

POTENTIAL OF MANGROVE FORESTS FOR CLIMATE CHANGE MITIGATION AND ADAPTATION IN BRAZIL



**SIMA
CLIM**



The cover of this report was created by Simone Mendes

Simone Mendes is a visual artist who defines herself as a Designer of Feelings. Her work spans various languages, ranging from murals to delicate watercolors on cotton paper. Early in her career, she illustrated textbooks, children's books, and magazines for various publishers. Over time, she deepened her research into pictorial techniques and created the Watercolor Laboratory, a workshop focused on teaching watercolor painting, democratizing access to artistic practice. Her work reveals a poetic and sensitive gaze that seeks to translate emotions into shapes and colors.

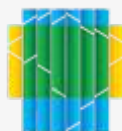




**SIMA
CLIM**

POTENTIAL OF MANGROVE FORESTS FOR CLIMATE CHANGE MITIGATION AND ADAPTATION IN BRAZIL

2025



Rede Clima
Mudanças Climáticas
Globais no Brasil



MINISTÉRIO DA
CIÊNCIA, TECNOLOGIA
E INOVAÇÃO



UNIÃO E RECONSTRUÇÃO

Synthesis Report:

Potential of Mangrove Forests for Climate Change Mitigation and Adaptation in Brazil

Coordinating Lead Authors:

Ângelo Fraga Bernardino (UFES)

Margareth da Silva Copertino (FURG)

Lead Authors:

Adriana Risuenho Leão (MMA)

Alessandra Larissa Fonseca (UFSC)

Andre Scarlate Rovai (Smithsonian Environmental Research Center, USA)

Clemente Coelho Junior (UPE)

Dan Friess (Tulane University, USA)

Francisco Carlos Rocha de Barros Junior (UFBA)

Gabriel Nuto Nóbrega (UFC)

Luiz Carlos Cotovicz Junior (UFPR)

Marcelo Cancela Lisboa Cohen (UFPA)

Paulo Roberto Pagliosa Alves (UFSC)

Tiago Osório Ferreira (USP)

Vanessa Hatje (UFBA)

Review Authors:

Luiz Drude de Lacerda (UFC)

Marília Cunha Lignon (UNESP)

Moacyr Cunha de Araujo Filho (UFPE)



**Dados Internacionais de Catalogação na Publicação (CIP)
(Câmara Brasileira do Livro, SP, Brasil)**

Brazilian mangroves as mitigation and adaptation solutions to climate change / [autores principais coordenadores Angelo F. Bernardino, Margareth Copertino]. -- 1. ed. -- Recife: Edições Saint Exupery, 2025. -- (Synthesis Report SIMACLIM ; 1)

Vários autores.

Bibliografia

ISBN 978-65-988223-2-3

1. Ecologia dos manguezais 2. Ecossistemas - Aspectos ambientais 3. Manguezais - Conservação 4. Manguezais - Ecologia 5. Meio ambiente - Conservação 6. Meio ambiente - Proteção 7. Mudanças climáticas - Aspectos socioambientais I. Bernardino, Angelo F.. II. Copertino, Margareth. III. Série.

25-290163

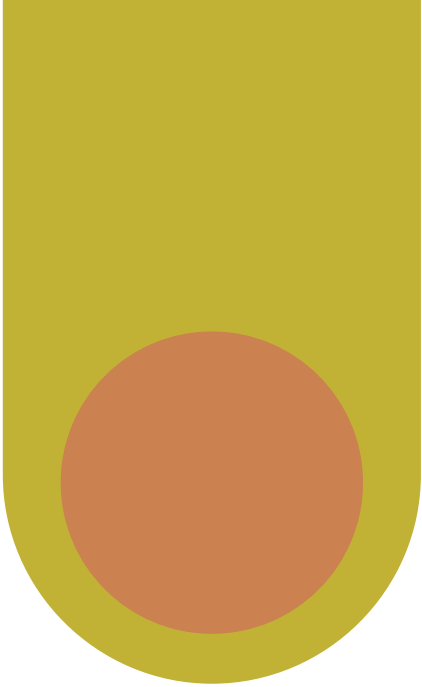
CDD-577.680981

Índices para catálogo sistemático:

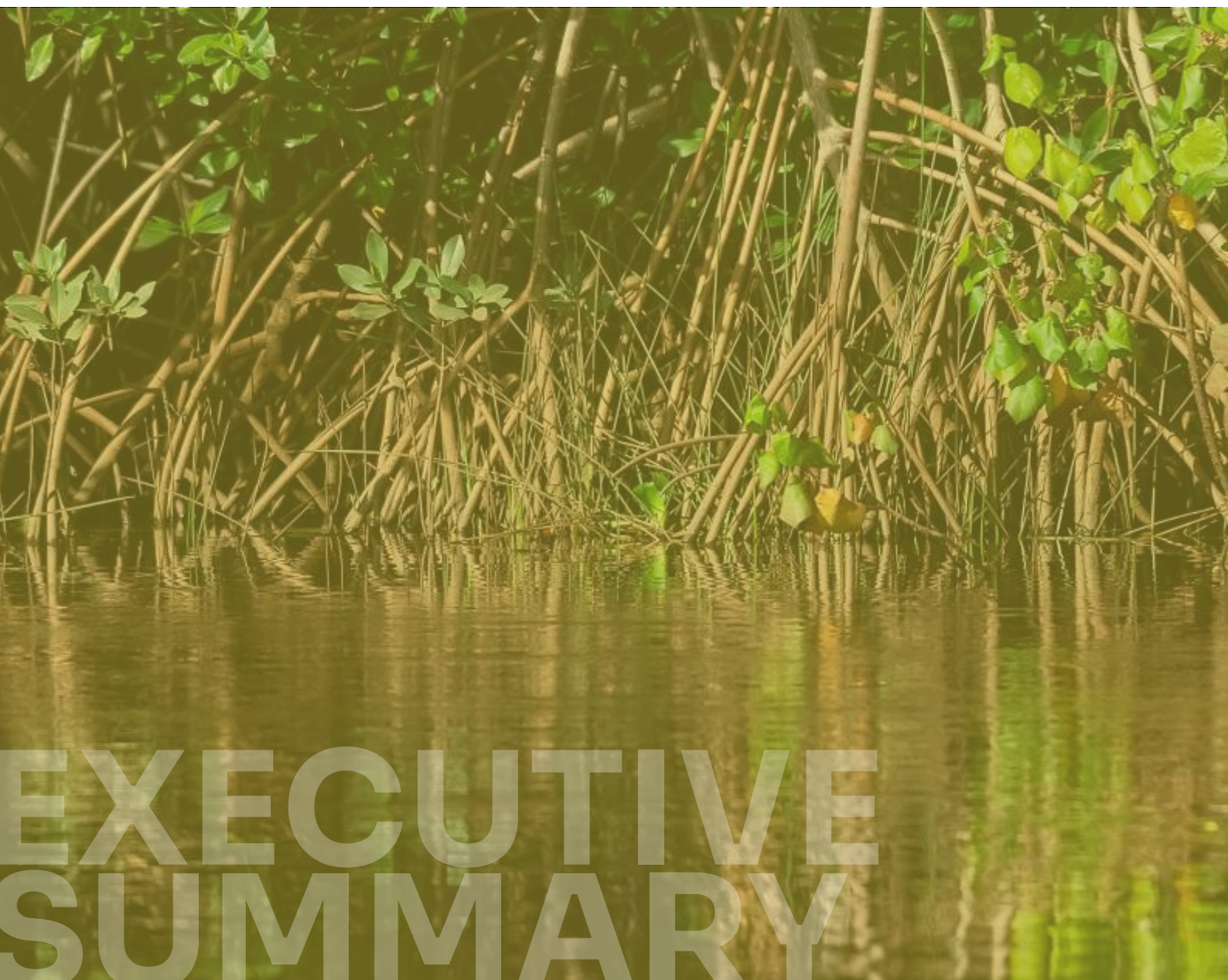
1. Manguezais brasileiros : Ecologia 577.680981
Maria Alice Ferreira - Bibliotecária - CRB-8/7964

SUMMARY

EXECUTIVE SUMMARY	5
1. INTRODUCTION	7
2. MANGROVES IN BRAZIL	12
3. ECOSYSTEM SERVICES: BENEFITS OF MANGROVES FOR SOCIETY	16
4. GEOCLIMATIC CONDITIONS, COASTAL TYPOLOGIES AND CARBON STOCKS	21
5. SOURCES AND SINKS OF GREENHOUSE GASES	25
6. MANGROVES CONNECTED TO THE COASTAL-MARINE LANDSCAPE	28
7. LOSSES AND THREATS	33
8. CLIMATE SCENARIOS AND THE FUTURE OF BRAZILIAN MANGROVES	37
9. POTENTIAL FOR RESTORATION	41
10. CARBON MARKET MODELS AND THE BRAZILIAN CONTEXT	46
11. PUBLIC POLICY	50
12. EDUCATION AND COMMUNICATION	54
13. PRIORITY THEMES AND ACTIONS	58
14. CONCLUSIONS	64
REFERENCES CITED	66



EXECUTIVE SUMMARY



EXECUTIVE
SUMMARY

EXECUTIVE SUMMARY

Brazil has the second largest expanse of mangrove forests on the planet (c.a. 1 million hectares), most of which are located within Conservation Units. Despite their relative successful preservation, Brazilian mangroves are being lost to various human pressures at a rate of approximately 0.1% per year (ca. 11,000 hectares per year).

During the last decade, there has been a fast advance in knowledge about the importance of Brazilian mangroves, highlighting natural services that benefit people's lives. These services include the provision of living resources in the form of food, coastal protection against climatic events, and their ability to remove carbon dioxide (CO₂) from the atmosphere and store it for hundreds to thousands of years. The latest evidence suggests that mangroves in Brazil accumulate around 4.5 million tons of carbon per year, and are forests that remove around 12 tons of equivalent CO₂ (CO₂eq) per hectare, making a limited but positive contribution to reducing the country's greenhouse gas emissions.

In the climate agenda and in international agreements, Brazil is ready to incorporate mangroves into mitigation measures in a similar way to the best practices being used around the world. This information allows mitigation of land use changes in Brazilian mangrove forests to be included in the national inventory of greenhouse gas emissions, as well as directing mitigation policies for the Brazilian coastal zone. The progress achieved also points to paths that must be followed to prevent setbacks in the protection of mangrove forests and supports the ProManguezal program towards the legal protection and valuation of mangroves for coastal communities. The limited data on mangrove restoration in Brazil indicates the need for regulatory advances to attract investments with the leadership of traditional communities, and integrated with the qualification of the population for participatory management in the territories. This synthesis shows that Brazil has a great opportunity to obtain resources through the conservation and restoration of mangroves, but it is necessary to establish regulatory models between the public and private sectors to attract international investment.

1

INTRODUCTION



1. INTRODUCTION

Mangroves are coastal ecosystems that occur in tropical and subtropical regions, occupying the intertidal zone of estuaries, deltas and coastal bays. Mangrove forests occur in regions flooded by a combination of salt and fresh water, subject to daily tidal oscillations and river flows. Because they occupy lowlands with frequent flooding cycles, mangroves are also classified as wetland ecosystems (Junk et al., 2014). Occupying the transition zone (ecotone) between continent and ocean, mangroves are among the most productive ecosystems on the planet and are recognized as important in the cycling of matter and nutrients (Alongi, 2002). High primary productivity results in large stocks of organic carbon in the biomass of trees and in the soil of mangroves, many times greater than that of continental forests. The accumulation of detritus and organic matter, coupled with the physical protection of the trees and soil, attracts a great abundance and diversity of marine and estuarine organisms, including fishery species that depend on the mangrove as part of their life cycle.

Brazil has the second largest mangrove area on the planet, with around 1.1 million hectares (11,414 km²), distributed along 23,110 km of coastline (taking into account all the estuaries and bays) between Amapá and Santa Catarina (Bunting et al., 2022). Around two thirds of these forests (over 750,000 hectares) are concentrated on the Amazon coast, in the states of Maranhão, Pará and Amapá. Considering the advanced state of degradation of mangrove forests around the world over the last 50 years, Brazil has been relatively successful in conserving these ecosystems, with around 90% of their extension located in a conservation unit (ICMBio, 2018). Approximately 85% of Brazilian mangroves have remained stable over the last 20 years, but around 9% of their area has been lost due to human activity, mainly shrimp aquaculture, urbanization and pasture conversion (Diniz et al. 2019; Bernardino et al., 2024a). This scenario reveals enforcement problems and legal gaps in its protection, as mangroves continue to be removed for the construction of highways, port expansion, the installation of shrimp farms, salt pans and pasture development, particularly in the transition to continental ecosystems (Ferreira & Lacerda, 2016; Hatje et al., 2016; Lacerda et al., 2022).

Mangrove forests expand and shrink as a result of natural cycles, including accretion and erosion of the coastline, and the effects of climate change. Given the current scenario, with rising sea levels and

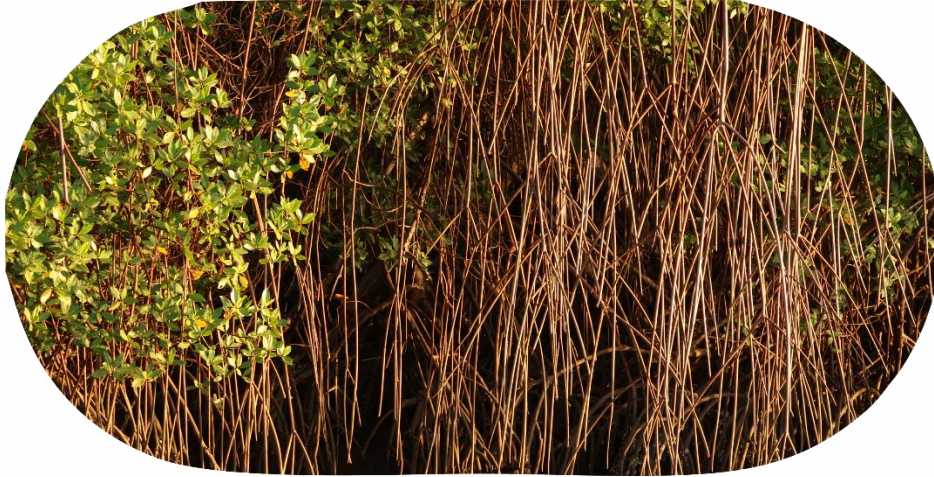


the intensification of extreme meteo-oceanographic events, mangrove forests are taking on an even more important role as physical barriers that protect the coastline from storm surges and wave energy (Alongi, 2002). As the sea advances, mangroves shrink along the coastline, but expand towards the mainland, as long as they are not impeded by anthropogenic or natural barriers. The conservation and restoration of mangroves to protect the coast are therefore fundamental as adaptation measures for Brazil's coastal cities, but also for the benefits they bring to the most vulnerable coastal populations. The continued provision of these services depends directly on the health of the forests and the state of conservation of the surrounding coastal ecosystems.

There has been remarkable progress in systematizing knowledge and valuing the numerous direct or indirect benefits that mangroves provide for coastal populations in the last decade (Barbier et al., 2010). These benefits, known as ecosystem services, include the provision of fishery and medicinal resources, water purification, coastal protection, climate regulation, as well as cultural practices and tourism (Spalding & Parrett, 2019; Owuor et al., 2024). The importance of mangroves for cities and coastal populations has stimulated conservation and restoration goals in several countries around the world, with the participation of governments and communities.

Mangroves are among the largest carbon sinks on the planet, contributing 10-15% of the carbon buried in coastal sediments (24 Tg C y⁻¹), exporting another 10-11% to the ocean (Alongi, 2020). This means that they are highly efficient at trapping carbon in soils for hundreds to thousands of years if left undisturbed, contributing directly to climate change mitigation. Recognizing the importance of this benefit, the term "blue carbon" was adopted to highlight this important role of mangroves alongside other vegetated coastal ecosystems, such as tidelands and seagrass meadows (Nellemann et al., 2009). Since then, studies on blue carbon have proliferated rapidly around the world, revealing the high density of organic carbon predominantly stored in the soils of these ecosystems (Kauffman et al., 2020). In Brazil, mangrove forests accumulate two to three times more organic carbon in their soil than the tropical terrestrial forests of the Amazon or the Atlantic Forest, and up to 10-fold more than other biomes such as the Caatinga or the Cerrado (Kauffman et al., 2018a; Rovai et al., 2022, Bernardino et al., 2024a).

However, as observed in other regions of the world, there is great spatial variability in carbon stocks in Brazilian mangrove soils, with numerous spatial gaps and methodological variability in estimates (Hatje et al., 2021; Hatje et al., 2023; Bernardino et al., 2024a).



If conserved, mangroves and other vegetated coastal ecosystems trap carbon for hundreds and even thousands of years. However, the loss or degradation of mangroves can turn these natural carbon sinks into sources of greenhouse gases (GHG). The first studies in Brazil have shown emissions of more than 1 ton of CO₂ per hectare of mangroves converted into shrimp farms or pastures in NE and Northern Brazil (Kauffman et al., 2018b; Bernardino et al., 2024a). When destroyed or degraded, the sequestration capacity of these forests is reduced or eliminated due to the loss of plant biomass and soils. Thus, preventing deforestation and soil degradation in mangroves is essential to avoid increasing CO₂ emissions into the atmosphere, which further intensify global warming. In addition, mangroves are "actionable" blue carbon ecosystems, as management and restoration actions can be implemented effectively. In addition to conservation, the restoration and rehabilitation of mangroves have the potential to generate additional carbon sequestration and/or avoid greenhouse gas emissions through the protection and recovery of these ecosystems (Bourgeois et al., 2024).

