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Whale shark (*Rhincodon typus*) along the Brazilian coast: occurrence, distribution, and environmental factors

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Abstract Whale sharks (*Rhincodon typus*) are charismatic fauna of significant tourist and environmental interest. Nevertheless, their distribution in Brazil requires further investigation. Few studies have been conducted on the species in Brazil, with most reports focusing on sightings in Rio de Janeiro's coast and the Saint Paul's Rocks. These studies mainly addressed seasonality, records of occurrence, and the influence of upwelling processes. While these studies are valuable for understanding the species, they are limited in scope, considering the extent of the Brazilian coast. Therefore, the present study compiled the records of *R. typus* occurrences throughout Brazil. This was achieved through an extensive review of scientific papers and notes, as well as personal communication with fishing and diving agents on social media. Consolidating existing knowledge by including 72 new occurrences to the published database, we described the distribution pattern of the whale shark within the Brazilian Exclusive Economic Zone. We pointed out that to the south, the records are linked more to chlorophyll-*a*, while further north, they are linked to temperature.

Keywords Marine ecology · Conservation · Citizen science · Spatial ecology · Species distribution

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Introduction

Rhincodon typus Smith, 1828, popularly known as whale shark, is the largest living fish species known which can exceed 18.8 m in length (Mcclain et al. 2015). It is classified as a k-strategist organism which means it has a late sexual maturation, high longevity, and slow growth. Like most elasmobranch species, it is on the IUCN's red list of endangered species in the "endangered" category worldwide, and in Brazil, it is classified as "vulnerable" being protected by national and international law (Pierce and Norman 2016; ICMBIO 2018). This species feeds mainly on larvae

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and eggs of fish and invertebrates, small crustaceans, fish, and squid (Compagno 1984).

Brazilian waters are not recognized as an environment where *R. typus* aggregates to feed, as is the case in the North of the Gulf of Mexico (Mckinney et al. 2012) and the Yucatan Peninsula (Hueter et al. 2007). However, the Cabo Frio (23° S) and Cabo de Santa Marta (29° S) upwelling systems are highly productive (Ciotti et al. 2010), enabling the generation of more favorable conditions for the occurrence of the whale shark. This phenomenon arises due to the coastal upwelling of the Western South Atlantic Central Water (WSACW), with a temperature range between 5 and 18 °C, and the continental run-off from the Estuary of La Plata River and Lagoa dos Patos, which are processes favor the enrichment of the euphotic zone (Knoppers et al. 2009). In the region of Cabo Frio and Santa Marta, coastal upwelling events of short duration are common, which result in an increase in the planktonic population (Valentin 1984).

Although most studies in Brazil have been carried out in regions with the highest incidence of the species, such as the Saint Paul's Rocks (Hazin et al. 2008; Macena and Hazin 2016; Macena 2010, 2016) and the Rio de Janeiro State (Di Beneditto et al. 2021), the other occurrences are extremely relevant when we take into account the need to better understand the ecology and behavior of the species on the Brazilian coast. Although reports of encounters with this species are mentioned during interviews conducted in other studies (Meneses et al. 2005; Faria et al. 2009; Sampaio et al. 2018), they are not accounted for by science due to the lack of concrete evidence.

Social media facilitates the dissemination and location of photos and videos, which results in an increase in the number of records of the species throughout the Brazilian Exclusive Economic Zone (EEZ). In the past, these animals were only reported in magazines and newspaper articles (Gudger 1922; Soto and Nisa-Castro-Neto 2000; Campos et al. 2005), making it difficult to carry out analyses in a way that is more consistent with reality. Therefore, social media have become a great working tool, especially when we are talking about a species whose sightings are carried out opportunistically (Coram et al. 2021; Morais et al. 2021).

Improving knowledge of the influence of environmental parameters on habitat use is essential for a better understanding of a species ecology, as well as to facilitate management (Macena and Hazin 2016; Davis et al. 2020). Therefore, in order to understand the distribution of the whale shark along the Brazilian EEZ and how this use occurs, we must associate the organism's information, such as its feeding habits, with occurrence information and oceanographic variables. Thus, here we bring some light to better understand the spatial and temporal distribution of *R. typus* in the western South Atlantic. This work also updates the records of occurrence of *R. typus* based on records of personal communication and compiles scattered data in different sources, thus serving as a possible database for future investigations regarding the species.

Methods

This study was performed in the EEZ of Brazil, which includes the coast, adjacent marine areas, and oceanic islands. The Trindade and Martin Vaz archipelago was not considered due to the geographical distance from the coast associated with a single reported record, which presents uncertainty about the exact location and year of occurrence. The Brazilian coastline is approximately 9000 km long (Short and Klein 2016), comprising 17 states with an EEZ area totaling 3.5 million km^2.

Data collection

Whale shark presence data were collected from multiple sources from May 19, 1922, until June 27, 2024: (1) Traditional bibliographic sources: a comprehensive review of scientific papers and notes was conducted to compile all previously published records of whale shark sightings within the EEZ. (2) Traditional media sources: records from newspapers and television reports were obtained by a search performed on the Google News platform using the Portuguese term "tubarão-baleia" (meaning "whale shark"). (3) Social media: on the social media Instagram, the filter "#tubaraobaleia" was used as a search term. For posts where the location was not specified, the profile owners were contacted to obtain more precise information about location, date, and, when possible, about environmental conditions at the time of the sighting. (4) Personal communications: during the social media data collection, some fishermen and divers provided additional information, such as pictures, dates, and locations of their whale shark records. These individuals also indicated contacts of other people who could have information not available on the internet.

