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Nature as a solution for shoreline protection against coastal risks associated with ongoing sea-level rise

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ABSTRACT

The risks from climate change are ever-growing, especially in more vulnerable and exposed regions such as coastlines. The rise in sea level and increase in the frequency and intensity of climate-induced coastal hazards are threatening the increasing coastal populations. Brazil, with its 8,500 km of coast, is one of the countries most at risk from coastal flooding and erosion. Nature-based solutions have been suggested as climate adaptation strategies with the greatest potential to counteract coastal hazards stemming from sea-level rise and safeguard coastal cities. However, there is still a knowledge gap in the scientific literature on the effectiveness of nature-based solutions, especially at large spatial scales in Central and South America. Here, we assessed the risks from climate-induced hazards of coastal erosion and flooding related to sea-level rise on the Brazilian coast, and the effectiveness of nature-based solutions as climate adaptation strategies. We reveal that nature-based shoreline protection can reduce by 2.5 times the risks to the Brazilian coastline. The loss of existing natural habitats would substantially increase the area and population at risk from these climate-induced hazards. Worrisomely, legal mechanisms to protect these natural habitats are few and being weakened. Only 10% of the coastal natural habitats are within protected areas, and these alone do not ensure coastal protection, as our results indicate that the loss of unprotected natural habitats has about the same risk as the total absence of natural habitats. Our results warn of the severe consequences of the continued loss of natural habitats along the coast. Thus, actions towards the maintenance and protection of coastal habitats are paramount for climate adaptation and to ensure the well-being and livelihoods of coastal populations. Brazil has a central role in demonstrating the benefits of strategies based on nature-based solutions for shoreline protection, favoring their implementation worldwide. We provide both the natural habitat maps and the maps with model results with spatial and numerical information so readers can explore the relations between the natural habitats and coastal risk indexes at a subnational level and foster their use by local stakeholders.

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1. Introduction

Climate change is an ever-growing risk to society, with the possibility of an increase of 3–4 degrees C or more above pre-industrial levels in the worst scenarios, resulting in substantial sea level rise (IPCC 2021, Strauss et al., 2021). Global mean sea level will continue to rise over the 21st century, reaching between 0.28 and 0.55 m in a very low greenhouse gasses scenario (SSP1-1.9) up to 0.63–1.01 m in a very high scenario (SSP5-8.5), which will transform coastlines worldwide (see IPCC 2021). Alongside the rise in sea level, an increase in the frequency and severity of extreme climate-induced hazards such as coastal flooding, erosion, and storm surges is also expected (Vousdoukas et al., 2018; Portner et al., 2022). For example, predictions suggest that extreme events that usually occur once per century will become at least yearly frequent in half of the world's coastlines by the end of the century (IPCC 2021). The typically high concentration of people along the coasts increases their exposure. Globally, an additional 2 billion people living i n coastal regions is expected in the next 30 years, possibly peaking at ca. 11 billion in 2100 (UN 2022). Notably, such an increase in global coastal population means that 1 billion people in coastal low-lying cities will face escalating risks from climate-induced hazards by mid-century (Pörtner et al., 2022).

Although the predictions for the future suggest a worrisome growth in risk to coastal populations, the global sea level has already risen by 15–25 cm, on average, with the highest rates of increase being recorded in the last couple of decades (IPCC 2021). The hazards from sea level rise that are already being imposed upon coastal communities reveal the high risk to natural, social and economic scopes of society. Worrisomely, predictions indicate that if the sea level rises a further 15 cm in addition to the current 2020 sea levels, the population potentially exposed to severe extreme events that occur once per century will increase by 20% (and will double if the rise reaches 75 cm, Pörtner et al., 2022). The current and upcoming risks require urgent adaptation strategies to increase shoreline protection.

These adaptation strategies have far lower costs than the economic and social damage of no action facing climate change (e.g. Tamura et al., 2019). Although gray infrastructure has been widely implemented worldwide, nature-based solutions (hereafter NbS) are the strategies with greater potential for coastal protection (Manes et al., 2022b; Pörtner et al., 2021; Morris et al., 2020; Silver et al., 2019; Morris et al., 2018; Forgiarini et al., 2019; Temmerman et al., 2013; Arkema et al., 2013). The presence of natural habitats, such as mangroves and coral reefs, may reduce climate-induced coastal hazards such as storm-induced erosion and flooding, attenuating storm surge and wave power and reducing the need for a coastal retreat with the population moving inland in response to rising sea levels (Morris et al., 2018; Forgiarini et al., 2019, Costanza et al., 2021; Eliff and Silva 2017). Natural habitats provide relatively sheltered areas along the shore, being important contributors to a more climate-resilient coast and essential cost-effective shoreline protection tools (Morris et al., 2020; Ferrario et al., 2014). Thus, NbS strategies capable of ensuring the permanence of a diverse composition of natural habitats enable nature-based coastal defense, protecting people and assets against climate change (Costa et al., 2016).

