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Marine biodiversity hotspots in the Abrolhos Region and Vitória-Trindade Seamount Chain, Brazil, with implications for conservation

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ABSTRACT

Tropical marine habitats are among the most biodiverse on Earth but are facing accelerated local and global threats. Well-planned marine protected areas (MPAs) are a countermeasure for biodiversity loss and an alternative to maintain ecosystem services and their sustainable uses. Despite the need to improve the ecological representativeness of the Brazilian system of MPAs, basic information on spatial patterns of species distribution and richness is still lacking for several regions. The Abrolhos Region and Vitoria-Trindade Seamount Chain (Abrolhos Seascape) are among the biologically richest marine areas in the Southern Atlantic, and expanding the protection of key habitats in this region can aid Brazil to achieve its national and international conservation goals. This study updated the habitat map and the potential distribution of 546 species of fishes, invertebrates, cetaceans, seabirds, and sea turtles, and identified biodiversity hotspots in the Abrolhos Seascape. Habitat classes were defined based on the probability of occurrence and a comprehensive updated database. Potential species occurrence models and the weighted endemism method, with additional weight to the threatened species,

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were combined to identify biodiversity hotspots. Our results indicate that although some habitats (e.g. shallow reefs, mangroves, estuaries, and deep ocean), are relatively well represented in the current MPAs, a large portion of habitats with high biodiversity and concentration of endemic and threatened species (e.g. rhodolith beds, mesophotic reefs, slopes and sinkholes), have very low or no representativeness in the current MPAs. Our analysis provides important insights for future conservation planning exercises and highlights the urgent need to effectively protect high biodiverse marine habitats, not only to conserve biodiversity, but also to maintain key ecosystem services in the Abrolhos Seascape.

Keywords: Habitat mapping, Ocean conservation, Marine protected areas.

INTRODUCTION

Coral reefs, algae bottoms, seamounts, oceanic islands, mangrove forests, and estuaries are among the most biodiverse and productive marine ecosystems on Earth. Currently, they face a multitude of global and local impacts, including climate change, overfishing, coastal sedimentation, mining and pollution (Brierley and Kingsford, 2009; Hoegh-Guldberg and Bruno, 2010; Islam and Tanaka, 2004; Manes et al., 2021; Pinheiro et al, 2023), which may synergistically interact to amplify habitat destruction and biodiversity loss (Dulvy et al., 2003; McCauley et al., 2015; O'Hara et al., 2019). The decrease in species richness, abundance, and functional diversity in marine environments directly impacts numerous ecosystem services they provide, such as fish harvests, coastal protection, tourism, recreation, long-term food security, and cultural practices (Barbier, 2012, 2017; Nellemann et al., 2009; Villasante et al., 2016).

With 8,500 km of coastline encompassing approximately 38° in latitude, Brazil holds more than 4.5 million km² of marine area under its jurisdiction, when the "Blue Amazon" area pledged under the United Nations Convention on the Law of the Sea is included (Prates and Irving, 2015). Partially isolated from the Caribbean by the Amazon-Orinoco plume and separated from the African coast by the vast Atlantic oceanic areas, the Brazilian Province (Briggs and Bowen, 2013) displays a high degree of endemism among both fish and invertebrates (Luza et al., 2023; Pinheiro et al., 2018). It is one of the largest biogeographic provinces in the world (Sealey and Bustamante, 1999; Spalding et al., 2007), and its coastal zones shelter extensive habitats such as the Atlantic Forest, mangrove belts, rocky shores, and coral reefs, all of which provide ecosystem services with critical economic, ecological, and social importance (Castro, 2006; Castro and Pires, 2001; Dutra et al., 2011a; 2011b; Leal and Câmara, 2003; Leão et al., 2003; Pinheiro et al., 2017).

Despite their abovementioned importance, the integrity of Brazilian marine and coastal habitats has been declining over the past 50 years. Mangrove belts underwent severe clearing due to land development and shrimp farming (Ferreira and Lacerda, 2016; Lacerda et al., 2021). Nearshore reefs have been largely destroyed by urbanization, pollution, and sedimentation (Costa Jr. et al., 2008; Fogliarini et al., 2022; Laborel-Deguen, 2019). Furthermore, unregulated fisheries activity has led to numerous stock reductions and "fishing down the food web" in multiple coastal locations (Eggertsen et al., 2024; Floeter et al., 2006; Freire and Pauly, 2010). Such regional and local impacts are further intensified by global impacts associated with climate change (Corazza et al., 2024; Soares et al., 2024; Destri et al., 2025).

A countermeasure to marine habitat destruction and biodiversity loss is the establishment of marine protected areas (MPAs), which are one of the main strategies for mitigating regional and local impacts, particularly unregulated fisheries, tourism, and other human activities (Edgar et al., 2008; Prates and Irving, 2015; Selig and Bruno, 2010). When effectively planned and positioned, MPAs have promoted the recovery of degraded environments, increases in fish populations and enhanced resilience to ocean warming (Francini-Filho and Moura, 2008; Gove et al., 2023; Rolim et al., 2022; Teixeira et al., 2018). Consequently, their establishment is a priority in international policy agreements (Barbier, 2012). Unfortunately, at the global scale, nearly 85% of marine species have less than 10% of their distribution range within MPA boundaries (Asaad et al., 2018), and more than 97% of the 17,348 marine species of fishes, mammals, and invertebrates evaluated, have less than 10% of their range covered by strictly protected areas (Klein et al., 2015).

The Brazilian context is similar. The current MPA network, although covering nearly 26.5% of the total Brazilian Exclusive Economic Zone (EEZ), fails to meet global conservation goals, especially in terms of species connectivity and ecological and biodiversity representativeness (Magris et al., 2016; 2021). In fact, MPAs in Brazil are unevenly distributed and largely concentrated in oceanic areas devoid of shallow habitats (Giglio et al., 2018; Magris and Pressey, 2018; Vilar and Joyeux, 2021). Currently, half of the Brazilian marine ecoregions have less than 10% of their area under protection. Fortunately, recent research suggests that by identifying strategic conservation priorities, it is possible to significantly increase representativeness with relatively small additions to the existing MPA network (Ferreira et al., 2022; Magris et al., 2021).