To ensure data accuracy, the records with identical characteristics (such as size, gender, and location) and occurring up to 7 days after the first observation were considered a single occurrence. Records that did not provide enough evidence of being the same animal were considered distinct. For records from traditional bibliographic sources, the location coordinates were obtained directly from the documents when available. In cases of coastal sightings without specific coordinates, an estimated location was assumed considering the observation point to be approximately 4 km from the coastline at the same latitude of the reported beach.

Spatial analysis

Kernel density analysis is a non-parametric method for estimating the probability density function of a random variable (Parzen 1962). This analysis is widely used in various fields such as marine spatial planning (Gandra et al. 2018), habitat use (Lees et al. 2016), and spatial pattern of marine populations (Harris et al. 2012; Kranstauber et al. 2012).

In this study, a kernel-density estimator (KDE) was employed to investigate the distribution of records for the species *R. typus* along the Brazilian EEZ. The coordinates of all *R. typus* sightings were imported into the QGIS software (version 3.32) (QGIS.org 2023). A kernel density map was then generated using these spatial data points and a search radius (bandwidth) of 2° (approximately 200 m). The density values were classified into five categories: Very low (0), Low (12.4768), Medium (24.9539), High (37.4304), and Very high (49.9073), using a continuous color scale. The Brazilian EEZ shapefile (Flanders Marine Institute 2023) was used as a mask to constrain the kernel density analysis inside these boundaries. The resulting kernel density map provided a visual representation of the probability distribution of whale shark sightings, highlighting areas with varying levels of occurrence.

Considering that the entire Brazilian coast encompasses a vast latitudinal range (approximately 5° N to 34° S), the geographic differences in the spatial patterns of whale shark sightings were examined by dividing the study area into smaller geographic units based on marine ecoregions. The records were classified according to their provinces (Cord et al. 2022) of occurrence in Northeast (NE), Abrolhos Bank (Abr), Southeast (SE), South (S), and Out of provinces. Following this classification, the number of whale shark sightings within each region was counted across the years. Potential shifts or variations in sighting frequencies were also evaluated on monthly and decennial scales to identify seasonal patterns and temporal trends. A G-test (Sokal and Rohlf 2013) was performed with all the provinces together to compare frequencies of records among half of the years.

The oceanographic variables collected for this study were the cumulative averages of seawater surface temperature and chlorophyll-a concentration (Table S1). The two variables were collected from NASA's MODIS-Aqua sensor database, using the cumulative average between 2002 and 2021 with a 4 ×4 km grid (NASA 2021). The samples and their respective coordinates were obtained using the SeaDAS software version 7.5.3, an open source program package for processing, visualization, analysis, and quality control of ocean color data, distributed by NASA OB.DAAC.

Principal Component Analysis (PCA) is a technique that linearly transforms a set of variables into a smaller set of uncorrelated variables that capture most of the information in the original dataset. The variables in this smaller set are called "principal components," and they are ordered by significance, with the first component being the most significant and the last one the least. The main objectives of this analysis include data reduction, the derivation of interpretable combinations of variables, and the description and understanding of the structure of correlations among them (Jolliffe and Cadima 2016). The PCA were performed using the Pearson correlation matrices between the variables latitude, sea surface temperature, and chlorophyll-*a* concentration in order to summarize and graphically visualize the relationships between variables, inferring trends or gradients.

Maxent distribution modeling uses the principle of maximum entropy from species presence data and environmental variables provided to the model to estimate the potential geographic distribution of the object of study. In this work, the mapping generated by the Java Maxent algorithm (Phillips et al. 2006) through the R package Dismo (Hijmans et al. 2017), in addition to estimating the spatial distribution, allows a comparison with the results generated by the kernel density.

Results

A total of 235 whale shark sighting records were analyzed. Eight records were excluded due to inconclusive information regarding their exact coordinates or occurrence date, resulting in a final dataset of 227 records. Seventy two new records were added to the list of records on the Brazilian coast (Table S1) from the media and social media between June 2004 and June 2024. The methods by which these records were obtained were classified as aerial sightings, fishing, recreational diving, scientific cruises, beach strandings, nautical tours, and seismic surveys (Fig. 1). With the exception of two records, not linked, all reported occurrences involved solitary individuals.

Fishing and diving records were the most frequent methods reported in the dataset (accounting for 22.2% and 25.0%, respectively) (Fig. 1). Among the more recent records (since 2004), social media, particularly Instagram (43 records), emerged as a significant platform for public encounter reports.

Records of whale shark occurrences were distributed along almost the entire Brazilian coast, though they become less frequent and more sparsely distributed at lower latitudes (Fig. 2). The northernmost record (excluding the Saint Paul's Rocks) was at latitude 2° S on the coast of the state of Ceará, while the southernmost record was at latitude 31° S (Rio Grande do Sul—South province). The kernel density map showed that the highest densities of records, classified as "Very high" and "High", are located in the Saint Paul's Rocks and in the Cabo Frio region in Rio de Janeiro State of Southeast province. In addition to these two hotspots, the coasts of São Paulo (Southeast province) and Bahia (Abrolhos province) also exhibited sectors with medium to high densities of whale shark sightings. Low densities prevail throughout the rest of the Brazilian coast, with extensive areas without any records. The coastline between