As a signatory of the Paris Agreement, which seeks to prevent the planet from warming to levels above 2°C, Brazil has clear climate targets that involve the agriculture and land use sectors. In its action plan, Brazil plans to zero deforestation in order to reduce GHG emissions associated with the loss of natural terrestrial forests in the Amazon, Cerrado, Caatinga, Pantanal, Pampas and Atlantic Forest



biomes. Therefore, preventing future losses and compensating for past losses is strategic to help Brazil achieve its emission reduction targets (Nationally Determined Contributions, NDC) within international climate agreements (Copertino, 2011, Bernardino et al., 2024a). The successful conservation and restoration of mangroves through blue carbon programs depends on scientific, political and financial aspects, but also on the involvement of coastal communities. Blue carbon projects therefore have the potential to promote environmental and social co-benefits while seeking to achieve climate mitigation goals.

The benefits provided by mangroves, particularly carbon sequestration and coastal protection, have placed these systems at the center of so-called **nature-based solutions (NbS)**¹, aiming for a more resilient future for the environment and society (IUCN, 2020). However, the enormous potential of mangroves as NBS requires solid ecological foundations, interdisciplinarity and the inclusion of traditional peoples in the production of knowledge (Lovelock et al. 2023).

To inform and assist public authorities, managers and Brazilian society, the Synthesis Center on Environmental and Climate Changes – SIMACLIM (<https://simaclim.com.br/>) created the working group on mangroves, with the aim of discussing and synthesizing current knowledge of these ecosystems, particularly in the context of climate change. This report synthesizes this knowledge, offering solid scientific bases for implementation of effective actions in climate adaptation and environmental conservation of mangrove forests. The document highlights the importance of Brazilian mangroves for the environment and for society, informing how these ecosystems can contribute to tackling the climate emergency and achieving national targets for reducing GHG emissions. It also highlights mechanisms to guarantee their conservation, the way of life and food security and climate resilience of coastal populations.

¹ Nature-based solutions (NBS) are initiatives that help protect, manage and restore natural environments, while providing and maintaining benefits for people (IUCN, 2020).

2

MANGROVES IN BRAZIL

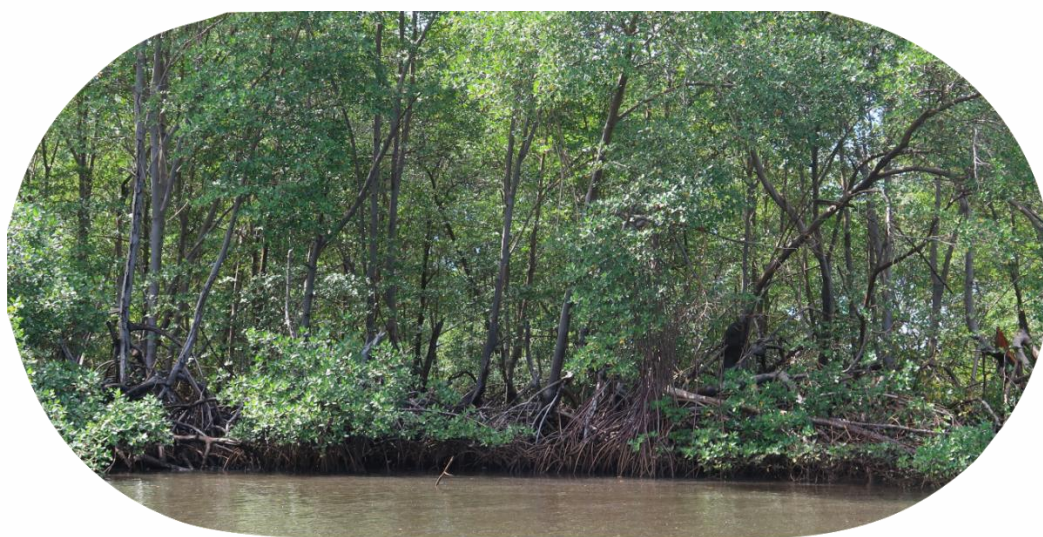


MANGROVES
IN BRAZIL

2. MANGROVES IN BRAZIL

Brazilian mangroves are distributed from Cape Orange (Amapá, 4°26' N) to the municipality of Laguna (Santa Catarina; 28°30'S), covering a wide range of climatic (precipitation and temperature), oceanographic, geological and geomorphological conditions (Schaeffer-Novelli et al., 1990; Lacerda et al., 2022). This results in variations in the structure and dynamics of the forest and the characteristics of its soils along the Brazilian coast (Schaeffer-Novelli et al., 1990). Different oceanographic, geological and climatic conditions influence the spatial distribution, the structure of the forest, the amount of plant biomass as well as the characteristics of mangrove soils (Bernardino et al., 2022; Ferreira et al., 2022). In addition to regional differences, Brazilian mangroves can be deltaic, estuarine, lagoonal, open coast and carbonate (Lana & Bernardino, 2018).

Due to the high variability of characteristics in the coastal zone, the Brazilian coast can be divided into five compartments (ICMBio, 2018). The Amazon Equatorial Coast (or Quaternary North Coast) runs from Cape Orange (AP) to Lençóis Maranhenses (MA), with climatic characteristics marked by a surplus of rainfall, with a humid tropical climate, with average rainfall of between 1,200 and 2,800 mm/year and temperatures ranging between 24 and 27°C.



In this segment, subject to a macrotidal regime (daily amplitudes between 4 and 8 metres), the largest mangrove trees in the country are found, colonized by plant species that can reach 30 m in height, and influenced by the meeting of large rivers (Oiapoque, Caciporé and



Amazonas) with the Tropical Atlantic Ocean. In this segment, the mangroves are often low in salinity (between 0 and 7), especially in the western portion of the Amazon River, where there is a mixture of mangroves and floodplain vegetation (Bernardino et al., 2022).

In the more brackish portions (salinities between 5–18) east of the mouth of the Amazon River, the mangroves are dominated by species such as *Rhizophora mangle*, *Avicennia* spp. and *Laguncularia racemosa*, and this is the segment of the Brazilian coast with the highest carbon stock in the aerial biomass (Kauffman et al., 2018a).

The Northeast Coast or Semi-Arid Northeast Coast stretches from the Lençóis Maranhenses National Park (MA) to the border between Rio Grande do Norte and Paraíba. It is characterized by a region with high wave energy, a mesomaré regime (daily variation between 2 and 4 m) and a semi-arid climate, with average annual rainfall of less than 800 mm concentrated in 3–4 months. This part of the coast is characterized by soils with salinities between 28 and 53 and forests with relatively low plant biomass. However, soil carbon stocks are comparable to those estimated for the Amazon coast but are potentially sensitive to shrimp farming and climate change (Kauffman et al., 2018a; 2018b; Nóbrega et al. 2019; Lacerda et al., 2024).

The east coast of Brazil stretches from Paraíba to Guanabara Bay (RJ), under the influence of micro-tides in a humid climate, with average annual rainfall of approximately 1,800 mm/year, with stretches of rainfall of less than 700 mm and others of rainfall of more than 2,400 mm. This section of the coast has mangrove forests growing in estuarine regions and bays protected from the direct action of the sea, but sometimes with intense urbanization. Mangrove soils also have a high contribution (>70%) to carbon stocks, although this is based on few studies (Bernardino et al., 2020, Gomes et al., 2021a; Hatje et al., 2021).

Brazil's Southern Granite Coast stretches from Guanabara Bay (RJ) to Praia do Sonho (SC). This region is marked by a humid tropical climate, with annual rainfall of between 1,000 and 1,500 mm, and by its proximity to the Serra do Mar Mountain range, creating a coastline full of protected bays that are home to extensive mangrove forests. The soils of the escarpments of this crystalline massif, covered by the Atlantic Forest, contribute significantly to the increase in iron (Fe) in



the mangrove soils and high levels of organic carbon (Ferreira et al., 2022).

This zone is home to important areas of lagoon and estuarine mangroves on the boundary between the tropical and subtropical zones, such as those in the Cananéia-Iguape region (SP) and Guaraqueçaba and Guaratuba Bays (PR), which are highly sensitive to climate change. Although smaller in tree size, these mangroves represent important stocks of carbon in the soil (Rovai et al., 2021).

At the southern limit of the Brazilian mangroves in Santa Catarina, under the quaternary and sandy plain, the forests are found within the small estuaries and lagoons, and have a lower aerial biomass probably due to thermal stress in the winter periods, as well as the lower availability of light (Schaeffer-Novelli et al., 2016; Pagliosa et al., 2024). On the other hand, despite the low height, e.g. not exceeding 4m in Laguna (SC), the density and branching of the trees is higher at the edge of the mangrove distribution, as is the ratio between the carbon stored in the aerial part and in the soil (Pagliosa et al., 2024).

3

ECOSYSTEM SERVICES: BENEFITS OF MANGROVES FOR SOCIETY



**ECOSYSTEM
SERVICES:
BENEFITS OF
MANGROVES FOR
SOCIETY**

3. ECOSYSTEM SERVICES: BENEFITS OF MANGROVES FOR SOCIETY

Ecosystem services (ES) are the benefits and contributions of nature to people, provided directly or indirectly (Millennium Ecosystem Assessment, 2005). These benefits derive from biodiversity itself, the landscape, ecological functions and the interaction between physical and biological processes (Figure 1).

The Common International Classification for Ecosystem Services - CICES identifies 62 ecosystem services in mangroves, classified as "provision", "regulation", "maintenance and cultural" (Czúcz et al., 2018). More recently, more than 300 ecosystem services have been identified in mangroves in various coastal regions (Binhat et al., 2022). The amount, types and importance of ES vary between regions, depending on environmental forcings, ecological processes and the value that human populations place on mangroves.

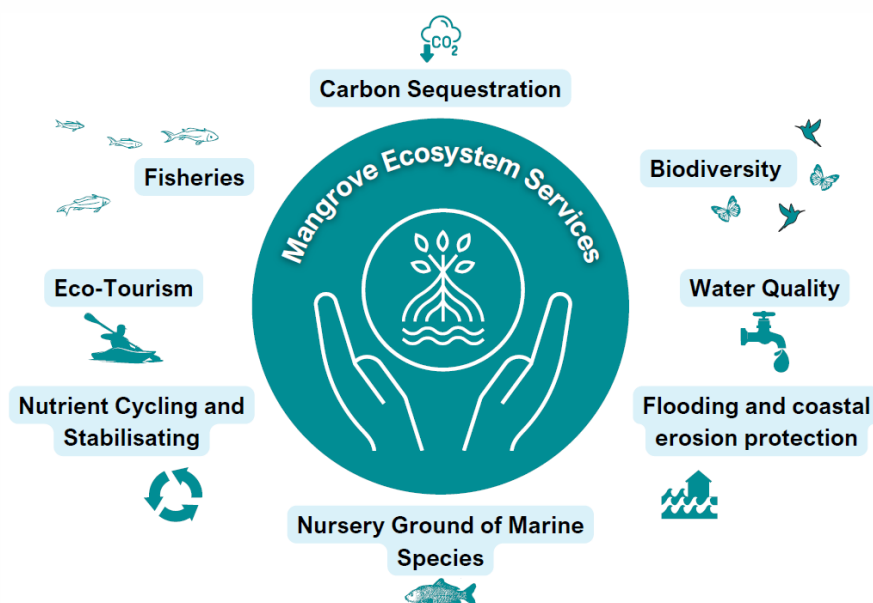


Figure 1. Ecosystem services provided by mangroves.

In Brazil, multiple benefits of mangroves have been mapped for coastal populations on the Amazon coast, which can be directly related to human well-being and the informal economy (Ouwor et al., 2024). Traditional populations of the Amazon coast benefit directly from mangrove food provision through the capture of commercially valuable species, and identify these forests as important for climate regulation and for the quality of the water they use.

The provision of fishing resources is fundamental for traditional populations living near conservation areas (Glaser, 2003; Prates, 2012, Gasparinetti et al., 2018; Owuor et al., 2024). As for small-scale (artisanal) fishing, Brazil has around 278,000 fishermen who carry out their activities in or near mangroves, highlighting this ecosystem as an important generator of income and employment for countless fishermen (Zu Ermgassen et al. 2021). Fish, crabs, oysters and shellfish are subsistence and a source of income for these populations, indirectly benefiting consumers in urban areas. These populations also realize that mangroves attract aquatic and terrestrial species, and often use these forests for educational, religious and cultural activities.



Mangroves play a fundamental role in adapting to climate change and reducing the risk of disasters in coastal zones, offering protection against storms, retaining excess sediment and nutrients and sequestering carbon (regulation service). According to the International Union for Conservation of Nature (IUCN), mangrove forests globally protect around 120 million people living in the vicinity of this ecosystem, offering at least five times more efficient and cost-effective coastal protection than built structures such as retaining walls, spikes and breakwaters (Slobodian et al., 2018).

In Brazil, mangroves fix up to four times more CO₂ and store up to ten times more carbon than other terrestrial forest and non-forest ecosystems present in the various Brazilian biomes (Kauffman et al., 2018a; Rovai et al., 2022; Bernardino et al., 2024a). In addition to the stocks associated with mangrove forests, lateral carbon flows from estuaries to the ocean, mainly in the form of bicarbonate (dissolved



inorganic fraction), have indicated highly significant values (Cabral et al., 2021). These carbon transfers reinforce the importance of mangroves in mitigating greenhouse gas emissions in marine areas adjacent to the coastal zone, although these benefits are yet non actionable in voluntary markets (Cabral et al., 2024)

Other services of Brazilian mangroves include the removal of pollutants and the immobilization of contaminants by the soil (Ferreira et al. 2024). In the Amazon River estuary, mangroves capture around 0.5 tons of microplastics in the water each year and directly benefit traditional populations who use untreated water from nearby rivers for their consumption (Rico et al., 2024).

The perception of communities is very useful for identifying and qualifying the importance of services in order to guide conservation actions. For example, a study around an Extractive Reserve (RESEX) in Pará showed that, according to 90% of residents, there is a high flow of services from fishing, intergenerational values, intrinsic value, nursery and breeding grounds, climate regulation, biodiversity conservation and protection from storms (Owuor et al., 2024).

The perception of the importance of these services is greatly influenced by the socio-demographic characteristics of the communities, such as education, way of life, source of income (fishing or other activities) and prior knowledge about ecosystem benefits and services. In general terms, the protection framework and the existence of conservation units in most of the areas where Brazilian mangroves are located reinforce their importance for coastal communities.

Many of these communities recognize that mangrove areas are fundamental to the provision of the many services that directly benefit them (e.g., Owuor et al., 2024). There is a clear gap in knowledge about the ecosystem value of Brazilian mangroves, since the available data is based on a few case studies and is geographically restricted, considering the large extent of Brazilian mangroves. These studies are of the utmost importance to strengthen the management of these areas with the leadership of traditional peoples, and to improve the perception of other sectors of society about our dependence on mangroves and the ecosystem services they provide (Table 1).

Table 1. Flow of ecosystem services from mangroves in the opinion of residents of the surrounding Extractive Reserve (PA). Adapted from (Owor et al., 2024).

Mangrove ecosystem services	High Flow (%)	Medium Flow (%)	Low Flow (%)
Fishing	95	4	1
Fishing vessels	8	6	86
Fishing gears	40	10	50
Mariculture	64	6	30
Phytotherapy	27	16	57
Firewood	18	6	76
Coal	8	6	86
Timber	8	9	83
Livestock feeding	1	2	97
Hunting	2	3	95
Bee keeping	7	7	86
Crafts and ornamentals	18	9	73
Recreation and tourism	69	12	19
Historical values for generations	91	4	5
Intrinsic values	93	3	4
Nursery and breeding ground	94	2	4
Flood control	76	9	15
Water purification	73	8	19
Sediment control	70	14	16
Climate regulation	89	6	5
Biodiversity conservation	96	3	1
Storm protection	87	5	8
Shoreline erosion	80	8	12

4

GEOCLIMATIC CONDITIONS, COASTAL TYPOLOGIES AND CARBON STOCKS



GEOCLIMATIC
CONDITIONS,
COASTAL TYPOLOGIES
AND CARBON STOCKS

04. GEOCLIMATIC CONDITIONS, COASTAL TYPOLOGIES AND CARBON STOCKS

The diversity of coastal environments in which Brazilian mangroves are found varies in terms of geological and climatic characteristics, hydrological regimes, tidal amplitudes, and river inputs of sediments and nutrients [Section 2], significantly influencing the composition and functioning of mangrove ecosystems (Ferreira et al., 2022; Beloto et al., 2023; Ruiz et al., 2024). The energy and amplitude of the tides affects the frequency and duration of flooding which, together with wave energy, enables distinct geomorphological conditions (Woodroffe et al., 2016).

The contribution of these environmental forcings gives rise to diverse coastal typologies such as deltas (dominated by rivers), estuaries (dominated by tides), coastal lagoons (dominated by wave and wind energy) and substrates of carbonate origin (i.e., *Halimeda* spp. calcareous algae reefs), all of which influence the capacity of these forests to sequester and store carbon over time (Breithaupt and Steinmuller, 2022).



Recent data also show the geochemical influence of soils on the stabilization capacity of organic material in mangrove soils. These studies suggest that soil health is an important parameter in determining the capacity of mangroves as carbon sinks, and indicate that changes in land use drastically alter their future storage capacity (Ruiz et al., 2024). This information has broad implications for the



choice of mangrove replanting and restoration areas, since additional carbon capture is often desirable in these projects.