Brazil was the first country to sign the Convention on Biological Diversity at the Earth Summit (Rio 92), committing to measures that reconcile conservation and sustainable use of natural resources. The Priority Areas for Conservation, Sustainable Use, and Benefit Sharing of Biodiversity (APZCM) is a collaborative effort and public political instrument established by the Brazilian Ministry of Environment to achieve these goals nationally (MMA, 2018). It represents an important pathway for guiding the identification of priority areas for the creation of MPAs and other management regulations. However, there has been limited progress in downscaling priority setting efforts for marine areas in Brazil, with no regional planning studies available so far.

The Abrolhos Region and Vitória-Trindade Seamount Chain (hereafter referred to as the Abrolhos Seascape) encompass one of the most extensive areas of "Extremely High" biological importance and priority for conservation action according to the APZCM (MMA, 2018) and was selected for this regional analysis. This region includes estuaries, mangrove forests, seagrass beds, rhodolith beds, seamounts, oceanic islands, and the largest coral reef areas in Brazil, which together form a center of marine biodiversity in the Southern Atlantic Ocean (Dutra et al., 2011b; Pinheiro et al., 2015; Werner et al., 2000). Currently, only parts of the shallow and mesophotic reefs, soft bottoms, mangroves, and estuaries of the region are protected, with several habitats still largely unprotected (e.g. rhodolith beds, buracas[1], and mesophotic reefs) (Moura et al., 2013).

One of the limitations for downscaling conservation planning is the lack of detailed data on habitat types and species distribution in smaller spatial scales. This study aims to reduce this gap by identifying marine biodiversity hotspots in the Abrolhos Seascape. We employ an adapted "biodiversity hotspots" framework (Myers, 1988) to the marine environment, developed by several authors, reducing the weight of endemism and threat metrics while emphasizing species richness (Jefferson and Costello, 2020). By combining an updated database of habitat distributions and species occurrences, with a weighted endemism approach considering endemic and threatened species, we identify the marine biodiversity hotspots in the region. Our results provide essential information to guide conservation decision-making and future conservation planning approaches.

MATERIALS AND METHODS

Study area

Located on the Brazilian coast, the study area covers approximately 893,000 km^2 of coastal and marine environments that includes the Royal Charlotte Bank, Abrolhos Bank, Vitória-Trindade Seamount Chain, and Oceanic Islands of Trindade and Martin Vaz, composing the Abrolhos

1 The "*buracas*" or sinkholes are depressions in the shelf formed by geophysical and biological processes representing unique structures recently described in Abrolhos (Bastos et al., 2013, 2016).

Seascape (Murphy et al., 2021). It includes marine areas with the bounding coordinates extending from 40°W to 25°W and 15°S to 25°S (Figure 1). It is within the Tropical Southwestern Atlantic ecoregion (Spalding et al., 2007) and includes the Ecologically or Biologically Significant Area (EBSA) of the Abrolhos Bank and Vitória-Trindade Chain (CDB, 2024).

To establish the geographic limits of the area, the coastline dataset provided by the Brazilian Geological Service was used (SGB, 2021), as well as the legal boundaries of the Brazilian marine territory (Brasil, 1993).

Habitat layer

We explored the application of multiple datasets to assess the potential distribution of marine and coastal habitats within the study region. First, we elaborated a marine habitat layer with distribution data for coral reefs, mangrove forests, unconsolidated sediments, rhodolith beds, and estuaries (Amado-Filho et al., 2012, 2017; Bastos et al., 2013, 2015; D'Agostini et al., 2019; Dutra et al., 2006; Ferreira et al., 2020; Holz et al., 2020; Horta et al., 2016; Magris et al., 2021; MMA, 2018; Soares Moura et al., 2013, 2021; Pinheiro et al., 2014, 2015, 2021; Prates, 2003; et al., 2018, 2021; Simon et al., 2022; Teixeira et al., 2018; Vieira et al., 2019).

To generate estimates of marine habitat occurrence probability using available data within each region of the study area, two spatial analysis methods were defined and implemented based on data availability and habitat types. Some data were vectorized as polygons, obviating the need for estimation methods. In such cases, a location overlay with the planning unit layer was performed, and each cell was classified accordingly. Kernel Density, Euclidean Distance, and Buffer methods in ArcGIS Pro (ESRI, 2023) were employed to project potential distributions of coastal and marine habitats. These methods involved combining layers of points representing the same habitat category as input for spatial analysis tools, guided by internally defined criteria detailed by habitat type. The Euclidean Distance tool estimated the distance to the nearest habitat occurrence point for each cell. This method was applied in areas with isolated habitat points, precluding the use of Kernel Density, which requires multiple points to create probability-based areas. Kernel Density computed a magnitude area per point unit by applying a density probability estimate, adjusting the surface to each input point's occurrence probability. In cases in which sufficient points were available for Kernel Density estimation, raster layers with different classification classes were generated based on occurrence probabilities.

Planning Units (PUs) are landscape units that compose the surface and represent the base layer of this study. These units work as cells on a grid square to enable spatial analysis. In total, two different dimensions were used to divide the region: (PU1) representing the continental shelf and the zones with depths up to 200 m, where there is more detailed information available; (PU2) to represent the marine zone with depths beyond 200 m where the information is scarcer and available in lower scales (Figure 1). Polygonal representations of oceanic island areas (Martin Vaz and Trindade) were created using the ESRI Satellite Imagery layer in ArcGIS Pro (ESRI, 2023). The polygons were delineated via manual vertex editing, employing ArcGIS Pro editing tools. The satellite imagery provided detailed visual information, enabling accurate boundary delineation for the terrestrial portion of the respective islands that were then removed from the PU layer. All planning units overlapping with habitat points were classified accordingly, without the need for spatial analysis methods.