The outstanding risks call for urgent adaptation measures to reduce the damage to coastal human populations, infrastructure, and economic activities. Studies on nature's contribution to shoreline protection are increasing in the scientific literature, although mainly under local scales and in the Global North (e.g. Salgado and Martinez 2017; Feagin et al., 2019; Storlazzi et al., 2017). Thus, despite growing evidence on nature's potential as a timely solution to buffer climate change risks, there is a knowledge gap on NbS′ effectiveness, especially in Central and South America's coastal cities (Castellanos et al., 2022). Thus, here we assess the contribution of the persistence of natural habitats for coastal protection and the increase in risks stemming from their loss. We use the Brazilian coast as a case study, since Brazil is a protagonist i n risks to Central and South America (PBMC 2016), due to continental-scale coastal proportions and high population increases, predicted to reach 230 million people by 2050 (UN 2022). Indeed, Brazil has been identified to be among the countries with the highest extent of coastal floods and the highest proportion of the population exposed to climate change if adaptation measures are not implemented (Tamura et al., 2019; Strauss et al., 2021). Local studies in Brazil have already identified the potential of specific natural habitats in reducing overall coastal vulnerability (e.g. Forgiarini et al., 2019 for dunes; Eliff and Kikuchi 2017, Siegle and Costa 2017 for coral reefs). However, no study to date has identified nature's contribution to coastal adaptation at large national scales. By identifying the power of NbS in its continental-scale natural coastal assets, Brazil can have a prominent role in fostering nature-based shoreline protection worldwide (Xavier et al., 2022). We provide evidence that the existing natural habitats along the Brazilian coast are paramount for shoreline protection, with a substantial increase in risks upon their loss. We discuss the implications of policies that enhance the conservation of these habitats and those that threaten their persistence.

2. Methods

2.1. Study area: Brazilian natural habitats

Brazil has six terrestrial biomes, all except for one reaching its 8,500 km of coast. On the continental coast, the Atlantic Forest takes up almost half of the coastline (45.1%), followed by the Pampa grasslands (24.2%), the Amazon rainforest (17%), the Caatinga shrubland (10.4%) and the Cerrado savannas (only 3.3%). Recently, the Brazilian Institute of Geography and Statistics (IBGE) has included the Coastal-Marine System as a designated environmental region within national maps, recognizing the importance of these areas (IBGE 2019). The marine portion of the Brazilian Coastal-Marine System falls within the 200 miles outward of the coastline for the Exclusive Economic Zone (IBGE 2019), whereas the terrestrial portion of the Coastal-Marine System (1.7% of the Brazilian territory) comprehends coastal ecosystems delimited by their vegetation, geology, geomorphology and soil type, and overlaps the limits of terrestrial biomes (e.g. mangroves belong both to the Coastal-Marine System and also to the original terrestrial biome, IBGE 2019). The coastline, both in the coastal and marine portions, is composed of many ecosystems, which include a variety of natural habitats such as coastal forests, mangroves, wetlands, sand-dune shrublands (locally known as *restingas*), grasslands, dunes, rocky shores, coral reefs among others (Mapbiomas 2022). These diverse ecosystems, in the transition between land and sea, provide habitat and refuge for thousands of species, and economic and social benefits for local communities.

The coast of the Amazon, in the north, is covered mainly by rainforests, mangroves, and grasslands (Mapbiomas 2022), plus some localized deepwater coral reefs (Moura et al., 2016). Cerrado and Caatinga, in the northeast, also have mangroves but are mostly covered by sandy beaches and associated *restingas* (Mapbiomas 2022), plus the largest coral reefs in the Southern Atlantic Ocean (Werner et al., 2010). The Atlantic Forest, in the southeast, is the most extensive biome along the coast and, thus, very heterogeneous, being covered mostly by sandy beaches and *restingas*, with some spots of mangroves, rainforests, and rocky shores (Mapbiomas 2022). Finally, the Pampa, the southernmost biome, is covered by beaches, dunes, and lagoons with wetlands (mostly salt marshes) (Mapbiomas 2022).

According to the most recent Demographic Census (2010) about 26.6% of the population lives in cities in the coastal zone of Brazil, which occupies only 4.1% of the Brazilian territory. A significant part of this population is engaged in activities directly or indirectly linked to tourism, oil and natural gas production, fishing, and services that meet the economic dynamics generated by cities close to the coastal zone (IBGE 2010). The highest rates of coastal population and urbanization are found in the Southeast region, followed by the Northeast, South, and finally the North region of Brazil (IBGE, 2010). The Southern region has the highest per capita income (US$ 320.32), followed by the Southeast region (US$ 318.19), the North (US$ 168.48), and finally, the Northeast (US$ 163.06) (IBGE, 2021).

Climate change impacts can already be observed o n the Brazilian coast, including a sea-level rise of more than 15 cm in 20 years o n the Amazon coast (between 1993 and 2015; ESA 2017). Aside from the current sea-level rise observed o n the coast, predictions indicate future further sea-level rise, changes in wind and wave climates, an increase in the frequency of extreme events and in temperature (PBMC 2016). Particularly, the sea-level is predicted to rise in future scenarios by an average of 40–80 cm by 2100 (SSP1-1.9 and SSP5-8.5, respectively) by 2100 (IPCC 2021). Although the sea-level rise is predicted to rise somewhat homogeneously all along the coast (IPCC 2021), higher increases in waves and tides are predicted for the South and Southeast regions, likely promot ing coastal erosion and flooding (PBMC 2016). A higher probability of flooding can be expected in areas that present more than 40% of changes in sea-level observed in the last 60 years – as is the case of several Brazilian coastal cities (PBMC 2016). Thus, some important cities on the Brazilian coast, such as Fortaleza (Northeast), Florianópolis, and Balneário Camboriú (South), have already invested in projects to widen the sand strip of their beaches to reduce coastal erosion. Other coastal protection undertakings such as sea piers and breakwaters have also been implemented with the same goal (PBMC 2016).