Coastal typologies dominated by large rivers (e.g., Amazon, São Francisco, Caravelas) receive considerable inputs of sediment carrying minerals, organic matter and nutrients from the soils upstream in the watershed. Large volumes of sediment may contribute to high annual rates of sedimentation and organic carbon accumulation in mangrove soils.

However, the large volume of inorganic sediment can have a 'diluting' effect on organic matter, resulting in relatively low soil organic carbon stocks (Passos et al., 2024). The input of nutrients, together with light and temperature, regulates primary productivity in mangroves, consequently influencing the partitioning of resources between aerial biomass (trunks, branches, leaves, flowers, fruits, propagules) and underground biomass (roots).

In environments dominated by large rivers, typical mangrove trees allocate more resources to the production of aerial biomass than to the production of roots, reducing the contribution of organic matter to the soil.

Thus, Brazilian mangroves dominated by deltaic coastal typologies have higher stocks of organic carbon in the aerial biomass when compared to the soil (Rovai et al., 2018; 2021; 2022; Kauffman et al., 2018; Bernardino et al., 2024). On the other hand, mangroves located in coastal typologies dominated by tides and/or waves, such as estuaries and coastal lagoons with less fluvial influence, have higher carbon stocks in soils compared to aerial biomass (Kauffman et al., 2018; Gomes et al., 2021a; Rovai et al., 2021; Hatje et al., 2023).

Thus, the typology of mangrove forests, together with the geoclimatic characteristics and mineralogy of the soils, play an important role in controlling the potential for carbon sequestration by mangroves.

Although there are still many gaps on the Brazilian coast where the stocks of mangrove forests remain undetermined, the existing data allow us to estimate average rates of accumulation and carbon stocks in both the aerial biomass and the soil of mangroves. Annually, 2.44 (95% median confidence interval: 1.64 to 3.71) and 2.14 (95% median confidence interval: 1.47 to 2.59) TgC/year of carbon are accumulated

in the aerial biomass and soils of Brazilian mangroves representing, respectively, 10 and 13.5% of the global totals (Rovai et al. 2022). Regarding the carbon stored in the aerial biomass and soils (between 0-100 cm deep), the estimated stocks are 50-100 and 207-215 TgC, respectively, equivalent to 7 - 8% of global stocks (Rovai et al., 2022; Hatje et al. 2023). These values could be even higher if data were added on carbon stocks in underground living biomass (rhizophores and roots), which are scarce in the literature and highly variable between coastal typologies and latitudes.

It should be noted that, while accumulation rates and carbon stock values in biomass and soils are important for quantifying emission factors, in the case of converting mangrove areas to other uses, the net balance of carbon flows (i.e. discounting ecosystem respiration and export) should be used to estimate the mitigation potential of mangroves in relation to greenhouse gas emissions from burning fossil fuels.

A study on the Amazon coast sought to determine this net balance, indicating that mangroves on the Amazon coast have a positive climate balance of $12.2 \pm 1.4 \text{ Mg CO}_2\text{eq}$ per hectare per year (Bernardino et al., 2024b). This indicates that if kept standing, mangrove forests remove more CO_2 from the atmosphere than they emit in greenhouse gases, highlighting their benefit for the country's climate adaptation.



5

SOURCES AND SINKS OF GREENHOUSE GASES



**SOURCES AND
SINKS OF
GREENHOUSE
GASES**

5. SOURCES AND SINKS OF GREENHOUSE GASES

Conserved mangrove forests are generally greenhouse gas sinks, acting as net sinks of atmospheric CO₂. However, under certain conditions, natural GHG emissions from these forests, particularly methane (CH₄) and nitrous oxide (N₂O), can offset CO₂ removals, reducing the climate mitigation benefit (called offset). These gases are emitted through the soil-atmosphere, water-atmosphere interface and by direct emissions from vegetation into the atmosphere.

Globally, it is estimated that total CH₄ emissions (average flux of 6.53 Tg CO₂e year⁻¹) reduce the carbon sequestration capacity of mangroves by 15 to 20% (Rosentreter et al., 2018; Cotovicz et al., 2024), which amounts to approximately 4 Tg CO₂ year⁻¹. These methane fluxes are stimulated by the presence of fresh water, so in mangroves with higher salinity (salinity > 30), the average offset would be only 7% (CH₄ emissions of ~1 Tg CO₂e year⁻¹ and organic carbon sequestration of ~4 Tg CO₂ year⁻¹) (Figure 2).

Additionally, eutrophic soils (e.g., enriched with organic matter and nutrients by shrimp farms) tend to release methane into the atmosphere (Nóbrega et al., 2016), reducing the overall climate benefit of mangroves. In that sense, keeping Brazilian mangroves preserved and uninfluenced by anthropogenic organic waste is fundamental to maintaining the climate benefits they offer.

In Brazil, recent studies have investigated the relationship between greenhouse gas emissions and organic carbon sequestration capacity in mangrove soils. In tropical mangroves in Rio de Janeiro and subtropical mangroves in Santa Catarina, low CH₄ concentrations and emissions were observed, with emission offsets of less than 3% (Yau et al., 2024).

However, in Amazonian mangroves influenced by large river inputs, CH₄ emissions from soils with low salinity (salinity 0.5 – 5.0) showed an average offset of 44%, while in brackish forests (salinity 5.0 – 18.0) this percentage fell to 11% (Bernardino et al., 2024b). These data corroborate other global studies, and indicate that saline mangroves are key ecosystems in the context of climate change since they combine high CO₂ sequestration capacity with low CH₄ emissions (Bernardino et al., 2024b; Cotovicz et al., 2024).

In addition to methane, it is worth highlighting the role of nitrous oxide (N_2O) as this is another potent greenhouse gas (Maher et al., 2016). Like other GHGs, N_2O fluxes in mangroves are controlled by various factors such as bioturbation (e.g. crab activity in the soil), salinity, climatic conditions and nitrogen input (Otero et al., 2020).

Conserved and saline mangroves can act as an N_2O sink resulting in a greater climate benefit (Cotovicz et al., 2024). However, mangroves that receive a high input of nitrogenous effluents, such as those located near shrimp farms, tend to increase N_2O fluxes to the atmosphere by up to 125%, thus reducing their GHG removal benefit (Queiroz et al., 2019).

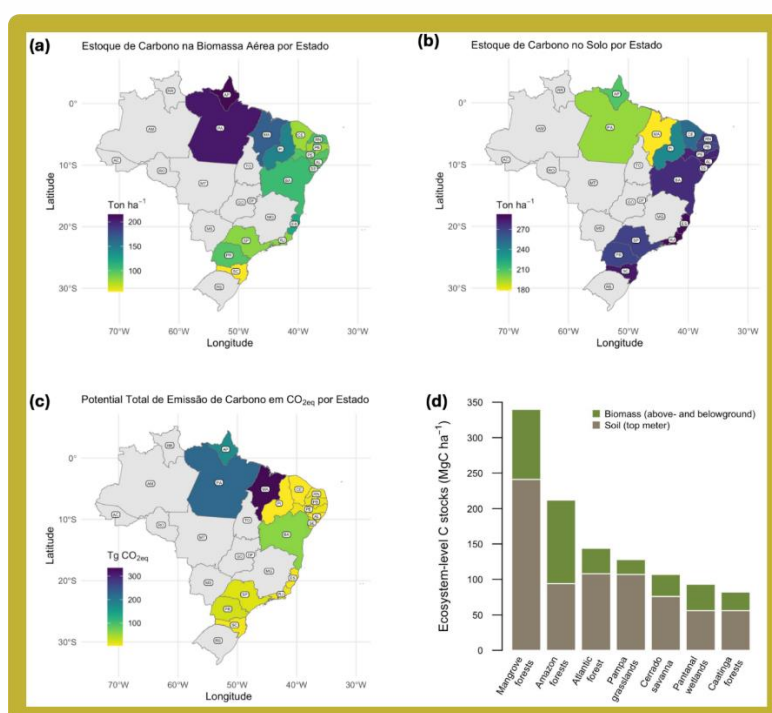


Figure 2. Mean estimates for carbon stocks (a) in the aerial biomass and (b) soils of Brazilian mangroves by state. (c) The total $\text{CO}_{2\text{eq}}$ emission potential by state represents the sum of the carbon stocks in the total biomass (aerial and subterranean) and soils. (d) Comparatively, Brazilian mangroves store between 2 and 4-fold more carbon in the soil per unit area (i.e., per hectare) than other terrestrial biomes, and are second in terms of aerial biomass only to the Amazon rainforest. Maps (a-c) produced from estimates generated by Rovai et al. (2018) and Rovai et al. (2021). It should be noted that the colors of the states represent carbon stocks that occur only in mangrove areas, which are difficult to visualize at this scale, and therefore the entire state was colored to facilitate visualization. In (c), underground biomass was estimated using a conversion factor of 0.5 in relation to aerial biomass. (d) Modified from Rovai et al. (2022).

6

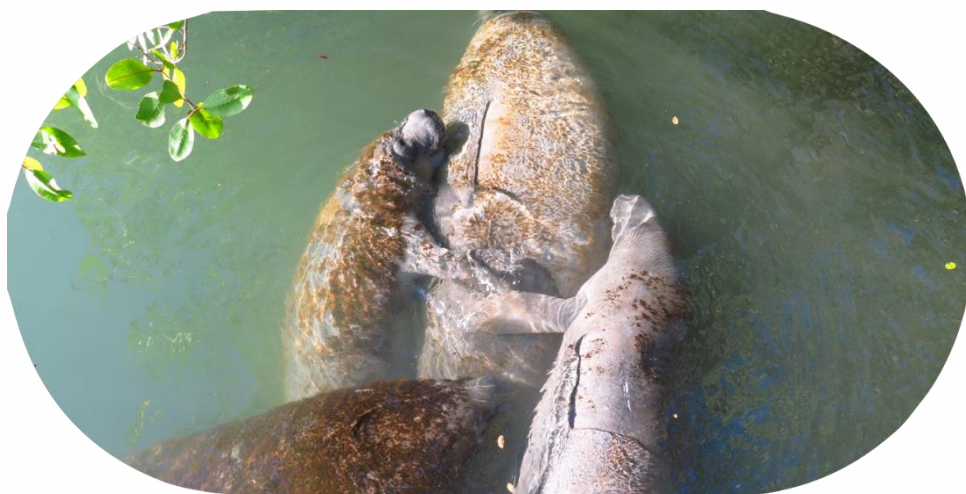
MANGROVES CONNECTED TO THE COASTAL- MARINE LANDSCAPE



MANGROVES
CONNECTED TO
THE COASTAL-
MARINE
LANDSCAPE

6. MANGROVES CONNECTED TO THE COASTAL-MARINE LANDSCAPE

Connectivity is an intrinsic and fundamental component of all ecosystems, influencing the dispersal and diversity of species, and ensuring the maintenance of ecological functions and ecosystem services (Lindemeyer et al., 2008). The distance between forests and ocean currents influence the dispersal of tree propagules and the genetic diversity of mangrove species (Sanches, 2019; Madeira et al., 2022). In addition, mangrove forests are connected to terrestrial ecosystems (e.g., Atlantic Forest sandbanks and forests, Amazonian grasslands and flooded forests, river basins) and marine ecosystems (e.g., tidal flats, sea grasses and coastal coral reefs) through hydrological flows that carry organisms and nutrients between and within these ecosystems (Howard et al., 2017).



Many tropical and subtropical coastal-marine landscapes are characterized by the proximity of mangroves to tidal flats, sea grass prairies, macroalgae beds and coral reefs, forming a mosaic of ecosystems (Ogden, 1997, Unsworth et al., 2008, Lowe & Falter, 2015). These landscapes are among the richest repositories of marine biodiversity, providing vital services for the survival and well-being of human populations (Nagelkerte et al., 2000, Moberg & Roenback, 2003). In Northeast Brazil, sea grass prairies and macroalgae beds develop between the barrier reef and mangroves on the coast (Copertino et al., 2016), allowing the transit of commercially valuable fish between these areas (Aschenbrenner et al., 2016, Silva et al., 2022). Many of the ecosystem goods and services identified for mangroves are shared with sea grass prairies (Creed et al., 2023) (Figure 3).

The physical structure, food resources and shading provided by the mangrove-grassland association benefits the juvenile stages of fish, maintaining the high density of these animals that return to the reef as adults (Nagelkerken et al., 2002, Nakamura & Sano, 2004, Silva et al., 2021). Several tropical fish populations use the landscape with cyclical migrations, on different time scales, between mangroves and other habitats (Reis-Filho et al., 2016; Souto-Vieira, 2023).



Figure 3. Sea grass meadows, exposed at low tide, adjacent to mangrove forest. Macapá River Estuary, Piau . @Margareth Copertino.

The relationship between mangroves and the Amazon River basin is an example of the importance of maintaining interconnectivity. A large part of commercial fishing in the Amazon River Basin is concentrated on fish species that make extensive migrations between the estuarine region and the headwaters of the rivers (Duponchelle et al., 2021). In that sense, actions that guarantee the flow of water and maintain the health of floodplain and mangrove forests, and other coastal wetlands, are fundamental to guaranteeing stocks and fisheries in the Amazon River Basin and possibly in many other estuarine areas and coastal bays in Brazil.

Mangroves are in constant exchange with the ocean through tides, waves and currents that occur on various time scales (Santos et al., 2021). This exchange promotes the export of organic matter and nutrients to the coastal zone, influencing food chains and amplifying animal abundance (Dittmar et al., 2006; Taillardat et al., 2019; Santos et al., 2021). These results corroborate an old hypothesis (Odum, 1980), in

which vegetated coastal ecosystems sustain a significant portion of the primary production of estuaries and the continental shelf.

Landscape fragmentation reduces proximity and the degree of interconnectivity, with negative consequences for mangrove biodiversity and adjacent habitats, resulting in a loss of ecological functions and associated services, as well as reducing the resilience of mangroves to the impacts of climate change (Skilleter et al. 2017). Thus, the integral protection of landscape mosaics is imperative to sustain the high productivity of fisheries and the livelihoods of coastal populations (Silva et al., 2022), maintain carbon stocks and coastal protection (Figura 4).

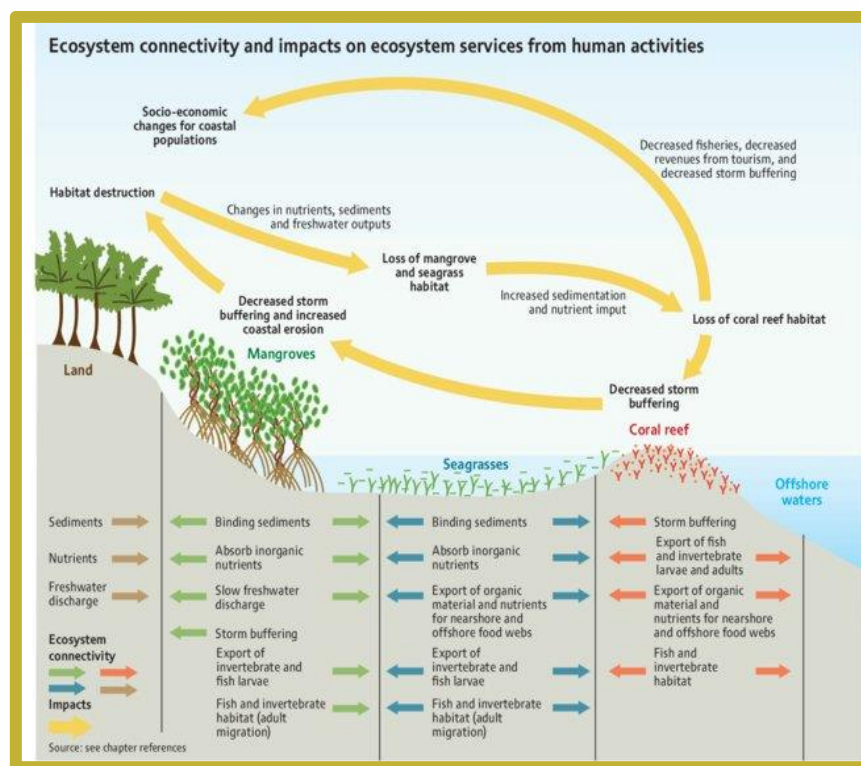


Figure 4. Connectivity between mangroves, prairies and coral reefs, showing the functions of each habitat. The interconnectivity relationships are indicated by arrows: mainland (brown arrow) mangrove (green arrow) grassland (blue arrow), coral reef (red arrow). At the top of the figure are human impacts that feed back into negative effects on ecosystem services (yellow arrows). Source: Silvestri & Kershaw (2010).

Figure 5 also provides an example of the life cycle of the gray fish that uses the 3 habitats (mangrove, prairie and coral reef).

