Identifying Suitable Areas for Common Bottlenose Dolphins in Anthropized Waters

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Abstract

Understanding the processes that determine the occurrence of species, especially for those exposed to human activities, is the key to appropriate management. Despite *Tursiops truncatus* being well-studied worldwide, information about transient groups of this common bottlenose dolphins and how groups are exposed to human activities is lacking. Here, we modelled and mapped how the environment and human activities drives bottlenose dolphin habitat suitability, and residence patterns in an anthropized area of the Southwestern Atlantic Ocean. We ran 300 distribution models, including six algorithms, and generated an ensemble model to predict the habitat suitability of the species. In parallel, we used photo-identification techniques to evaluate dolphins' degree of residence pattern. Primary productivity, seabed slope and port activities explained dolphins' habitat suitability. The most suitable areas for bottlenose dolphins included coastal waters, nearby port complexes and shipping routes. We also identified a low degree of residence in Cabo Frio and Rio de Janeiro city waters, but calves were constantly sighted there, indicating an important area for caring and nursing. The high overlap between the dolphins' most suitable areas and human activities, such as ports, vessel traffic and fisheries spots, plus the presence of calves in these areas, highlights the need for safeguard measurements to protect these animals from threats. In addition, our results may be used to support management decisions, such as fisheries regulations and the creation of new marine protected areas to conserve critical habitats of this species.

1 Introduction

Distribution studies are critical to assess the effects of the environment and human activities on several species (Morris and Doak 2002; Rodrigues et al. 2006). Species Distribution Models (SDM) have been increasingly used to determine the potential distribution and identify suitable habitats for conservation purposes (Guisan et al. 2017). However, the distribution of marine organisms is not well studied as it occurs for terrestrial organisms (Redfern et al. 2006, Robinson et al. 2011). In addition, the distribution of these organisms is mainly explained based exclusively on environmental variables (e.g. di Tullio et al. 2016; McBride-Kebert et al. 2019; de Rock et al. 2019) neglecting the importance of human activities in affecting species distributions.

For years, studies of marine species with high movement ability have been challenging for researchers (Redfern et al. 2006). Marine mammals, like dolphins, use to live in open and fluid environments, with few or no physical barriers to limit their access to resources, such as highly mobile prey (Sims et al. 2008; Melo-Merino et al. 2020). Their distribution changes over time due to changes in their biological and ecological requirements (Forcada 2018). As a result, these animals used to have higher mobility and larger home ranges when compared to terrestrial mammals (Tucker et al. 2014). Eventually, individuals or entire populations can have a high degree of association with specific areas, which is in general related to resource availability, leading to repeatedly revisit these areas or constantly use them (e.g. Nathan et al. 2008; Passadore et al. 2018; Akkaya Baş et al. 2019).

The common bottlenose dolphin (*Tursiops truncatus*), hereafter called bottlenose dolphin, is a cosmopolitan species found in coastal and oceanic environments (e.g. Milmann et al. 2016; Zanardo et al. 2017; Tardin et al. 2020). As top predators, this species is susceptible to several impacts on the environment, such as the accumulation of contaminants in high concentrations, reflecting the health of the ecosystem (Smith and Gangolli 2002). The species has ecological plasticity, *i.e.*, worldwide populations vary considerably in terms of habitat use, residence pattern, behavior, and diet (Fruet et al. 2011; Lodi et al. 2014; Tardin et al. 2020; Carmen et al. 2021; Pace et al. 2021). However, information about some populations is still scarce. Although this species is found on almost the entire Brazilian coast (Lodi et al. 2017), most studies analyzed populations with temporary or permanent residence at a local scale (Simões-Lopes & Fabian 1999, Fruet et al. 2011). Recently, two distinct subspecies, a coastal and an offshore one, were recognized through genetics and morphological evidence in the Southwestern Atlantic (Costa et al. 2016; Simões-Lopes et al. 2019).