2.2. Defining coastal risks

We used the Coastal Vulnerability model from the Integrated Valuation of Ecosystem Services and Trade-offs software (InVEST) to assess the risk to the Brazilian coast (following Arkema et al., 2013; Silver et al., 2019; Zamboni et al., 2022). InVEST is a software suite widely used to map and assess ecosystem services (Sharp et al., 2020). The Coastal Vulnerability model generates a risk index along the coastline based on six biophysical factors: wind speed, wave power, surge potential, relief, sea-level rise, and degree of protection provided by natural habitats. For wind speed and wave power, the model ranks coastlines by their relative risk to wind speed and storm waves, as they can increase coastal erosion and inundation surges. Global data for both wind speed and wave height were provided in the InVEST model database, obtained from WaveWatch III developed by National Oceanic and Atmospheric Administration/National Centers for Environmental Predictions (NOAA/NCEP) (Tolman 2009). Wave power is also influenced by water depth, calculated from bathymetry. Shallower waters with stronger wind are more prone to higher storm surge elevation in waves (i.e. greater storm surge potential). Thus, the model ranks the relative risk to surge potential along the coast based on their distance to the continental shelf, i.e. larger distances between the coast and the edge of the continental shelf lead to greater estimated risk. We used bathymetry and continental shelf limits from the national marine database (Geological Survey of Brazil, CPRM; http://www.cprm.gov.br/; Fig. S1). Additionally, coastlines that are in higher elevations (i.e. further from mean sea level) are more sheltered than low lands. Thus, the model ranks shorelines by their relative elevation based on relief data. We used Brazilian digital elevation models (DEM) as input for relief data (Weber et al., 2004; Fig. S1). Finally, we used the local mean sea level rise trends between 1993 and 2015 to compare regions that are already more at risk by increased sea levels (ESA 2017; Fig. S1). It is important to note that here we use the most updated terminology and concepts from the Intergovernmental Panel on Climate Change (IPCC 2013; IPCC 2021) for 'risk', 'vulnerability', 'exposure', and 'hazard' (see Foden et al., 2018 and Pörtner et al., 2022 for more details), as opposed to the terminology used in InVEST's Coastal Vulnerability model, which is based on IPCC (2007).

The model generates several points along the Brazilian coastline at 1 km from each other (i.e. 1 km resolution), resulting in 11,821 points for the entire coast. For each point, the model extracts the value of each variable and these are comparatively converted into relative risk scores based on the full range of values. Thus, each variable is classified into relative degrees (scores) of risk to coastal flood and erosion from 1 (lowest risk) to 5 (highest risk). To assign these scores to each point, the range of values from each variable is divided into 5 percentiles, where each percentile represents a degree of risk. For example, higher values of wind speed and wave power lead to greater risk, and shorter distances from the coast to the continental shelf can lead to greater surge potential. Similarly, higher values of observed sea level rise indicate areas that are already more at risk. Thus, between the 0–20 percentile values of wind speed, wave power, surge potential, and sea level rise are classified as the lowest risk (score 1) and values between 80 and 100 percentile are classified as the highest risk (score 5) (Table S1). The contrary is true for relief values, where the highest values mean that the coastline is more sheltered when compared to lowland areas. Thus, for relief, the 80–100 percentile values represent the lowest risk scores (Table S1).

Lastly, beyond the physical variables, the model incorporates the degree of protection from natural habitats to assess the risk to the coastline. Because some natural habitats provide more protection than others, they receive different risk scores. Natural habitats with the highest protection, and thus lowest risk include coastal forests, mangroves, and coral reefs, whereas the highest risk index is assigned to areas without any natural habitats. Additionally, different natural habitats can protect greater distances than others. Thus, we also included estimates on the protection distance provided by each natural habitat identified for the Brazilian coast (see Table S2 for risk scores and protection distances for all natural habitats). We obtained maps for the natural habitats from Mapbiomas Collection 6 database for 2000 and 2020 (Mapbiomas, 2022) and the global database Allen Coral Atlas, updated in 2021 (https://allencoralatlas.org/atlas/#4.04/-9.5786/-39.0672) (Table S2). In the end, the model generates a risk index using all scores from each of the six biophysical variables calculating their geometric mean values (Sharp et al., 2020).

Although the model does not require data on population concentration to assess risk, we used a human population density map (average people per km2) for 2020 (CIESIN 2022) to highlight the areas with the greatest concentration of people potentially affected by coastal erosion, known as the "exposure" in climate change jargon (IPCC 2021). We compare the current risk indexes in these areas currently with the risk of the loss of natural habitats. All maps used in this work were adapted using ArcMap 10.5.

2.3. Assessing the benefits of nature-based solutions

The model outputs include a spatially explicit representation of coastal risk to climate-induced hazards of erosion and inundation and the role of natural habitats for coastal protection. Thus, to assess nature's role in coastal protection, we used the following scenarios: i) assuming that the last 20 years of degradation did not occur on coastal natural habitats to assess the protection lost with recent degradation, i.e. using the proportions of natural habitats from the year 2000 (except for coral reefs and seagrass, which were not available and thus we used their current proportions) (see the difference in proportions of natural habitats between both periods in Table S3, and an interactive map of both periods accessing https://plataforma.brasil.mapbiomas.org/, Mapbiomas 2022); ii) the current proportions of natural habitats along the Brazilian coastline for the year 2020; iii) assuming the continued degradation of natural habitats within all unprotected areas until only habitats in protected areas remain, and; iv) total absence of all natural habitats (i.e. the current natural habitats no longer provide coastal protection). We compared the risk indexes under these scenarios to calculate the benefits provided by natural habitats on the coastline and to identify regions that would be at greater risk from their loss. The maps for all-natural habitats used to run the model in all scenarios evaluated, and the coastal risk indexes generated in this work for each scenario are available in KMZ and shapefile format in the Supplementary Material.

