises	2017	10.3354/meps12257
Floeter J., van Beusekom J.E.E., Auch D., Callies U., Carpenter J., Dudeck T., Eberle S., Eckhardt A., Gloe D., Hänselmann K., Hufnagl M., Janßen S., Lenhart H., Möller K.O., North R.P., Pohlmann T., Riethmüller R., Schulz S., Spreizenbarth S., Temming A., Walter B., Zielinski O., Möllmann C.	Pelagic effects of offshore wind farm foundations in the stratified North Sea	2017	10.1016/j.pocean.2017.07.003
Cranmer A., Smetzer J.R., Welch L., Baker E.	A Markov model for planning and permitting offshore wind energy: A case study of radio-tracked terns in the Gulf of Maine, USA	2017	10.1016/j.jenvma.n.2017.02.010
Heinänen S., Žydelis R., Dorsch M., Nehls G., Skov H.	High-resolution sea duck distribution modeling: Relating aerial and ship survey data to food resources, anthropogenic pressures, and topographic variables	2017	10.1650/CONDO R-16-57.1
Garthe S., Peschko V., Kubetzki U., Corman A.-M.	Seabirds as samplers of the marine environment - A case study of northern gannets	2017	10.5194/os-13-337-2017
Cook A.S.C.P., Robinson R.A.	Towards a framework for quantifying the population-level consequences of anthropogenic pressures on the environment: The case of seabirds and windfarms	2017	10.1016/j.jenvma.n.2016.12.025
Forney K.A., Southall B.L., Slooten E., Dawson S., Read A.J., Baird R.W., Brownell R.L., Jr.	Nowhere to go: Noise impact assessments for marine mammal populations with high site fidelity	2017	10.3354/esr00820
Bray L., Kassis D., Hall-Spencer J.M.	Assessing larval connectivity for marine spatial planning in the Adriatic	2017	10.1016/j.marenv.res.2017.01.006
Garthe S., Markones N., Corman A.-M.	Possible impacts of offshore wind farms on seabirds: a pilot study in Northern Gannets in the southern North Sea	2017	10.1007/s10336-016-1402-y
Raoux A., Tecchio S., Pezy J.-P., Lassalle G., Degraer S., Wilhelmsson D., Cachera M., Ernande B., Le Guen C., Haraldsson M., Grangeré K., Le Loc'h F., Dauvin J.-C., Niquil N.	Benthic and fish aggregation inside an offshore wind farm: Which effects on the trophic web functioning?	2017	10.1016/j.ecolind.2016.07.037
Green R.E., Langston R.H.W., McCluskie A., Sutherland R., Wilson J.D.	Lack of sound science in assessing wind farm impacts on seabirds	2016	10.1111/1365-2664.12731
Ross-Smith V.H., Thaxter C.B., Masden E.A., Shamoun-Baranes J., Burton N.H.K., Wright L.J., Rehfish M.M., Johnston A.	Modelling flight heights of lesser black-backed gulls and great skuas from GPS: a Bayesian approach	2016	10.1111/1365-2664.12760
Dierschke V., Furness R.W., Garthe S.	Seabirds and offshore wind farms in European waters: Avoidance and attraction	2016	10.1016/j.biocon.2016.08.016

Goyert H.F., Gardner B., Sollmann R., Veit R.R., Gilbert A.T., Connelly E.E., Williams K.A.	Predicting the offshore distribution and abundance of marine birds with a hierarchical community distance sampling model	2016	10.1890/15-1955.1
Wade H.M., Masden E.A., Jackson A.C., Furness R.W.	Incorporating data uncertainty when estimating potential vulnerability of Scottish seabirds to marine renewable energy developments	2016	10.1016/j.marpol.2016.04.045
Welcker J., Nehls G.	Displacement of seabirds by an offshore wind farm in the North Sea	2016	10.3354/meps11812
Coates D.A., Kapasakali D.-A., Vincx M., Vanaverbeke J.	Short-term effects of fishery exclusion in offshore wind farms on macrofaunal communities in the Belgian part of the North Sea	2016	10.1016/j.fishres.2016.02.019
Bray L., Reizopoulou S., Voukouvalas E., Soukissian T., Alomar C., Vázquez-Luis M., Deudero S., Attrill M.J., Hall-Spencer J.M.	Expected effects of offshore wind farms on Mediterranean Marine Life	2016	10.3390/jmse4010018
Skov H., Heinänen S., Thaxter C.B., Williams A.E., Lohier S., Banks A.N.	Real-time species distribution models for conservation and management of natural resources in marine environments	2016	10.3354/meps11572
Kemper G., Weidauer A., Coppack T.	Monitoring seabirds and marine mammals by georeferenced aerial photography	2016	10.5194/isprsarchives-XLI-B8-689-2016
Debusschere E., De Coensel B., Vandendriessche S., Botteldooren D., Hostens K., Vincx M., Degraer S.	Effects of offshore wind farms on the early life stages of <i>dicentrarchus labrax</i>	2016	10.1007/978-1-4939-2981-8_23
Busch M., Garthe S.	Approaching population thresholds in presence of uncertainty: Assessing displacement of seabirds from offshore wind farms	2016	10.1016/j.eiar.2015.08.007
Haelters J., Dulière V., Vigin L., Degraer S.	Towards a numerical model to simulate the observed displacement of harbour porpoises <i>Phocoena phocoena</i> due to pile driving in Belgian waters	2015	10.1007/s10750-014-2138-4
Cleasby I.R., Wakefield E.D., Bearhop S., Bodey T.W., Votier S.C., Hamer K.C.	Three-dimensional tracking of a wide-ranging marine predator: Flight heights and vulnerability to offshore wind farms	2015	10.1111/1365-2664.12529
Zipkin E.F., Kinlan B.P., Sussman A., Rypkema D., Wimer M., O'Connell A.F.	Statistical guidelines for assessing marine avian hotspots and coldspots: A case study on wind energy development in the U.S. Atlantic Ocean	2015	10.1016/j.biocon.2015.06.035
Šaškov A., Dahlgren T.G., Rzhano Y., Schläppy M.-L.	Comparison of manual and semi-automatic underwater imagery analyses for monitoring of benthic hard-bottom organisms at offshore renewable energy installations	2015	10.1007/s10750-014-2072-5
Vanermen N., Onkelinx T., Courtens W., Van de walle M., Verstraete H., Stienen E.W.M.	Seabird avoidance and attraction at an offshore wind farm in the Belgian part of the North Sea	2015	10.1007/s10750-014-2088-x
Brabant R., Vanermen N., Stienen E.W.M., Degraer S.	Towards a cumulative collision risk assessment of local and migrating birds in North Sea offshore wind farms	2015	10.1007/s10750-015-2224-2
Vanermen N., Onkelinx T., Verschelde P., Courtens W., Van de walle M., Verstraete H., Stienen E.W.M.	Assessing seabird displacement at offshore wind farms: power ranges of a monitoring and data handling protocol	2015	10.1007/s10750-014-2156-2