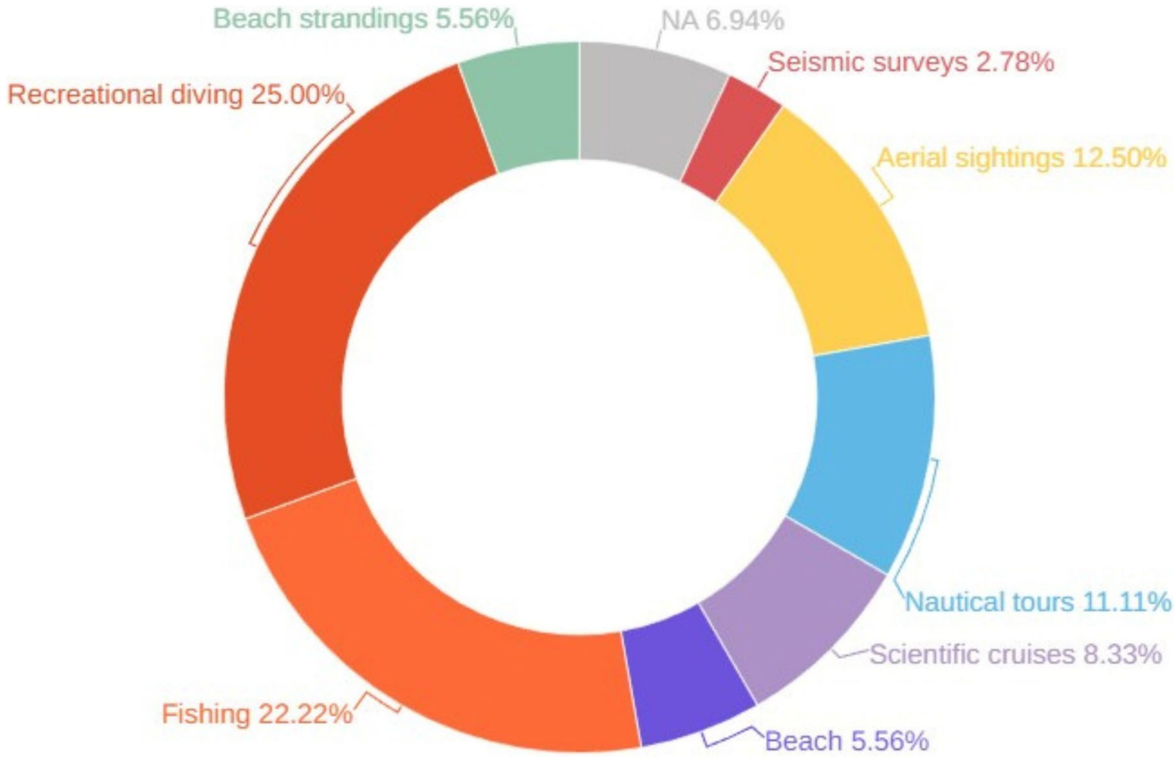

Fig. 1 Relative distribution of the sighting records by category (2004–2024)

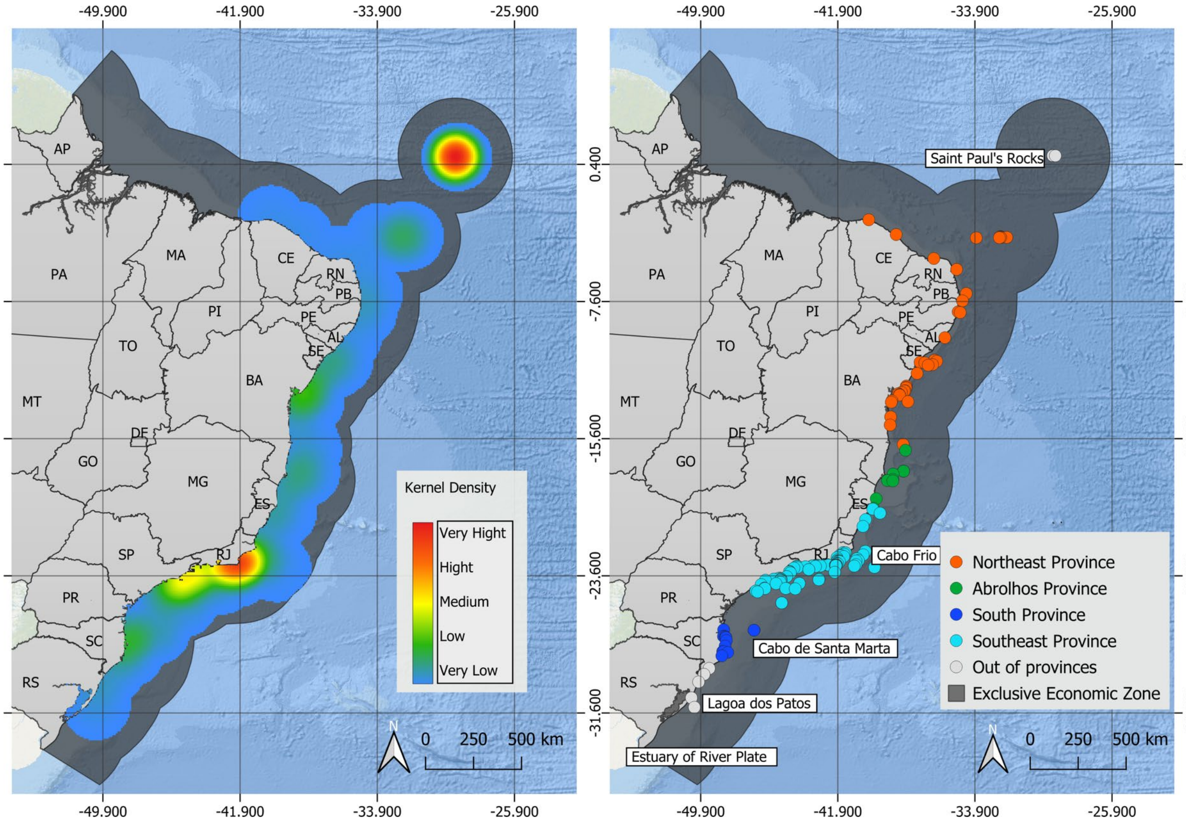

Fig. 2 Kernel density map of the frequency of whale shark sightings (1922–2024) and provinces (Cord et al. 2022) through the Brazilian coast

Paraná (South province) and southern São Paulo, for example, had a large gap in whale shark sightings even though it is a region that has marine study centers and tourist regions.