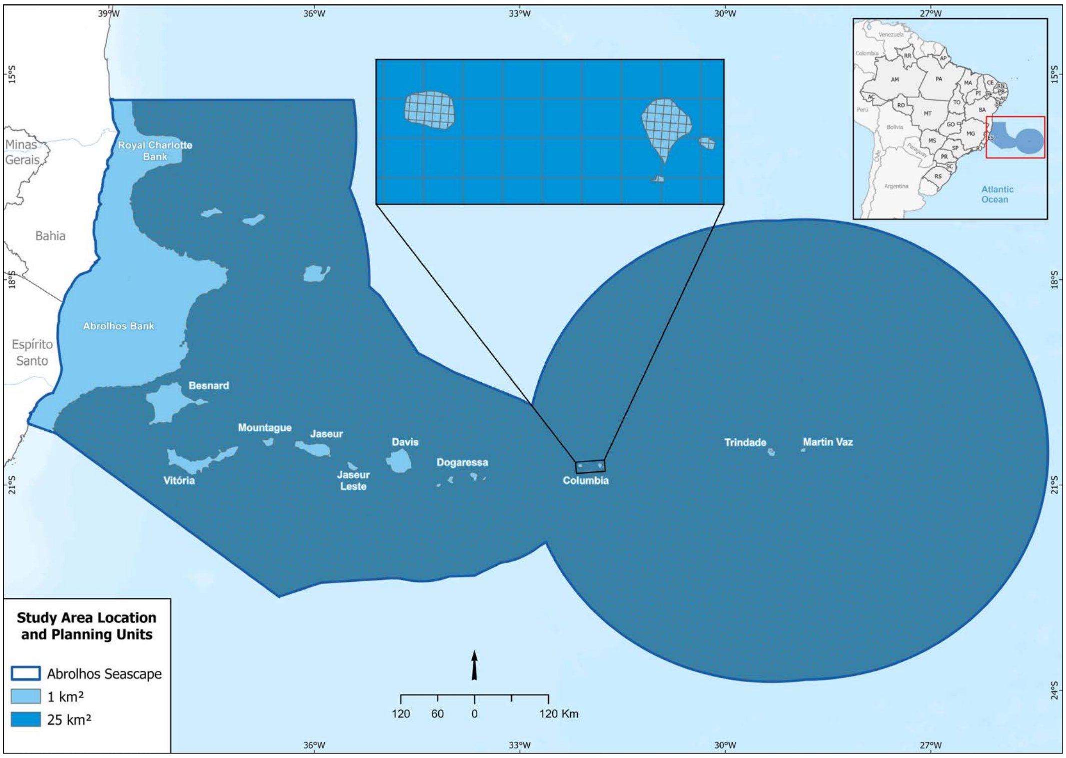

Figure 1. Study area located in the Southwestern Atlantic Ocean, Brazil, encompassing the Abrolhos Bank, Royal Charlotte Bank and the Vitória-Trindade Seamount Chain (Abrolhos Seascape). Two different dimensions were used to represent de Planning Units (PU): PU1 (1 km²) representing the continental shelf and the zones with depths up to 200 m; PU2 (25 km²) representing the marine zone with depths beyond 200 m.

Modelling species occurrence

We compiled georeferenced data of the study area available in the literature and online open databases (points of occurrence, polygons of home ranges, and species distribution models) for all species of fishes (Condini et al., 2022; Dutra et al., 2006; Guabiroba et al., 2022; Mazzei et al., 2021; Pinheiro et al., 2015; Teixeira et al., 2018), birds (ICMBio, 2016b, 2019; Nunes et al., 2022), cetaceans (IBAMA and ICMBio, 2011; ICMBio, 2016a; MMA, 2018; Rossi-Santos et al., 2006), chelonians (Guimarães, 2017; ICMBio, 2023; MMA, 2018; Marcovaldi et al., 2011), and invertebrates (Amaral et al., 2008; Dutra et al., 2006; Lage et al., 2011; Medeiros, 2019; Meirelles et al., 2015; Mies et al., 2020; Simões et al., 2004; Simone, 2005; Soares et al., 2018; Teixeira et al., 2018). Species deemed as threatened were incorporated based on the latest revisions of species lists provided by the International Union for Conservation of Nature (IUCN), the Chico Mendes Institute for Biodiversity Conservation (ICMBio), and the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA). In cases in which discrepancies arose, priority was given to the higher threat category. For cetacean, bird, chelonian, and pelagic fish species, we used models of potential distribution already available from literature and the database listed in the 2nd Update of Priority Areas for Conservation, Sustainable Use, and Sharing of Benefit of Brazilian Biodiversity, an effort from the Brazilian Ministry of Environment (MMA, 2018). These models are represented as polygons of the areas of distribution of threatened species.

To address the gap in species distribution information at the local scale, which precluded the use of traditional species distribution models, we assessed the hypothetical potential occurrence of substrate-dependent fish and invertebrates by considering their bathymetric and habitat ranges. This approach systematically analyzes the association of each species with these characteristics, as documented in the literature (e.g. Roberts et al., 2020), to generate polygons that represent their potential occurrences. The analysis presented here does not conform to traditional species distribution models that rely solely on observed records. Instead, this methodology is integrated into an approach known as "FishCake," as described by Teixeira et al. (2018), which offers a systematic framework for delineating areas where benthic-associated species are likely to occur conservatively. This approach enables the integration of maps depicting both endangered species (conservation targets) and commercially significant species (fishing opportunity costs), thereby enhancing systematic conservation planning efforts.

We used the classification proposed by Pinheiro et al. (2018) to select the reef resident and benthonic fish species (here considered as demersal species) and used data from the FishBase (Froese and Pauli, 2024) to classify those species not listed by these authors. Pelagic fish species were excluded from this analysis, as their distribution may not be associated to specific habitats (Roberts et al., 2020). For these species, we used potential distribution models, when available in the literature.

The FishCake model envelops the habitat and the bathymetric bands of each species as their inferred distribution areas and has been used for a list of species known to occur in Abrolhos. This approach has the main advantage of producing homogeneous results among the target species. Despite not being applicable to pelagic species and showing limitations due to the current situation of occurrences, it conservatively represents the suitable environments for the distribution of demersal species.

Weighted endemism and biological importance

The "weighted endemism" method can be defined by the combination of information on species richness and extent of distribution (Crisp et al., 2001; Guerin et al., 2015; Kier and Barthlott, 2001; Williams et al., 1994). When data from multiple species are analyzed together, we can represent the set of biological and ecological information available in a more synthetic, objective, and spatially explicit map known as Biological Importance Map. These maps highlight areas where species of restricted distribution occur, having higher values of weighted endemism.