Fijn R.C., Krijgsveld K.L., Poot M.J.M., Dirksen S.	Bird movements at rotor heights measured continuously with vertical radar at a Dutch offshore wind farm	2015	10.1111/ibi.12259
Thaxter C.B., Ross-Smith V.H., Bouten W., Clark N.A., Conway G.J., Rehfish M.M., Burton N.H.K.	Seabird-wind farm interactions during the breeding season vary within and between years: A case study of lesser black-backed gull <i>Larus fuscus</i> in the UK	2015	10.1016/j.biocon.2015.03.027
Certain G., Jørgensen L.L., Christel I., Planque B., Bretagnolle V.	Mapping the vulnerability of animal community to pressure in marine systems: Disentangling pressure types and integrating their impact from the individual to the community level	2015	10.1093/icesjms/fsv003
Johnston A., Thaxter C.B., Austin G.E., Cook A.S.C.P., Humphreys E.M., Still D.A., Mackay A., Irvine R., Webb A., Burton N.H.K.	Modelling the abundance and distribution of marine birds accounting for uncertain species identification	2015	10.1111/1365-2664.12364
Janßen H., Schröder T., Zettler M.L., Pollehne F.	Offshore wind farms in the southwestern Baltic Sea: A model study of regional impacts on oxygen conditions	2015	10.1016/j.seares.2014.05.001
Debusschere E., De Coensel B., Bajek A., Botteldooren D., Hostens K., Vanaverbeke J., Vandendriessche S., Van Ginderdeuren K., Vincx M., Degraer S.	In situ mortality experiments with juvenile sea bass (<i>dicentrarchus labrax</i>) in relation to impulsive sound levels caused by pile driving of windmill foundations	2014	10.1371/journal.pone.0109280
Bradbury G., Trinder M., Furness B., Banks A.N., Caldow R.W.G., Hume D.	Mapping Seabird Sensitivity to offshore wind farms	2014	10.1371/journal.pone.0106366
Johnston A., Cook A.S.C.P., Wright L.J., Humphreys E.M., Burton N.H.K.	Modelling flight heights of marine birds to more accurately assess collision risk with offshore wind turbines	2014	10.1111/1365-2664.12191
Wade H.M., Masden E.A., Jackson A.C., Thaxter C.B., Burton N.H.K., Bouten W., Furness R.W.	Great skua (<i>Stercorarius skua</i>) movements at sea in relation to marine renewable energy developments	2014	10.1016/j.marenvres.2014.09.003
Winiarski K.J., Miller D.L., Paton P.W.C., McWilliams S.R.	A spatial conservation prioritization approach for protecting marine birds given proposed offshore wind energy development	2014	10.1016/j.biocon.2013.11.004
Winiarski K.J., Miller D.L., Paton P.W.C., McWilliams S.R.	Spatially explicit model of wintering common loons: Conservation implications	2013	10.3354/meps10492
Rossington K., Benson T., Lepper P., Jones D.	Eco-hydro-acoustic modeling and its use as an EIA tool	2013	10.1016/j.marpolbul.2013.07.024
Furness R.W., Wade H.M., Masden E.A.	Assessing vulnerability of marine bird populations to offshore wind farms	2013	10.1016/j.jenvman.2013.01.025
Soanes L.M., Atkinson P.W., Gauvain R.D., Green J.A.	Individual consistency in the foraging behaviour of Northern Gannets: Implications for interactions with offshore renewable energy developments	2013	10.1016/j.marpol.2012.08.006
Groom G., Stjernholm M., Nielsen R.D., Fleetwood A., Petersen I.K.	Remote sensing image data and automated analysis to describe marine bird distributions and abundances	2013	10.1016/j.ecoinf.2012.12.001
Christel I., Certain G., Cama A., Vieites D.R., Ferrer X.	Seabird aggregative patterns: A new tool for offshore wind energy risk assessment	2013	10.1016/j.marpolbul.2012.11.005

Plonczkier P., Simms I.C.	Radar monitoring of migrating pink-footed geese: Behavioural responses to offshore wind farm development	2012	10.1111/j.1365-2664.2012.02181.x
Masden E.A., Reeve R., Desholm M., Fox A.D., Furness R.W., Haydon D.T.	Assessing the impact of marine wind farms on birds through movement modelling	2012	10.1098/rsif.2012.0121
Mateos-Rodríguez M., Thomas L., Arroyo G.M.	The development and use of a method to fill time gaps in migration counts	2012	10.1525/cond.2012.100053
Buckland S.T., Burt M.L., Rexstad E.A., Mellor M., Williams A.E., Woodward R.	Aerial surveys of seabirds: The advent of digital methods	2012	10.1111/j.1365-2664.2012.02150.x
Mateos-RODRÍ M., Antonio-Román Muñoz I., Arroyo G.M.	Assessment of offshore wind farm effects on birds and needs to plan their future development in Spain	2012	10.13157/arla.59.2.2012.217
Pérez Lapeña B., Wijnberg K.M., Stein A., Hulscher S.J.M.H.	Spatial factors affecting statistical power in testing marine fauna displacement	2011	10.1890/10-1887.1
Perrow M.R., Gilroy J.J., Skeate E.R., Tomlinson M.L.	Effects of the construction of Scroby Sands offshore wind farm on the prey base of Little tern <i>Sternula albifrons</i> at its most important UK colony	2011	10.1016/j.marpolbul.2011.06.010
Lindeboom H.J., Kouwenhoven H.J., Bergman M.J.N., Bouma S., Brasseur S., Daan R., Fijn R.C., De Haan D., Dirksen S., Van Hal R., Hille Ris Lambers R., Ter Hofstede R., Krijgsveld K.L., Leopold M., Scheidat M.	Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; A compilation	2011	10.1088/1748-9326/6/3/035101
Pérez Lapeña B., Wijnberg K.M., Hulscher S.J.M.H., Stein A.	Environmental impact assessment of offshore wind farms: A simulation-based approach	2010	10.1111/j.1365-2664.2010.01850.x
Thompson P.M., Lusseau D., Barton T., Simmons D., Rusin J., Bailey H.	Assessing the responses of coastal cetaceans to the construction of offshore wind turbines	2010	10.1016/j.marpolbul.2010.03.030
Andersson M.H., Öhman M.C.	Fish and sessile assemblages associated with wind-turbine constructions in the Baltic Sea	2010	10.1071/MF09117
Desholm M.	Avian sensitivity to mortality: Prioritising migratory bird species for assessment at proposed wind farms	2009	10.1016/j.jenvman.2009.02.005
Masden E.A., Haydon D.T., Fox A.D., Furness R.W., Bullman R., Desholm M.	Barriers to movement: Impacts of wind farms on migrating birds	2009	10.1093/icesjms/fsp031
Rothery P., Newton I., Little B.	Observations of seabirds at offshore wind turbines near blyth in northeast england	2009	10.1080/00063650802648093
Wilhelmsson D., Malm T.	Fouling assemblages on offshore wind power plants and adjacent substrata	2008	10.1016/j.ecss.2008.04.020