The distribution of records in each decade showed a substantial increase in the number of records of *R. typus* on the Brazilian coast and its oceanic islands (Fig. 3). There was a large gap in records between the decades of 1930 s and 1960 s (Fig. 3).

Examining the frequency of occurrences over the years, it was possible to identify that, excluding the period prior to 1980, only 4 years had no publicly known occurrence of whale sharks: 1980, 1981, 1988, and 2022 (Fig. 4). The annual average of records on the Brazilian coast was approximately 5 records per year. Over the 44 years of analysis, 26 years presented values above this average, while 18 years presented frequencies below it. In addition, it was also noted that in the last decade, most records occurred in the Southeast biogeographic province, while the records in the Saint Paul's Rocks (out of provinces) occurred mainly between the years 2000 and 2005 (Fig. 4), the observation period of a research project focused on the species in the region that used opportunistic presence data-only (Hazin et al. 2008) and dedicated survey data from 2005 to 2014 (Macena and Hazin 2016—data not analyzed).

Monthly analysis of the time series revealed a distinct pattern in whale shark occurrences (Fig. 5). The Southeastern and Out of province showed greater variances ($\sigma^2 = 50$; $\sigma^2 = 12$) in relation to the monthly occurrence of records, while the others showed variances lower than 4. The whale sharks' frequencies of records of all the provinces together at the first half of the year (27.0 $\pm$5.2; mean $\pm$standard deviation) was higher ($G = 12.71$; $p < 0.05$) than the second half (9.0 $\pm$3.4). This pattern is further highlighted by a peak frequency on April, while October had the lowest frequency value.

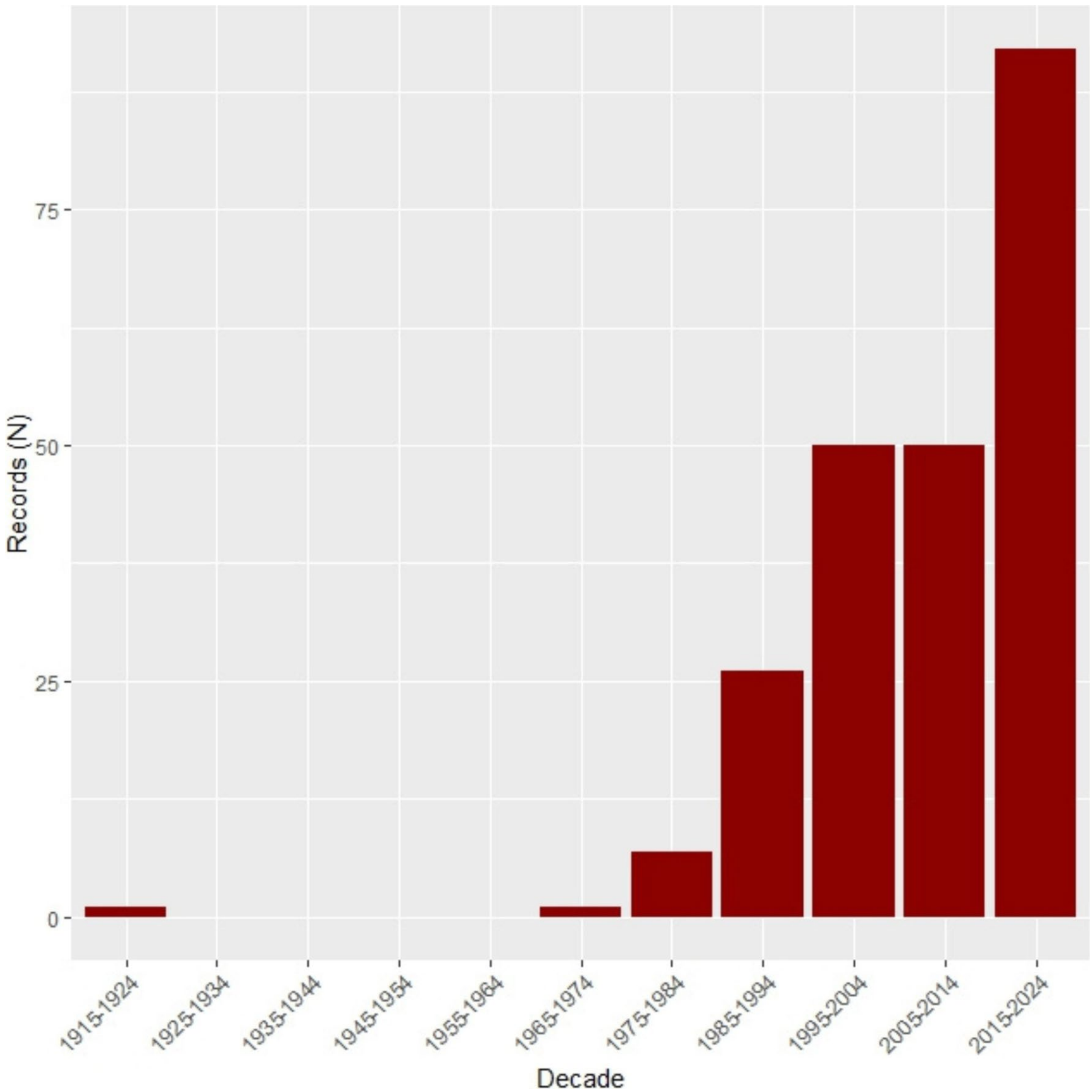

Fig. 3 Decadal distribution of whale shark records between 1922 and 2024 on the Brazilian coast

Eight records did not present specific identification for month and were represented by "NA."