In the present study, we focus on the offshore ecotype, *Tursiops truncatus truncatus*, which is the unique subspecies that occurs in the study area, Rio de Janeiro State waters (Simões-Lopes et al. 2019). These waters are surrounded by the most populated area in Latin America, housing an important industrial pole, including oil and gas exploitation, and several port complexes (IBGE 2010; ANTAQ 2021). Due to the cumulative nature of different activities and their unique characteristics, such as habitat variability and threatened species, this area is considered a top conservation priority in Brazil (Magris et al. 2021). To support appropriate safeguard plans for bottlenose dolphins, we aimed to (i) model how the environment and human activities drives bottlenose dolphins habitat suitability, (ii) map the modelled suitable and unsuitable areas and (iii) analyze the individuals' residence pattern. Considering that these animals have high energy requirements, we hypothesized that oceanographic characteristics related to prey distribution are the main driver influencing the bottlenose dolphin habitat suitability.

2 Material And Methods

2.1 Study area

Our study area is defined by the geopolitical boundaries of the Rio de Janeiro State, from the coastline to the territorial sea of 200 nautical miles (Fig. 1), in the Southeastern Brazilian coast located on the Southwestern Atlantic Ocean (SWAO). It comprises part of two sedimentary basins: Campos Basin and Santos Basin, both explored by the oil and gas industry, with vessel traffic and exploration, drilling, and extraction activities (ANP 2021). Industrial fish activities are also common in the area comprising approximately 50,000 t of fisheries resources captured per year (Fiperj 2020). Two subareas were chosen, the Cabo Frio coast, comprised the municipalities of Arraial do Cabo, Cabo Frio, and Búzios, and the Rio de Janeiro coast, comprised the municipalities of Rio de Janeiro and Niterói (Fig. 1). There, we carried out systematic photo-identification surveys that were later used to investigate residence patterns.

The Cabo Frio subarea (CF) has a narrow and irregular continental shelf showing depressions and steep slopes and the 100m isobath is found at a maximum distance of 10km from the coast (Duarte and Viana 2007; Reis et al. 2013). The warm and oligotrophic Tropical Water flows southward carried by the Brazil Current, but during springer and summer, the South Atlantic Central Water recurrently emerges due to a wind-driven upwelling, resulting in high primary and fish productivity (Carbonel 1998; Mazzoil et al. 2008).

The Rio de Janeiro subarea (RJ) has a more extensive continental shelf and consequently a less pronounced slope than CF. The 100m isobath is located 80km from the coast (Reis et al. 2013). This subarea is surrounded by of the most populous cities in Latin America, Rio de Janeiro city, having six million inhabitants (IBGE 2010). This subarea is continuously exposed to several human threats such as overfishing, submarine outfalls, and eutrophic waters from Guanabara Bay (Carreira and Wagener 1998; Rangel et al. 2007; Tubino et al. 2007; Amorim and Monteiro-Neto 2016).

2.2 Distribution

2.2.1 Data collection

We compiled occurrence records of common bottlenose dolphins from several sources which included primary and secondary data from 1983 to 2021 (Supplementary Table 1). Environmental layers (minimum, mean and maximum) for our study area were obtained from three different public databases: Bio-Oracle (Assis et al. 2018), Global Marine Datasets for Species Distribution Modelling and Environment Visualisation (Basher et al. 2018) and Ocean Climate Layers for Marine Spatial Ecology (Sbrocco and Barber 2013) at 5 arcminutes resolution. Port activity layers were obtained from the ocean-based pollution layer (Halpern et al. 2015) at 30 arcseconds resolution (Table 1). All layers were standardized for 5 arcminutes resolution and used as explanatory variables for the bottlenose dolphin habitat suitability.

Table 1
Data source of environmental and anthropogenic layers used as explanatory variables to model the suitable areas for common bottlenose dolphin (*Tursiops truncatus truncatus*) occurrence in Rio de Janeiro State.