Larsen J.K., Guillemette M.	Effects of wind turbines on flight behaviour of wintering common eiders: Implications for habitat use and collision risk	2007	10.1111/j.1365-2664.2007.01303.x
Fox A.D., Desholm M., Kahlert J., Christensen T.K., Petersen I.K.	Information needs to support environmental impact assessment of the effects of European marine offshore wind farms on birds	2006	10.1111/j.1474-919X.2006.00510.x
West A.D., Caldow R.W.G.	The development and use of individuals-based models to predict the effects of habitat loss and disturbance on waders and waterfowl	2006	10.1111/j.1474-919X.2006.00520.x
Perrow M.R., Skeate E.R., Lines P., Brown D., Tomlinson M.L.	Radio telemetry as a tool for impact assessment of wind farms: The case of Little Terns <i>Sterna albifrons</i> at Scroby Sands, Norfolk, UK	2006	10.1111/j.1474-919X.2006.00508.x
Garthe S., Hüppop O.	Scaling possible adverse effects of marine wind farms on seabirds: Developing and applying a vulnerability index	2004	10.1111/j.0021-8901.2004.00918.x
Koschinski S., Culik B.M., Henriksen O.D., Tregenza N., Ellis G., Jansen C., Käthe G.	Behavioural reactions of free-ranging porpoises and seals to the noise of a simulated 2 MW windpower generator	2003	10.3354/meps265263

B. Supporting information of Chapter III

Supplementary material 3.1.

Information about the scientific cruises carried out by Waterbirds and Sea Turtles Laboratory - Federal University of Rio Grande and BirdLife Seabirds' Tracking selected for modelling.

Tabel SM 3. 1. Sampling effort by scientific cruise realized by Waterbirds and Sea Turtles Laboratory /FURG projects, year, predominant season, number of Counting Stations (CS) and seabirds' species detected.

Area sampled	Scientific Cruise	Year	Season	Counting Stations	Species
21°–32°S; 37°–52°W	CI	2011	Warm	143	PA/PC/AG/TC
	Talude I	2009		121	PA/PI/AG/TC
23°–35°S; 41°–52°W	Talude III	2010	Warm	183	PA/PC/PI/AG/TC
	Talude V	2012		227	PA/PC/PI/AG/TC
	Talude VIII	2014		142	PA/PC/PI/AG/TC
	Talude II	2010		117	PA/PC/PI/AG/TC
	Talude IV	2011		203	PA/PC/PI/AG/TC
	Talude VI	2013	Cold	203	PA/PC/PI/AG/TC
	Talude VII	2014		145	PA/PC/PI/AG/TC
	Talude IX	2015		93	PA/PC/PI/AG/TC
21°–23°S; 28°–43°W	Trindade I	2011	Cold	121	PC/AG/TC
	Trindade II	2011	Warm	77	TC
	Trindade III	2012	Warm	156	PI/AG
	Trindade IV	2014	Cold	65	TC
	Trindade V	2014	Cold	62	TM
	Trindade VII	2015	Warm	75	TM

Tabel SM 3. 2 Seabird trackings selected to modelling, data owners' information and sampling period.

Species	Tracking number	Data owner	Sampling period
Wandering Albatross	460	Richard Phillips	02/2004 - 10/2004
<i>Diomedea exulans</i>	462	Richard Phillips	02/2003 - 03/2007
	1405	Richard Phillips	11/2007 - 12/2009
	1503	Richard Phillips	01/2012 - 03/2012
Atlantic Yellow-nosed Albatross	1104	Ben Dilley; Peter Ryan	10/2014 - 12/2014
<i>Thalassarche chlororhynchos</i>	1412	Leandro Bugoni	01/2015 - 05/2015
	1560	Leandro Bugoni	08/2019 - 02/2020
Atlantic Petrel	966	Jacob González-Solís; Peter Ryan	08/2010 - 07/2013
<i>Pterodroma incerta</i>			
White-chinned Petrel	439	Richard Phillips	02/2003 - 10/2003
<i>Procellaria aequinoctialis</i>	1396	Richard Phillips	04/2015 - 07/2015
	1500	Richard Phillips	01/2015 - 11/2015
	1558	Richard Phillips	12/2009 - 01/2010
Spectacled Petrel	554	Leandro Bugoni	08/2006 - 08/2007
<i>Procellaria conspicillata</i>	858	Peter Ryan	10/2009 - 05/2010
Great Shearwater	662	Robert Ronconi; Peter Ryan	09/2009 - 06/2010
<i>Ardenna gravis</i>	663	Robert Ronconi; Peter Ryan	11/2009 - 11/2010
	665	Robert Ronconi; Peter Ryan	08/2006 - 03/2010
	982	Jacob González-Solís; Peter Ryan	11/2008 - 01/2014

Supplementary material 3.2.