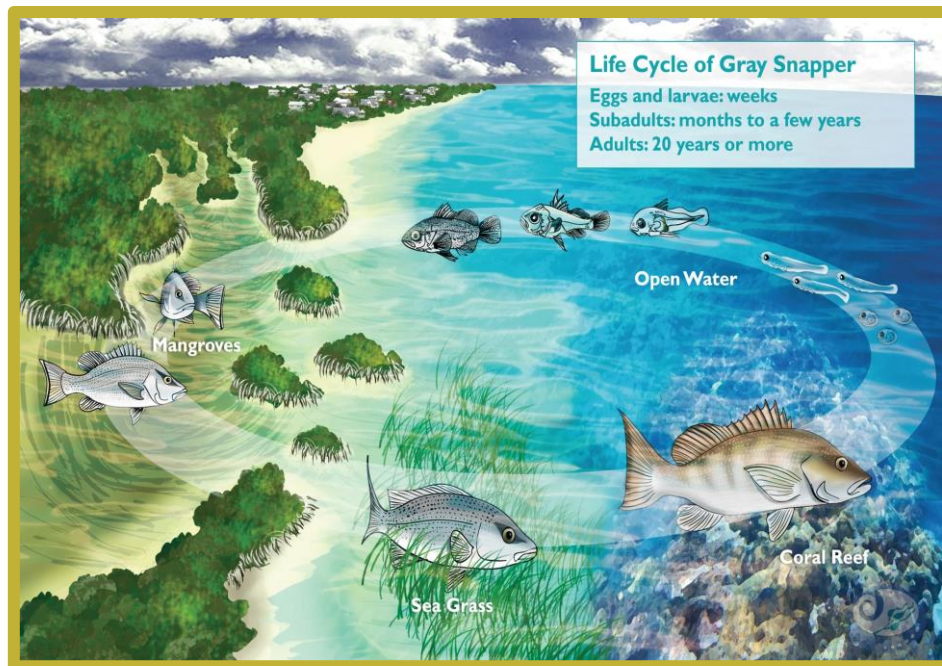


Figure 5. Life Cycle of Gray Snapper.

7

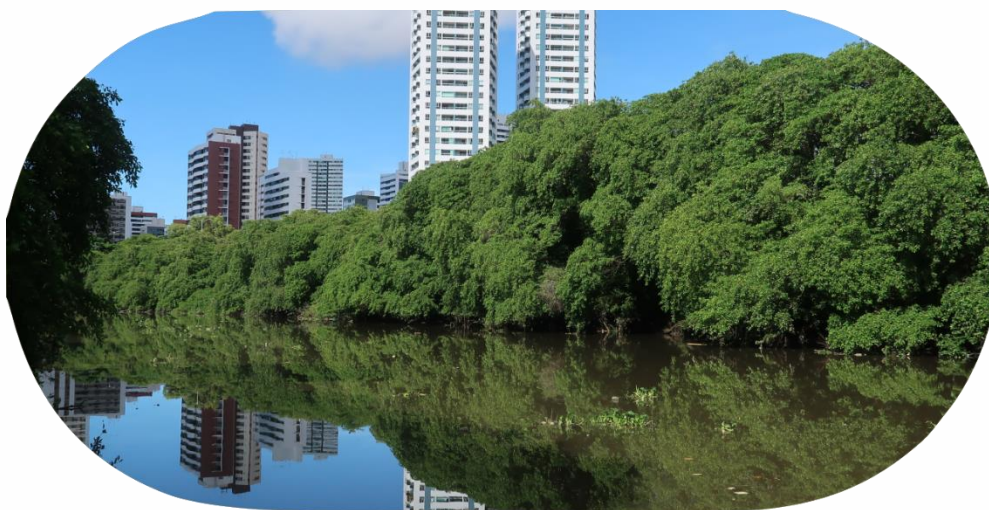
LOSSES AND THREATS



LOSSES
AND
THREATS

7. LOSSES AND THREATS

In Brazil, mangrove forests continue to be threatened by a variety of anthropogenic causes. The most recent assessments by the MapBiomass project (2022) show a net loss of approximately 11,000 hectares (2% of the total area) of mangrove forests between 2000 and 2021, equivalent to a rate of 0.13% per year (Copertino et al., 2024). The main recent causes of anthropogenic losses include the suppression of vegetation for pasture (c.a 4% of the converted area), but coastal shrimp farming, extreme weather events, salt production and urban expansion are still historical sources of mangrove loss (Gomes et al., 2021a; Vanin et al., 2024).



In the Amazon region, around 750 hectares (0.1% of the country's total mangrove area) of mangroves are lost annually through conversion to pastures and fields, potentially releasing around 1 million tons of CO₂eq into the atmosphere (Bernardino et al., 2024a, Table 2). Another serious problem for mangrove conservation was the revision of the forestry code in 2012, which allowed the use of salt marshes for shrimp farming more flexible. This measure not only intensified the loss of extensive mangrove areas (i.e., apicum), but also reduced the area available for restoration, and natural migration of the forest towards the mainland in a likely scenario of rising Mean Relative Sea Level (NRM) (Pagliosa et al., 2012).

Shrimp farming in Brazil is an activity historically responsible for the loss of considerable areas of mangroves, especially in the semi-arid region of the Northeast, where mangroves occupy ephemeral estuaries impacted by severe droughts (Lacerda et al., 2021). The conversion of mangroves to shrimp ponds results in an average emission of 1.4 Mg

CO₂eq per hectare, representing a loss of 52 to 80% of C stocks, thus intensifying global warming (Kauffman et al., 2018b, Table 2).

These emissions occur due to the oxidation of the most labile (easily degraded) fraction of organic matter, which loses its physicochemical protection due to the biogeochemical alteration of soils (Santos-Andrade et al., 2021; Ruiz et al., 2024). In addition to the change in land use and the loss of accumulated carbon content, the disposal of effluents from shrimp farming in adjacent regions accelerates the decomposition of organic matter and the loss of C stocks (Suarez-Abelenda et al., 2014; Nóbrega et al., 2019). The disposal of shrimp effluents increases the phosphorus and nitrogen content in soils, causing eutrophication, which further reduces the net carbon sequestration capacity and the resilience of vegetation to climate change (Nóbrega et al., 2014; Barcellos et al., 2019).

Table 2. Forest emission rates from the loss of mangrove forests in Brazil due to human activities or climatic events (values in tons of CO₂eq equivalent per hectare).

Stressor	Region	Emission factor (CO ₂ eq per hectare)	Reference
Shrimp farming	Northeast (CE)	1,390 Mg	Kauffman et al. (2018b)
Shrimp farming	North (PA)	1,073 Mg	Bernardino et al. (2024a)
Pasture	North (PA)	1,845 Mg	Bernardino et al. (2024a)
Weather	Southeast (ES)	993 Mg	Gomes et al. (2021a)
Not identified	Southeast (SP)	1,395 Mg	Rovai et al. (2022)

The loss of mangrove forests associated with salt extraction has also caused significant impacts, similar to those caused by shrimp farming. A clear example is observed in the mangroves of semi-arid regions in the Northeast, where mangroves affected by this activity have carbon stocks up to 12 times lower compared to well-preserved areas (Lacerda et al., 2024; Rodrigues et al., 2024).

Increased salinization and reduced sediment input from Brazil's estuaries due to the damming of upstream rivers puts the health of

mangroves at risk (Gomes & Bernardino, 2020; Queiroz et al., 2022; Costa et al., 2023). Predictions of sea level rise also threaten many urban mangroves in Brazil.

The disorderly growth of cities and the construction of infrastructure result in deforestation and landfill of mangroves, converting them into important sources of CO₂ and preventing their expansion to higher areas.

In the Southeast region, with a high population density, mangrove forests may have little space for accommodation towards the continent or are in a condition of eutrophication and limited sediment input, which limits the ability of forests to adapt to rising sea levels (Godoy & Lacerda, 2015; Bernardino et al., 2020; Ward et al., 2023).

In Brazil, there are still limitations to making accurate predictions about the response of mangroves to sea level rise. However, the main coastal urban regions with the greatest damming and degradation of rivers and estuaries will likely be the most affected.

In addition to anthropogenic activities, climate change and the increased frequency and intensity of extreme weather events are growing threats. Extreme events associated with strong El Niño events have led to mangrove mortality in several parts of the world, including Brazil (Servino et al., 2018; Gomes et al., 2021a). Forest mortality causes a loss of carbon and other ecosystem services, such as the retention of pollutants and the production and export of litter to coastal zones (Gomes et al., 2021b; Queiroz et al., 2022) (Figura 6).



Figure 6. Main natural and anthropic threats to Brazilian mangroves.

8

CLIMATE SCENARIOS AND THE FUTURE OF BRAZILIAN MANGROVES



CLIMATE SCENARIOS
AND THE FUTURE OF
BRAZILIAN MANGROVES

8. CLIMATE SCENARIOS AND THE FUTURE OF BRAZILIAN MANGROVES

Changes in Mean Relative Sea Level (MRSL) alter the extent of mangroves and associated features in the coastal zone. The MRSL near the mouth of the Amazon River, i.e., where the most extensive mangrove areas in Brazil occur, will increase at a rate of 3 mm year⁻¹ by the end of the 21st century (Larour et al., 2017), close to the most recent global estimates of between 3.1 and 3.4 mm year⁻¹ (Dangendorf et al., 2017; Nerem et al., 2018).

These rates are expected to accelerate between 5 (low emissions scenario) and 10 mm year⁻¹ (high emissions scenario) by the year 2100 (Kopp et al., 2014). In many locations, the increase in MRSL has caused drowning of mangroves, mechanical suffocation by excessive sand deposition or erosion, resulting in significant losses of biomass and area (Sasmito et al., 2015).



Global projections suggest that mangroves may follow the increase in MRSL until between 2055 and 2070 considering an increase of 52–98 cm by 2100 (GHG atmospheric concentration trajectory RCP 8.5) (Sasmito et al., 2015). Studies also indicate that mangroves can withstand a sea level rise of up to 7 mm year⁻¹ (Saintilan et al., 2020), but these values are extremely dependent on local sediment input conditions. For example, historical sedimentation rates (c.a. 5 decades) of mangroves in Brazil vary between 1.8 and 5.4 mm year⁻¹ suggesting that many mangroves may be close to their limit of adaptation to sea level rise (Sanders et al., 2010; Bernardino et al., 2020; Ward et al., 2023; Passos et al., 2024).

In part, the ability of mangroves to adapt to the elevation of the MRSL is related to lateral migration to other features of the tidal flats, such as the hypersaline flats, also known as 'salgados' or 'apicuns'. However, the occupation of these features by shrimp farms, salt pans, as well as irregular urban occupations, prevents the natural transition dynamics between these features, reducing the potential for compensation for losses due to coastal erosion (Lara et al., 2002; Cohen et al., 2018; Leo et al., 2019) (Figure 7).



Figure 7. Aerial view of the mangrove swamp in the Cabo Orange National Park in Amapá. @Victor Moriyama.

The resilience of mangroves in the face of an increase in MRSL is also influenced by the coastal typologies where these forests are located (deltas, estuaries, lagoons, carbonate substrate), varying in relation to tidal height and river discharge and sediment input (McKee et al., 2007; Spencer et al., 2016; Cohen et al., 2020; 2024). Mangroves in microtidal typologies and without significant input of river sediments are more vulnerable than plains dominated by large rivers, as well as macrotidal coasts, where the volume, transport and deposition of sediments is much greater (Lovelock et al., 2015; Hagger et al., 2022).

Mangroves can to some extent 'respond' to MRSL elevation by producing additional below-ground biomass to 'adjust' to soil elevation. In addition, the vegetation retains sediment contributing to



the vertical increase of the substrate (Lovelock et al., 2015; Bernardino et al., 2020; Saintilan et al., 2020). However, this adjustment is limited and the loss of mangroves due to MRSL elevation can cause the oxidation of carbon deposits that have accumulated in the soil for hundreds to thousands of years.

Climatic extremes involving, for example, severe droughts or intense rainfall, combined with the rise in the MRSL, will result in changes in estuarine salinity gradients with effects on the distribution and structure of mangroves (Cohen et al., 2021). In regions where there is a decrease in river discharge (e.g. estuaries in the northeast and southeast of the country), the increase in the MRSL will cause mangroves to migrate upstream. However, in regions with an increase in river discharge (e.g., estuaries in the south of the country), a rise in sea level is likely to cause a contraction in mangrove areas. Therefore, monitoring precipitation rates and sea level rise are essential for projecting the fate of mangroves (Cohen et al., 2012).

Another important factor is temperature, which has facilitated the expansion of mangroves towards higher latitudes (Osland et al., 2021). In Brazil, the migration of mangroves to subtropical regions is still limited by the low salinity (<5‰) of coastal lagoons and probably by low temperatures. However, the increase in MRSL could promote the salinization of these coastal water bodies and contribute to the expansion of Brazilian mangroves beyond their current southern limit (Yao et al., 2022).

Studies show that mangroves are progressively losing their ability to adapt to climate-induced changes and to provide their ecosystem services, especially in relation to their role in protecting the coast (Oppenheimer and Glavovic, 2022). In this context, it is essential to evaluate the local characteristics of Brazilian mangroves and how they have responded to the increase in MRSL on a millennial-secular scale.

In summary, recent studies suggest that certain mangroves can tolerate high rates of increase in MRSL. However, an assessment of the vulnerability of mangroves along an extremely heterogeneous coastline such as Brazil's requires local information on the responses of these forests to past changes in MRSL (Holocene-Anthropocene), hydrodynamics, geomorphology and, of course, projections of increases in MRSL, precipitation and temperature.

9

POTENTIAL FOR RESTORATION



POTENTIAL
FOR RESTORATION

9. POTENTIAL FOR RESTORATION

While the conservation of mangroves is important and probably more relevant to Brazil, interest in restoring and rehabilitating these ecosystems has increased considerably, mainly with a view to maintaining fisheries, combating the climate crisis and achieving national and international biodiversity conservation targets.

Compared to other wetland ecosystems, mangrove forests are easy to manage and can achieve great success in restoration projects, as long as it is associated with the removal of local stressors and the re-establishment of natural hydrological conditions. International protocols to guide restoration projects exist and have been produced by people with extensive experience in restoration around the world (Beeston et al., 2023).

Restoration projects require analysis of a series of ecological variables before putting the restoration itself into practice. Without considering the biophysical potential of the region and local historical, social, political and financial characteristics, mangrove forest restoration projects often fail. Considering the high volume of resources earmarked for restoration projects and the frequent failure of restoration projects, monitoring their development is a crucial part of this process as it allows for adaptive management and the reporting of progress to funding bodies. Since the central objectives of mangrove ecological restoration should be to recover the integrity of the mangrove system, including biodiversity, ecological processes and ensuring climate resilience, a robust monitoring plan should be drawn up (Cadier et al., 2020; Ferreira et al., 2023).

Recent studies show the importance of choosing monitoring metrics that demonstrate the recovery of mangrove ecosystem services, including carbon dynamics and sediment elevation, to ensure the climate resilience of these ecosystems in the near future (Ruiz-Jaen & Aide, 2005). Assessing the degree of success can take years and even decades, considering the structural development of the forest and the re-establishment of ecological functions (e.g., carbon sequestration, soil accretion, and recovery of associated biodiversity) (Mckee & Faulkner 2000; Bourgeois et al., 2024). Conclusions based on short-term results should be viewed with caution, even if they appear to be positive.

Biophysical potential for Restoration

The potential for mangrove restoration is related to the history, time and nature of the degradation, the land situation and the degree of reversibility of the impacts, the latter being related to the possibility of removing environmental stressors and re-establishing connectivity with river inputs and regular tidal flooding (Worthington et al., 2020). From a biophysical point of view, the possibility of re-establishing hydrological flows (river inputs and tidal action) is essential to ensure the success of mangrove restoration initiatives. Coastal typologies dominated by rivers or meso- and macro- tidal regions have favorable characteristics for mangrove restoration. The greater hydrodynamics and constant subsidy of sediments and nutrients in these areas favor the potential for re-establishing ideal biophysical conditions for induced restoration (planting) or for allowing mangroves to recover naturally (Worthington et al., 2020).

In Brazil, an estimated 90,000 hectares of mangroves were lost between 1996 and 2010, mainly along large urban centers on the coasts of the Northeast and Southeast (Bunting et al., 2022). However, around 48,000 hectares (4% of the area lost) have high potential for recovery because they are located in coastal regions with high sediment discharge (deltas), high tidal range (meso- and macrotidal regimes) and free of anthropogenic installations (Worthington et al., 2020) (Figure 8). If this area is successfully restored, this could represent an increase of at least 19 million tons of carbon, including soil and biomass (Worthington & Spalding, 2018).

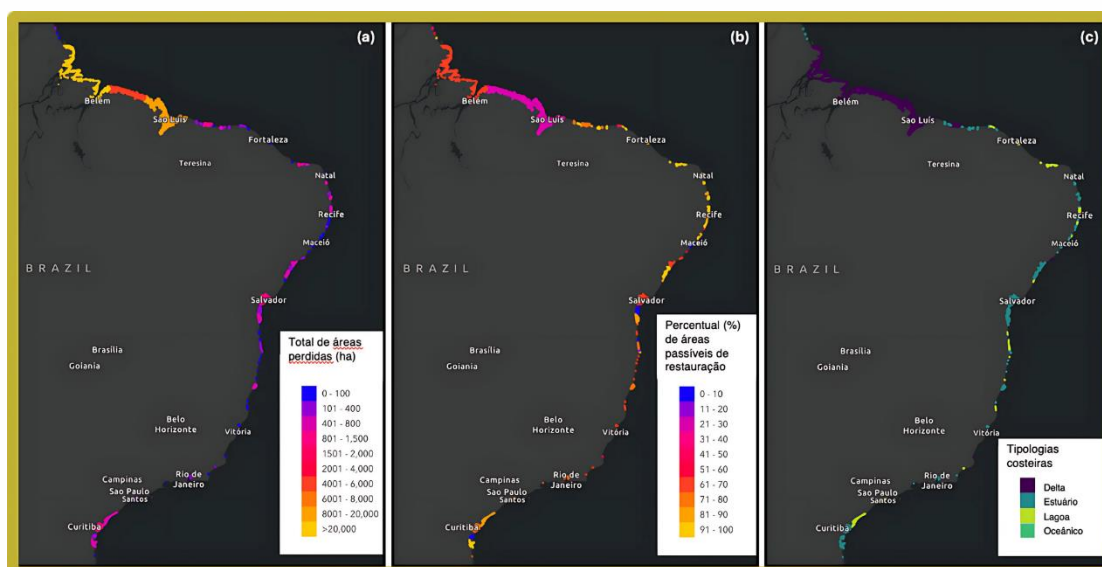


Figure 8. Total mangrove areas (ha) lost (a), percentage (%) of mangrove areas that could be restored (b) and distribution of mangroves in different coastal



typologies along the Brazilian coast. Oceanic-type mangroves refer to those exposed directly to the ocean with little or no river input. Maps adapted from <https://maps.oceanwealth.org/#/mangrove> (accessed 10/11/2024).