Layers	References
Environmental	
Bathymetry	MARSPEC
Current velocity (minimum, mean and maximum)	Bio-ORACLE
Distance to coast	GMED
Primary productivity (minimum, mean and maximum)	Bio-ORACLE
Salinity	Bio-ORACLE
Sea surface temperature (minimum, mean and maximum)	Bio-ORACLE
Seabed slope	GMED
Anthropogenic	
Port activities (ocean-based pollution)	Halpern et al.

2.2.2 Data analyzes

We carried out all the analyzes in the R environment (R Core Team 2021) and used the R package ‘biomod2’ (Thuiller et al. 2020) to generate the Species Distribution Models. To avoid spatial autocorrelation, we randomly filtered occurrence records within a radius of 9.2 km (~ 5 arcminutes) using the 'spThin' package (Aiello-Lammens et al. 2015). We checked multicollinearity among the explanatory variables using the 'usdm' package (Naimi et al. 2014) and those with Variance Inflation Factor (VIF) > 3 were excluded from the model (Zuur et al. 2010).

Since it was not possible to obtain true absence data, we randomly generated five sets of 1000 pseudo-absences. We used six algorithms for two types of data requirements: presence-absence models using regression (Generalized Linear Models - GLM and Generalized Additive Models - GAM), boosting (Random Forest - RF and Generalized Boosting Model - GBM), discrimination techniques (Flexible Discriminant Analysis - FDA), and presence-background models using Maximum Entropy models - MaxEnt (see Guisan et al. 2017) to a brief explanation of each algorithm). For model calibration, we used 70% of records for training and 30% for testing using cross-validation techniques at a constant prevalence at 0.5 (Guisan et al. 2017). Each algorithm was replicated ten times and the importance of each variable was retrieved running ten permutations using the 'get_variables_importance' function of the 'biomod2' package (Thuiller et al. 2020). This test shuffles a variable in the dataset and compares the predictions of the reference model and the shuffled model via Pearson's correlation. The higher the correlation index, the more influence the variable has on the model (Thuiller et al. 2020).

We generated response curves for bottlenose dolphin habitat suitability as a function of each explanatory variable included in our final models (Supplementary Fig. S1). The metric used for the evaluation of each model was the Area Under the Curve (AUC) from the Receiver Operating Characteristic (ROC) (Fielding and Bell 1997). All replicates with AUC > 0.7 were selected and aggregated for a final ensemble model using weighted-by-AUC mean (pAUC) (Araújo and New 2007). To include a measure of uncertainty, which is suggested for any SDMs (Zurell et al. 2020), we generated a committee averaging map that indicates the coefficient of variation of the algorithms (Supplementary Fig. S2).

2.3 Residence pattern

We investigated residence pattern based on photo-identification data from long-term cetacean monitoring projects conducted by the *Laboratório de Bioacústica e Ecologia de Cetáceos*, *Projeto Baleias & Golfinhos do Rio* and *Projeto Ilhas do Rio*, and by large scale scientific cruises, such as *Projeto de Monitoramento de Cetáceos da Bacia de Santos*. The photo-identification technique consisted of taking dorsal fin images during surveys and comparing the natural marks (i.e., nicks, notches, scars) in each dorsal fin by photo-identification protocols that allowed a reliable individual identification (Hammond et al. 1990). Then, for identified individuals, we calculated the individual residence index as the number of days individual dolphins were sighted divided by (i) the number of days of total effort and (ii) the number of days of effort from the first sighting to the last one. We also calculated residence as (iii) the number of seasons individual dolphins were sighted divided by the number of seasons of effort.

These residence indices were standardized, and individual dolphin identified was categorized in three levels (low, medium or high, set out by us according to the data) through the analysis of Agglomerative Hierarchical Clustering using the Ward distance method and the squared Euclidean distance measure. This analysis generates a matrix of dissimilarity through pre-established parameters. We calculated the cophenetic correlation coefficient to evaluate whether the analysis distortion was significant, assuming a suitable clustering of the data when the value was above 0.7 (Rohlf 1970).

