Ministry of Science, Technology and Innovation

CLIMATE CHANGE AND BRAZIL

State of the art and frontiers of knowledgment

Editora Ibict

Brasília, 2025

Climate change is here to stay. It is at the center of the public agenda. Failing to address it could cost years of development, exacerbate vulnerabilities, and increase inequalities. Understanding the ongoing phenomena and their multiple impacts– on society, the economy, and ecosystems – is essential for generating effective public policies, guiding private sector action, combating misinformation, and mobilizing society to face the enormous challenge ahead.

The worsening climate emergency is unfolding amid political, military, and commercial conflicts that challenge the multilateral system. The Brazilian Presidency of COP30 has called for the ethical responsibility of leaders and the coordinated action of public, private, and third-sector institutions. It is urgent to mobilize capacities and resources to reverse the cause of the problem– the increase in atmospheric concentrations of greenhouse gases– and to implement adaptation measures that can save lives, minimize losses and damage, and prevent disproportionate effects on vulnerable populations.

Congratulations to the Ministry of Science, Technology, and Innovation and the various institutions and researchers who, through this book, synthesize the best scientific knowledge on the topic. This work complements and guides the various initiatives that, since 2023, have repositioned climate change as a strategic national agenda through the Climate Plan and its sectoral Mitigation and Adaptation plans, the Ecological Transformation Plan, and several other public action instruments.

Let us take action.

Ministry of Science, Technology and Innovation

CLIMATE CHANGE AND BRAZIL

State of the art and frontiers of knowledgment

PRESIDENCY OF THE REPUBLIC

Luís Inácio Lula da Silva
President of the Republic

Geraldo José Rodrigues Alckmin Filho
Vice President of the Republic

MINISTRY OF SCIENCE, TECHNOLOGY AND INNOVATION

Luciana Barbosa de Oliveira Santos
Minister of Science, Technology and Innovation

Luis Manuel Rebelo Fernandes
Executive Secretary

Andrea Latgé
Secretary of Strategic Policies and Programs

Osvaldo Luiz Leal de Moraes
Director for Climate and Sustainability

Ministry of Science, Technology and Innovation

CLIMATE CHANGE AND BRAZIL

State of the art and frontiers of knowledgment

Editora Ibict

Brasília, 2025

International Cataloging-in-Publication Data

C639 Climate change and Brazil: state of the art and frontiers of knowledgment / Osvaldo Luiz Leal de Moraes; et al. (org.). – Brasília, DF: Editora Ibict, 2025.
477 p. : il.

Includes Bibliography.
ISBN (digital): 978-85-7013-246-8
ISBN (físico): 978-85-7013-244-4
DOI: 10.22477/9788570132468
1. Climate change. 2. Climate - Brazil. 3. Climate crisis. 4. Biodiversity - Brazil. I. Moraes, Osvaldo Luiz Leal de, org. II. Título.

CDU 551.583

Librarian Stella Dourado CRB-5/2013

How to cite:

MORAES, Osvaldo Luiz Leal de (Org.). **Climate change and Brazil:** state of the art and frontiers of knowledgment. Brasília, DF: Editora Ibict, 2025.

address: **Ibict – Instituto Brasileiro de Informação em Ciência e Tecnologia**
Setor de Autarquias Sul (SAUS), Quadra 05, Lote 06, Bloco H – 5° andar
CEP: 70.070-912 - Brasília, DF.

CONTENTS

PRESENTATION

The Ministry of Science, Technology and Innovation (MCTI) presents in this book the contributions of Brazilian scientists to the science of climate change. The book is one of the MCTI's deliverables for COP30. The concept of this work goes beyond collecting information about what we know. It also sheds light on the challenges that lie at the forefront of knowledge. The book is ambitious. The task is not easy. On the other hand, it is also necessary.

The MCTI has affiliated research units (UPs) whose institutional missions encompass areas of knowledge that are closely related to the theme of the book. On the other hand, there are also areas of knowledge in which the expertise lies outside these units. Therefore, the book contains contributions from researchers both inside and outside the ministry.

The diversity of the chapters reflects a holistic view of how this topic should be approached. The climate agenda cannot be limited to the greenhouse gas agenda. The planet is a whole, and other global agendas must run in parallel. We must not forget the biodiversity agenda and its specific COPs, not to mention the United Nations Conference on the Oceans. We cannot ignore the disaster agenda and the Sendai Framework. This is why the book is so ambitious.