The method is a spatially explicit index, given by the application of a continuous weighting function, with emphasis on species with smaller distribution ranges and progressively smaller weights for species with greater distribution ranges. In this way, areas where species of restricted distribution are concentrated have higher values of weighted endemism. For example, to compose the index of a given PU, a species that occurs only in this PU contributes a thousand times more than a species with distribution in a thousand PUs.

To estimate the weighted endemism value of each species in the database, we used a georeferenced implementation of weighted endemism (Guerin et al., 2015) via the 'weighted.endemism' function in the R environment (R Core Team, 2017). In this approach, the records of the species georeferenced by the centroid of the occurrence cells (PUs) are used to find the minimum convex polygon of the spatial range of each species. For this polygon, the maximum distance between the vertices is estimated, which returns as the weight of the range. This weight can also be modified according to the conservation status of the species to assign greater importance to endangered species. The input data for the function are the species registration tables, containing the longitude and latitude for each PU cell in which the species occurs. The function automatically generates a raster layer and a list containing the endemism values of each advanced cell in the same geographic extent as the input data, a list of the weight for each species (used to generate the final values for each PU), and a matrix of the occurrence of species against the cells of the layer.

Additional weighting for endangered species

Aiming to highlight the distribution of threatened species, we implemented an additional weight for these species in the spatial analysis. This weighting followed the conservation status of each species. A function that decreases the distribution weight resulting from the initial endemism analysis was implemented, as it is an inverse relationship. It increases the value of weighted endemism, causing the PUs where species with the highest degree of threat occur to have progressively larger values of weighted endemism. Notably, species categorized as "Critically Endangered" have a 50% reduction in weight, whereas "Endangered" species have a 40% decrease. In turn, "Vulnerable" species undergo a 30% weight reduction and a 10% decrease is applied to "Near Threatened" species.

Map elaboration

To represent the set of biological information available for the Abrolhos Seascape in a more synthetic and objective way, we elaborated maps combining information about species richness and distribution extent to represent the variation of biological importance in the region and thus guide conservation actions. For species richness and threatened species richness maps, we used the species occurrence matrix to generate raster layers symbolized by stretching values along a color ramp, highlighting areas with higher species richness.

For the final Map of Biodiversity Hotspots, we employed species richness and distribution extent data, processed using the weighted endemism method and weighted by threatened species category, as explained in the previous section. The final values were classified using the Quantile method (ESRI, 2023), which creates classes with equal numbers of features, employing PUs as features. The dataset was divided into ten classes of biological importance, with Class 1 representing the lowest importance, and Class 10 representing the highest biological importance. We merged classes 1, 2, 3, and 4 considering the low spatial precision of data in the deep areas they covered and their low biological importance. Finally, we analyzed the top 10% quantile (Class 10) as the potential biodiversity hotspot for the region.

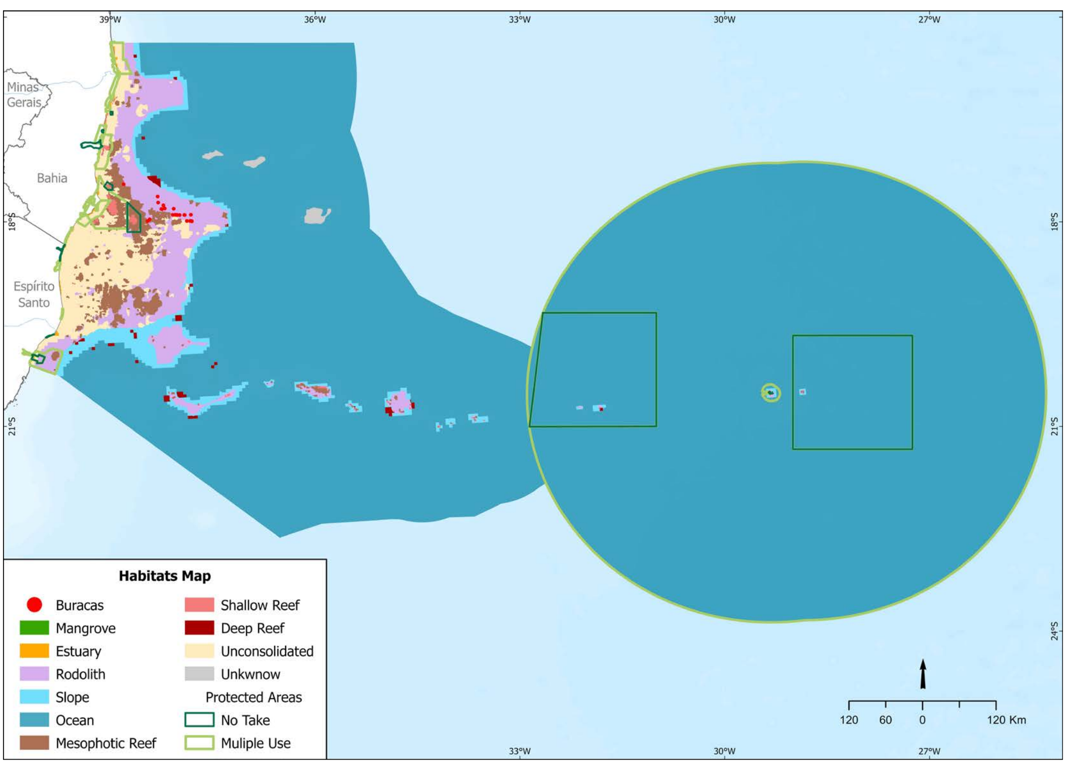

Figure 2. Habitat classification in the study area. Different habitat classes were delineated using spatial analysis methods to estimate the probability of habitat occurrence based on available data. Vectorized data were overlaid with planning unit layers for classification. Kernel Density, Euclidean Distance, and Buffer methods in GIS software were employed to project potential habitat distributions. Euclidean Distance was used in areas with isolated habitat points, while Kernel Density required multiple points for probability estimation. The protected areas in the region are also shown divided in two classes: No-take and Multiple Use.