Script for the analyses performed in RStudio version 1.4.1106.

```
## Mean wind speed at 10 m above the sea level (monthly averages (2010 to 2014))##

#rWind' v.1.1.7 package for download and manage surface wind data from the Global
Forecasting System <https://www.ncei.noaa.gov/products/weather-climate-
models/global-forecast>#

#rasterfile: https://coastwatch.pfeg.noaa.gov/erddap/griddap/erdQAwindmday.html#

>library(rWind)

>zw <- raster(file.choose(), varname="wind_speed") #zonal windy mensal windy velocity
m/s#

>e <- extent (r1, r2, c1, c2) #geographic área#

>rzw <- crop(zw, e)

>writeRaster(rzw, filename="filename.tif", overwrite=TRUE)

>mw <- raster(file.choose(), varname="y_wind") #meridional windy mensal windy
velocity m/s#

>e <- extent (r1, r2, c1, c2) #geographic área#

>rmw <- crop(mw, e)

>writeRaster(tc, filename="filename.tif", overwrite=TRUE)

>predwind <- stack(rzw, rmw)

> writeRaster(predwind, filename="filename.tif", overwrite=TRUE)

#####

#Species Distribution Modelling - sdm package, disponible in
http://www.biogeoinformatics.org/#

#install_github('babaknaimi/sdm')#

>library(sdm)
```

```
>library(raster)

>library(rgdal)

>library(openxlsx)

>library(usdm)

##Species occurrences. Presence only#

>sp <- shapefile('specie.shp')

>plot(sp)

>head(sp@data)

##Environmental variables rasterfiles##

>lst <- list.files(pattern='tif$')

>lst

>area<- extent (r1, r2, c1, c2) #geographic área#

>preds <- stack(lst)

>preds

##Environmental variables collinearity: variance inflation factor (VIF)#

>v <- vifstep(preds)

>v

>preds <- exclude(preds)

>preds

>vifcor(preds)

>plot(preds)

##Ecological niche modellig. Presence only (d) and background (d2)##

>d <- sdmData(Occurrence~., train=sp, predictors = preds)

>d

>d2 <- sdmData(Occurrence~., train=sp, predictors = preds, bg=list(n=10000))
```

```
>d2

>m<-sdm(Occurrence~.,data=d2,methods=c('maxent'),replication=c('cross'),
cv.folds=10, test.percent=30)

>gui(m)# AUC and TSS results#

>varimp <- getVarImp(m)#Variable importance#

>varimp

>plot(varimp)

#Spatial prediction: Niche suitability index (NSI) map#

>p <- predict(m, newdata=preds, filename="filename.img", mean=T)

>p

>plot(p)

#####

# Boyce Index (BI)#

>library(ecospat)

#The argument fit is a vector containing the predicted suitability values#

#The argument obs is a vector containing the predicted suitability values of the validation
points (presence records)#

>obs<-read.table(file = "species_presence.csv", header = TRUE, sep = ";")

>head(obs)

>obsp<-obs[,1:2]

>fit <- raster("predict_species.asc")

>ecospat.boyce (fit, obs, nclass = 0, window.w = "default", res = 100, PEplot = TRUE)

>boy

>write.xlsx(boy, "species_boyce.xlsx")

#####
```

##ENMTools provides metrics for measuring similarity between ENMs predictions.
These include Schoener's *D* (Schoener 1968).#

```
>library(ENMTools)
```

```
>warm <-raster("specie1_warm.img")#Niche suitability index rasterfile, warm season.#
```

```
>cold <-raster("specie1_cold.img")#Niche suitability index rasterfile, cold season.#
```

```
>raster.overlap(warm,cold)
```

```
#####
```

Supplementary material 3.3.

Variable Importance values for Ecological Niche Modellings.

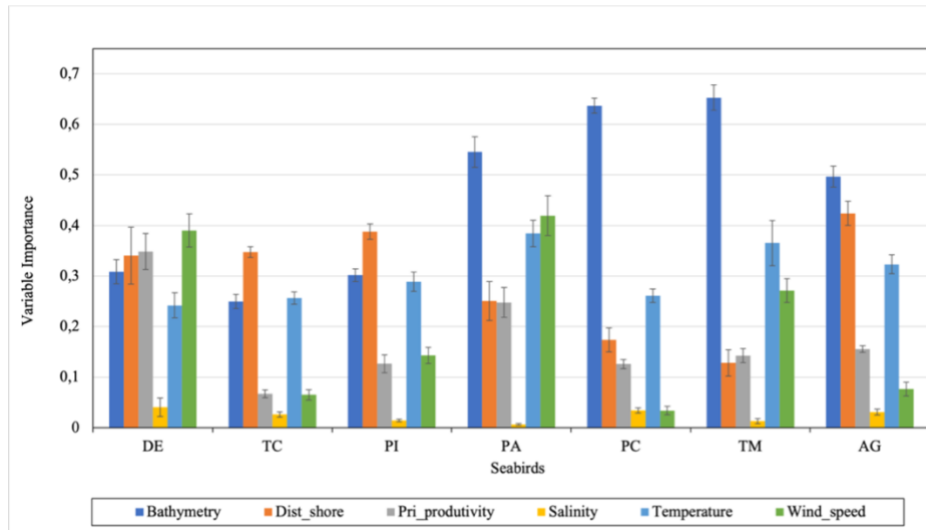


Figure SM 3. 1. Variable Importance values for warm months' Ecological Niche Modellings. Variable Importance for Bathymetry (m); Distance from the Nearest Shore (m); Sea Surface Primary Production (g/m³/day); Sea Surface Salinity (PSS); Sea Surface Temperature (°C) and Wind speed (m/s) used to modelling the niche for: DE - Wandering Albatross, TC - Atlantic Yellow-nosed Albatross, PI - Atlantic Petrel, PA - White-chinned Petrel, PC - Spectacled Petrel, TM - Black-browed Albatross and AG - Great Shearwater.