We divided the resulting risk indexes into three categories, with areas with the lowest risk (overall risk indexes of 1–2.33), intermediate risk (overall risk indexes of 2.33–3.66), and highest risk (overall risk indexes of 3.66–5) (following Arkema et al., 2013). We compared the proportion of the coastline under each of the risk indexes.

2.4. Assessing the natural habitats' protection levels

We estimated the level of protection of natural habitats by overlaying the map of the Brazilian protected areas system from the Brazilian Ministry of Environment database (MMA 2022) with the map of natural habitats' to calculate the area of each habitat that is currently protected. Values were calculated using a 1 km buffer along the shoreline (except for the coral reefs, rock, and rubbles, and seagrass maps, which were used in their entirety). The Brazilian protected areas system is composed of Strictly Protected Areas (IUCN Categories I–IV) and Sustainable Use Protected Areas (IUCN Categories V–VI). The maps were processed and the areas were calculated using ArcMap 10.5.

Additionally, we also identified areas that are not currently protected but are priorities for conservation. We selected unprotected areas where risks are lowest under current conditions but, if lost, would be under intermediate and highest risks, which indicates the need for their protection.

3. Results

Our study shows that natural habitats provide important protection against climate-induced hazards along the Brazilian coastline. Under current conditions, i.e. with all currently remaining natural habitats, less than half of the Brazilian coastline is under the lowest risks (48% of the coastline, in 5,675 points along the coast). Most of the coast is currently at greater risk, under intermediate (47%) and highest (5%) risk indexes (Fig. 1, Fig. 2). In the absence of all-natural habitats, the coastline extension under the lowest risk would drop to only 19% (2,227 points), representing a loss of 2.5 times in coastal protection. There is also a large increase in the extent of the coastline under intermediate and highest risks to 64% and 17%, respectively (Fig. 2). Thus, the proportion of the coastline under intermediate to highest risks would rise from 52% to 81% in the absence of the current natural habitats.

The current risks to the coastline could have been much smaller if the recent loss of natural habitats in the last 20 years had not happened

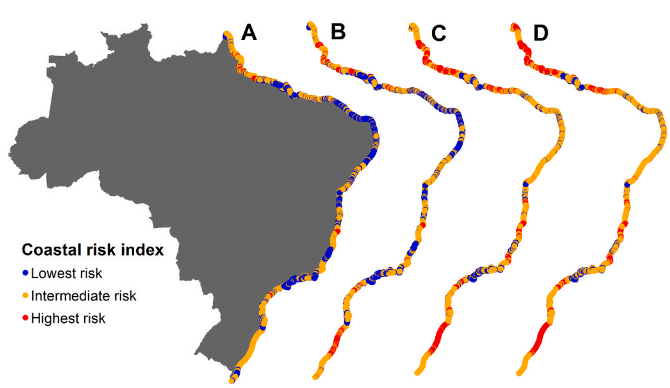

Fig. 1. Coastal risks along the Brazilian coastline under different configurations of natural habitats. Risks are shown for conditions A) without the degradation that happened in the last 20 years (i.e. using coastal natural habitats in 2000), B) under current extension of natural habitats (in 2020), C) with continued degradation until all natural habitats are lost, except for the ones currently within protected areas, and D) with the loss of all natural habitats along the coast. The coastal risk index varies 1 to 2.33 (highest risk), 2.34 to 3.66 (intermediate risk) and 3.67 to 5 (lowest risk).

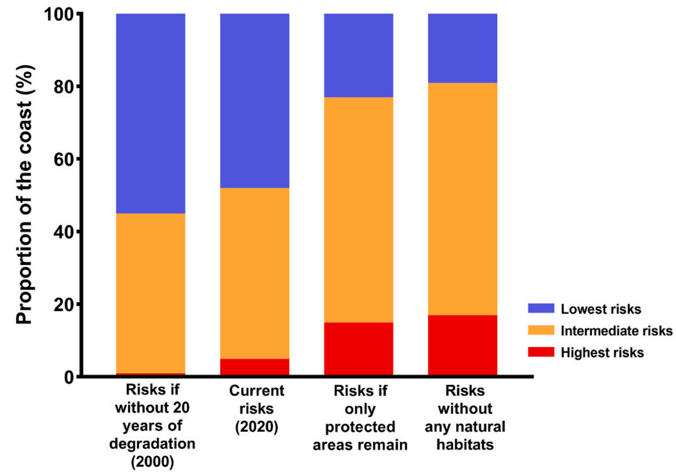

Fig. 2. Proportion of the coastline associated with different configurations of natural habitats. The figure shows the proportion of the Brazilian coastline under each risk category. Risks are shown for conditions A) without the degradation that happened in the last 20 years (i.e. using coastal natural habitats in 2000), B) under current extension of natural habitats (in 2020), C) with continued degradation until all natural habitats are lost, except for the ones currently within protected areas, and D) with the loss of all natural habitats along the coast. The coastal risk index varies 1 to 2.33 (highest risk), 2.34 to 3.66 (intermediate risk) and 3.67 to 5 (lowest risk).