RESULTS

Updated habitat map

The analysis based on the updated database and inferred distribution performed in this study enabled the generation of an updated habitat map for the Abrolhos Seascape (Figure 2). Figure 3 and Table SI1 show the percentage of each habitat represented in the current no-take and multiple use marine protected areas (MPAs).

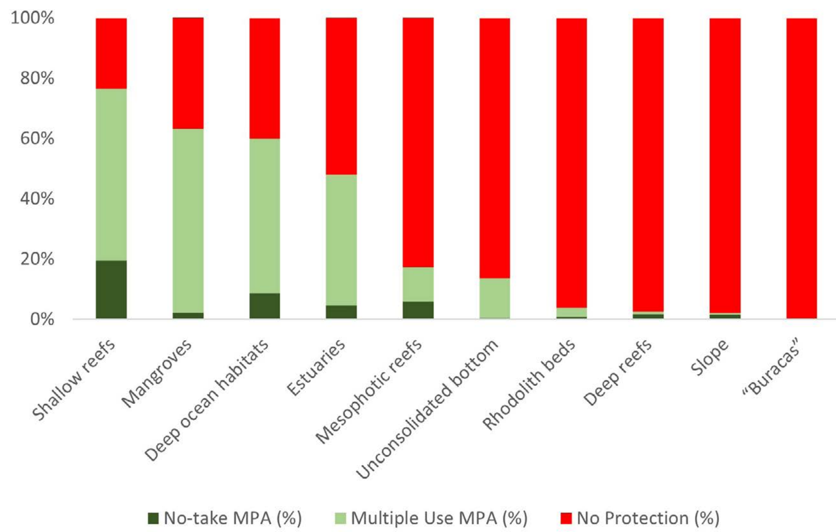

Figure 3. Percentage of the different habitat classes within marine protected areas (MPA) in the study area. In the graph, "No-take MPA" denotes formally declared MPA where all extractive uses are not allowed. "Multiple use MPA" represent formally declared MPA where sustainable extractive uses are allowed under management regimes (including artisanal fisheries). "No protection" include all areas with no formal protection or regulation, thus susceptible to various anthropogenic impacts.

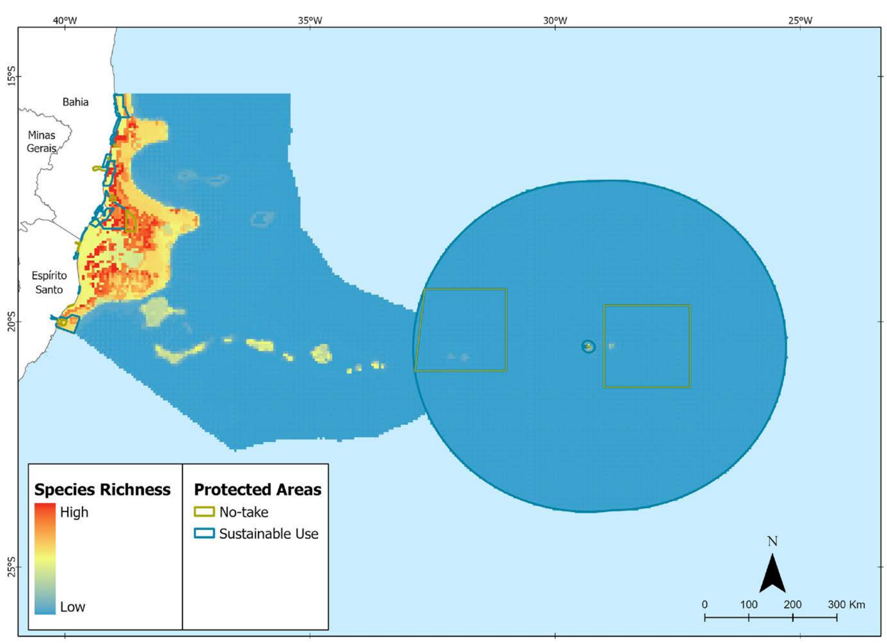

Figure 4. Species richness in the study area. In the map, species richness can be visualized using a color gradient ranging from blue (indicating low richness) to red (representing high richness) for all 546 species analyzed.

Species richness

Figure 4 shows the overall richness for all 546 target species in the database. Total species richness is higher in the reef habitats of the continental shelf, especially in the shallow and mesophotic reefs. It is lower but relatively stable along the Vitória-Trindade Seamount Chain.

A total of 134 species (24.5% of the 546 analyzed) fall into the threat categories (Near Threatened, Vulnerable, Endangered, and Critically Endangered) (ICMBio, 2022; IUCN, 2022). The map representing the species richness considering only endangered species shows a similar pattern to the overall species richness map (Figure 5).

Biodiversity hotspots

The final map of Biodiversity Hotspots in the Abrolhos Seascape gathers information on the general distribution of all 546 species using the method of weighted endemism and considering the 143 threatened species weighted according to their conservation status (Figure 6). This map highlights important areas for overall species richness, threatened species, and species with restricted distribution.

The highest biodiversity importance class (class 10, Figure 6) follows the distribution of shallow and part of the mesophotic reefs, as well as some coastal areas and rhodolith beds, in the continental shelf and in the Vitoria-Trindade Seamount Chain. Class 9 (Figure 6) includes a similar portion of mesophotic reefs, 23% of the mapped *buracas*, and smaller portions of all other habitats occurring on class 10 (Table SI2). Classes 5, 6, 7, and 8 cover most of the remaining shelf areas and seamount tops, whereas class 4 and lower cover mainly deep ocean areas (Table SI2).

The analysis of the area of each biological importance class represented in the present MPAs (Figure 7 and Table SI3) shows that 35% of the areas with the highest biodiversity importance (class 10) are within the present MPA network, covering mainly shallow and mesophotic reefs, as well as the surroundings of the oceanic islands. However, classes 5 to 9 have lower percentages within the present MPAs, reflecting the low representation of habitats such as rhodoliths, deep reefs, slopes, and *buracas*. In contrast, areas with lower biological importance (classes 4 and lower) are well represented, reflecting the large areas of ocean covered by the Trindade and Martin-Vaz MPA mosaic.