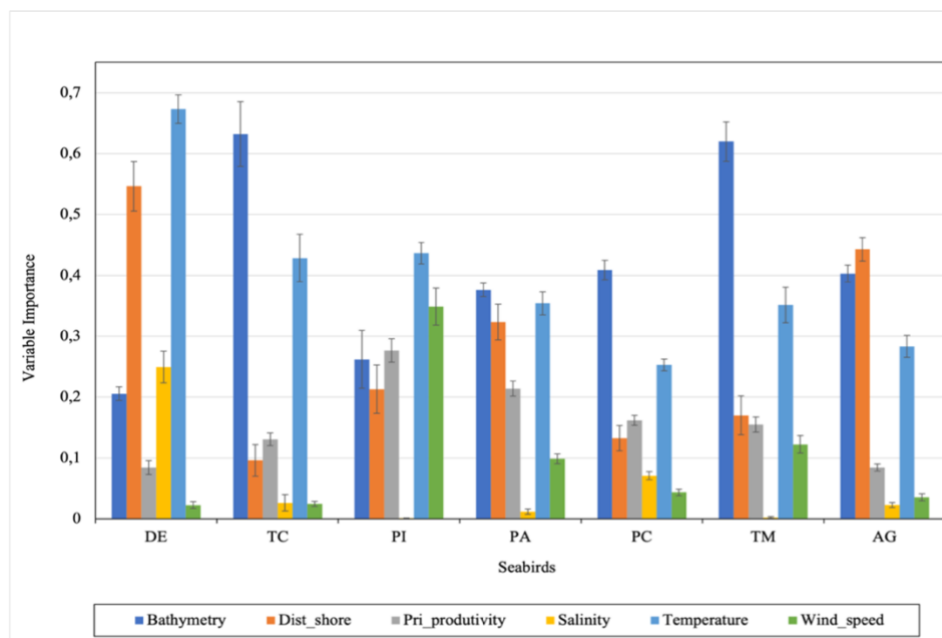


Figure SM 3. 2. Variable importance values for cold months' Ecological Niche Modellings. Variable Importance for Bathymetry (m); Distance from the Nearest Shore (m); Sea Surface Primary Production (g/m³/day); Sea Surface Salinity (PSS); Sea Surface Temperature (°C) and Wind speed (m/s) used to modelling the niche for: DE - Wandering Albatross, TC - Atlantic Yellow-nosed Albatross, PI - Atlantic Petrel, PA - White-chinned Petrel, PC - Spectacled Petrel, TM - Black-browed Albatross and AG - Great Shearwater.

Supplementary material 3.4.

Seasonal spatial predictions of ecological niche models (ENM) to all species in warm and cold modelling, with niche suitability index (NSI) >0.5 to 0.7 and >0.71 to 1.

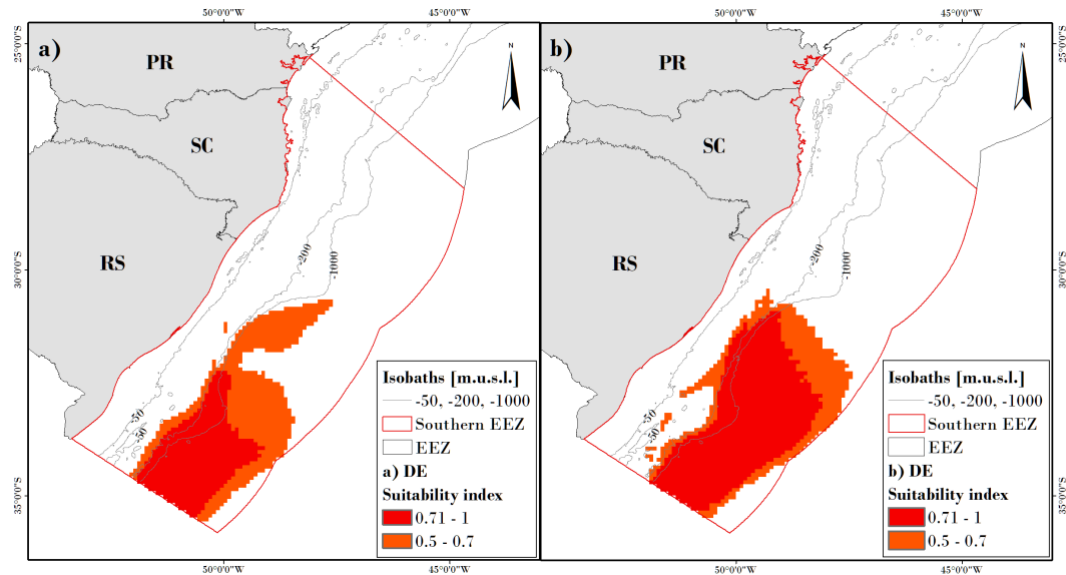


Figure SM 3. 3. Seasonal spatial predictions of Ecological Niche Models (ENM) to Wandering Albatross (DE), displayed as Niche Suitability Index (NSI) >0.5 to 0.7 and >0.71 to 1, to a) warm months and b) cold months modelling

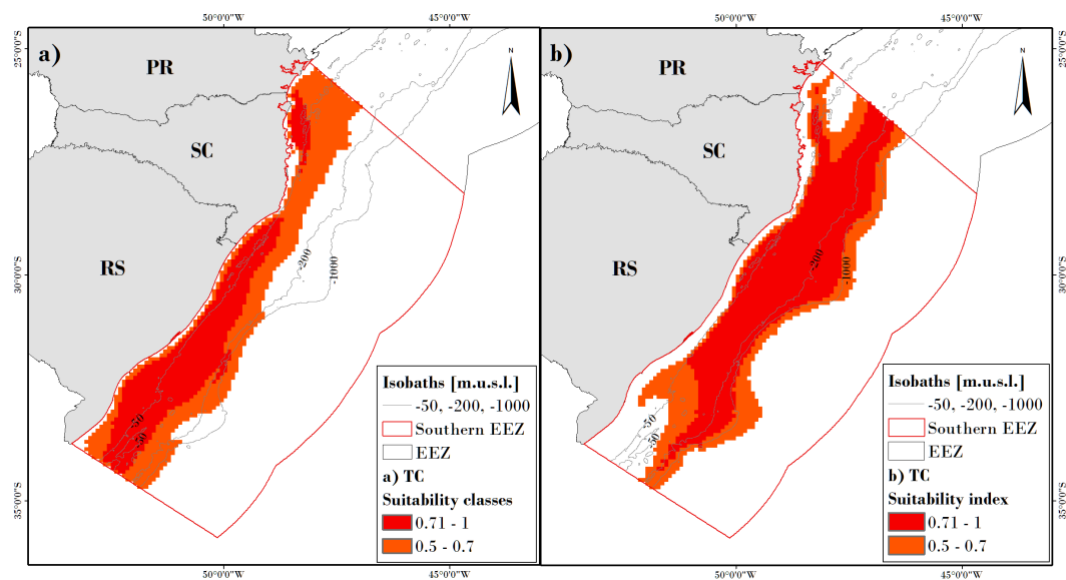


Figure SM 3. 4. Seasonal spatial predictions of Ecological Niche Models (ENM) to Atlantic Yellow-nosed Albatross (TC), displayed as Niche Suitability Index (NSI) >0.5 to 0.7 and >0.71 to 1, to a) warm months and b) cold months modelling.