The book is presented as a framework in which empirical research should meet decision-making processes. Researchers tend to focus too much on their own area of expertise and seem to move away from the policy-making process. But these two fields are interrelated and their results influence each other to a great extent. The dynamic interaction between science and policy is driven by the urgent need to solve complex problems facing today's societies. And climate change is perhaps the most urgent.

Science, technology and innovation are important to public policy because they drive economic growth and national development, provide evidence-based elements for effective problem solving, and foster innovation in various sectors. The integration of science, technology and innovation (STI) enables governments to develop more robust policies, foster collaborative ecosystems, use data and digital tools for better decision-making and ensure that public services are innovative, efficient and inclusive.

In this context, a coordinated and integrated policy involving the different actors of the national science, technology and innovation system and public decision-makers is essential to achieve a fairer, more inclusive and sustainable society.

This is the vision that guides MCTI's work. It is in this context that this book fits.

Luciana Santos
Minister of State for Science, Technology and Innovation

FOREWORD

We live in a time when accelerated technological change, geopolitical tensions and the climate emergency are intertwined, reshaping the global economy and redefining relationships between nations. The fragmentation of global value chains, the race for strategic technologies and the energy transition present us with new challenges, but also new opportunities. Brazil, with its biodiversity, its scientific potential and its predominantly renewable energy matrix, cannot just be a bystander: it must position itself as a strategic player in this scenario of profound change. The diversity of the chapters in this book reflects a holistic view of how this issue should be approached.

There is no doubt that the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Framework Convention on Climate Change (UNFCC) have produced information and led negotiations that can result in actions that lead to the sustainability of the planet. But the climate agenda cannot be limited to the greenhouse gas agenda. The planet is a whole, and other global agendas must run in parallel. We must not forget the biodiversity agenda and its specific COPs, not to mention the United Nations Conference on the Oceans. We cannot ignore the disaster agenda and the Sendai Framework. That is why the book is so ambitious.

As shown in the book, it is impossible not to take into account that climate projections suggest that the average annual temperature in Brazil could rise between 2.5 and 4.5°C in most parts of the country by 2100. Areas such as the semi-arid Northeast and the southern Amazon could experience prolonged and severe droughts, affecting agricultural production, water resources and public health. Alarmingly, science has also recently provided us with evidence of a strong link between extreme weather conditions and atmospheric carbon emissions from the Amazon, suggesting that degradation and climate change could transform the forest from its historical role as a CO_2 absorber to a worrying source of carbon emissions.

Ecological niche modeling shows that up to 43% of plant species in the Amazon could lose at least 30% of their range by 2070. Of the approximately 8,000 species studied in the Amazon, including thousands of plant species and hundreds of vertebrate (mainly mammals and birds) and invertebrate (bees) species, 26% could be threatened with extinction due to climate change if pessimistic greenhouse gas emission scenarios are applied. In a scenario where the Paris Agreement targets are met, this figure could reach only 14%. In the Atlantic Forest, of the approximately 1,300 species assessed, including collections of various plant species and hundreds of vertebrates (mammals, amphibians and birds) and invertebrates (especially moths), 31% are at risk of extinction due to climate change, if pessimistic greenhouse gas emission scenarios are also applied. The Brazilian coastal and marine region is home to a variety of habitats, including lagoons, bays, inlets, river deltas, mudflats, mangroves, sandbanks, coral reefs, seagrass beds and upwelling areas. These ecosystems are severely threatened by climate change, which is already altering species richness and community structure in key areas, including rocky coasts, beaches, coastal bays and lagoons, mangroves, macroalgae beds and seagrass beds. Brazilian mangroves and coral reefs are particularly at risk. Although they cover only 0.1 % of the sea floor, coral reefs harbor 25 % to 30 % of all known marine species and 65 % of fish, making their biodiversity comparable to that of tropical forests. These reefs provide human communities with food through fishing, support tourism, provide pharmaceuticals and protect coastlines from erosion. This crucial role underscores why repeated scientific warnings about coral bleaching and mortality, affecting more than 26 species, have grown louder over the past two decades.