In the project planning phase, mapping the biophysical potential for restoring Brazilian mangroves is extremely useful in identifying the most favorable regions for restoration, thus guiding macro-planning for actions. After this stage, it is possible to analyze specific local characteristics such as the history of degradation, the possibility of removing stressors, the land situation, as well as social and political aspects (Beeston et al., 2023). Defining restoration objectives and targets also guides the execution and monitoring of project success, where it is recommended to choose metrics that indicate the restoration of key ecological processes in mangroves including carbon sequestration, nutrient flow and biodiversity (Cadier et al., 2020).

Although many studies prioritize simple metrics such as structural diversity and plant density because they are more economical and quicker to respond to, these metrics are not always related to the ecological recovery of mangroves (Cadier et al., 2020). Thus, more robust metrics that include indications of ecosystem function should be prioritized to monitor and evaluate the success of mangrove restoration measures. To enable the sharing of experiences and success rates in restoration projects, it is essential to use unified tools for archiving standardized information on projects and evaluating proposed actions (Gatt et al., 2024).

Restoration Projects in Brazilian Mangroves

Until the end of the 1990s, mangrove forest restoration projects in Brazil were limited to isolated, small-scale experimental attempts, with results rarely reported in the scientific literature (Rovai, 2012). Between 1994 and 2010, reforestation efforts represented a total area of around 2,600 hectares (concentrated in the southeast and south of the country), equivalent to around 10% of the area of mangroves lost in the last two decades.

Even today, very little is known about the success of the initiatives and most of the projects lacked experimental design and systematic medium- or long-term monitoring, limiting conclusions and hindering learning. Since 2010, there has been growing interest in mangrove restoration projects in Brazil, involving research institutions, Non-



Governmental Organizations, private foundations and communities, with public or private funding (e.g. Amazon Fund; Petrobras and other companies).

These projects are aimed at increasing research into restoration ecology, training human resources, improving cultivation techniques (e.g. nurseries) and environmental education activities with communities. Little is known, however, about the results and success rates of reforestation actions, most of which are carried out on an experimental and educational basis.

The first major mangrove restoration initiative coordinated at the national level comes from the recently created "Mangroves of Brazil" program, which is investing R\$47.3 million in the recovery of around 1,800 hectares (2,200 soccer fields) of vegetation in degraded areas and mangroves and dunes. In 2023, the program considered eight proposals (out of 30 submitted) from non-profit institutions covering several states of the federation¹.

In addition to regenerating vegetation and monitoring biodiversity, the projects must involve the participation of coastal communities, environmental education and citizen science. To date, the lack of systematized implementation and monitoring protocols makes it difficult to evaluate the success of these initiatives, and it would be important for funding institutions to demand that information from these projects be shared on an open access platform to evaluate the results and degree of success of past projects. Any restoration project needs effective monitoring throughout its execution, as well as transparency about the results. It is therefore necessary to adhere to universal tools for standardizing and archiving the actions and results of restoration projects (Gatt et al., 2024).

¹

https://www.funbio.org.br/programas_e_projetos/florestaviva/manguezaisdobrasil-2/

10

CARBON MARKET MODELS AND THE BRAZILIAN CONTEXT



**CARBON MARKET
MODELS AND THE
BRAZILIAN CONTEXT**

10. CARBON MARKET MODELS AND THE BRAZILIAN CONTEXT

The carbon sequestered and stored by mangrove forests can contribute to zero-emission climate goals for nations within the global framework of limiting global warming to 2°C (UNFCCC, 2015). At the national level, countries can account for their sources of carbon sequestration and emissions through their GHG emissions inventory process, which is determined by the forestry and land use sector.

In this sector, the benefits obtained by protecting and better managing existing stocks, or by restoring lost forests, can be accounted for using methods validated by the IPCC (IPCC, 2019). Emissions targets based on these standards can form part of the Nationally Determined Contributions (NDCs) document, which are updated continuously and represent the country's commitments to mitigate climate change (Brazil, 2023; Bernardino et al., 2024a).

Mangroves can contribute to the generation of carbon credits, either by mitigating degradation or preventing the loss of forests (avoiding emissions), or through the additional sequestration obtained by actions to restore degraded areas, or by management actions that induce a net carbon benefit. The advantages of these combined actions are that multiple benefits can be obtained beyond the sequestered carbon, arising from the maintenance or increase of ecosystem services associated with these forests (Vanderklift et al., 2019).

This is a way of ensuring economic benefits from blue carbon, which would result in an international flow of funds via carbon credit markets. Determining the areas where obtaining credits is most financially rewarding, combined with commercial guarantees and financial returns on investments in restoring or protecting mangrove forests, is fundamental for the country. Models of potential investment areas exist and indicate that deforestation mitigation actions can result in obtaining credits at a low cost of implementing these strategies (Zeng et al., 2021).

For example, on the Amazon coast, mitigation actions for the removal of mangrove forests with annual losses of around 750 hectares could generate credits for the maintenance of around 1 million tons of CO₂eq per year (Bernardino et al., 2024b). The prices of a ton of blue carbon in



voluntary markets are highly variable, but are close to 27–30 US dollars (USD) per ton, indicating that the benefits of mitigating forests in Brazil are very high (~30 million USD per year), considering the low costs for their conservation (Zeng et al., 2021; Bernardino et al., 2024b).

These figures primarily consider the financial benefits obtained from actions that avoid emissions from the conversion of mangrove forests, without taking into account co-benefits from their protection, since financial markets for other mangrove ecosystem services generally do not exist.

Many nations have made rapid progress in adopting carbon markets linked to mangrove forests and other blue carbon ecosystems. Collective and pioneering projects and initiatives in Indonesia, Australia and Colombia are already using carbon offsetting through the conservation of mangrove forests. These initiatives set future targets for reducing or avoiding carbon emissions. Several countries have already included mangroves in their national greenhouse gas emissions calculations and nationally determined contributions (Herr & Landis, 2016), especially small island nations (Friess, 2023). Emissions associated with mangrove losses are considered in the inventory of emissions in the land use sector (LULUCF), which are constantly updated according to the observed transition.

In Indonesia, emission factors are detailed to include differences in wetland forest subtypes and their specific carbon stock and associated emissions, allowing for greater certainty in emissions (Tier 3; Murdyiarso et al., 2024). In Australia, a country with a mangrove area similar to Brazil, wetland restoration actions are eligible for carbon credits after verification of sequestration rates, using new models that have been agreed by the Australian government's clean energy sector (Lovelock et al., 2023).

In the corporate sector, a growing number of commercial blue carbon credit projects have been established (Wylie et al., 2016) with a strong increase in the number of new projects currently being verified by credit validation agencies. However, many blue carbon projects still suffer from a number of problems during their operation, including scientific limitations, financial viability and land tenure conflicts (e.g., Macreadie et al., 2022).



To overcome these difficulties and increase the chances of success for blue carbon projects in Brazil, it is essential to implement appropriate regulations that attract investment, including public and private co-financing models (Friess et al., 2022). In addition, it is necessary to adapt current verification methodologies to fit the national context, in a similar way to what is done in other countries (e.g., Carruthers, et al., 2024).

Blue carbon is a great opportunity for Brazil as its coastal cities can voluntarily implement local mangrove conservation and restoration projects. It is important to note that the verification and accreditation of blue carbon projects depends on local scientific information - obtained in situ or estimated from data and conversions used in the literature. This information includes mapping and determining stocks, estimates of carbon sequestration and accumulation rates in the soil, emissions associated with losses and degradation (capture/emissions balance), as well as predicting the effects of climate change (sea level rise, shoreline narrowing, erosion and hydrological changes) on the stability of stocks.

These are some of the fundamental requirements demanded by certifiers of carbon credit projects. Investments in blue carbon ecosystems must go beyond simply sequestering and storing carbon in the soils of these environments: they must also include investments in biodiversity, local communities and the promotion of climate justice.

11

PUBLIC POLICY



PUBLIC
POLICY

11. PUBLIC POLICY

Public policies aim to promote economic development linked to social inclusion and environmental protection, making ideas effective and enabling instruments for territorial management to promote social, economic and environmental justice (da Rocha et al., 2020). The Brazilian legislation has several instruments for promoting territorial planning, such as the National Coastal Management Plan (Law 7,661/1988), the Water Resources Plan (Law 9,433/1997) and the Municipal Master Plans (Law 10,257/2001). In addition to these is the National Plan for Adaptation to Climate Change (Brasil, 2016). All this framework has in common the perspective of promoting healthy territories based on the definition of public policies considering participatory governance (Abrahão & Asmus, 2018).

The Brazilian Forest Code, by Decree No. 23,793 of January 23rd, 1934, strengthened the protection of mangroves and was reinforced in the same year with the Water Code, Decree No. 24,643 of July 10, 1934. But it wasn't until 1965 that the mangrove forest and all forms of forest gained protection, with Federal Law No. 4,771/1965, still under the name of the Forest Code, establishing the so-called Permanent Preservation Areas (APP). In 2012, it was amended by Federal Law No. 12,651, maintaining the mangrove swamp as an APP throughout its entire length, in both rural and urban areas (article 4, item VII). In addition, Article 3 included some definitions, including mangrove (item XIII), reproducing the same wording as Conama Resolution 303/2012; salt marsh (item XIV); apicum (item XV) and wetlands (item XXVI) (Rosario & Abuchahla, 2018).

Intensive land use, flexible use of APP areas and the suppression of mangroves make coastal cities more vulnerable to extreme weather events (Brasil, 2016). Despite this, by 2023, around 80% of the country's cities did not have a risk and disaster reduction plan (Santana Filho et al., 2023). This scenario suggests that public territorial planning policies are not achieving their objectives, which could lead to environmental, social and economic losses over the next decade.

On the other hand, several key social actors in territorial governance, such as teaching and research institutions, educators, traditional peoples and NGOs, are working together to propose territorial management strategies aimed at resilient and healthy cities. For example, the National Community-Based Tourism Policy (PNTBC) is



currently being drafted (Barreto & Lanzarini, 2023) and Bill 2,933-A/2023 criminalizes the crime of ecocide. The PNTBC lists initiatives to promote responsible tourism with community protagonism, based on values of solidarity economy, respect for the environment and social justice (Barreto & Lanzarini, 2023).

There have been attempts to backtrack, such as CONAMA Resolution 500/2020, which would make it easier to clear apicum areas - an essential part of the mangrove forests - for urban occupation and aquaculture. The intense mobilization of scientists and society was fundamental in overturning this resolution and guaranteeing the protection of the apicuns (Copertino et al., 2020; Bernardino et al., 2021). Subsequently, the Resolution was declared unconstitutional, with the immediate restoration of the validity and effectiveness of CONAMA Resolutions Nos. 284/2001, 302/2002 and 303/2002.

One of the most recent advances in mangrove protection was the creation of the National Program for the Conservation and Sustainable Use of Brazilian Mangroves - ProManguezal (Decree No. 12,045 of June 5th, 2024). The initiative defines guidelines, implementation axes and lines of action for the conservation, recovery and sustainable use of mangroves. The decree emphasizes the need to consider mangroves in their entirety, including washes, mangrove forests and apicuns.

The ProManguezal is the result of more than a decade of work by representatives of academia, the federal government and civil society, among other partners, and incorporates important elements of social representation in its planning and construction, with the active participation of traditional populations and communities.

Public policies for mangrove conservation must advance on two fronts: preparing the coastal region to adapt to ongoing climate change and strongly reducing historical pressures on the ecosystem (aquaculture, agriculture, logging, the fishing industry and urban, industrial and tourist facilities; ICMBio, 2018). New public policy proposals must essentially consider the maintenance of existing forests, the restoration of degraded mangroves, and the definition of space for their migration especially in urban areas and under the scenario of increased sea level rise (Table 3).

Table 3. Set of standards necessary to guarantee the conservation of mangroves in the coastal zone.

Pressure	Effect	Existing Law	Future Solutions
Climate change	Rising sea levels	Occupation of land use in the coastal zone by municipal and state laws	▪ Establish urban areas of public interest to maintain mangroves ▪ Legislation for the specific protection of wetlands and transitional brackish wetlands, generally located behind mangrove areas.
Urban occupation or removal of mangroves	Cities	CONAMA Resolution 303/2002	▪ Prioritize infrastructure that favors the function and structure of the mangrove, e.g. install elevated roads instead of embankments; ▪ Establish urban areas of public interest to maintain mangroves ▪ Legislation to establish a green belt around the mangroves (even in degraded areas)
	Pressure for shrimp farming	CONAMA Resolutions 284/2001, 302/2002 and 303/2002	▪ Increase from 17 to 30% of mangroves in full protection UCs ▪ Encourage mangrove restoration, in line with CONAMA 429 (Recovery of APPs) ▪ Review the article of the Forest Code (Law No. 12.651, of May 25, 2012; Art. 11-A; § 1) where the practice of shrimp farming in apicuns/mangrove areas was legalized. ▪ Prevent shrimp farming inside any type of Conservation Unit, similar to MMA Normative Instruction No. 03 of 16/04/2008, for federal Conservation Units.

12

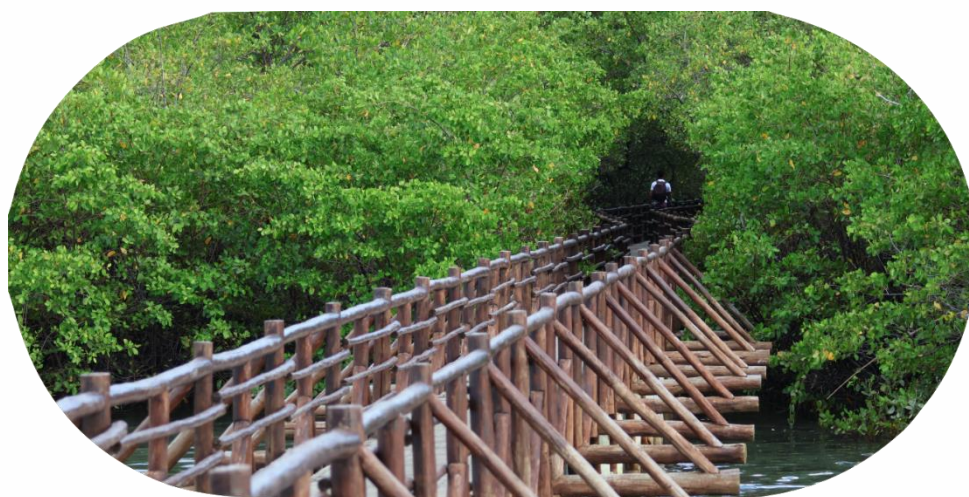
EDUCATION AND COMMUNICATION

EDUCATION AND
COMMUNICATION

12. EDUCATION AND COMMUNICATION

The 2022 demographic census indicates that more than half of the Brazilian population (~111 million) lives near the coast, less than 150 km from the sea, in more than 400 coastal municipalities (IBGE, 2024). Many of the coastal cities were built around estuaries, bays and lagoons with mangroves, which highlights the socio-environmental importance of these ecosystems. Among the various ecosystem services provided by mangroves, cultural benefits stand out. Mangroves can be seen as a living space for teaching and learning about global ecological processes of adaptation, resilience and biogeochemical cycles, presenting tangible examples between theory and practice (Almeida et al., 2023).

The First Meeting on Environmental Education in Mangrove Areas (ENEAAM) took place in the 90s. From 1994 to 2008 there were 15 meetings, interspersed with Regional Meetings (EREAAM), in 13 municipalities in 10 states, boosting publications, especially since 2005. These meetings introduced educational and communication strategies and were open to community leaders and mangrove stakeholders. Proposals discussed at the meetings were incorporated into educational practices aimed at improving expression skills within the school community, as well as the creation of pedagogical tools within communities (Almeida et al., 2023).



The BiomaBrasil Institute has contributed to the training of public-school teachers with the "Didactic Guide to Brazil's Marvelous Mangroves" project. Since 2007, the project has trained 680 education professionals from 189 schools in 15 coastal municipalities, covering topics such as mangrove ecology, connectivity, environmental



impacts, climate change and environmental citizenship, among others (Massei et al., 2024). The records of this and other projects fed into a monitoring platform, coordinated by a Management Committee formed by the Ministry of the Environment and Climate Change (MMA), through the Department of Environmental Education and Citizenship-DEA (Raymundo et al., 2024).

The general objective of the Political Pedagogical Project for the Coastal and Marine Zone (PPPZCM) is to create pedagogical and institutional guidelines that contribute to the development of educational processes with a focus on the sustainable use and conservation of biodiversity in Brazil's Coastal and Marine Zone. The platform called Monitora/PPPZCM is a technological tool for the collective and collaborative monitoring and evaluation of each of the educational initiatives that make up the operational axis of the project, making it possible to increase visibility, transparency and critical analysis of the progress and challenges in implementing the guidelines and objectives of the PPPZCM (Raymundo et al., 2024). The platform has 419 actions registered along the Brazilian coast, almost half of which are on the northeastern coast.