The temperature in the occurrence areas varied between 20.06 and 27.75 °C, with an average value in the records of 24.66 °C, while the concentration of chlorophyll-a varied between 0.0727 and 13.4438 mg/m^3, with an average of 1.3005 mg/m^3. It was also possible to identify those records at higher latitudes in the southern hemisphere that were especially related to higher concentrations of chlorophyll-a, while records close to the equator were more related to higher temperatures (Fig. 6). However, the effects of these two variables are not enough to determine locations with the presence and absence of the species, even though they show influence in the occurrence records.

The distribution zone of the species predicted by the Maxent model (Fig. 7) increases towards the south. Despite the absence of observations north of the South province and south of the Southeast province, particularly between −26.7° S and −25° S latitude, a region that includes the Cananeia estuaries

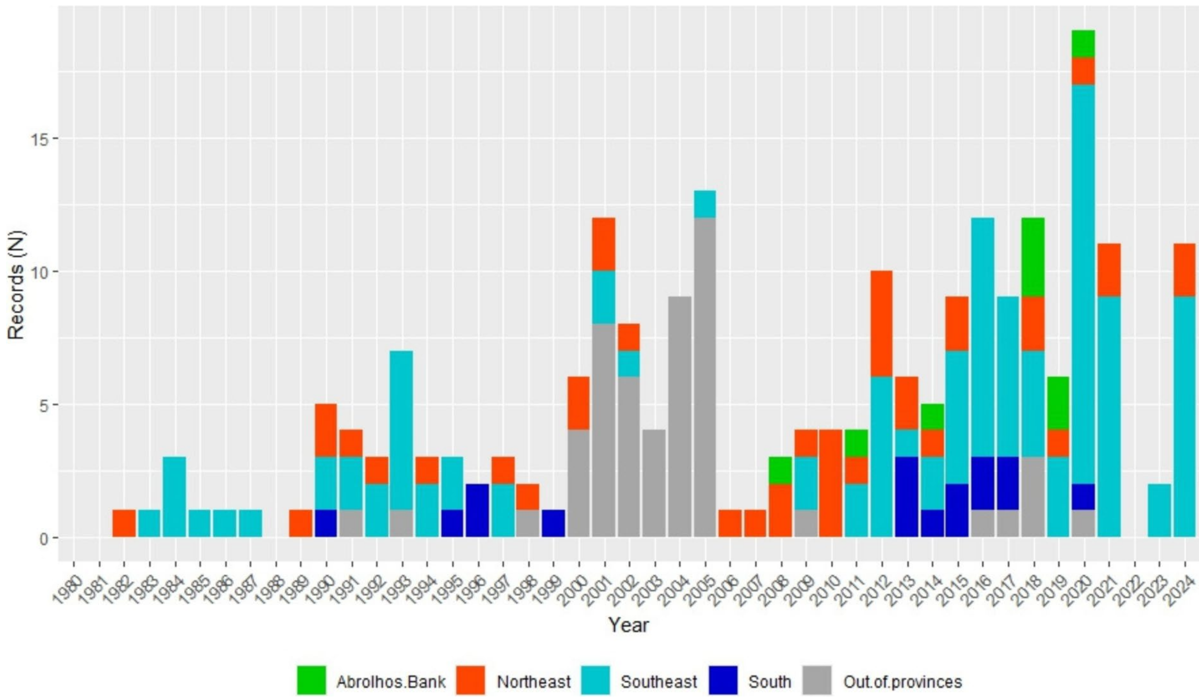

Fig. 4 Distribution of whale shark records on the Brazilian coast over the years (1922–2024) with the respective contributions of each region

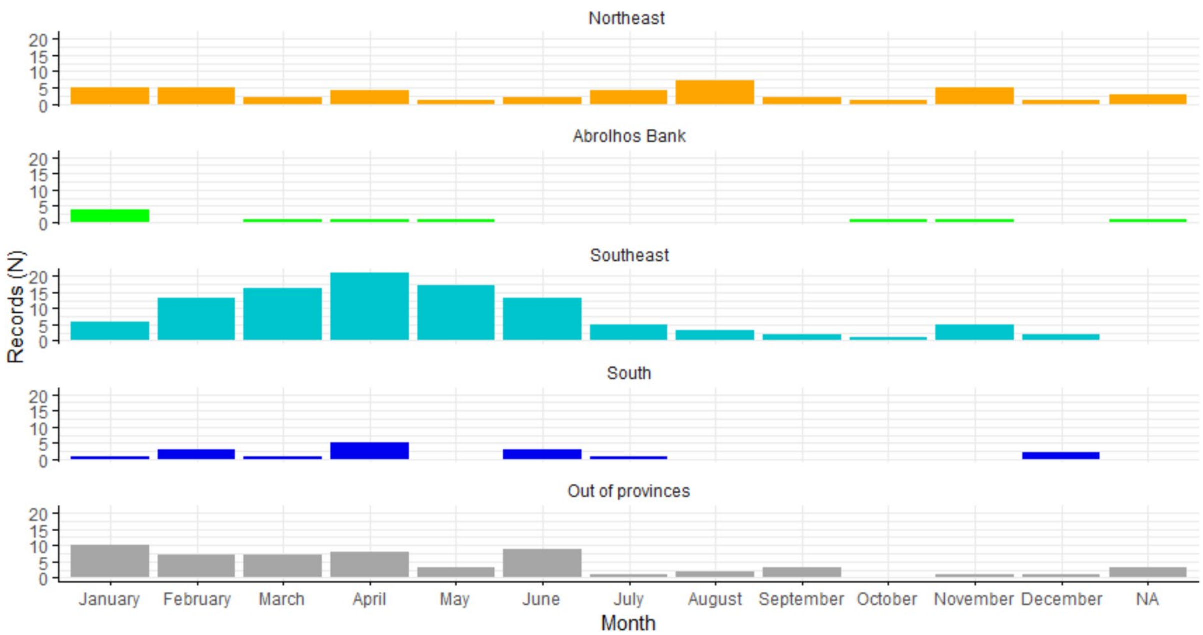

Fig. 5 Seasonal distribution of whale shark sightings reported along the Brazilian coast by provinces (1922–2024)