3 Results

The filtering technique retained 62 records from 445. After multicollinearity inspection, six of the 14 explanatory variables were selected: minimum and maximum current velocity (CURmin and CURmax, respectively), port activities (port), minimum primary productivity (PPmin), seabed slope (slope), and minimum sea surface temperature (SSTmin) (Supplementary Table 2).

For the final ensemble model (pAUC > 0.7), we considered 207 out of 300 models. Algorithms' performances varied and, in general, FDA had the lowest pAUC values (mean = 0.76) and GBM the highest (0.81) (Table 2). The PPmin (0.65), slope (0.18), and port (0.10) were the most important variables (Table 2). Overall, bottlenose dolphin habitat suitability had a non-linear positive relationship with port, a negative relationship with slope, and was higher in average values of PPmin (Supplementary Fig. S1). The most suitable areas for the species distribution were in shallow waters within the continental shelf. The highest suitability values were in the coastal area displayed in the East-West direction, including the two subareas (CF and RJ) and three bays: Ilha Grande, Sepetiba, and Guanabara (Fig. 2).

Considering CF and RJ subareas, a total of 614 individuals were cataloged between 2011 and 2018. Fifty-seven (9.3%) individuals were recaptured at least once and included in the residence analysis. Of these, 39 individuals had a low residence degree (68.4%), seven had a medium degree (12.3%) and 11 had a high degree (19.3%) (Supplementary Fig. 3). The cophenetic correlation coefficient of 0.73 indicated that the dendrogram was well clustered.

4 Discussion

We showed that the offshore bottlenose dolphins (*Tursiops truncatus truncatus*) are, in general, transient in Rio de Janeiro waters (low degree of residence), but with a small subset of individuals with medium or high degree of residence in specific areas. These bottlenose dolphins also occur in coastal areas and continental shelf waters, up to the slope, likely influenced by environmental conditions and human activities. We found that the most suitable areas for these dolphins occur in high primary productivity sites, along the continental shelf, and in more gentle slopes, from shallow water, less than 50m deep. Shallow waters tend to be more productive, presenting a greater abundance of fishes (Fiperj 2020), which are typical prey of these dolphins. Indeed, the predicted suitable areas for bottlenose dolphins, including CF and RJ subareas. These are surrounded by fishing landing ports that land more than 90% of the local fishing resources caught in the study area (Fiperj 2020) reinforcing that these sites likely have high prey availability.

Primary productivity was an important predictor to explain suitable areas for bottlenose dolphins. However, bottlenose dolphins were not usually sighted in regions with the highest values for primary productivity, such as Ilha Grande, Sepetiba and Guanabara bays. These values were equivalent to those usually found in eutrophic waters (e.g. Marins et al. 2010; Aguiar et al. 2011; Castelo et al. 2021). The absence of bottlenose dolphins in those areas could be associated with the co-occurrence of other dolphins' species. Indeed, these bays are also inhabited by resident populations of Guiana dolphins, *Sotalia guianensis* (e.g. Ribeiro-Campos et al. 2021). An aggressive interaction between bottlenose and Guiana dolphins were reported in Baía Norte, Southern Brazil (Wedekin et al. 2004), an area where both species overlap their niches by sharing consumptions of demersal mullet species; therefore, it is suggested that potential interspecific competition between both dolphin populations may be a limiting factor for the occurrence of bottlenose dolphins (Teixeira et al. 2021) which avoid these areas even if the habitat is suitable for their occurrence as indicated by our results. On the other hand, bottlenose dolphins are usually sighted outside the three bays, such as CF and RJ subareas (e.g. Tardin et al. 2013, 2019; Laporta et al. 2017). The frequent occurrence of groups in these two subareas, most of them including calves (87.5%), suggests that both subareas may be important for feeding and breeding bottlenose dolphins.