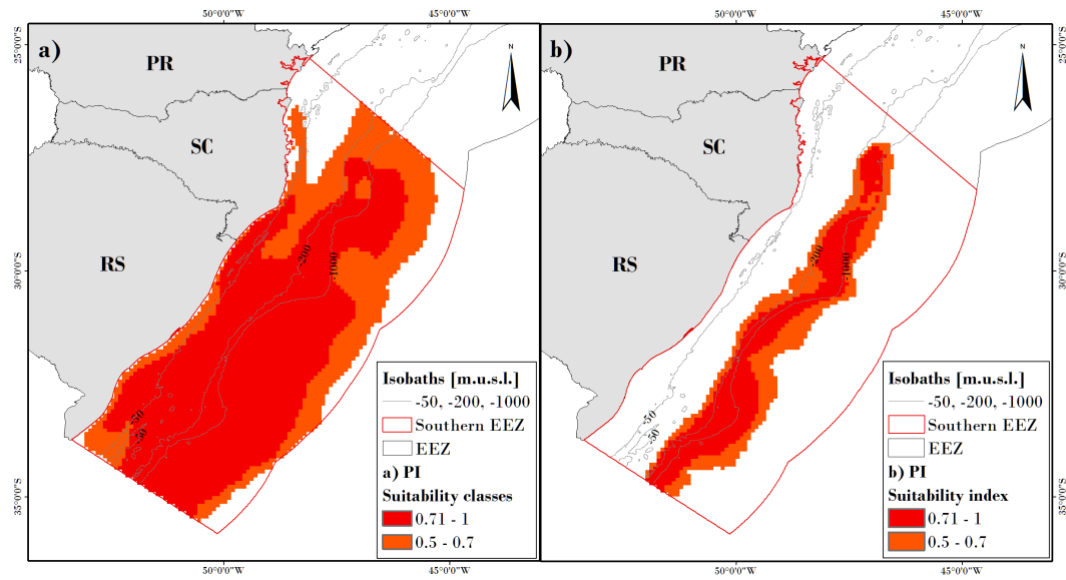


Figure SM 3. 5. Seasonal spatial predictions of Ecological Niche Models (ENM) to Atlantic Petrel (PI), displayed as Niche Suitability Index (NSI) >0.5 to 0.7 and >0.71 to 1 , to a) warm months and b) cold months modelling.

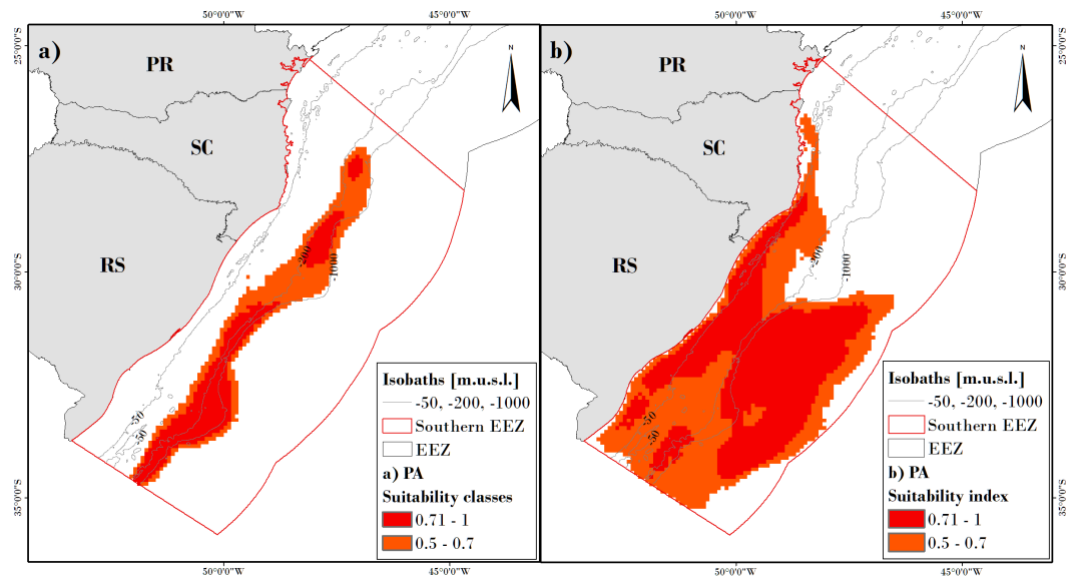


Figure SM 3. 6. Seasonal spatial predictions of Ecological Niche Models (ENM) to White-chinned Petrel (PA) displayed as Niche Suitability Index (NSI) >0.5 to 0.7 and >0.71 to 1 , to a) warm months and b) cold months modelling.

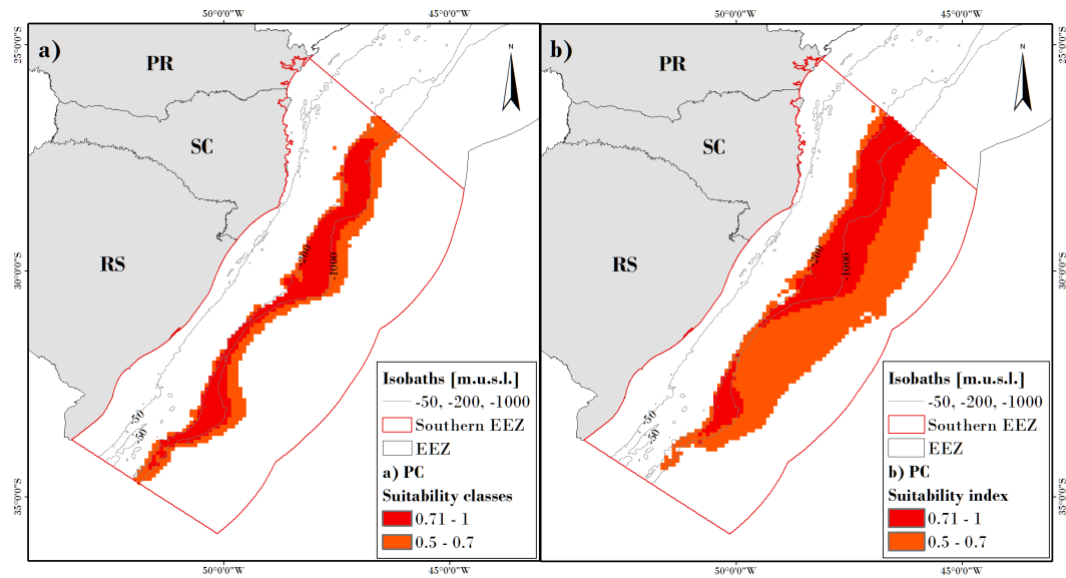


Figure SM 3. 7. Seasonal spatial predictions of Ecological Niche Models (ENM) to Spectacled Petrel (PC), displayed as Niche Suitability index (NSI) >0.5 to 0.7 and >0.71 to 1, to a) warm months and b) cold months modelling.