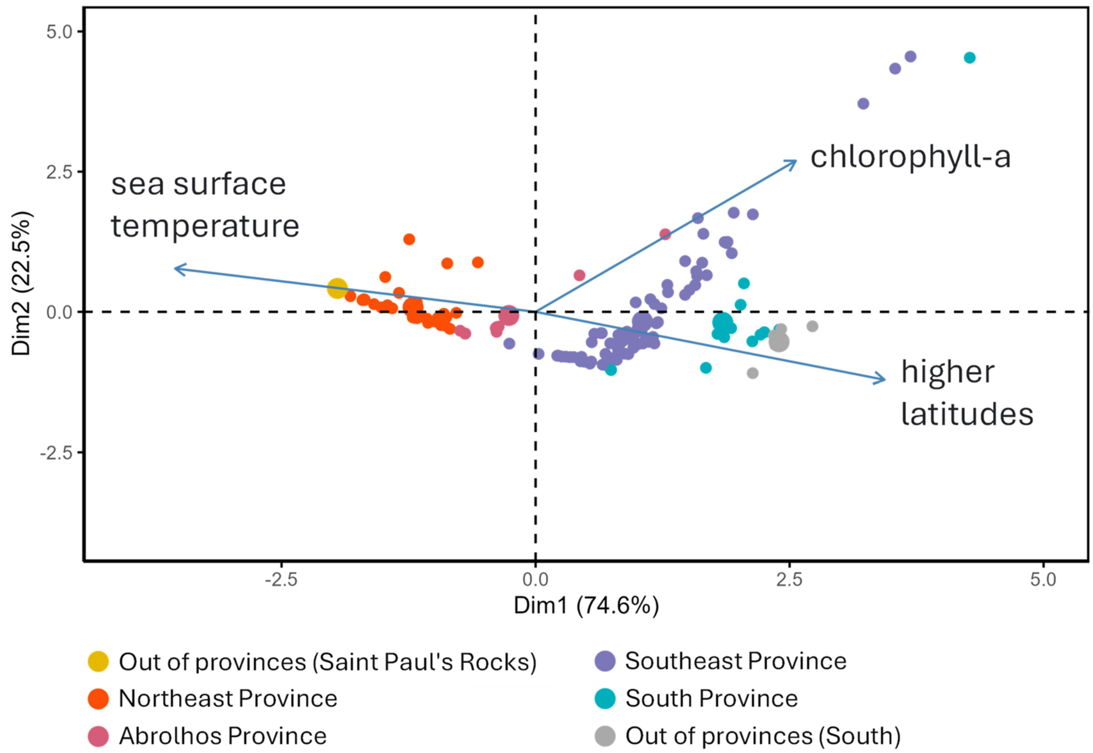

Fig. 6 Arrangement of environmental variables (sea surface temperature and chlorophyll-a) in relation to dimensions 1 and 2 of the PCA (Principal Component Analysis) ordered by higher latitudes with sightings distribution colored by provinces

(− 25° S), Paranagua estuary complex (− 25.5° S), Guaratuba estuary (− 25.8° S), and Babitonga Bay estuary (− 26.1° S), the model suggested that this region has suitable confitions for the occurrence of the species. In the provinces of Abrolhos and Northeast, the distribution remained concentrated in short distance from the coastline. On the other hand, from the extreme northern coast of the EEZ (4.4° N) to the upper limit of the coast of Ceara (− 2.9° S), the model indicated a scenario of prediction of null or very low distribution, with an increase in the predicted rate of occurrence, at zero latitude, as it moved away from the coast of Maranhão (MA).

Discussion

From the analysis of kernel density, we identified the two main areas of occurrence of *R. typus* in Brazil, in agreement with previous studies carried out with the species (Lubbock and Edwards 1981; Soto and Nisa-Castro-Neto 2000; Hazin et al. 2008; Macena and Hazin 2016; Di Beneditto et al. 2021). The fact that the Saint Paul's Rocks and Cabo Frio region in the state of Rio de Janeiro have more records is related to extensive research and observation in the region, as well as the favorable conditions for the whale shark, in the case of the Saint Paul's Rocks (Macena and Hazin 2016), and the well-defined upwelling system that occurs in Cabo Frio (Di Beneditto et al. 2021), providing an abundance of food for the species. The Maxent model, by providing a distribution prediction that aligns with the sampling data, except for the region between the Southeast and South provinces, along with the presence of marine research projects and tourism activities in these areas, leads us to consider the possibility that these regions may exhibit at least one environmental component that distinguishes them from the areas where whale sharks have been sighted.