As of 2025, Brazilian schools will have to work in the classroom with themes associated with climate change and the protection of biodiversity, following the sanction of Federal Law No. 14.926/2023, which modifies the National Environmental Education Policy (PNEA - Federal Law No. 9.795/99), adding the study of these subjects among the objectives of national environmental education.

The promotion of the Decade of Ocean Science for Sustainable Development and the Decade of Restoration, promulgated by the UN, as well as the Sustainable Development Goals, find in environmental education and citizen science a space to catalyze social engagement in the face of the environmental crisis and climate emergency. The Brazilian Citizen Science Network (RBCC), the Brazilian Environmental Education Network (REBEA) and the Coastal and Marine Environmental Education Network (REACOMAR) are formed and self-managed by Brazilian social organization, with representatives from academia, NGOs, educators, who bring socio-environmental issues related to mangroves into their various practices.

Programs and projects, linked to teaching and research institutions and NGOs, reinforce school practice in order to engage children and



young people in the conservation of the seas, coastal ecosystems and mangroves. Of particular note is the Blue School Program, supported by the Ministry of Science, Technology and Innovation, which creates a network of schools and partners and guides actions to diversify learning, which is already present in 21 Brazilian states.

Regional and local actions, such as the Sea Schools in Santos and Santa Catarina, linked to the Municipal Education Departments, promote teacher training, the production of educational materials and experiences in the mangroves as a teaching-learning strategy. In the field of citizen science, the RestoreSea and Raízes da Cooperação projects provide the Scientist of the Sea application (<https://raiz.top/>) to promote analysis of the structure and health of mangroves, organizing and sharing geo-referenced results in accessible language for students, educators and environmental managers. These actions are necessary, since the training of educators, the production of educational material and tools to be applied in the educational sphere are identified as limitations to promoting environmental and scientific education, with a focus on mangroves, in schools (Fonseca et al., 2024).

In addition to these networks, and in accordance with the recommendations of the 1st Intergovernmental Conference on Environmental Education in Tbilisi (1977) and Decree No. 4,281 of June 25th, 2002, the Interinstitutional Commissions for Environmental Education (CIEAs) connect the various state secretariats, such as the environment and education, and other social actors, such as representatives of teaching and research institutions and NGOs.

The CIEAs work at the state level of the Brazilian federation to identify, analyze and propose actions and participatory processes in the construction and monitoring of environmental education policies and programs. These organizational structures are the basis for the promotion of climate-critical Environmental Education and should be considered to enable actions in favour of the conservation and restoration of mangroves, as a strategy for mitigating and adapting to the climate emergency.

13

PRIORITY THEMES AND ACTIONS



PRIORITY THEMES
AND ACTIONS

13. PRIORITY THEMES AND ACTIONS



Promoting Interdisciplinarity and Social Participation

It is now widely recognized that maintaining the ecosystem services provided by mangroves depends on the knowledge accumulated by various groups in society, including indigenous communities, quilombolas and traditional fishing communities.

Exclusive reliance on scientific knowledge can result in limited and socially unjust interventions, as they tend to be based on partial evidence and mainly reflect the predominant interests of academia (Ludwig et al., 2022). One way of integration is the active participation of traditional peoples, which serves as a tool for the different types of accumulated knowledge to influence and promote environmental solutions (Glaser, 2003).

This transdisciplinary research strategy allows other actors to contribute to sustainable development and the common good in alternative and potentially more effective ways, especially when tackling current complex problems such as climate change (Lawrence et al., 2022). Thus, considering that the inclusive approach of peoples with traditional knowledge and academia can be more efficient in terms of implementing public policies, it is essential to invest in research that seeks to intensify these interactions.

Monitoring Climate Change

In order to understand the effects of climate change on mangroves, monitoring studies should be carried out at different time scales. Studies on relatively short time scales (i.e., snapshot, monthly, seasonal or lasting only a few years) can identify some of these effects, such as the impacts of extreme events like major storms, floods, droughts and severe heat waves.

However, to understand the effects of an increase in the frequency of extreme events or even chronic effects on decadal time scales, including rising ocean water temperatures or rising sea levels, long-term monitoring and research is needed. These long-term studies are essential to investigate changes in the relationships between biodiversity, mangrove functioning, public health and human well-being.

Monitoring mangrove cover over longer time scales can be carried out using remote sensing. Although sensing is important, there are limitations to what can actually be monitored. For example, when assessing ecosystem services and the health of mangrove forests, determining the cause of changes in mangrove cover often cannot be established (e.g., Neres et al., 2024).



In addition, many other effects are not assessed using remote sensing alone (i.e., changes in provisioning and cultural services, changes in biodiversity). Thus, implementing public policies to increase investment in long-term research and monitoring of Brazilian mangroves would be important to foster the formation and



enhancement of research networks in existing national programs (e.g., Long-Term Ecological Program, PPBio).

Reducing Spatial Gaps

In order for mangroves and other blue carbon ecosystems to be evaluated in terms of the benefits associated with their conservation and restoration, as well as included in the national GHG inventory, it is essential to improve the resolution in quantifying carbon storage and accumulation rates along the Brazilian coast. This requires that the planning and experimental design of projects be robust, cost-effective, aligned with public policies and take into account the variability of carbon stocks and accumulation rates, which can vary by orders of magnitude within the same ecosystem (Hatje et al., 2021; 2023). In addition, it is necessary to consider GHG flows within and between different coastal regions.

Differentiating carbon accumulation capacity between ecosystems should prioritize organic carbon accumulation rates over time, rather than just comparing stocks. This approach is more effective for identifying "hotspots" of carbon accumulation, which are essential for conservation and restoration strategies. The assessment of blue carbon ecosystems should also be done on a landscape scale, so that carbon transfers between ecosystems are accounted for. In addition, the net balance of carbon flows is necessary to estimate the mitigation potential of mangroves in relation to greenhouse gas emissions from the burning of fossil fuels.

However, there is still little knowledge about the net lateral exchange of carbon species by tides, especially the export of alkalinity, which is recognized as a long-term carbon storage mechanism in coastal waters (Ovalle et al., 1990). This process can account for between 25% and 40% of carbon balances in mangroves and tidal flats (Bogard et al., 2020; Reithmaier et al., 2023). Predicting how the balance of carbon fluxes in mangroves will be affected by climate change is crucial to assessing the permanence of the organic carbon stored in these ecosystems and their ongoing potential for removing atmospheric CO₂.

In the experimental planning of projects, careful stratification must be employed, taking into account the variations in environmental conditions (e.g., geomorphology, climate zone, hydrodynamics,



distance from the coast and vegetation cover) that influence carbon accumulation and associated fluxes. It is essential to ensure the use of best practices in field procedures, including sample collection and laboratory methods for determining carbon content, accumulation and emission rates, the origin of carbon stocks and the uncertainties associated with each method.

This ensures that high-quality data is obtained, based on robust and conservative calculations of the status (baselines) and additionality resulting from restoration and conservation actions. In order to reduce information gaps, the involvement of coastal and traditional communities is essential. In addition, this involvement will maximize the potential socio-economic benefits, increasing the likelihood that future blue carbon projects will generate multiple co-benefits for both people and the environment.

Inventory and Monitor GHG Flows (Emissions and Removals)

Knowing the net balance of carbon flows makes it possible to estimate the mitigation potential of mangroves in relation to greenhouse gas emissions from burning fossil fuels. Anthropogenic impacts on coastal ecosystems generally intensify greenhouse gas (GHG) emissions, creating opportunities for actions to protect and restore these ecosystems, with the aim of mitigating the effects of climate change and generating multiple co-benefits.

To this end, it is essential to produce data that quantifies the baseline conditions and projects the benefits in terms of reducing GHG emissions. Acquiring this information for restoration initiatives is therefore essential, since the limited volume of spatial and temporal data that currently exists limits progress in applying it to public policies.

Mapping Ecosystem Services

It is essential to make progress in mapping and determining and valuing the ecosystem services of mangroves along the entire Brazilian coast. In Brazil, the ecosystem services provided by mangroves are public goods, and therefore threatened by land ownership or degradation of these ecosystems. It is therefore necessary to value these services in order to manage them effectively, including risk and feasibility analyses of projects that propose suppressing the



vegetation. This data is essential for efficient territorial coastal management, and can even guide estimates of environmental data and the recovery of degraded areas by public bodies.

To map and manage mangroves with a focus on their long-term protection and the well-being of coastal communities, it is essential to integrate traditional ecological knowledge with academic knowledge, based on validated data. This approach must go beyond carbon-related benefits to cover the full range of ecosystem services, quantifying them and attributing value to them on a local scale. The mapping of ecosystem services and a fair capitalization of the services that depend on responsibility for understanding the benefits and community management (Albuquerque et al., 2021).

Perfecting the Science of Restoration

In order to achieve restoration goals, the risks of large projects must be reduced by adopting implementation and monitoring protocols that have already been validated, tested and replicated. Mangrove restoration requires investing in capacity building for traditional and/or local communities, as well as mechanisms to match restoration opportunities with interested potential investors.

The creation of public-private partnerships for mangrove restoration, in conjunction with local communities, is highly recommended in order to make blue carbon projects viable and incentivize them with the aim of obtaining credits.

All the priority themes listed above are in line with recent plans for the conservation and restoration of mangroves (e.g., ProManguezaI, MMA) and Brazilian biomes (Native Vegetation Restoration Plan) and with existing research networks.

14

CONCLUSIONS



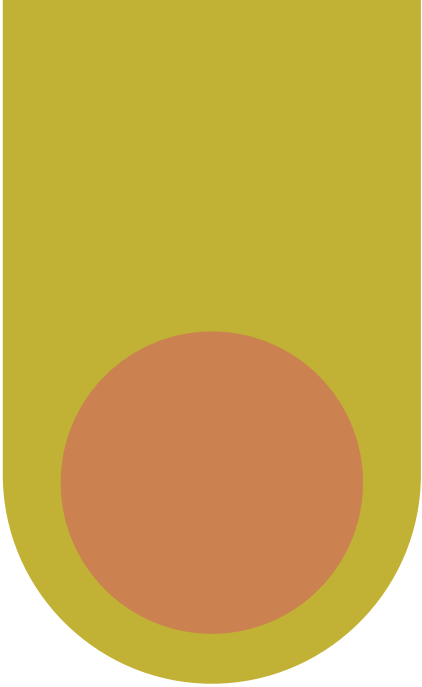
CONCLUSIONS

14. CONCLUSIONS

Brazil has a tremendous expanse of mangroves with significant ecological and climatic potential and which support the lives of millions of people through the conservation and sustainable use of these forests. Brazilian mangroves sequester and store carbon at levels compatible with other tropical nations, and are in a remarkable state of conservation as a result of successful public policies and a robust legal framework. Mangroves provide a range of direct and indirect benefits to the Brazilian population, and benefit economic sectors of relevance to the country. Considerable scientific progress has been made in recent years through studies of mangrove forests from the north to the south of the country, and today allows for a better understanding of their cultural, social and economic value.

With the knowledge acquired about mangroves, the country can advance in strategies established in climate agreements and use the mitigation and restoration of these forests in its inventory of greenhouse gas emissions. There are forest cover monitoring platforms that, together with field studies, already provide estimates of emissions avoided by the degradation and removal of mangrove forests in some regions of Brazil. The advancement of carbon market projects using blue carbon requires important technical and legal regulations in order to attract international investment and thus make new mitigation and restoration measures viable.

There are important regional threats, regulatory weakening and scientific uncertainties about the future of mangroves, and about the associated effects of climate and rising mean sea level. Some of these uncertainties should be the focus of long-term studies in Brazil and the attention of regulatory bodies in order to increase the climate resilience of these forests. **Mangrove forests will be key to our adaptation to a more unpredictable climate and a changing ocean in the coming decades, especially in coastal urban areas where the potential for damage to infrastructure and people is greatest.**



REFERENCES



REFERENCES CITED

- ABRAHÃO, G. R., ASMUS, M. Sistema de governança em Unidades de Conservação. *Desenvolvimento e Meio Ambiente*, v. 44, p. 104 – 117, 2018. DOI: <https://doi.org/10.5380/dma.v44i0.54962>
- ALMEIDA, R.; SCHAEFFER-NOVELLI, Y.; DELGADO-MENDEZ, J. M.; ABUCHAHILA, G. M. O. COELHO-JR, C. Contribution of Environmental Education to Mangrove Conservation. In: NOVELLI, Y. S et al (Eds.): *Brazilian Mangroves and Salt Marshes*. Springer Nature Switzerland, 2023.
- ALONGI, D. M. Present state and future of the world's mangrove forests. *Environmental Conservation*, v. 29, pp. 331– 49, 2002.
- ALONGI, D. M. Global significance of Mangrove Blue Carbon for Climate Change *Mitigation*, v. 2, n. 67, p. 1-15, 2020.
- ASCHENBRENNER, A., HACKRADT, C. Q., FERREIRA, B. P. Spatial variation in density and size structure indicate habitat selection throughout life stages of two SW Atlantic snappers. *Marine Environmental Research*, v. 113, pp. 49–55, 2016.
- BARBIER, E. B, HACKER, S. D, KENNEDY, C, KOCH, E. W, STIER, A. C, SILLIMAN, B. R. The value of estuarine and coastal ecosystem services. *Ecological Monographs*, v. 81, pp. 169–93, 2010.
- BARCELLOS, D., QUEIROZ, H. M., NÓBREGA, G. N., DE OLIVEIRA FILHO, R. L., SANTAELLA, S. T., OTERO, X. L., FERREIRA, T. O. Phosphorus enriched effluents increase eutrophication risks for mangrove systems in northeastern Brazil. *Mar. Pollut. Bull.* v. 142, p. 58–63, 2019. DOI: <https://doi.org/10.1016/j.marpolbul.2019.03.031>
- BARRETO, L. M. T, LANZARINI, R. S. B. Política Nacional de Turismo de Base Comunitária : subsídios e orientações técnicas. Natal, RN. Ministério do Turismo, 2023.
- BEESTON, M., CAMERON, C., HAGGER, V., HOWARD, J., LOVELOCK, C., SIPPO, J., et al (Eds.): *Best practice guidelines for mangrove restoration*. Washington DC: Global Mangrove Alliance, 2023.
- BERNARDINO, A. F., SANDERS, C. J., BISSOLI, L. B., GOMES, L. E. O., KAUFFMAN, J. B., FERREIRA, T. O. Land use impacts on benthic bioturbation potential and carbon burial in Brazilian mangrove ecosystems. *Limnology and Oceanography*, v. 65, p. 2366–2376, 2020. DOI: <https://doi.org/10.1002/lno.11458>
- BERNARDINO, A. F., NOBREGA, G. N., FERREIRA, T. O. Consequences of terminating mangrove's protection in Brazil. *Marine Policy*, v. 125, p. 1–3, 2021.
- BERNARDINO, A. F., MAZZUCO, A. C. A., SOUZA, F. M., SANTOS, T. M. T., SANDERS, C. J., MASSONE, C. G., COSTA, R. F., SILVA, A. E. B., FERREIRA, T. O., NÓBREGA, G. N., SILVA, T. S. F., KAUFFMAN, J. B. The novel mangrove environment and composition of the Amazon Delta. *Current Biology*, v. 32, 3636–3640.e2, 2022.
- BERNARDINO, A. F., MAZZUCO, A. C. A., COSTA, R. F., SOUZA, F., OWUOR, M. A., NÓBREGA, G. N., SANDERS, C. J., FERREIRA, T. O., KAUFFMAN, J. B., 2024a. The inclusion of Amazon mangroves in Brazil 's REDD + program. *Nature Communications*, v. 15, p. 1549–1559. DOI: <https://doi.org/10.1038/s41467-024-45459-w>
- BERNARDINO, A. F., QUEIROZ, H. M., NÓBREGA, G. N., COPPO, G. C., SANDERS, C. J., SILVA, A. E. B., KAUFFMAN, J. B., COSTA, R. F., PACHECO, C. F., VASSOLER, A., PEREIRA, A. P., RUIZ, F., FERREIRA, T. O. Soil greenhouse gas fluxes partially reduce the net gains in carbon sequestration in mangroves of the Brazilian Amazon. *Environmental Research*, v. 263, 120102, 2024.
- BOGARD, M. J., BERGAMASCHI, B. A., BUTMAN, D. E., ANDERSON, F., KNOX, S. WINDHAM-MYERS, L. Hydrologic Export Is a Major Component of Coastal Wetland Carbon Budgets. *Global Biogeochemical Cycles*, v. 34, n. 8, pp. 1–14, 2020. <https://doi.org/10.1029/2019GB006430>
- BRASIL. Decreto nº 12.045, de 5 de junho de 2024. Institui o Programa Nacional de Conservação e Uso Sustentável dos Manguezais do Brasil. Diário Oficial da União: seção 1, Brasília, DF, 6 jun. 2024.
- BRASIL, 2016. Plano Nacional de Adaptação à Mudança do Clima: volume 1: estratégia geral: portaria MMA no 150 de 10 de maio de 2016 / Ministério do Meio Ambiente.
- BRASIL, 2023. Brazil's National Forest Reference Emission Level for Results- based payments for REDD+ under the United Nations Framework Convention on Climate Change.
- BREITHAUPT, J. L., STEINMULLER, H. E. Refining the global estimate of mangrove carbon burial rates using sedimentary and geomorphic settings. *Geophysical Research Letters*, v. 1, n. 18, e2022GL100177, 2022.
- BUNTING, P.; ROSENQVIST, A.; HILARIDES, L.; LUCAS, R.M.; THOMAS, N.; TADANO, T.; WORTHINGTON, T. A.; SPALDING, MURRAY, N. J.; REBELO, L.-M. 2022. Global Mangrove Extent Change 1996–2020. *Remote Sens*, v. 14, n. 15, 3657, 2022.
- CABRAL, A., DITTMAR, T., CALL, M., SCHOLTEN, J., REZENDE, C., ASP, N., GLEDHILL, M., SEIDEL, M., SANTOS, I. Carbon and alkalinity outwelling across the groundwater- creek-shelf continuum off Amazonian mangroves. *Limnology and Oceanography Letters*, v. 6, pp. 369–378, 2021. DOI: <https://doi.org/10.1002/lol2.10210>
- CABRAL, A., REITHMAIER, G.M.S., YAU, Y. Y. Y., COTOVICZ, L., BARREIRA, J., VIANA, B., HAYDEN, J.,