(Figs. 1 and 2), which would increase the proportion of the coastline under the lowest risks to 55% (6,466 points, Fig. 2). Thus, as a consequence of the loss of these natural habitats, the proportion of areas under intermediate to highest risks increased from 45% to 52% (Fig. 2).

Most of the existing natural coastal habitats in the Brazilian coastline are currently unprotected, with only 10.4% within protected areas (mostly within areas of strict protection, IUCN categories I-IV; Table S4). The habitats with the greatest percentage of protection are beaches and dunes (30%) and wooded *restingas* (26%), whereas coral reefs are left with less than 2% protection (~2 km^2 protected; Table S4). Importantly, although mangroves are the natural habitats with the largest area o n the Brazilian coast (4,575 km^2), only 4.6% of them are currently protected (Table S4). Due to so little area protected, our results indicate that the natural habitat's persistence provided by the protected area network alone is insufficient to ensure shoreline protection (Fig. 1). If natural habitats are lost in all unprotected areas on the coastline, risks are very similar to their complete absence, with 77% and 81% of the coastline under intermediate to highest risks, respectively (Fig. 2). Thus, all regions with unprotected natural habitats that are currently under the lowest risks and that upon their loss would be under intermediate or highest risks were identified as priorities for conservation (Fig. 3). Such changes from lowest to intermediate or highest risk indexes reveal that the natural habitats alone are responsible for considerably reducing risks to a large portion of the coast (Fig. 3).

In the absence of natural habitats, the worsening of risk values occurs o n most of the coast. Most of the coastline (73%) will have its risk increased by 25–30% without the natural habitats (Fig. S2). Only 11% of the coastline would have no change in risks in the absence of natural habitats, and these areas are precisely the ones that are already at high risk (Fig. S2). Currently, the highest-risk regions are mainly located in the northernmost and southernmost regions of the country, in the southern Pampa biome and the northern Amazonian coast (Figs. 1 and 4). The Pampa biome, dominated by grasslands and sandbanks, is almost exclusively under intermediate and highest risks (Fig. 4). Contrastingly, although the Amazonian coast has a high cover of natural habitats, risks stem from high sea level rise, surge potential, and wind exposure (Fig. S3, Fig. 4). Nevertheless, the regions that are protected by large extents of natural habitats such as mangrove forests and coral reefs (e.g.

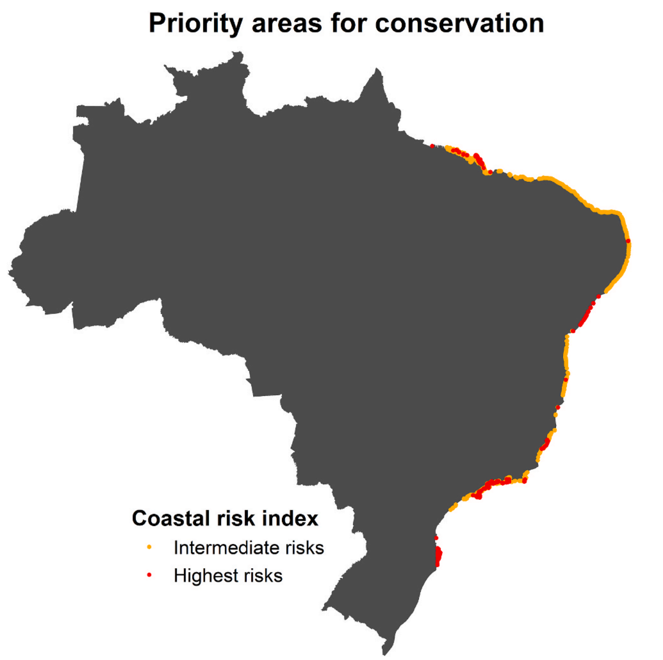

Fig. 3. Priority areas for conservation of natural habitats to ensure coastal protection. Figure shows areas that are under lowest risk under current conditions (year 2020), but with the loss of currently unprotected natural habitats will be under intermediate and highest risks. Because the natural habitats are ensuring the protection of these areas, they are considered priorities for conservation.

the Amazonian mangroves and the northern coral reef banks) are under the lowest risks (Fig. 4), but would severely suffer from the loss of these natural habitats (Fig. 1). The most populated regions in Brazil are currently mainly under the lowest and intermediate risks (Fig. 5C), but would also suffer from the loss of natural habitats leading to a substantial increase of areas under intermediate- and high-level risks (Fig. 5D).

4. Discussion

The pursuit of strategies to promote climate change adaptation is critical to ensure human well-being in coastal regions. Brazil, with its 8,500 km of coastline, has a central role in demonstrating the opportunities to design NbS and promote their implementation worldwide. Because the identification of areas under greater risk is key for decision-makers to plan for the future in a changing climate, we identified regions that most benefit from the protective service of natural habitats, and that would severely suffer from their loss. Our results demonstrate nature's contribution to shoreline protection by revealing a 2.5 times risk reduction to the Brazilian coast. Our results warn of the severe consequences stemming from the continued loss of coastal natural habitats, which substantially increases the amount of the coastal areas and population exposed to climate-induced hazards. Thus, actions towards the protection of these habitats considering the relationship between people and nature are imperative to ensure climate adaptation against coastal hazards and safeguard coastal human populations.