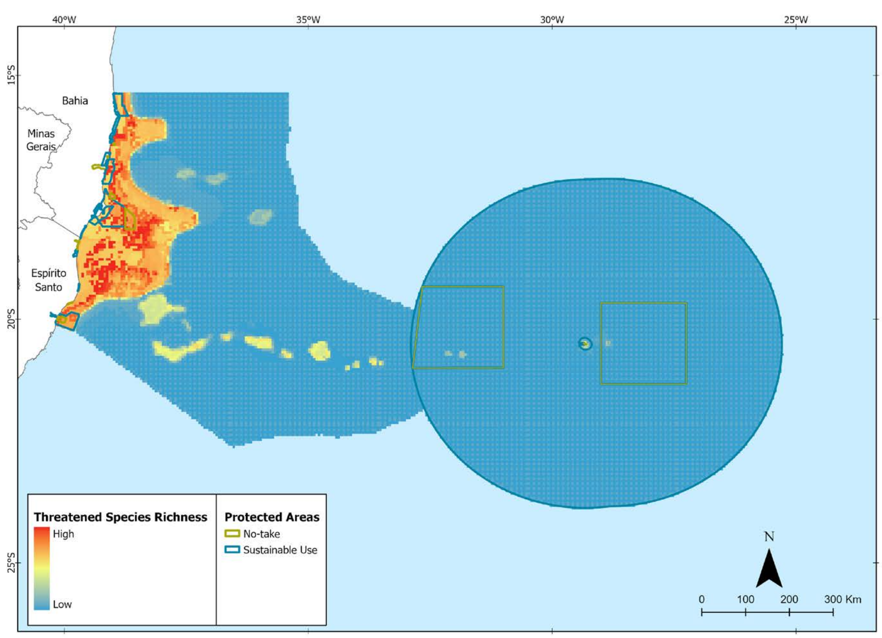

Figure 5. Species richness considering only the endangered species occurring in the study area. In the map, species richness can be visualized using a color gradient ranging from blue (indicating low richness) to red (representing high richness) for the 134 endangered species analyzed.

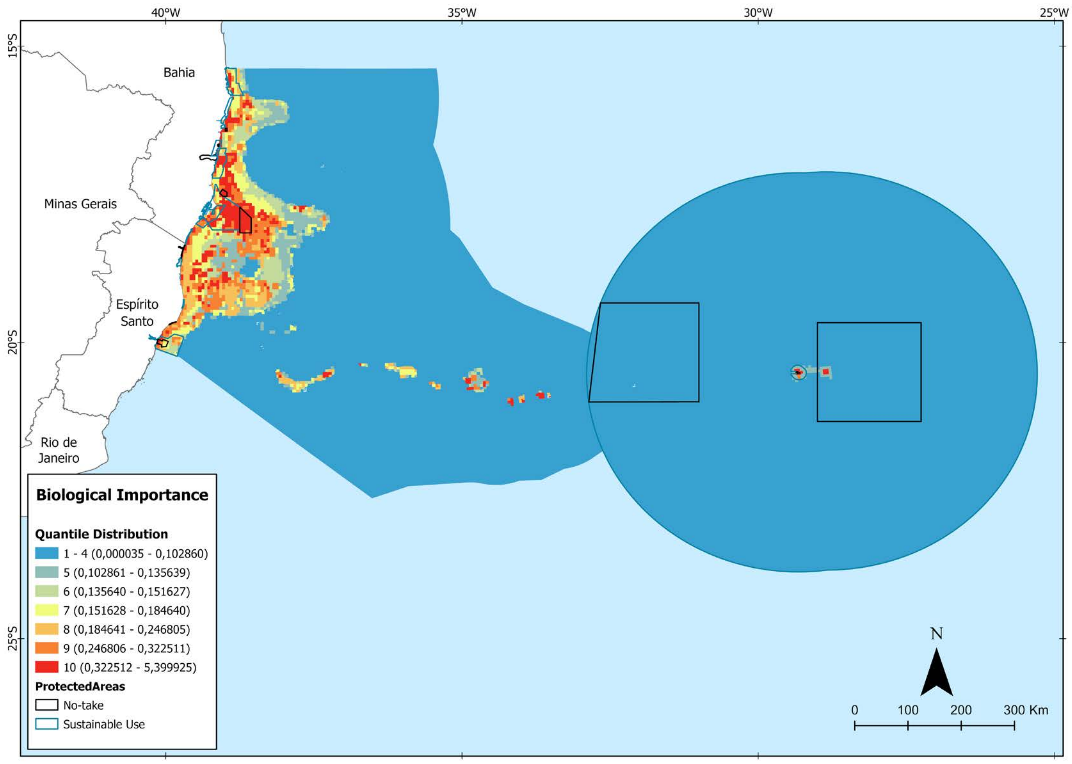

Figure 6. Biodiversity hotspots in the study area. The map shows the distribution of all 546 species analyzed by the weighted endemism method and assigning different weights to threatened species. The color scheme represents the ten classes of biological importance obtained by the quantile method, ranging from 1 (blue, representing lower biological importance) to 10 (red, indicating higher biological importance and the top biodiversity hotspots). Under parenthesis are the weighted endemism scores. Classes 1 to 4 were merged in the map, considering the low spatial precision of data in the deep areas they covered and the low biological importance of these classes.