Considering CF subarea, bottlenose dolphins are already known to occur primarily in shallow and productive areas (Tardin et al. 2019). On a larger scale, on the shelf break of South and Southeast regions, the frequency of sightings is greater in areas close to the 500m isobath than in deeper waters (di Tullio et al. 2016), but worldwide bottlenose dolphins show plasticity in habitats used. This species tends to use shallow water with higher primary productivity either in sheltered or open waters with gentle slopes occurring in Australia, Namibia, Spain, and the United States (Cañadas et al. 2002; Zanardo et al. 2017; McBride-Kebert et al. 2019; de Rock et al. 2019). However, this species is also found in steeper slopes with high primary productivity caused by upwelling in shelf break or as barriers during feeding tactics in shallow habitats (Cañadas et al. 2002; McBride-Kebert et al. 2019).

Residence patterns in a specific area also vary among populations worldwide, from high (e.g. Simões-Lopes and Fabian 1999; Laporta et al. 2017; Carmen et al. 2021; Bennington et al. 2021) to low (e.g. Zolman 2002; Balmer et al. 2008; Akkaya Baş et al. 2019; Pace et al. 2021). Low residence patterns can indicate that the species use larger habitats than the studied area (Zanardo et al. 2016; Cobarrubia-Russo et al. 2019), while a high residence pattern to specific locations may suggest critical habitats for vital activities (Simões-Lopes and Fabian 1999; Ingram and Rogan 2002). Indeed, large range movements (from 700 to ca. 1.700 km) were observed for bottlenose dolphins tagged with satellite tags or photo-identified in Brazil (Cremer et al. 2018). Thus, it is likely that the individuals analyzed in the present study belong to a large population and groups remain in a certain area for short-term periods or regularly visit it to feed or breed. An individual variance in terms of residence may suggest complex habitat, social or population structures (Zolman 2002; Blasi and Boitani 2014). Residence in a specific area may be linked to the high availability of food resources and low predation risks (Knip et al. 2012; Habel et al. 2016). On the other hand, resident individuals tend to be more exposed to local threats (Warkentin and Hernández 1996; Atkins et al. 2016). Even those dolphins with low residence patterns might be exposed to local threats in our study area. The most suitable areas for the species, for example, are areas close to port complexes and shipping routes. These areas are surrounded by four port complexes (located on Campos municipality, Guanabara, Sepetiba and Ilha Grande bays), and are affected by nearby ports along the coast (located on Macaé, Búzios, Cabo Frio municipalities and Guaíba Island) (ANTAQ 2021). There is also high vessel traffic associated with oil and gas exploration occurring in the Campos and Santos basins (ANP 2021). The effects of port complexes and related activities, such as vessel traffic, on dolphins' populations are well-reported worldwide (e.g. Halpern et al.

2015; Walker et al. 2019). Collisions of dolphins with vessels or their propellers, for example, may cause mutilation and even the death of individuals (van Waerebeek et al. 2007; Schoeman et al. 2020). Noisy areas, such as those near port complexes and shipping routes, may also change dolphin behavior and acoustic repertoire, cause acoustic masking, and lead to temporary or permanent habitat abandonment (Guerra et al. 2014; Marley et al. 2017; Erbe et al. 2019). Additionally, as aforementioned, we found that the highest suitable areas for bottlenose dolphins overlap with important fisheries activities (Fiperj 2020) increasing bycatch risks.

Besides, these suitable areas also have high levels of contaminants (Vidal et al. 2020), which may cause various adverse effects on cetaceans, such as contamination of calves crossing the placenta or through lactation, and immunosuppression of both calves and adults, which may result in skin diseases and even death (Moura et al. 2009; Bossart 2011; Vidal et al. 2020). Therefore, individuals occurring in this area may be under all these risks.