Notably, Brazil is likely among the countries with the highest concentration of people benefiting from nature-based coastal risk reduction worldwide (Ferrario et al., 2014). Indeed, the importance of NbS is being increasingly recognized in national policies such as the National Plan for Adaptation to Climate Change and the National Program for Coastline Conservation (Xavier et al., 2022). However, the loss of natural habitats in the last decades indicates that recognition 'in paper' has still limited practical application. In fact, the tides have been turning in a much opposite direction, with the natural habitats being increasingly threatened by the dismantling of environmental agencies' financing, infrastructure, and staff, or by actions that actively reduce their legal

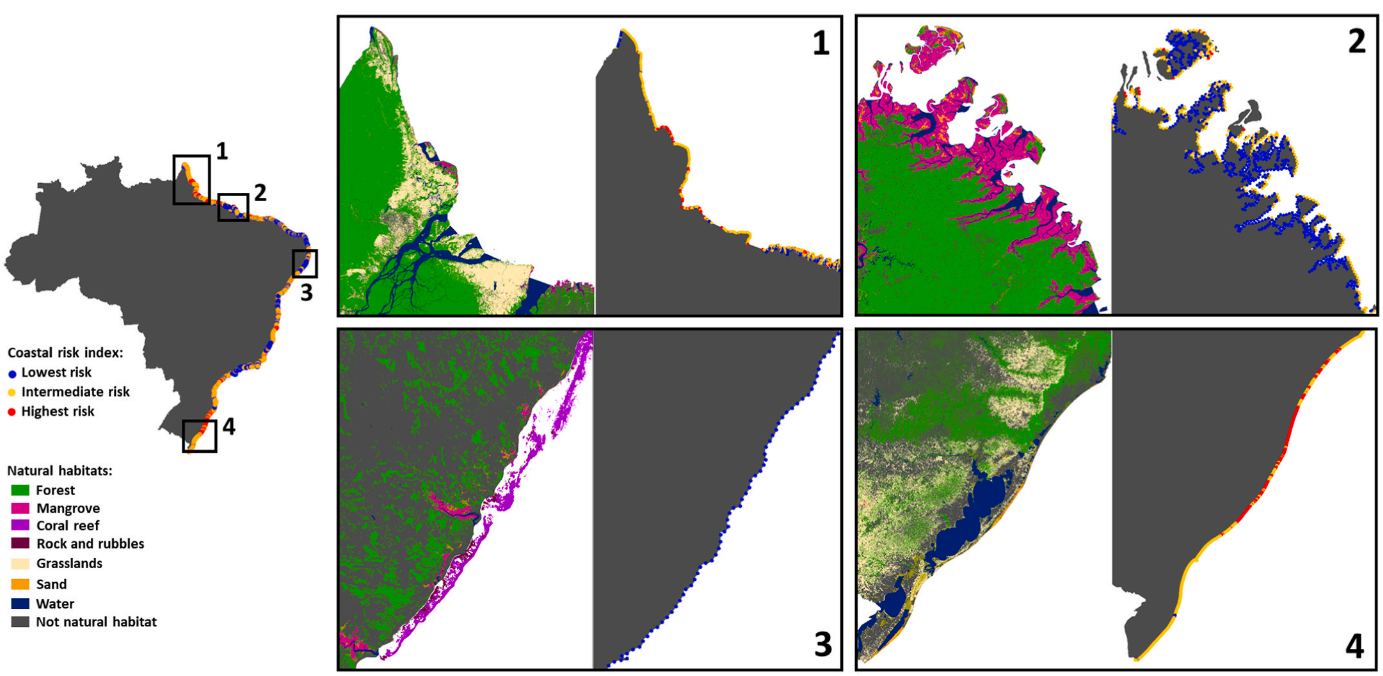

Fig. 4. Comparison between risk indexes and natural habitats on key areas along the coast. The four key regions are indicated with inset. For each key area, the map on the left shows current natural habitat and the map on the right shows the category of risk (blue = lowest, orange = intermediate, red = highest): 1) Amazon coast, with intermediate and high risk levels. Although the region is characterized by dense forest cover, the grasslands in the coastline and the high risk from the physical variables (Fig. S3) grants a high risk. 2) Amazonian mangroves. The region with highest mangrove cover in the coast is currently under the lowest risk levels. 3) Northeastern coral reefs. The region is protected by coral reefs, rocks and rubbles and coastal forests with mangroves. 4) Pampa biome. The region currently with the highest risk in the country. The region in the inset is mainly dominated by grasslands, sandbanks and urbanization.