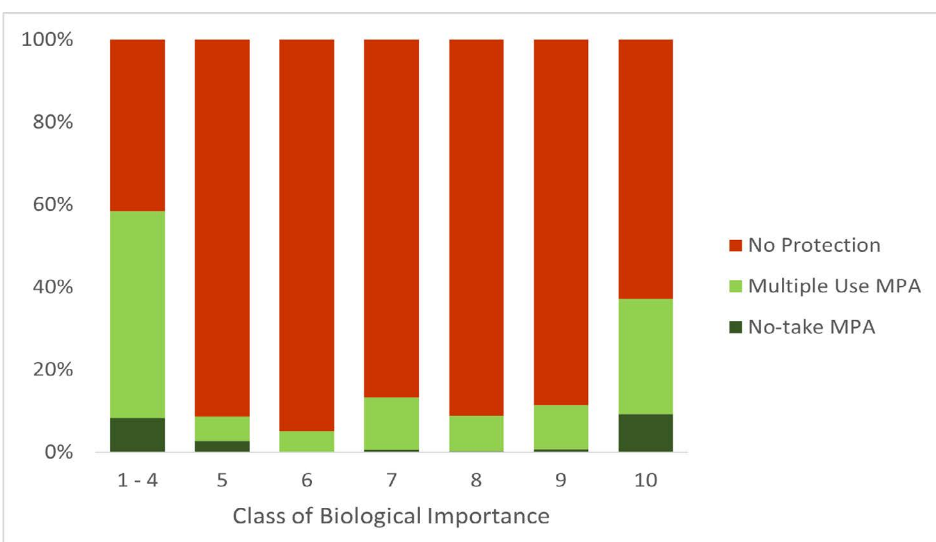

Figure 7. Percentages of the classes of biological importance within marine protected areas (MPA) in the study area. The Classes of Biological Importance range from Class 1 (representing lower biological importance) to Class 10 (indicating higher biological importance). The MPA categories are the same as on Figure 3.

DISCUSSION

The Abrolhos Seascape, despite being home to the highest known marine biodiversity in the Southern Atlantic Ocean (Dutra et al., 2011; Freitas et al., 2011), has important knowledge gaps that hinder effective conservation and sustainable use of its biodiversity. Mapping key habitats and ecosystems is of great importance to advance planning of MPAs and other conservation measures (Cogan et al., 2009). Our updated map of the Abrolhos Seascape habitats, obtained by the compilation and analysis of various information sources, synthesizes current knowledge on spatial patterns of biodiversity within the region (Figure 2). We expanded the habitat map to important areas, such as the Royal Charlotte Bank and the Vitoria-Trindade Seamount Chain, adding to previous efforts focused only on the Abrolhos Bank (Moura et al., 2013; Prates, 2003).

There are still large information gaps for biodiversity patterns in mesophotic, slope, and deep habitats and ecosystems in the Abrolhos Seascape. Thus, our detailed compilation effort and hotspot delineations towards mesophotic and deep reefs plausibly add important information about biodiversity distribution and connectivity in the Abrolhos Seascape.

The analysis of habitat representativeness in the current network of MPAs of the study area (Figure 3; Table SI1) indicates that although some habitats, such as shallow reefs, mangroves, estuaries, and deep ocean habitats, are relatively well represented within the present MPA network. Other habitats, such as rhodolith beds, mesophotic reefs, slopes, and sinkholes (*buracas)*, have very low or no representativeness at all. These ecosystems are unique and ecologically linked and have key roles for biodiversity conservation and fisheries sustainability in the region (Olavo et al., 2011; Moura et al., 2013, 2021; Simon et al., 2016, 2022). Among them, the sinkholes (*buracas*) have especially high concentrations of fishes, lobsters, and other marine fauna (Bastos et al., 2013; 2016; Cavalcanti et al., 2013), plausibly deserving protection.

Shallow reefs and surrounding algae bottoms are important nursery sites for key and threatened species (Eggertsen et al., 2017; Roos et al., 2020). Mesophotic and shallow coral reefs are linked physically and biologically, being important refuges for shallow coral reef taxa such as corals and sponges. Moreover, these areas are also considered sources of larvae that could contribute to the resiliency of shallow reefs (Lesser et al., 2018).

Rhodolith beds also have important roles as reef fish habitats and migration corridors between shallow and deeper reefs (Moura et al., 2021; Anderson et al., 2023), functioning as a migration matrix linking shallow coastal reefs and mesophotic ones (Santos et al., 2023). The shelf-edge reefs are also very important for maintaining reef fish diversity, life cycles, and are essential for supporting multi-species fisheries (Olavo et al., 2011). Available data on the spatial distribution of reef fish spawning aggregations corroborates the importance of rhodolith beds, slopes, and mesophotic reefs for reef fish species reproduction in the Abrolhos Seascape (Bezerra et al., 2021; Freitas et al., 2011), highlighting their importance for conservation.

The offshore banks and seamounts of the Vitória-Trindade chain are also key for biodiversity conservation in the region (Guabiroba et al., 2022; Meirelles et al., 2015; Pinheiro et al., 2015). They function as stepping stones for reef fishes between mainland and the oceanic islands of Trindade and Martim Vaz, thus shaping patterns of speciation (Pinheiro et al., 2017).

The maps of biological richness (Figure 4) and richness of threatened species (Figure 5) highlight the importance of shallow and mesophotic reefs, as well as rhodolith beds for concentrating biodiversity. However, it is worth noting that the analysis method for these maps disregards the higher relative importance of species with restricted distribution, such as species that occur exclusively in the Vitória-Trindade Seamount Chain. The relative importance of the seamount tops is highlighted in the final map of this study, generated using the weighted endemism method for all species (Figure 6).

The biodiversity hotspot analysis (Figure 6) shows that areas of highest biological importance in the Abrolhos Seascape are concentrated in the shallowest parts of the continental shelf and in the seamounts of the Vitória-Trindade Seamount Chain. By considering the upper 90th quantile of the most biologically important planning units (class 10 on Figure 6) - equivalent to 1.25% of the total study area - it represents the occurrence of all species analyzed in this effort. Near 85% of these species have more than 10% of their estimated area of occurrence in the study area within this hotspot. This upper biodiversity class represents a conservative delimitation of a biodiversity hotspot in Abrolhos, considering the definition adopted by other marine studies that considered the upper 2.5-5.0% biodiversity richest areas as biodiversity hotspots (Jefferson and Costello, 2020).

This hotspot includes 87% of the shallow reefs, 60% of the estuaries, 36% of the mesophotic reefs, 15% of the soft bottoms, 12% of mangroves, as well as smaller areas of rhodoliths, deep reefs and slopes (Table SI2). The only shallow habitats not represented in this hotspot are the *buracas* that occur in classes 5 to 9. These cover a relatively small area in the Abrolhos bank and would require specific attention in a conservation strategy.