Understanding residence patterns together with the predictions of suitable habitats can contribute to safeguarding critical areas for these dolphins. Our study identified the most suitable habitats for bottlenose dolphins in an area with multiple human activities that may expose them to several different impacts. We also found that dolphins vary in how they use the area, suggesting complex social or populational structures. By mapping these critical areas and characterizing how dolphins use them, our findings may support additional and more effective conservation actions. For instance, a creation of MPAs to better manage local human activities, and then protect critical habitats for this important top predator since the MPAs network along Rio de Janeiro State does not encompass most of the highest suitable sites for bottlenose dolphins. Moreover, effective management of fisheries focusing on the protection of the ecosystem and reducing the bycatch of this species and any other marine species is urgently needed.

Declarations

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Data availability Part of the data used in this study can be found at https://sispmcprd.petrobras.com.br/sispmc. Data not available on the previous website can be requested from the corresponding author.

Conflict of interest The authors declare no competing interests.

Ethics approval This is an observational study and no ethical approval is required.

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Tables

Table 1 Data source of environmental and anthropogenic layers used as explanatory variables to model the suitable areas for common bottlenose dolphin (*Tursiops truncatus truncatus*) occurrence in Rio de Janeiro State.

Layers	References
Environmental	
Bathymetry	MARSPEC
Current velocity (minimum, mean and maximum)	Bio-ORACLE
Distance to coast	GMED
Primary productivity (minimum, mean and maximum)	Bio-ORACLE
Salinity	Bio-ORACLE
Sea surface temperature (minimum, mean and maximum)	Bio-ORACLE
Seabed slope	GMED
Anthropogenic	
Port activities (ocean-based pollution)	Halpern et al.

Table 2 Summary statistics of distribution modeling of common bottlenose dolphin (*Tursiops truncatus truncatus*) in the Rio de Janeiro State, Brazil. This includes evaluation scores of each algorithm and ensemble, importance of each variable and number of models of each algorithm in the ensemble model.

Algorithms	Evaluation scores	Variable Importance						Models in ensemble
	pAUC	CURmin	CURmax	Port	PPmin	Slope	SSTmin	
GLM	0.79	0.05	0.04	0.03	0.68	0.29	0.06	35
GAM	0.78	0.07	0.05	0.08	0.82	0.33	0.04	27
RF	0.79	0.06	0.10	0.22	0.39	0.14	0.23	42
GBM	0.81	0.05	0.05	0.03	0.75	0.16	0.08	38
FDA	0.76	0.03	0.34	0.24	0.15	0.07	0.18	24
MaxEnt	0.79	0.02	0.08	0.04	0.99	0.12	0.01	41
Ensemble	0.79	0.05	0.10	0.10	0.65	0.18	0.10	207

Abbreviations: GLM = Generalized Linear Models; GAM = Generalized Additive Models; RF = Random Forest; GBM = Generalized Boosting Model; FDA = Flexible Discriminant Analysis; MaxEnt = Maximum Entropy; pAUC = partial Area Under a Curve; CURmin = Current velocity (minimum); CURmax = Current velocity (maximum); Port = Port activities (proximity to port complexes and shipping routes); PPmin = Primary Productivity (minimum); Slope = Seabed slope; SSTmin = Sea surface temperature (minimum).