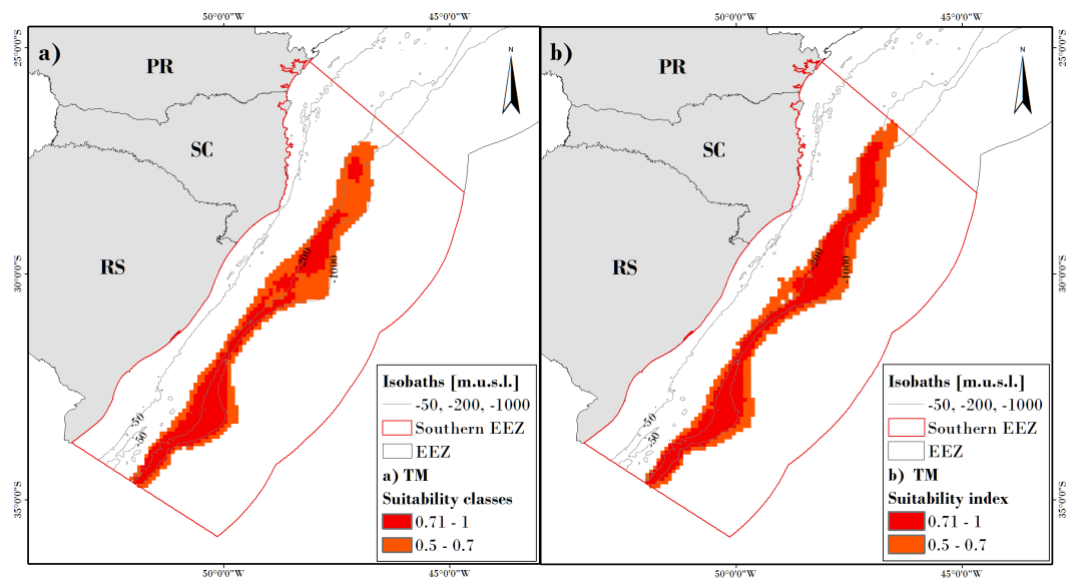


Figure SM 3. 8. Seasonal spatial predictions of Ecological Niche Models (ENM) to Black-browed Albatross (TM), displayed as Niche Suitability Index (NSI) >0.5 to 0.7 and >0.71 to 1, to a) warm months and b) cold months modelling.

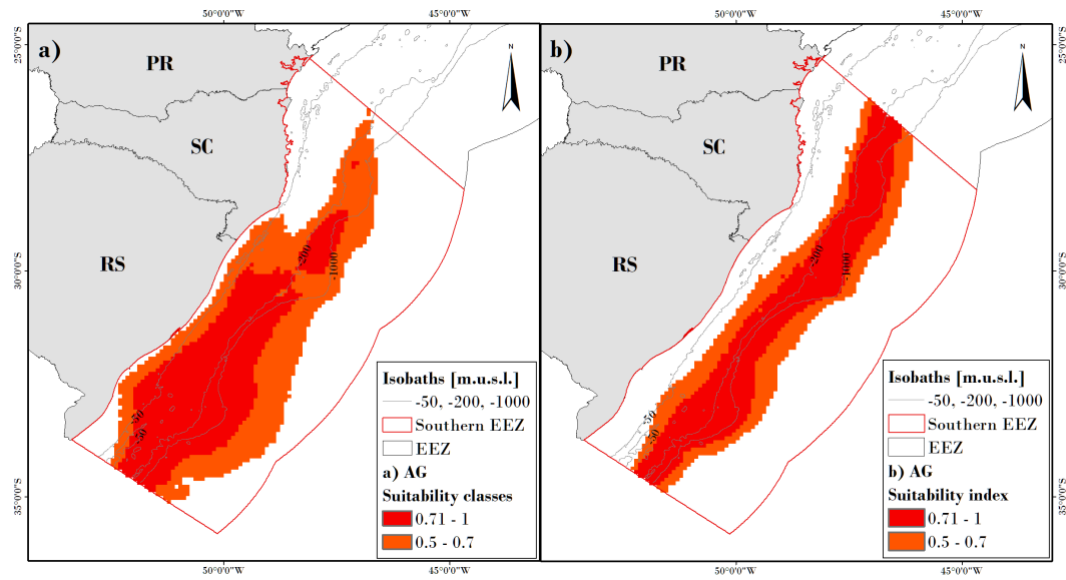


Figure SM 3. 9. Seasonal spatial predictions of Ecological Niche Models (ENM) to Great Shearwater (AG), displayed as Niche Suitability Index (NSI) >0.5 to 0.7 and >0.71 to 1, to a) warm months and b) cold months modelling.

Supplementary material 3.5.

Richness index (RI) modellings mapped with Niche Suitability Index (NSI) >0.5 and >0.8 by season.