- BOUILLON, S., BRANDINI, N., HATJE, V., REZENDE, C., FONSECA, A., SANTOS, I. Large porewater-derived carbon outwelling across mangrove seascapes revealed by radium isotopes. *Journal of Geophysical Research: Oceans*, v. 129, e2024JC021319, 2024. DOI: <https://doi.org/10.1029/2024JC021319>
- CADIER, C., BAYRAKTAROV, E., PICCOLO R AND ADAME, MF. Indicators of Coastal Wetlands Restoration Success: A Systematic Review. *Frontiers in Marine Science*. v. 7, 600220, 2020.
- CARRUTHERS, T. J. B.; JONES, S. B.; TERRELL, M. K.; SCHEIBLY, J. F.; PLAYER, B. J.; BLACK, V. A.; EHRENWERTH, J. R.; BIBER, P. D.; CONNOLLY, R. M.; CROOKS, S.; CUROLE, J. P.; DARNELL, K. M.; DAUSMAN, A. M.; DEJONG, A. L.; DOYLE, S. M.; ESPOSITO, C. R.; FRIESS, D. A.; FOURQUEREAN, J. W.; GEORGIOU, I. Y.; GRIMSDITCH, G. D.; HE, S.; HILLMANN, E. R.; HOLM, G. O. Jr.; HOWARD, J.; JUNG, H.; JUPITER, S. D.; KISKADDON, E.; KRAUSS, K. W.; LAVERY, P. S.; LIU, B.; LOVELOCK, C. E.; MACK, S. K.; MACREADIE, P. I.; MCGLATHERY, K. J.; MEGONIGAL, J. P.; ROBERTS, B. J.; SETTELMYER, S.; STAVER, L. W.; STEVENS, H. J.; SUTTON-GRIER, A. E.; VILLA, J. A.; WHITE, J. R.; WAYCOTT, M. Identifying and filling critical knowledge gaps can optimize financial viability of blue carbon projects in tidal wetlands. *Frontiers in Environmental Science*, v. 12, e1421850, 2024. DOI: <https://doi.org/10.3389/fenvs.2024.1421850>
- COHEN, M. C. L.; RODRIGUES, E.; ROCHA, D. O. S.; FREITAS, J.; FONTES, N. A.; PESSENDA, L. C. R.; DE SOUZA, A. V.; GOMES, V. L. P.; FRANÇA, M. C.; BONOTTO, D. M.; BENDASSOLLI, J. A. Southward migration of the austral limit of mangroves in South America. *Catena*, v. 195, 2025.
- COPERTINO, M. S. Add coastal vegetation to the climate critical list. *Nature*, v. 473, n. 7347, pp. 255–255, 2011. DOI: <https://doi.org/10.1038/473255a>
- COPERTINO, M. S.; CIOTTI, A. M.; LANARI, M.; TARDIN, R.; MAZZUCO, A. C. A.; MOSER, G.; MAGRIS, R. A.; FRÉDOU, F. L.; BOTTA, S.; KIKUCHI, R. K. P. K.; CARDOSO, L. G.; GIARRIZZO; NAGATA, R.; LEONEL, J. 2024. O histórico de mudança e o estado atual da biodiversidade na zona marinha costeira. Em: Sumário para tomadores de decisão: Diagnóstico Marinho-Costeiro da Plataforma Brasileira de Biodiversidade e Serviços Ecosistêmicos. No prelo.
- COSTA, Y., MARTINS, I., CARVALHO, G. C., Barros, F. Trends of sea-level rise effects on estuaries and estimates of future saline intrusion. *Ocean and Coastal Management*, v. 236, 106490, 2023. DOI: <https://doi.org/10.1016/j.ocecoaman.2023.106490>
- COTOVICZ, L. C.; ABRIL, G.; SANDERS, C. J.; TAIT, D. R.; MAHER, D. T.; SIPPO, J. Z.; HOLLOWAY, C.; YAU, Y.; SANTOS, I. Methane oxidation minimizes emissions and offsets to carbon burial in mangroves. *Nature Climate Change*, v. 14, p. 275–281, 2024. DOI: <https://doi.org/10.1038/s41558-024-01927-1>
- DA ROCHA, S. A. N., GUIMARÃES, S. O., LOUREIRO, C. F. B. As políticas públicas como instrumento efetivo para o planejamento territorial e sua relação com o desenvolvimento sustentável. *Revista Brasileira de Planejamento e Desenvolvimento*, v. 9, n. 4, p. 547, 2020.
- DINIZ, C., CORTINHAS, L., NERINO, G., RODRIGUES, J., SADECK, L., ADAMI, M., SOUZA-FILHO, P.W.M. Brazilian Mangrove Status: Three Decades of Satellite Data Analysis. *Remote Sensing*, v. 11, 808, 2019.
- DUPONCHELLE, F., ISAAC, V. J., DORIA, C. R. C., VAN DAMME, P. A., et al. Conservation of migratory fishes in the Amazon basin. *Aquatic Conservation Marine Freshwater Ecosystems*, v. 31, pp. 1087–1105, 2021.
- DUKE, N. C.; KOVACS, J. M.; GRIFFITHS, A. D.; PREECE, L.; HILL, D. J. E.; VAN OOSTERZEE, P.; MACKENZIE, J.; MORNING, H. S.; BURROWS, D. Large-scale dieback of mangroves in Australia. *Marine and Freshwater Research*, v. 68, p. 1816, 2017. <https://doi.org/10.1071/MF16322>
- FERREIRA, A. C., LACERDA, L. D. Degradation and conservation of Brazilian mangroves, status and perspectives. *Ocean and Coastal Management*, v. 125: pp. 38–46, 2016.
- FERREIRA, A. C.; LACERDA, L. D.; RODRIGUES, J. V.; BEZERRA, L. E. A. New contributions to mangrove restoration/rehabilitation protocols and practices. *Forest Ecology & Management*, v. 31, p. 89–114, 2023. <https://doi.org/10.1007/s11273-022-09903-2>
- FERREIRA, T. O.; QUEIROZ, H. M.; NÓBREGA, G. N.; DE SOUZA JÚNIOR, V. S.; BARCELLOS, D.; FERREIRA, A. D.; OTERO, X. L. Litho-climatic characteristics and its control over mangrove soil geochemistry: A macro-scale approach. *Science of the Total Environment*, v. 811, p. 152152, 2022.
- FONSECA, A. L., BAGGIO, M. R., & NUNES, M. R. M. D. Manguezal, o espaço de vivência transdisciplinar para a promoção da ciência cidadã e da cultura oceânica. Em: D. de Castro & L. H. F. Pimenta (Eds.): Os mangues do sul do Brasil. Via Sapiens: 2024.
- FRIESS, D. A. The potential for mangrove and seagrass blue carbon in Small Island States. *Current Opinion in Environmental Sustainability*, 64, 101324, 2023.
- GASPARINETTI, P., JERICO-DAMINELLO, C., SEEHUSEN, S. E., VILELA, T. Os valores ecossistêmicos dos manguezais brasileiros, instrumentos econômicos para sua conservação e o estudo de caso do Salgado Paraense. FUNBIO: GEF Mangue, PNUD, 2018.
- GATT, Y. M.; WALTON, R. W.; ANDRADI-BROWN, A. A.; SPALDING, M. A.; ACOSTA-VELAZQUEZ, J. A.; ADME, M. F.; BARROS, F.; BEESTON, M. A.; BERNARDINO, A. F.; BUELOW, C. A.; CADIER, C. et al. The mangrove restoration tracker tool: meeting

- local practitioner needs and tracking the progress toward global targets. *One Earth*, v. 7, p. 1-14, 2024.
- GLASER, M. Interrelations between mangrove ecosystem, local economy and social sustainability in Caete estuary, North Brazil. *Wetlands Ecology and Management*, v. 11, pp. 265-272, 2003.
- GOMES, L. E. O., BERNARDINO, A. F. Drought effects on tropical estuarine benthic assemblages in Eastern Brazil. *Science of the Total Environment*, v. 703, 135490, 2020.
- GOMES, L. E. O., SANDERS, C. J., NOBREGA, G. N., VESCOVI, L. C., QUEIROZ, H. M., KAUFFMAN, J. B., FERREIRA, T. O., BERNARDINO, A. F. Ecosystem carbon losses following a climate-induced mangrove mortality in Brazil. *Journal of Environmental Management*, v. 297, 113381, 2021a.
- GOMES, L. E. O., VESCOVI, L. C., BERNARDINO, A. F. The collapse of mangrove litterfall production following a climate-related forest loss in Brazil. *Marine Pollution Bulletin*, v. 162, 111910, 2021b.
- HATJE, V.; SOUZA, M. C. B. N.; RIBEIRO, L. F.; EÇA, G. F.; BARROS, F. Detection of environmental impacts of shrimp farming through multiple lines of evidence. *Environmental Pollution*, v. 1, pp. 1-13, 2016. DOI: <https://doi.org/10.1016/j.envpol.2016.06.056>.
- HATJE, V., MASQUÉ, P., PATIRE, V. F., DÓREA, A., BARROS, F. Blue carbon stocks, accumulation rates, and associated spatial variability in Brazilian mangroves. *Limnology and Oceanography*, v. 66, p. 321-334, 2021. DOI: <https://doi.org/10.1002/lno.11607>
- HATJE, V., COPERTINO, M., PATIRE, V. F., OVANDO, X., OGBUKA, J., JOHNSON, B. J., KENNEDY, H., MASQUE, P., CREED, J. C. Vegetated coastal ecosystems in the Southwestern Atlantic Ocean are an unexploited opportunity for climate change mitigation. *Communications Earth & Environment*, v. 4, 160, 2023.
- Herr, D., LANDIS, E. Coastal blue carbon ecosystems. Opportunities for Nationally Determined Contributions. Policy Brief. Gland, Switzerland: IUCN and Washington, DC, USA: TNC - 2016.
- HOWARD, J., SUTTON-GRIER, A., HERR, D., KLEYPAS, J., LANDIS, E., MCLEOD, E., PIDGEON, E., SIMPSON'S. Clarifying the role of coastal and marine systems in climate mitigation. *Frontiers in Ecology and Environment*, v. 15, pp. 42-50, 2017.
- HOLMQUIST, J. R., WINDHAM-MYERS, L., BLISS, N., CROOKS, S., MORRIS, J. T., MEGONIGAL, J. P., TROXLER, T., WELLER, D., CALLAWAY, J., DREXLER, J., FERNER, M. C., GONNEEA, M. E., KROEGER, K. D., SCHIELE-BEERS, L., WOO, I., BUFFINGTON, K., BREITHAUP, J., BOYD, B. M., BROWN, L. N., ... WOODREY, M. (2018). Accuracy and precision of tidal wetland soil carbon mapping in the conterminous United States. *Scientific Reports*, v. 8, 9478, 2018. DOI: <https://doi.org/10.1038/s41598-018-26948-7>
- ICMBio, 2018. Atlas dos Manguezais do Brasil. Instituto Chico Mendes de Conservação da Biodiversidade, Brasília, DF, 176p.
- IPCC, 2019. Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use. Ch 7. Wetlands. Lovelock, C. E., EVANS, C., BARROS, N., PRAIRIE et al.
- JUNK, W. J., PIEDADE, M. T. F., LOURIVAL, R., WITTMANN, F., KANDUS, P. Lacerda, L. D.; BOZELLI, R. L., ESTEVES, F. A., NUNES DA CUNHA, C., MALTCHICK, L., SCHOENGART, J. & SCHAEFFER-NOVELLI, Y., Agostinho, A. Brazilian wetlands: Definition, delineation and classification for sustainable management and protection. *Aquatic Conservation: Marine and Freshwater Ecosystems*, v. 24, pp. 5-22, 2014.
- KAUFFMAN, J. B., BERNARDINO, A. F., FERREIRA, T. O., GIOVANNONI, L. R., GOMES, L. E. O., ROMERO, D. J., JIMÉNEZ, L. C. Z., Ruiz, F. Carbon stocks of mangroves and salt marshes of the Amazon region, Brazil. *Biology Letters*, v. 14, 20180208, 2018a. DOI: <https://doi.org/10.1098/rsbl.2018.0208>.
- KAUFFMAN, J. B., BERNARDINO, A. F., FERREIRA, T. O., BOLTON, N. W., GOMES, L. E. O., NÓBREGA, G. N. Shrimp ponds lead to massive loss of soil carbon and greenhouse gas emissions in northeastern Brazilian mangroves. *Ecology and Evolution*, v. 8, 5530-5540, 2018b. DOI: <https://doi.org/10.1002/ece3.4079>
- LACERDA, L. D.; FERREIRA, A. C., BORGES, R. & WARD, R. D. Mangroves of Brazil. In: Dr. Das, S. C., Ashton, E. and THAMMINENI, P. (Eds): Mangroves: Biodiversity, Livelihoods and Conservation. Springer Verlag: Berlin, 2022.
- LACERDA, L. D.; FERREIRA, A. C., BORGES, R. & WARD, R. D. Challenges to mangroves of the equatorial semiarid coast of Brazil in the Anthropocene. *Coastal Futures*: Cambridge, 2024.
- LANA, P. C., BERNARDINO, A. F. Brazilian Estuaries: A Benthic Perspective. Springer International Publishing, 2018.
- LAWRENCE M. G., WILLIAMS S., NANZ, P., RENN, O. Characteristics, potentials, and challenges of transdisciplinary research. *One Earth*, v. 5, n. 1, pp. 44-61, 2022. DOI: <https://doi.org/10.1016/j.oneear.2021.12.010>.
- LOVELOCK, C. E., FELLER, I. C., REEF, R., HICKEY, S., BALL, M. C. Mangrove dieback during fluctuating sea levels. *Sci. Rep.* v. 7, pp. 1-8, 2017. DOI: <https://doi.org/10.1038/s41598-017-01927-6>
- LOVELOCK, C. E., ADAME, M. F., BRADLEY, J., DITTMAN, S., HAGGER, V., HICKEY, S. M., HUTLEY, L. B., JONES, A., KELLEWAY, J. J., LAVERY, P. S.,