Figures

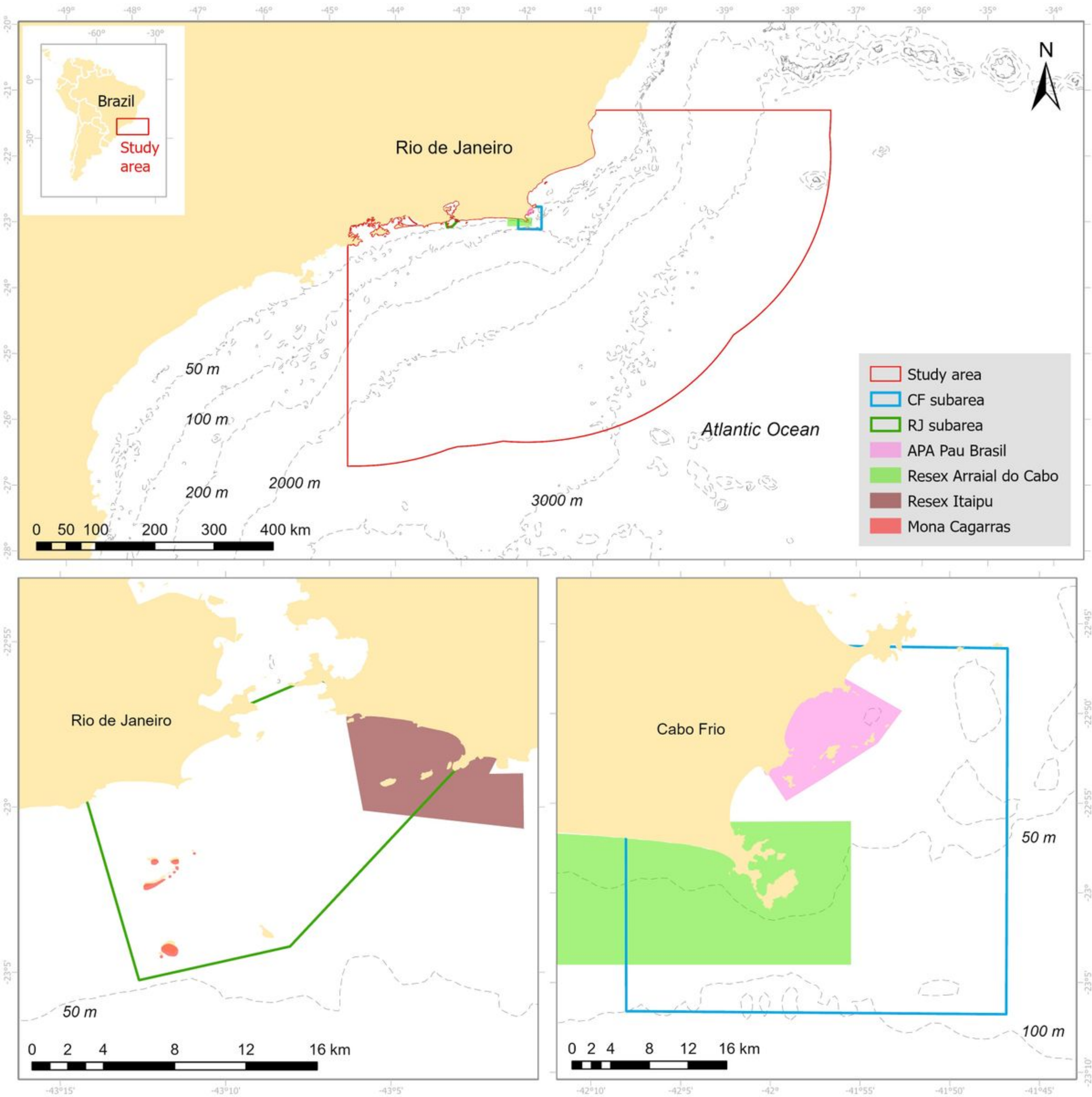

Figure 1

Study area encompassing the coastal limits of Rio de Janeiro State, Southeastern Brazil, subareas of Cabo Frio (CF) and Rio de Janeiro (RJ), and marine protected areas located in Rio de Janeiro, Brazil. APA Pau Brasil = *Área de Proteção Ambiental do Pau Brasil* (IUCN category VI); Resex Arraial do Cabo = *Reserva Extrativista Marinha do Arraial do Cabo* (IUCN category V); Resex Itaipu = *Reserva Extrativista Marinha de*

Itaipu (IUCN category V); Mona Cagarras = *Monumento Natural das Ilhas Cagarras* (IUCN category III). For more details on categories, see Day et al. (2019, http://dx.doi.org/10.25607/OBP-694).