It is estimated that the extent of degraded forests in the Amazon region is greater than the total deforested area. About 14% of the degraded Amazon forests are subsequently deforested again, indicating that these are partially independent processes. On the other hand, Brazil has the greatest potential in the world for restoring tropical forests through natural regeneration. Secondary forests differ from primary forests in their stage of development, species composition, structure and functionality, and have a net carbon absorption rate 11 to 20 times higher than primary forests. In other words, the book suggests that we can take policy action to curb forest degradation and invest in strategies to regenerate our forests. This is essential to mitigate the climate crisis.

Climate change is also expected to affect minimum river flows, which are responsible for sustaining water use and ecosystems during dry periods. Models indicate that minimum flows will decrease in most parts of Brazil, with fluctuations of more than 50% in the southern Amazon and parts of the Northeast. Intermittency (completely dry rivers) could increase in the northeastern region. In addition, periods of water scarcity (up to two months) tend to increase when the available river flow is lower than that currently used as a reference for water use planning. It is worth noting that hydroclimatic extremes can affect not only groundwater recharge but also groundwater quality. Changes in recharge can affect the storage capacity of aquifers and the availability of groundwater. The potential decline in surface water availability in some regions due to climate change may also increase pressure on groundwater, which will significantly affect usable reserves under conditions of overexploitation and altered recharge conditions.

Our scientists show that the loss of arable land is the main reason for the losses in rural areas. The semi-arid regions of the Northeast will become drier, while the eastern part of the Brazilian Amazon will become a savannah-like biotope. Cassava could disappear from the semi-arid regions of the northeast. Maize production in the Agreste region in the northeast is also likely to be severely affected. Some plants whose seeds are adapted to the tropical climate could migrate to the south of Brazil or to higher altitudes to compensate for the rising temperatures. This migration may lead to competition between areas and the migration of labor from rural areas to more favorable regions. Other factors likely to stress agricultural systems include reduced water flow and irrigation potential, increased incidence of pests and diseases, changes in biomes and declines in animal and plant biodiversity.

The book takes an in-depth look at the interactions between climate change and public health. It shows how the impact on cardiovascular health is exacerbated by extreme events such as heat and cold waves, which cause dehydration, hypercoagulability and cardiovascular problems, particularly in vulnerable populations. The text contributes by showing how uncontrolled urbanization has made the urban environment an exacerbating factor of the climate and health crisis. Impermeable soils, the loss of green spaces and the concentration of activities in central regions create heat islands, alter rainfall patterns and favor the increase of respiratory and cardiovascular diseases. In the area of infectious diseases, the effects of climate change are equally devastating. The impact of climate change on waterborne bacterial diseases is currently being analyzed and requires coordinated action across all sectors. The lack of adequate sanitation, increased flooding and the spread of rodents put entire communities at risk. The chapter also analyzes arboviruses such as dengue, whose spread is directly linked to rising global temperatures, uncontrolled urbanization and poverty. The spread of Aedes aegypti, facilitated by worsening climate and environmental conditions, poses a major public health challenge. The Amazon is once again proving to be an epicenter of vulnerability due to deforestation, migration flows and fragile health systems. Although mortality rates are falling, it is clear that malaria is becoming more prevalent, particularly in the Brazilian Amazon. Transmission is strongly influenced by factors such as deforestation, climate variability and human mobility. Cities are becoming high-risk areas and require policies that integrate ethics, sustainability and public health into urban planning.

Between 1991 and 2020, 23,923 disasters caused 2,297 deaths, affected more than 77 million people and had an economic impact of more than R$300 billion. In particular, disasters related to extreme rainfall events, which account for about 33% of the total, are responsible for 93% of the total deaths and 66% of those affected. These data show the high potential for death and destruction from these events, especially when they affect urban areas characterized by multiple dimensions of vulnerability, such as fragile and inadequate infrastructure, irregular settlement of slopes and floodplains largely due to a lack of spatial planning, and characterized by significant social inequality. Disasters of geological origin, especially landslides, are a prime example: they are much rarer than other types of disasters, but are among the deadliest, especially when they occur in densely populated areas on or near vulnerable slopes. The factors that determine the occurrence and magnitude of disasters therefore only become clear by analyzing the combination of natural hazards and social and structural vulnerabilities at the local level. Therefore, the chapter on disasters underlines the holistic vision of the MCTI.