- MCCREADIE, P. I., MAHER, D. T., MCGINLEY, S., MCGLASHAN, A., PERRY, S., MOSLEY, L., ROGERS, K., SIPPO, J. Z. An Australian blue carbon method to estimate climate change mitigation benefits of coastal wetland restoration. *Restoration Ecology*, v. 31, n. 7, e13739, 2023.
- LUDWIG D., BLOK V., GARNIER M., MACNAGHTEN P., POLS A. What's wrong with global challenges? *Journal of Responsible Innovation*, v. 9, n. 1, p. 6-27, 2022. DOI: <https://doi.org/10.1080/23299460.2021.2000130>
- MACCREADIE, P. I., ROBERTSON, A. I., SPINKS, B., ADAMS, M. P., ATCHISON, J. M., BELL-JAMES, J., BRYAN, B. A., CHU, L., et al. Operationalizing marketable blue carbon. *One Earth*, v. 5, 485, 2022.
- MAHER, D. T., SIPPO, J. Z., TAIT, D. R., HOLLOWAY, C., SANTOS, I. R. Pristine mangrove creek waters are a sink of nitrous oxide. *Scientific Reports*, v. 6, 25701, 2016. DOI: <https://doi.org/10.1038/srep25701>
- MASSE, K., SUASSUNA, F., MOTTA E SOUZA, M., MUZZI, M., SCELZA, G. C., SANTOS, M. E. N., COELHO-JR, C., PAIVA, L. M., RÊGO, P. R. M., OLINTO, A., PINHEIRO, B. R. Experiências Exitosas de Formação Socioambiental na Zona Costeira dos estados da Paraíba, Pernambuco e Alagoas. Em: Da implantação ao monitoramento do Projeto Político Pedagógico da Zona Costeira e Marinha do Brasil. Organização: RAYMUNDO, M., H. A., TROVARELLI, R. A., BRANCO, E. A., BRIANEZI, T. São José dos Campos: INPE; ANPPAS, pp. 133-144, 2024.
- MILLENNIUM ECOSYSTEM ASSESSMENT. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC, 2005.
- MURDYIARSO, D., SWALLS, E., HERGOUALC'H, K., BHOMIA, R., SASMITO, S.D. Refining greenhouse gas emission factors for Indonesian peatlands and mangroves to meet ambitious climate targets. Proceedings of the National Academy of Sciences of the United States, 2024.
- NELLEMAN, C., CORCORAN, E., DUARTE, C.M., VALDRÉS, L., YOUNG, C. D., FONSECA, L., GRIMSDITCH, G. Blue Carbon: The Role of Healthy Oceans in Binding Carbon. UN Environment, GRID-Arendal, 2009.
- NERES J. N., STENZEL G. M. R., MIELKE, M. S., BARROS F. Mangrove forest health condition from space and the use of in situ data. *Marine Environmental Research*, v. 201: 106704, 2024. DOI: <https://doi.org/10.1016/j.marenvres.2024.106704>
- NÓBREGA, G. N. N., OTERO, X. L. L., MACÍAS, F., FERREIRA, T. O. O. Phosphorus geochemistry in a Brazilian semiarid mangrove soil affected by shrimp farm effluents. *Environmental Monitoring Assessment*, v. 186, pp. 5749-5762., 2014. DOI: <https://doi.org/10.1007/s10661-014-3817-3>
- NÓBREGA, G. N., FERREIRA, T. O., SIQUEIRA NETO, M., QUEIROZ, H. M., ARTUR, A. G., MENDONÇA, E. D. S., SILVA, E. D. O., OTERO, X. L. Edaphic factors controlling summer (rainy season) greenhouse gas emissions (CO₂ and CH₄) from semiarid mangrove soils (NE-Brazil). *Science of the Total Environment*, v. 542, pp. 685-693, 2016. DOI: <https://doi.org/10.1016/j.scitotenv.2015.10.108>
- NÓBREGA, G. N., FERREIRA, T. O., SIQUEIRA NETO, M., MENDONÇA, E. DE S., ROMERO, R.E., OTERO, X. L. The importance of blue carbon soil stocks in tropical semiarid mangroves: a case study in Northeastern Brazil. *Environmental Earth Sciences*, v. 78, p. 369, 2019. DOI: <https://doi.org/10.1007/s12665-019-8368-z>
- OGDEN, J. C. Ecosystem interactions in the tropical coastal seascape. In: Birkeland C, Ed. Life and Death of Coral Reefs. New York: Chapman & Hall, 1997.
- OTERO, X. L., MÉNDEZ, A., NÓBREGA, G. N., FERREIRA, T. O., SANTISO-TABOADA, M. J., MELÉNDEZ, W., MACÍAS, F. High fragility of the soil organic C pools in mangrove forests. *Marine Pollution Bulletin*, v. 119, p. 460-464, 2017. DOI: <https://doi.org/10.1016/j.marpolbul.2017.03.074>
- OTERO, X. L., ARAÚJO, J. M. C., BARCELLOS, D., QUEIROZ, H. M., ROMERO, D. J., NÓBREGA, G. N., SIQUEIRA NETO, M., FERREIRA, T. O. Crab Bioturbation and Seasonality Control Nitrous Oxide Emissions in Semiarid Mangrove Forests (Ceará, Brazil). *Applied Sciences*, v. 10, 2215, 2020. DOI: <https://doi.org/10.3390/app10072215>
- OVALLE, A. R. C., REZENDE, C. E., LACERDA, L. D & SILVA, C. A. R. Factors affecting the hydrochemistry of a mangrove tidal creek in Sepetiba Bay, Rio de Janeiro, Brazil. *Estuarine, Coastal & Shelf Science*, v. 31, pp. 639-650, 1990. DOI: [https://doi.org/10.1016/0272-7714\(90\)90017-L](https://doi.org/10.1016/0272-7714(90)90017-L)
- OWUOR, M., SANTOS, T. M. T., OTIENO, P., MAZZUCO, A. C. A., IHEATURU, C., BERNARDINO, A.F. Flow of mangrove ecosystem services to coastal communities in the Brazilian Amazon. *Front. Environ. Sci.* v. 12, 2024. DOI: <https://doi.org/10.3389/fenvs.2024.1329006>
- PAGLIOSA, P. R., ROVAI, A. S., FONSECA, A. L. Carbon mismanagement in Brazil. *Nature Climate Change*, v. 2, n. 11, p. 764, 2012. DOI: <https://doi.org/10.1038/nclimate1718>
- PAGLIOSA, P., ZANETTI, A., FONSECA, A. L. Os manguezais e o carbono azul. In D. DE CASTRO & L. H. F. PIMENTA (Eds.): Os mangues do sul do Brasil. Via Sapiens, 2024.
- PASSOS, T., BERNARDINO, A. F., PENNY, D., BARCELLOS, R., PASSOS, F. U., NOBREGA, G. N., FERREIRA, T. O., KAUFFMAN, J. B., SANDERS, C. J. Low carbon accumulation in a macro-tidal mangrove forest on the Amazon coast. *Limnology and Oceanography*, v. 68, pp. 1936-1948, 2023. DOI: <https://doi.org/10.1002/lno.12396>

- POLETTE, M. Legislation. In: SCHAEFFER-NOVELLI, Y. (Edit.): Mangrove Ecosystems: Between Land and Sea. Caribbean Ecological Research, 1995.
- PROJETO MAPBIOMAS – Mapeamento Anual de Cobertura e Uso da Terra na Zona Costeira - Coleção 7, 2022.
- QUEIROZ, H. M., ARTUR, A. G., TANIGUCHI, C. A. K., SILVEIRA, M. R. S. DA, NASCIMENTO, J. C. DO, NÓBREGA, G. N., OTERO, X. L., FERREIRA, T. O. Hidden contribution of shrimp farming effluents to greenhouse gas emissions from mangrove soils. *Estuarine Coastal and Shelf Sciences*, v. 221, pp. 8-14, 2019. DOI: <https://doi.org/10.1016/j.ecss.2019.03.011>
- QUEIROZ, H. M., FERREIRA, T. O., FANDIÑO, V. A., BRAGANTINI, I. O. B. F., BARCELLOS, D., NÓBREGA, G. N., FERREIRA, A. D., GOMES, L. E. O., BERNARDINO, A. F. Changes in soil iron biogeochemistry in response to mangrove dieback. *Biogeochemistry* v. 158, pp. 357-372, 2022. DOI: <https://doi.org/10.1007/s10533-022-00903-1>
- RAYMUNDO, M. H. A., TROVARELLI, R. A., BRANCO, E. A., BRIANEZI, T. (Org): Da implementação ao monitoramento do Projeto Político Pedagógico da Zona Costeira e Marinha do Brasil. São José dos Campos: INPE; ANPEA - 2024.
- REIS-FILHO, J. A., GIARRIZZO, T. & BARROS, F. Tidal migration and cross-habitat movements of fish assemblage within a mangrove ecotone. *Marine Biology*, v. 163, 111, 2016. DOI: <https://doi.org/10.1007/s00227-016-2885-z>
- REITHMAIER, G. M. S., CABRAL, A., AKHAND, A., BOGARD, M. J., BORGES, A. V., BOUILLON, S., BURDIGE, D. J., CALL, M., CHEN, N., CHEN, X., COTOVICZ, L. C., EAGLE, M. J., KRISTENSEN, E., KROEGER, K. D., LU, Z., MAHER, D. T., PÉREZ-LLORENS, J. L., RAY, R., TAILLARDAT, P., SANTOS, I. R. Carbonate chemistry and carbon sequestration driven by inorganic carbon outwelling from mangroves and saltmarshes. *Nature Communications*, v. 14, n. 1, 8196, 2023. DOI: <https://doi.org/10.1038/s41467-023-44037-w>
- RICO, A., REDONDO-HASSELERHARM, P. E., SCHELL, T., SANDERS, C. J. BERNARDINO, A. F. Microplastic burial potential and ecological risks in mangrove forests of the Amazon River delta. *Science of the Total Environment*, v. 957, 177666, 2024.
- ROSARIO, R. P. G., E ABUCHAHLA, G. M. O. Arcabouço legal de proteção aos manguezais. In: Atlas dos Manguezais do Brasil. Brasília: Instituto Chico Mendes de Conservação da Biodiversidade, 2018.
- ROSENTERER, J. A., MAHER, D. T., ERLER, D. V., MURRAY, R. H., EYRE, B. D. Methane emissions partially offset “blue carbon” burial in mangroves. *Science Advances*, v. 4, eaao4985, 2018. DOI: <https://doi.org/10.1126/sciadv.aao4985>
- ROVAI, A. S., TWILLEY, R. R., CASTAÑEDA-MOYA, E. et al. Global controls on carbon storage in mangrove soils. *Nature Clim Change*, v. 8, pp. 534-538, 2018. DOI: <https://doi.org/10.1038/s41558-018-0162-5>
- ROVAI, A. S., COELHO-JR, C., ALMEIDA, R., CUNHA-LIGNON, M., MENGHINI, R. P., TWILLEY, R. R., CINTRON-MOLERO, G., SCHAEFFER-NOVELLI, Y. Ecosystem-level carbon stocks and sequestration rates in mangroves in the Cananéia-Iguape lagoonal estuarine system, SE Brazil. *Forest Ecology and Management*, v. 479, 118553, 2021.
- ROVAI, A. S., TWILLEY, R. R., WORTHINGTON, T. A., RIUL, P. Brazilian mangroves: blue carbon hotspots of national and global relevance to natural climate solutions. *Frontiers in Forests and Global Change*, v. 4, 787533, 2022. DOI: <https://doi.org/10.3389/ffgc.2021.787533>.
- RUIZ, F., BERNARDINO, A. F., QUEIROZ, H. M., OTERO, X. L., RUMPEL, C., FERREIRA, T. O. Iron's role in soil organic carbono (de)stabilization in mangroves under land use change. *Nature Communications*, v. 15, 10433, 2024. DOI: <https://doi.org/10.1038/s41467-024-54447-z>
- RUIZ-JAEN, M. C., AND AIDE, T. M. Restoration success: how is it being measured? *Restoration Ecology*, v. 13, pp. 569-577, 2005.
- SANDERS, C. J., SMOAK, J. M., SANDERS, L. M., NAIDU, A. S., PATCHINEELAM, S. R. Organic carbon accumulation in Brazilian mangal sediments. *Journal of South American Earth Sciences*, v. 30, pp. 189-192, 2010.
- SANTANA FILHO, D. M., FERREIRA, A. J., GOES, E. F., CAMPOS, A. C. P. Nota Técnica 1: Governança de Desastres, Trade-off e Adaptação Norte e Nordeste do Brasil. Editora Iyaleta. Iyaleta – Pesquisa, Ciências e Humanidade, 2023.
- SANTOS-ANDRADE, M., HATJE, V., ARIAS-ORTIZ, A., PATIRE, V. F., DA SILVA, L. A. Human disturbance drives loss of soil organic matter and changes its stability and sources in mangroves. *Environmental Research*, v. 202, 111663, 2021.
- SCHAEFFER-NOVELLI, Y., CINTRÓN-MOLERO, G., ADAIME, R. R., DE CAMARGO, T. M., CINTRON-MOLERO, G., DE CAMARGO, T. M. Variability of mangrove ecosystems along the Brazilian coast. *Estuaries*, v. 13, pp. 204-218, 1990. DOI: <https://doi.org/10.2307/1351590>.
- SCHAEFFER-NOVELLI, Y., SORIANO-SIERRA, E. J., VALE, C. C., BERNINI, E., ROVAI, A. E., PINHEIRO, M. A. A., SCHMIDT, A. J., ALMEIDA, R., COELHO JR, C. C., MENGHINI, R. P., MARTINEZ, D. I., ABUCHALA, G. M. O., CUNHA-LIGNON, M., CHARLIER-SARUBO, S., SHIRAZAWA-FREITAS, J., CINTRON-MOLERO, G. Climate changes in mangrove forests and salt marshes. *Brazilian Journal of Oceanography*, v. 64, pp. 37-52, 2016.

SERVINO, R. N., GOMES, L. E. O., BERNARDINO, A. F. Extreme weather impacts on tropical mangrove forests in Eastern Brazil. *Science of the Total Environment*, 628-629, pp. 233-240, 2018.

SPALDING, M., PARRETT, C. L. Global patterns in mangrove recreation and tourism. *Marine Policy*, v. 111, 103540, 2019.

SUÁREZ-ABELENDA, M., FERREIRA, T. O., CAMPS-ARBESTAIN, M., RIVERA-MONROY, V. H., MACÍAS, F., NÓBREGA, G. N., OTERO, X. L. The effect of nutrient-rich effluents from shrimp farming on mangrove soil carbon storage and geochemistry under semi-arid climate conditions in northern Brazil. *Geoderma*, v. 213, pp. 551-559, 2014. DOI: <https://doi.org/10.1016/j.geoderma.2013.08.007>

YAU, Y. Y. Y., CABRAL, A., REITHMAIER, G., COTOVICZ, L. C., JR, BARREIRA, J., ABRIL, G., MORANA, C., BORGES, A. V., MACHADO, W., GODOY, J. M., BONAGLIA, S., SANTOS, I. R. Efficient oxidation attenuates porewater-derived methane fluxes in mangrove waters. *Limnology and Oceanography*, v. 69, pp. 1997-2014, 2024. DOI: <https://doi.org/10.1002/lno.12639>

VANDERKLIFT, M. A., MARCOS-MARTINEZ, R., BUTLER, J. R. A., COLEMAN, M., LAWRENCE, A., PRISLAN, H., STEVEN, A. D. L., AND THOMAS, S. Constraints and opportunities for market-based finance for the restoration and protection of blue carbon ecosystems. *Marine Policy*, v. 107: 103429, 2019.

VANIN, G. T., LACERDA, E. R., MORI, G. M. Drivers of mangrove area change and suppression in Brazil from 2000 to 2020. *Conservation Biology*, e14426, 2024.

WARD, R. D., LACERDA, L. D., CERQUEIRA, A. C., HUGO, V., HERNANDEZ, O. C. Impacts of sea level rise on mangroves in northeast Brazil. *Estuarine*

Coastal and Shelf Science, 108382, 2023. DOI: <https://doi.org/10.1016/j.ecss.2023.108382>

WOODROFFE, C. D., ROGERS, K., MCKEE, K., LOVELOCK, C. E., MENDELSSOHN, I. A., SAINTILAN, N. Mangrove sedimentation and response to relative sea level rise. *Annual Review of Marine Science*, v. 8, pp. 243-266, 2016.

WORTHINGTON, T. A., ZU ERMGASSEN, P. S. E., FRIESS, D. A. et al. A global biophysical typology of mangroves and its relevance for ecosystem structure and deforestation. *Scientific Reports*, v. 10, 14652, 2020. DOI: <https://doi.org/10.1038/s41598-020-71194-5>

WYLIE, L., SUTTON-GRIER, A. E., MOORE, A. Keys to successful blue carbon projects: lessons learned from global case studies. *Marine Policy*, v. 65, pp. 76-84, 2016.

UNSWORTH, R. K. F., DE LEON, P. S., GARRARD, S. L., et al. High connectivity of Indo-Pacific seagrass fish assemblages with mangrove and coral reef habitats. *Marine Ecology Progress Series*, v. 353, 213-224, 2008.

ZENG, Y., FRIESS, D.A., SARIRA, T. V., SIMAN, K., KOH, L. P. Global potential and limits of mangrove blue carbon for climate change mitigation. *Current Biology*, v. 31, pp. 1-7, 2021.

ZU ERMGASSEN, P. S. E., MUKHERJEE, N., WORTHINGTON, T. A., ACOSTA, A., ARAUJO, A. R. R., BEITL, C. M., CASTELLANOS-GALINDO, G. A., CUNHA-LIGNON, M., DAHDOUH-GUEBAS, F., DIELE, K., PARRETT, C. L., DWYER, P. G., GAIR, J. R., JOHNSON, A. F., KUGURU, B., LOBO, A. S., et al. Fishers who rely on mangroves: modelling and mapping the global intensity of mangrove-associated fisheries. *Estuarine Coastal and Shelf Science*, v. 248, 107159, 2021.



The complexity of the effects of global environmental and climate change, including their future projections, requires interdisciplinary and transdisciplinary approaches. These approaches are essential for understanding the interactions between social, biophysical, and ecological systems, characterizing the risks of impact, vulnerability, possibilities for mitigating their causes, and adaptation solutions. The Synthesis Center on Environmental and Climate Change (SIMACLIM) has as its main mission to integrate accumulated and ongoing research from various national and international research networks and groups, organizing information and assisting in Brazilian government planning to achieve goals established in agreements on climate change. SIMACLIM is funded by the Ministry of Science, Technology and Innovation (MCTI) through the National Fund for Scientific and Technological Development (FNDCT), FINEP Process 01.22.0584.00.

<https://simacлим.com.br/>

@simacлим

General Coordination:

Moacyr Cunha de Araujo Filho

Advisory Board:

Aloísio Lopes de Melo (MMA)

Ana Paula Leite Prates (MMA)

Jean Pierre Henry Balbaud Ometto (Rede Clima)

Lilium Beatris Chagas de Moura (MRE)

Márcio Rojas da Cruz (MCTI)

Moacyr Cunha de Araujo Filho (Rede Clima)

Oswaldo Luiz Leal de Moraes (MCTI)

Pedro Ivo Ferraz da Silva (MRE)

Administrative Management:

Leonardo Bruto Vieira da Costa

Executive Secretariat:

Claudia von Sohsten Cavalcanti

Érica Menero

Izabelle Lima Cabral

Communications Advisor:

Pedro Zanforlin Marcondes de Carvalho

REALIZAÇÃO:



SIMACLIM

Centro de Síntese em Mudanças Ambientais e Climáticas

APOIO:



Rede Clima
Mudanças Climáticas
Globais no Brasil



Conselho Nacional de Desenvolvimento
Científico e Tecnológico



UFPE



INOVAÇÃO E PESQUISA

MINISTÉRIO DA
CIÊNCIA, TECNOLOGIA
E INOVAÇÃO



UNIÃO E RECONSTRUÇÃO