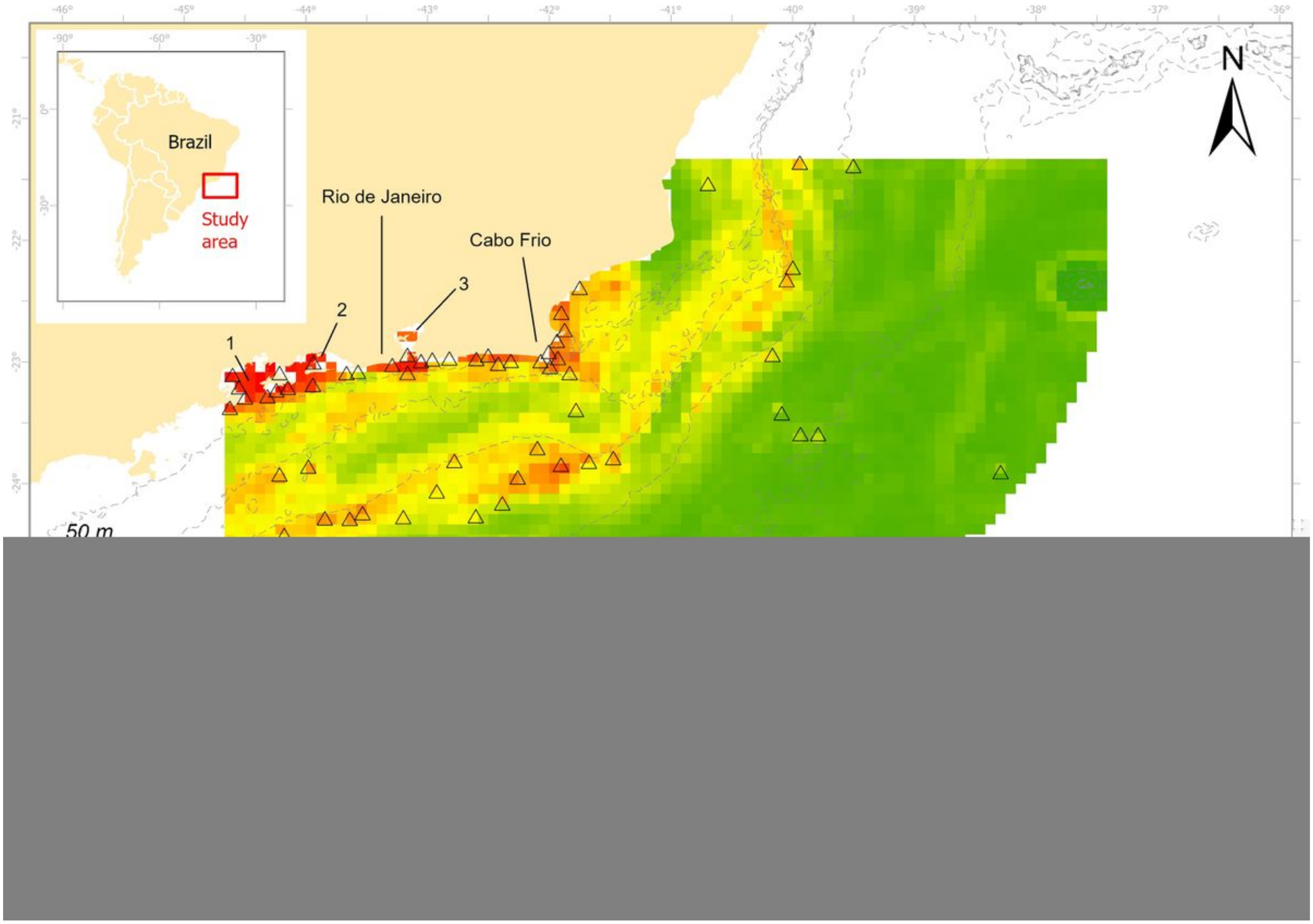

Figure 2

Habitat suitability calculated by weighted mean for the common bottlenose dolphin, *Tursiops truncatus truncatus*, in Rio de Janeiro, Brazil. 1 = Ilha Grande bay; 2 = Sepetiba bay; 3 = Guanabara bay.

Supplementary Files

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