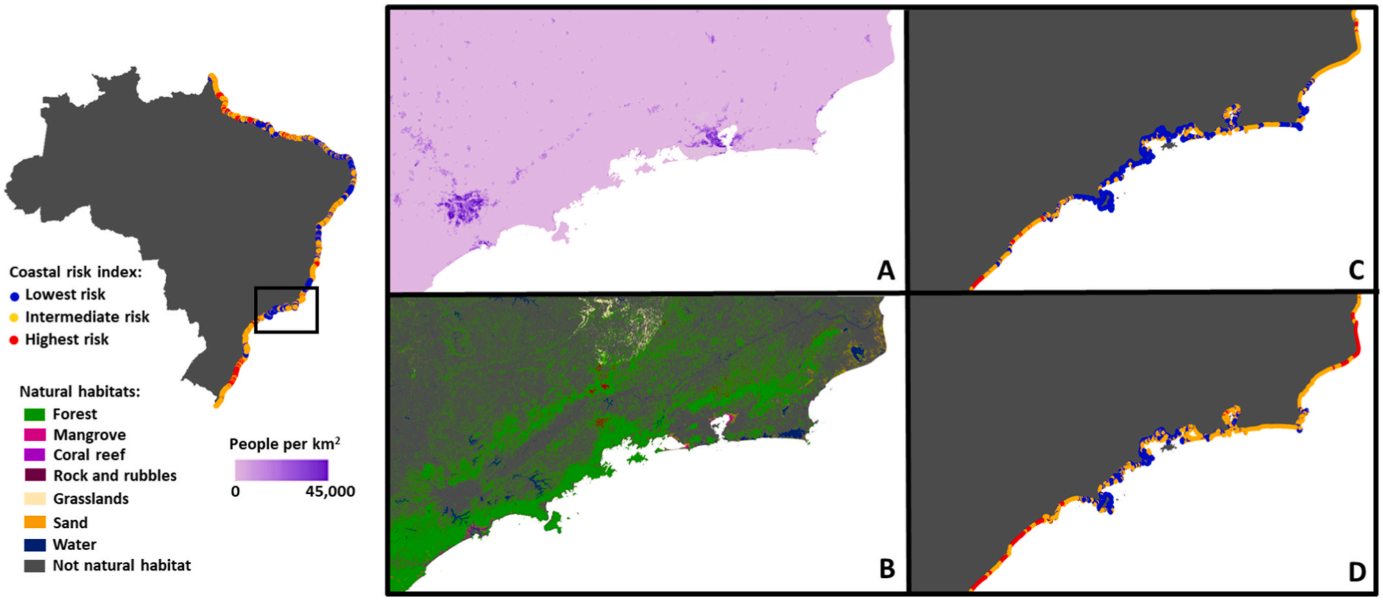

Fig. 5. Coastal risks for the most populated region in Brazil. A) Map showing the most populated regions in Brazil in 2020, the cities of Rio de Janeiro (RJ) and São Paulo. Source: Human population density map (average people per km^2) was obtained from the Center for International Earth Science Information Network for 2020 (CIESIN 2022). B) Natural habitats map. C) Coastal risks under current conditions (2020). D) Coastal risks in the absence of natural habitats.

protection status (e.g. Vale et al., 2021a; Barbosa et al., 2021). An example was the recent attempt by the Brazilian Ministry of the Environment to reduce the protection status of mangroves (Otonni et al., 2021; Vale et al., 2021a; Bezerra et al., 2022) placing 110,000 km^2 of mangroves at risk (Rosa and Azevedo 2020). After an intense mobilization by the scientific community and civil society, the change was finally reverted by the Brazilian Supreme Court in December 2021. This change would have been disastrous not only for the mangroves themselves but also for the people that depend on their key role in the maintenance of fisheries and attenuation of climate-related hazards (e.g. Ferreira and Lacerda 2016; Bernadino et al., 2021, Otonni et al., 2021). Thus, it is imperative to include the relationship between nature and its multiple stakeholders within decision-making on the coastal system, especially given the socioecological complexity of the land-sea interface (Gonçalves et al., 2021). Similarly, in 2020, the revocation of the law granting permanent protection of dunes and *restingas* is threatening the resilience of the Brazilian coastal region, allowing sprawl of real estate and urban infrastructure on these sand-dominated areas (CONAMA Resolution 303/2002; Soares et al., 2022). Our results highlight the importance of these and other coastal natural habitats, and the damage stemming from their loss. Thus, actions geared towards the protection and sustainable use of those habitats should increase, but the current administration seems to be going in the opposite direction, putting the people and assets on the Brazilian coast at risk.

While ecosystem degradation reduces the adaptive capacity of the coastline, the conservation of habitats, especially those providing greater risk reduction to climate-induced hazards, is imperative for the protection of people and infrastructure against sea-level rise (Arkema et al., 2013). Although the protected areas system has been key to safeguard ecosystems in Brazil, that protection is biased towards terrestrial and, to a lesser extent, marine environments (Jenkins et al., 2015; Schiavetti et al., 2013), mostly disregarding coastal ecosystems. Assuming continued unchecked degradation of ecosystems in Brazil, our results warn that the mere 10% of coastal natural habitats within protected areas would be insufficient to ensure shoreline protection. Thus, an expansion of the protected area system towards coastal habitats must be based on sound science and systematic conservation planning to optimize biodiversity conservation and shoreline protection (e.g. Magris et al., 2020; D'Arrigo et al., 2020). Instead, protected areas are often implemented opportunistically, usually in remote places and areas unsuitable for commercial activities, regardless of their value for biodiversity conservation (Margules and Pressey 2000), let alone the adaptation to climate change. In 2018, for example, Brazil sharply increased marine protected areas cover from 1.5 to 25% in a single move, by creating two very large protected areas around two remote oceanic islands, which was heavily criticized by the scientific community (Giglio et al., 2018; Silva 2019; Vilar and Joyeux 2021). As we have shown here, even with ~900,000 km^2, these areas fail to protect the natural habitats that ensure coastal adaptation. But creating new protected areas is not enough, as the lack of enforcement on existing protected areas reduces their effectiveness (Gray CLHill et al., 2016). For example, the National Native Vegetation Protection law mandates that all mangroves and *restingas* along the coast should be permanently protected (Brasil 2012), which is an important legal instrument for climate change adaptation and mitigation (Pinto and Voivodic 2021; Rezende et al., 2018). However, although protected 'on paper', they still endure large deforestation rates (Mapbiomas 2022). Thus, beyond increasing Brazil's protected areas on the coast, efforts must be made to enforce protection (Pacheco et al., 2018).