Whale sharks exhibit a notable preference for specific types of plankton, such as sergestids,

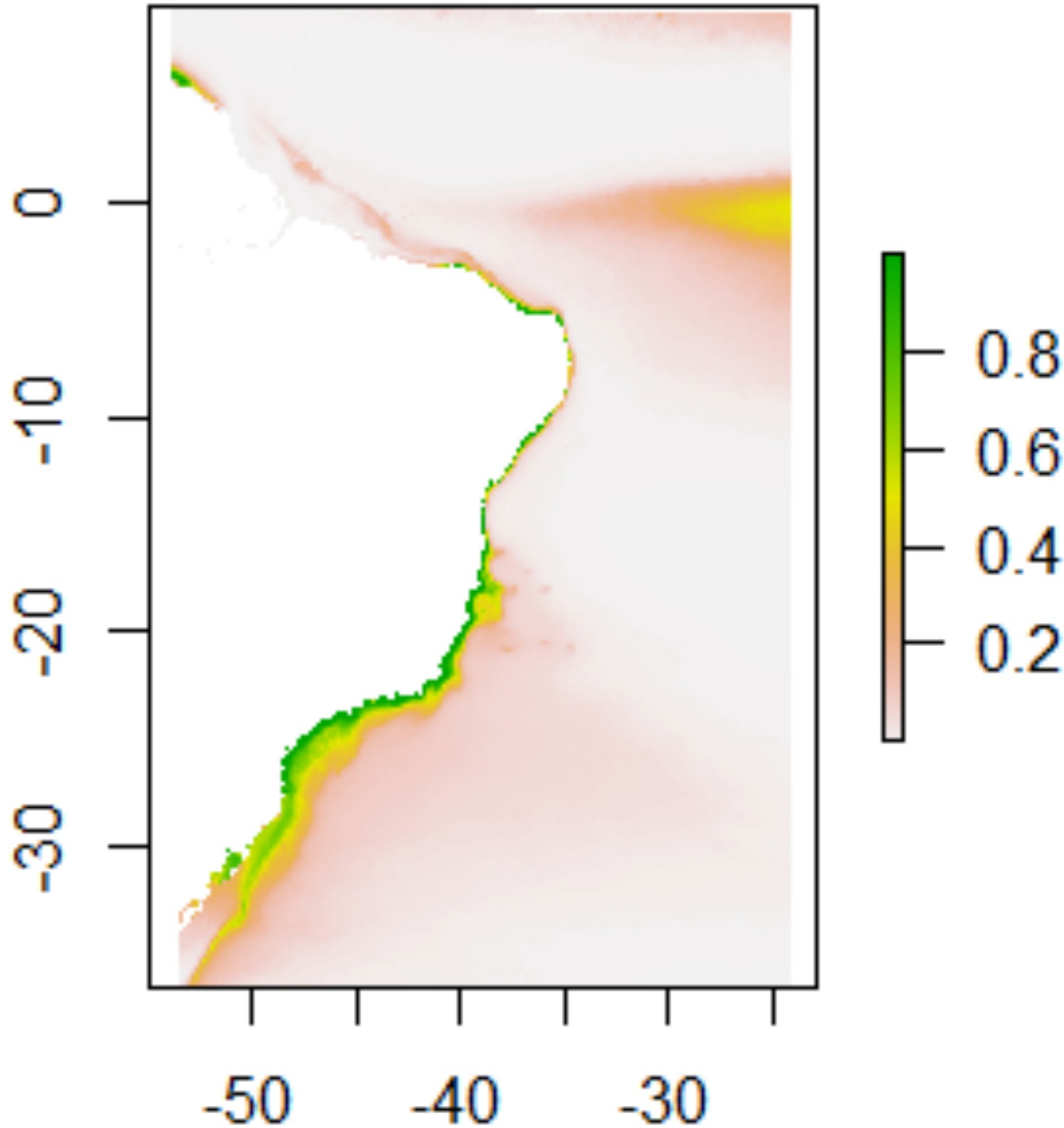

Fig. 7 Predictive species distribution by the Maxent model defined by seawater surface temperature and chlorophyll-a concentration

copepods, and chaetognaths (Motta et al. 2010), but the species also feeds on schools of bait fishes (Fontes et al 2024). This indicates that not only the quantity of planktonic organisms is decisive but also their quality and diversity play a crucial role. Therefore, understanding the interplay between estuarine dynamics and plankton composition is essential for predicting the distribution patterns of whale sharks along the Brazilian coast. This highlights the need for comprehensive studies that consider both biotic and abiotic factors influencing plankton communities to better inform conservation strategies for these filter-feeding sharks.

Estuaries, as dynamic regions that heavily influence their surrounding environments (Dyer 1989), contribute with large amounts of suspended sediments and materials of continental origin. The influence of estuarine outflows on adjacent marine environments can create distinct ecological zones with unique planktonic communities (Xia et al. 2024). These contributions, with high nutrient input from estuaries can promote the growth of phytoplankton that may not align with the dietary preferences of whale sharks (Dove et al. 2012). Additionally, the physical conditions of estuarine waters, characterized by fluctuating salinity and turbidity, further shape the types of plankton present (Xu et al. 2022; Wang et al. 2024), often favoring species that are not optimal for whale sharks. Consequently, this variation in plankton composition can lead to the absence of whale sharks in such regions due to the low concentration of their preferred food resources (de Oliveira Carvalho et al. 2022; Marsili et al. 2023).

When observing the distribution of sightings over time, there was an increase over the decades that may be mainly related to the increased use of smartphones and social media by the citizen scientists (Vohland et al. 2021). On the other hand, we also need to highlight the decline in the population of *R. typus*, resulting from the interactions with humans as in collisions between large ships and individuals of the species (Womersley et al. 2022). The records occurred mostly in the first half of the year (Fig. 6), during the austral summer and autumn seasons. It is aligned with the literature, considering that the species is usually related to temperate regions and warmer waters (Sequeira et al. 2012; Di Beneditto et al. 2021; Womersley et al. 2024a, b). In any case, this result helps us to define the best times to expand awareness efforts for communities in the region.