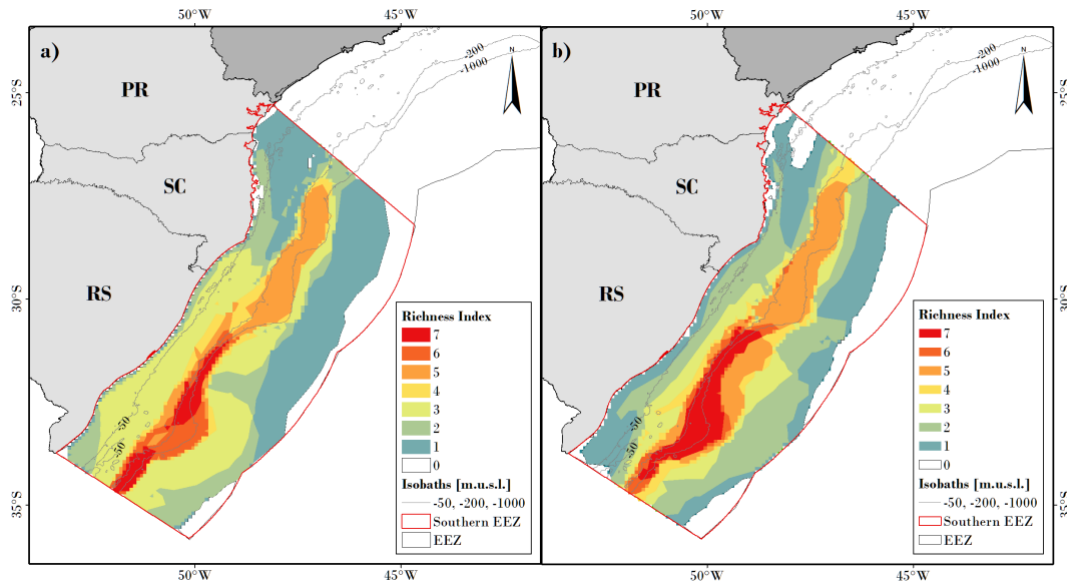


Figure SM 3. 10. Richness index mapped for niche suitability index (NSI) >0.5 of the southern Brazilian Exclusive Economic Zone in a) warm and b) cold months.

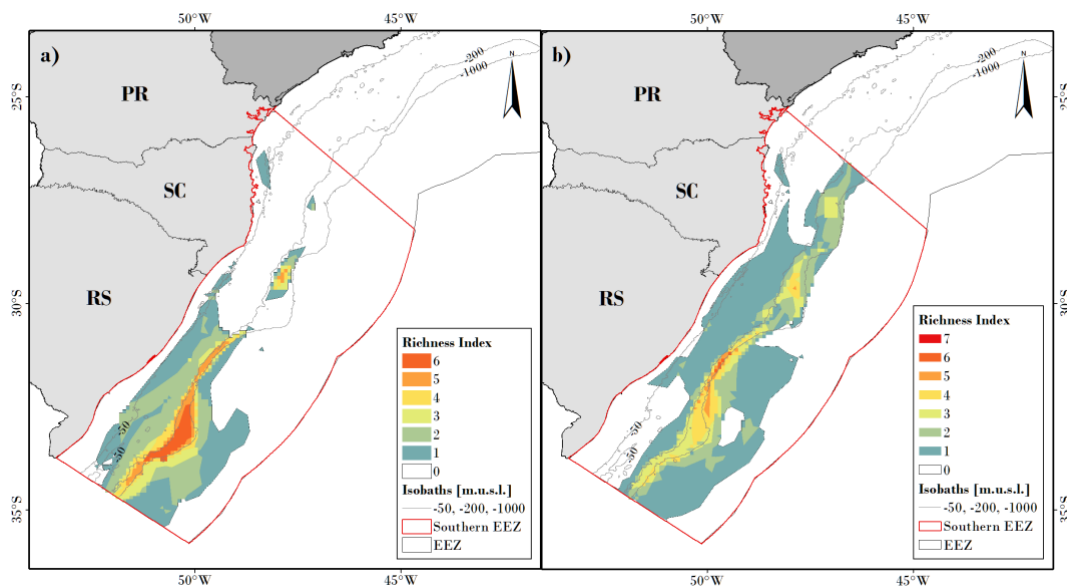


Figure SM 3. 11. Richness index mapped for niche suitability index (NSI) >0.8 of the southern Brazilian Exclusive Economic Zone in a) warm and b) cold months.

Supplementary material 3.6.

Richness index (RI) by bathymetric area.

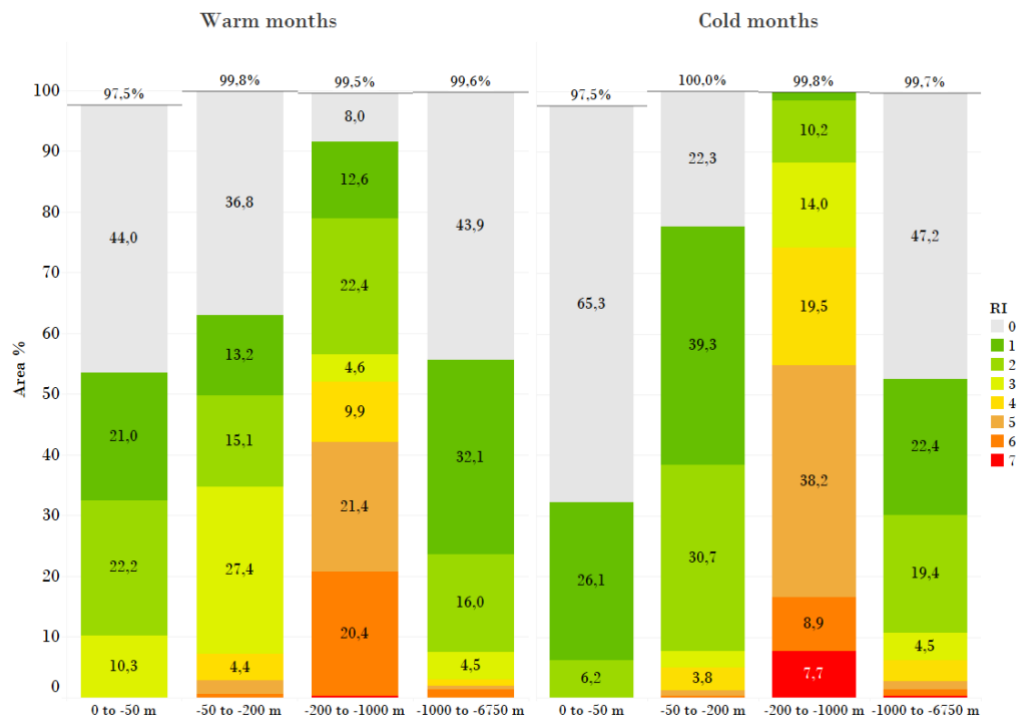


Figure SM 3. 12. The proportion of richness index (RI) by bathymetric area of the southern Brazilian Exclusive Economic Zone, in warm (October-March) and cold (April-September) seasons. Note: Total RI areas do not sum 100% of the area because areas of the islands (e.g. Florianópolis island) are not considered in the ecological niche modelling (NoData pixel in the modelling raster). Also, the conversion of raster to vector file may cause distortions in total areas.