We identified priority regions for conservation all along the coastline, including highly urbanized and populated areas. D ensely populated areas have greater exposure to climate change, and, therefore, accounting for people and infrastructure is paramount for adaptation planning (Arkema et al., 2013). Although we did not explicitly include socio-economic factors in the analysis, we show that the loss of natural habitats would severely imperil the most populated regions in the country (e.g. Rio de Janeiro). The priority areas identified here often coincide with previously identified top priorities for biodiversity conservation nationwide (e.g. Magris et al., 2020; Chatwin 2007). Their protection, therefore, provides multiple potential benefits. On top of the protection of remaining natural habitats, habitat restoration could be a key complementary strategy to enhance nature-based climate adaptation (Manes et al., 2022a; Silver et al., 2019). This is particularly important for regions identified to be already at risk, associated with degraded or having little natural habitats left to ensure their protection. Further studies should assess the priorities for the restoration of such coastal natural habitats, considering the identified risks stemming from climate change to guide further action. Noteworthy, for some regions, neither protection nor reforestation of ecosystems would be effective to increase shoreline protection. This is the case for the Pampa biome, which naturally has lower-protection habitats such as grassland fields and salt marshes. For such cases where nature alone is not capable of counteracting risks that are already high, hybrid strategies with natural habitats alongside built infrastructure such as seawalls and elevating dikes can be considered to increase shoreline protection (e.g. Tamura et al., 2019; Strain et al., 2022).

Therefore, protecting and restoring lost and degraded natural habitats can be particularly important to increase their resilience to climate change systematically. Especially since the role of these natural habitats for climate change adaptation could be eventually undermined by climate change itself (Castellanos et al., 2022; Cooley et al., 2022). For instance, although coral reefs are the first line of defense, they are highly sensitive to ocean warming and acidification, which can, in turn, weaken their role as wave attenuators (Eliff and Silva 2017; Ferrario et al., 2014; Siegle and Costa 2017). Ever-growing risks are already leading natural habitats to reach (or even surpass) their hard adaptation limits, i.e. when risks are so great that they cannot be avoided by adaptation (Pörtner et al., 2022). Thus, together with the protection and restoration of habitats, climate mitigation is paramount to reducing the magnitude of climate change per se (Pörtner et al., 2021, Strauss et al., 2021), especially for tropical ecosystems (Manes and Vale 2022). Importantly, actions capable of addressing biodiversity loss and ecosystem degradation often simultaneously contribute to climate mitigation and adaptation (Shin et al., 2022).

To ensure that all these strategies will succeed to promote adaptation, it is pivotal to establish coastal governance and adaptive management as key instruments for integrating multiple stakeholders and conservation actions (Xavier et al., 2020). Understanding coastal habitats as socio-ecological systems, i.e. integrated systems with reciprocal feedbacks between people and nature, allows for the development of more holistic, integrative and participatory management and governance models (Xavier et al., 2020). In fact, to ensure that natural habitats work as nature-based solutions they must be able to provide social benefits for people (IUCN 2020). In this sense, 'ecosystem-based management' emerges as an integrated approach that expands traditional management strategies. This approach incorporates adaptive management, the use of scientific knowledge, stakeholders involvement, and the integration of human activities to ensure people's resilience and well-being (Long et al., 2015). These strategies can be particularly relevant for climate adaptation because they generally take place at regional and local levels and are based on social, political, financial, and environmental coastal assets (Celliers et al., 2020). Although there are still very few studies of ecosystem-based management in Brazil in comparison to increasing worldwide trends (Xavier et al., 2020), many of its core principles have been identified in the National Plan for Adaptation to Climate Change and the National Program for Coastline Conservation (Xavier et al., 2022). Our study contributes with key information needed for decision-making which can be used to guide further coastal governance and planning in coastal cities by identifying the role and promoting the engagement of multiple stakeholders in implementing NbS strategies to promote effective climate adaptation.

Here we provide the first nationwide study to reveal nature's outstanding contribution to coastal populations, in a country with one of the largest coasts in the Global South. We expect our work serves as a model for the assessment of nature's contribution to shoreline protection for other nations under similar conditions, and, given the scale of our analysis, it also provides valuable perspectives for biodiversity conservation globally. We provide evidence of the potential of nature's environmental, social, and economic contributions, which are foundational for advancing the Sustainable Development Goals (Wood et al., 2018). Importantly, nations should strive to recognize nature as an indispensable base for the achievement of these goals for sustainability on a global scale (Pires et al., 2021). Our results are particularly important since we are currently under the United Nations Decade of the Ocean (2021–2030), which aims at the sustainable development of the ocean based on adaptation and science-informed policy and governance (UNESCO-IOC 2021, 2022). These results also align with the Ocean Decade Challenge Five "Unlock ocean-based solutions to climate change" and Sustainable Development Goal (SDG) 14 "Life below water", where we contribute to a better understanding of the ocean-climate nexus. Addressing such knowledge gaps with innovative science focusing on ocean-based solutions is relevant for the 2030 Agenda and numerous global policy frameworks (UNESCO-IOC 2021, 2022). Thus, our work can both inform local governance and contribute to national and global societal goals. We show that to keep a safe environment for human and natural systems in coastal regions, we must cherish coastal natural habitats for their nature-based shoreline protection abilities for climate adaptation, and strive for their immediate protection, sustainable use, and recovery.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data used in this analysis has been made available in Supplementary Material

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2023.106487.

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