The class 10 hotspot has relatively high representation in the current MPA network (35% - Figure 7) in the Abrolhos Bank, but remains unprotected in the Royal Charlotte Bank and the Vitória-Trindade Chain (Figure 6). It is important to note that only 9% of the area is under no-take protection, and part of the present multiple use MPAs covering shallow habitats in the region have had no implementation since their creation in the 1990s (e.g., Ponta da Baleia/Abrolhos State Environmental Protected Area), leaving these areas virtually unprotected.

The biodiversity importance of the Abrolhos Bank shallow reefs has been known for decades (Dutra et al., 2006; Leão, 1982, 2002; Leão et al., 2003) and has driven the creation of the Abrolhos National Park in the 1980s (Mazzillo, 2005). Despite being less investigated compared to the Abrolhos Bank reefs, recent inventories confirm the ecological importance of both, the Royal Charlotte Bank (Negrão et al., 2021) and the Vitória-Trindade Chain (Guabiroba et al., 2022; Meirelles et al., 2015; Pereira-Filho et al., 2012; Pinheiro et al., 2015), strengthening the importance of protecting these areas.

On the other hand, the lower importance classes (1 to 4 – Figure 6) also have a high percentage of protection (58.5% - Figure 7), which is due to the presence of the mosaic of protected areas of Trindade, Martin Vaz, and Columbia Seamount, which comprises mainly deep oceanic habitats. These are also the least known areas of the seascape, highlighting the mismatch between comprehensive conservation planning and action in Brazil (Giglio et al., 2018; Magris and Pressey, 2018). It is also concerning that the Classes 5 to 9 are underrepresented in the current MPA network (Figure 7) as they concentrate high biodiversity, particularly of threatened species, in mesophotic reefs, rhodolith beds, *buracas*, and slopes (Figures 4 and 5).

This work paves the pathway for refinement of the biodiversity conservation component of the Priority Areas and Actions for Biodiversity Conservation, Sustainable Use, and Benefit Sharing of Brazilian Biodiversity (MMA, 2018). For example, in the Biological Importance map of this National effort, there is no differentiation in importance among continental shelf habitats in the Abrolhos Region and Vitória-Trindade Seamount Chain, which are all classified as of “Extremely High Biological Importance.” Thus, the upper classes of biological importance represented here (Figure 6) are equivalent to a subdivision of the “Extremely High Biological Importance” class of the national effort and should not be viewed as downgraded in importance.

By comparing results from this study with data about the main human uses in the region (Marchioro et al., 2005; Teixeira et al., 2018), there are clear overlaps between biologically important areas and potentially degrading human activities. The first clear overlay is with fisheries, which are concentrated on the shelf, including reef and sediment domain habitats (Teixeira et al., 2018). Some fishing communities have organized and requested the creation of sustainable use MPAs such as Extractive Reserves for improving the sustainable management of their fishing areas (Dutra et al., 2012; Moura et al., 2009), but most fishermen operate in open access areas. A well-designed MPA network has the potential to improve fisheries (Di Lorenzo et al., 2020; Fontoura et al., 2022; Green et al., 2014), but previous processes for expanding MPAs in the region have faced conflicts with this sector (Teixeira et al., 2018). Improvements to the design of the MPA network in Abrolhos to protect biodiversity, fisheries, and other compatible uses are needed, as well as a broader understanding about the potential benefits of the network to local communities (Dutra et al., 2012).

Previous efforts for the spatial compilation of biodiversity and geological data had important roles in avoiding the uncontrolled expansion of economic activities in the region, such as oil and gas exploitation and shrimp farming (Dutra et al., 2012; Marchioro et al., 2005). The expansion of these activities was avoided, creating better conditions for conservation and sustainable development in the region, favoring activities such as fisheries and tourism that can be planned to be compatible with biodiversity conservation (Dutra et al., 2012).

This study provides an updated and comprehensive contribution to the biodiversity conservation of the Abrolhos Seascape. Both the analysis of habitat representativeness and the species analysis show that there are important gaps in the current MPA network in the region. As a next step, we recommend adding information on current uses in the region, providing analysis of costs and opportunities, as well as information on biological connectivity and resilience to climate change for advancing a systematic conservation planning process in the Abrolhos Seascape.

This effort and similar approaches can qualify decision-making processes, sharing updated information at the adequate scale for advancing marine conservation, and can serve as baseline information for the ecosystem-based Marine Spatial Planning effort Brazil will be implementing in the following years.

CONCLUSION

Identifying hotspots of biologically rich, endemic, and threatened biodiversity is crucial for implementing adequate and effective conservation strategies in the Abrolhos Seascape and elsewhere. By mapping distribution areas of various groups of marine organisms and analyzing them in a unified approach, we were able to identify biodiversity hotspots that deserve attention in conservation policy and planning for the Abrolhos Seascape. Of particular importance are several key habitats that aggregate biodiversity and promote connectivity within the seascape that are currently poorly protected: shallow and mesophotic reefs and rhodolith beds of the Royal Charlotte Bank and Vitória-Trindade Seamount Chain, as well as mesophotic reefs, rhodolith beds, *buracas*, and slopes in the Abrolhos Bank. Our findings support decision-making in designing marine protected areas and other conservation measures, emphasizing the urgent need for protection actions to achieve effective biodiversity conservation and maintain ecosystem services in the Abrolhos Seascape.

Data availability statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Supplementary material

Supplementary data for this article is composed of:

Table SI1. Proportion of protection of the different habitat classes within the marine protected areas in the Abrolhos Seascape.

Table SI2. Total area and proportion of protection of the different biological importance classes in the Abrolhos Seascape.

Table SI3. Synthesis of the biological importance classes and respective percentages within marine protected areas of no-take, multiple use and areas with no protection in the Abrolhos Seascape.

It can be found online at Zenodo: https://doi.org/10.5281/zenodo.15318736

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Author contributions

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B.H.C.: Conceptualization; Methodology; Data collection and analysis; Writing - review and editing; Supervision.

A.S.: Data collection and analysis; Writing - original draft preparation; Writing - review and editing.

M.I.G.M.: Methodology; Data collection and analysis; Writing - review and editing.

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Conflicts of interest

The authors have no relevant financial or non-financial interests to disclose.

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