Finally, and as a grand finale, the book argues that by the end of the century, GDP losses due to climate impacts on agriculture could be between 0.4% and 1.8% per year, depending on the emissions scenario. Indirect impacts transmitted through production chains and cross-sectoral linkages tend to amplify direct losses, increasing the urgency of adaptation measures with a systemic approach. The authors of the Economy chapter emphasize that the impacts of climate change are not neutral: They disproportionately affect the poorest, most marginalized and historically vulnerable regions. Economics must therefore contribute to a climate justice approach by analyzing the distributional impacts of climate policies, taking into account variables such as income, ethnicity, gender, geographic location and access to public goods. The development of compensatory instruments, such as conditional transfers, adaptation funds and safety mechanisms targeting vulnerable groups, must be implemented. Policies that address the informal economy and local production chains, which are often neglected in traditional models, are essential for community resilience.

The book also presents a critical point at which empirical research must meet decision-making processes. Researchers tend to focus too much on their own area of expertise and seem distant from policy-making processes. But these two fields are interconnected and their results influence each other immensely.

Science thrives on curiosity, experimentation and validation, and seeks to discover replicable and generalizable truths. Conversely, public policy encompasses the rules, regulations and strategies developed by governments and organizations to address social challenges, promote progress and allocate resources. While science strives for objectivity and universal truths, public policy is influenced by a variety of factors, including political ideologies, public opinion, economic considerations and ethical principles.

In many countries, scientific societies play an important role in mediating between scientific advances and public policy making. In Brazil, the Brazilian Academy of Sciences and the Brazilian Society for the Advancement of Science have advocated the use of scientific knowledge in government decisions and have also published studies and proposals on strategic issues for the country's sustainable development. Particularly noteworthy are the contributions on climate change and biodiversity written by renowned researchers.

The National Conferences on Science, Technology and Innovation, the last of which took place in July 2025, mobilized large sectors of society for debates and proposals to build an integrated development project with a social, economic and environmental focus.

The scope and depth of this series of proposals illustrates the great challenge of effectively translating them into public action.

The dynamic interaction between science and public policy is therefore essential to solve the complex problems that characterize contemporary societies. Among them, climate change appears to be the most urgent.

It is not easy to translate scientific discoveries into actionable policies. Policy makers must navigate a complex environment characterized by uncertainty, conflicting interests and value judgments. They have to balance scientific knowledge with other considerations such as feasibility, cost-effectiveness and social values.

The relationship between science and public policy is complex and therefore deserves intense debate within and between the communities involved. This dynamic and symbiotic relationship represents a critical intersection where research and decision-making processes come together to shape societal development, address complex challenges and promote progress. Science and policy are inextricably linked, influencing and informing each other in a variety of ways to create a synergistic relationship that drives innovation, promotes sustainable development and improves the well-being of individuals and communities. In other words, perhaps that is precisely the goal of this book: to spark a discussion about how the knowledge our scientists produce can be used to shape the public policy that Brazil and our planet so desperately need.

President Lula's government has understood that the formulation of public policies must be centered on scientific knowledge and innovation, which are fundamental to building a sovereign and resilient Brazil. We know that sovereignty is not limited to territorial defense: it includes the country's ability to respond to global crises- especially climate change - with its own solutions. Investing in science, technology and innovation therefore means strengthening national autonomy, reducing external dependence and creating the conditions for Brazil to lead a productive and social transformation process geared towards sustainability. In this context, a coordinated and integrated policy involving the different actors of the National Science, Technology and Innovation System (SNCTI), whether at federal, state or municipal level, is essential for us to promote green reindustrialization and social development. Globally, the state must play a crucial role in fostering partnerships, sharing the risks and benefits of innovation and formulating long-term strategies that balance economic growth, ecosystem preservation and collective well-being. Putting the SNCTI at the service of the ecological transition will ensure that Brazil is prepared to face global challenges with solutions that are rooted at home.

Science is not only a vector of sovereignty and innovation, but also an instrument of social justice. It enables the formulation of policies that eliminate inequalities, expand access to quality education, strengthen the health system, ensure food security and promote inclusion. Without science, the country remains trapped in outdated production structures, but with effective, long-term policies, the opportunity to create green jobs and democratize access to goods and services opens up and improve the lives of the population. The COP30, which will take place in Brazil, represents a milestone in this vision: It is a historic opportunity to reaffirm to the world that scientific knowledge, sustainable innovation and social justice must go hand in hand to create a shared future capable of uniting development and climate responsibility.