Considering the spatial distribution over time, we identified that in the last 10 years, sightings have been done mainly in the southeast region, located far from the southernmost distribution of the species in the Southwest Atlantic. This pattern suggests that specific oceanographic processes, such as seasonal upwellings, might play a more significant role influencing the chances of whale shark occurrences than factors like temperature and latitude alone. This result may also be related with the increased dissemination of images of the area known to be conducive to the organism and to the cessation of the whale shark research (i.e., no dedicated surveys conducted) in Saint Paul's Rocks after 2015 (BCL Macena, pers. comm.). It was expected that Fernando de Noronha and Atol das Rocas would present higher densities of whale shark records due to their proximity to feeding areas in the Gulf of Mexico (Mckinney et al. 2012), as well as the presence of a great diversity of research made in both regions and a high density of tourist activities in Fernando de Noronha, enabling greater chances of encountering the species. However, the results showed a low number of records in these regions.

These relationships presented between the two environmental variables, and the occurrence records are pertinent observations when we consider that *R. typus* uses regions with favorable conditions for their ecological needs (Hutchinson 1944). Places at higher latitudes would indicate a decrease in the abundance of tropical species caused by the colder waters; however, the greater availability of food would be a plausible justification for the displacement towards these places (Macpherson 2002; Tittensor et al. 2010). One of the hotspots of *R. typus* records being located in the region of Rio de Janeiro, where a well-defined upwelling system occurs, supports the relationship between higher chlorophyll concentrations and the species' records. The Saint Paul's Rocks, on the other hand, do not follow the same relationship presenting higher concentrations of zooplankton biomass even on the lower latitudes (Melo et al. 2012).

It is important to highlight that the data used in the analysis come from diverse sources, including scientific research records, personal communications, and news reports, which may introduce bias in the observations. Different methodologies and heterogeneous sampling effort over time may result in an underestimation of occurrences in less accessible and visited areas. The lack of financial support for research along the Brazilian coastline further limits data consistency and, consequently, the reliability of predictive models. Therefore, caution is necessary when interpreting the results, as they may have been influenced by the sampling effort.

Data from personal communication highlights the significant contribution of social agents, such as divers and fishermen, to species observation. This aligns with findings from studies involving other species (Coram et al. 2021; Morais et al. 2021). In the case of whale sharks, sightings within the Brazilian

EEZ are largely opportunistic, making the implementation of long-term monitoring programs particularly challenging. Therefore, collaboration with these communities or accessing to their records online is essential for improving our understanding of spatial distribution patterns (Cooper et al. 2007). Whale shark is easily identified due to its size and unique characteristics such as its spots and stripes which also becomes an advantage in the use of data recorded by any person or citizen scientists, by reducing doubts in validating the record. These patters can also be used to identify individuals, which could help with identifying groups and re-sightings (Arzoumanian et al. 2005; Brooks et al. 2010). Such a system would enable researchers to monitor occurrences and reoccurrences at the individual level over the medium and long term, potentially providing insights into population dynamics in the future. Another important point to be noted is that analysis of posts on websites and social media revealed a public interest in whale sharks, with frequently asked questions (i.e., comments) about their taxonomic classification, potential dangers they may pose, and general information about the species. Knowing this, the need for environmental education and awareness-raising actions becomes evident, even for a charismatic species.

Conclusion

The biodiversity records made by citizen scientists showed that it is extremely necessary to inform society about the importance of carrying out photographic records allowing scientists to use them to build and consolidate knowledge. The 43 new records that came from social media and other unofficial sources reinforce the idea that society can help science detect and expand access to the occurrence of whale sharks in unmonitored locations, mainly due to the fact that these records represent 19% of the total records compiled.

We acknowledge that due to the lack of financial incentives, the idealized scenario where we will have onboard observers present in all or even a good portion of the vessels present in Brazilian waters is far away. For this reason, we increasingly pursue to encourage the population to register species of elasmobranchs, marine mammals, among other groups. The reaffirmation of the Saint Paul's Rocks and the Cabo Frio region presenting the highest densities of records of the species indicates the need to disseminate information to society, mainly in the state of Rio de Janeiro, where the population may eventually come across the species.

Brazil is a country of great extension and environmental diversity; it was identified that different stretches have records linked in specific ways to oceanographic variables. It can be pointed out that to the south the records are more linked to chlorophyll-*a*, while further north to temperature. The records of the species in the Brazilian EEZ indicate to be very underestimated, and this information should be taken into account when we draw conclusions, since we may be masking, through sampling problems, the real influence of the variables and the occurrence of the species. New studies about the species are needed, mainly in the southwest region of the Atlantic Ocean, to better understand the reasons why these organisms are in our ecosystem, as well as the reasons why we do not find them in certain stretches, whether by the absence of the organism itself, the presence of estuaries that alter the conditions due to the input of various substances and materials or even by the lack of observations by the community. The findings presented here provide valuable insights for future research on *R. typus* and contribute with information to the development of effective marine spatial planning and conservation strategies that consider the habitat preferences of this marine species.

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Author contribution MLDF: conceptualization, data curation, methodology, data analysis, data interpretation, and writing—original draft, review, and editing.

VCLR: figure treatments, data interpretation, and writing—review and editing.

CB: data interpretation and writing—review and editing.

BCLM: data curation, data interpretation, and writing—review and editing.

RHAF: coordination, conceptualization, data interpretation, and writing—review and editing.

All authors read and approved the final manuscript.

Data availability This manuscript has data included as electronic supplementary material. Any additional data will be made available on reasonable request.

Declarations

Ethical Consideration This research relied solely on data from personal communication, social media or bibliographic sources, adhering strictly to all applicable legal and ethical guidelines. No approval of research ethics committees was required to accomplish the goals of this study.

Conflict of interest The authors declare no competing interests.

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