Ultimately, this is perhaps the goal of this book: to show how the knowledge produced by our scientists can be translated into the public policies that Brazil and the planet urgently need.

The Editors

1. UNDERSTANDING CLIMATE VARIABILITY AND CHANGE IN BRAZIL: A REVIEW

Jose A. Marengo[1], Lincoln M. Alves[2], Sin C. Chou[2]

INTRODUCTION

According to the European Copernicus observatory (https://climate.copernicus.eu/), 2024 was the hottest year on record, being the first to exceed 1.5°C above pre-industrial levels (1850-1900), reaching 1.6°C. Scientists consider this 1.5°C limit to be the ceiling necessary to prevent the worst consequences of global warming, such as the disappearance of island countries. This limit is also the limit agreed upon in the Paris Agreement in 2015. However, this milestone does not mean that the planet has definitively broken the 1.5°C barrier and the goals of the Paris Agreement. To consider that the limit has been definitively violated, it would take several years with temperatures above this threshold. Each of the last 10 years, from 2015 to 2024, is among the 10 warmest years on record. High global temperatures, coupled with record global levels of water vapor in the atmosphere in 2024, triggered unprecedented heat waves, droughts, fires, and heavy rains, causing significant impacts and misery for millions of people.

In Latin America and the Caribbean, 2024 was the hottest year on record, with temperatures 0.95°C above the average for the period 1991–2020. In Brazil, according to INMET (National Institute of Meteorology), 2024 was the hottest year since 1961, with temperatures 0.79°C above

1 Centro Nacional de Monitoramento e Alerta de Desastres Naturais, CEMADEN, São Jose dos Campos, SP.

2 Instituto Nacional de Pesquisas Espaciais, INPE, São Jose dos Campos, SP.

corresponding author: jose.marengo@cemaden.gov.br

normal between 1991 and 2020. According to the WMO (WMO 2025), 2024 was the hottest year on record in many parts of South America. Among the cities with the highest maximum temperatures in 2024, the municipalities of Goiás (GO) stand out, with 44.5ºC on October 6; Cuiabá (MT), with 44.1ºC, also on October 6; Indiaporã (SP), with 43.3ºC on October 8; Aragarças (GO), with 43.3ºC on October 3; and Rio de Janeiro (Guaratiba neighborhood), with 43.2ºC on November 28.

Most of Brazil is under the influence of the monsoon regime, consistent with rainfall variations that are generally more abundant in spring and summer and scarcer in fall and winter. In general, precipitation in northwestern Brazil remains intense throughout the year. In Central Brazil, seasonal precipitation variation is influenced by the seasonal migration of the South Atlantic high-pressure system. South of the equator, winter is the dry season in the tropical zone (0-25°S), except coastal regions along the Atlantic, particularly on the northeast coast. In most of southern Brazil, where water vapor is available throughout the year, dynamic atmospheric conditions favor relative maxima of precipitation in autumn, winter, and spring in different regions. Southern Brazil is a transition region between the summer monsoon and winter regimes in mid-latitudes, with rainfall distributed evenly throughout the year (Grimm and Tedeschi, 2009).

The seasonal rainfall cycle in Brazil is affected by interannual variations, which can interfere, for example, by causing drought during the rainy season or an unusually abundant rainy season. An essential source of interannual variability is the El Niño and La Niña events, as well as the tropical and southern Atlantic Ocean. In the northern region of the country, a rainy equatorial climate prevails, characterized by virtually no dry season. In the northeast, the rainy season is limited to a few months, characterizing a semi-arid environment. The Southeast and Midwest regions are influenced by both tropical and mid-latitude systems, with a well-defined dry season in winter and a rainy season in summer, characterized by convective rains. The southern region of Brazil, due to its latitudinal location, is more influenced by mid-latitude systems, where frontal systems are the leading cause of rainfall throughout the year. Regarding temperatures, the North and Northeast regions of Brazil experience high temperatures with minimal variability throughout the year, characteristic of a tropical climate. In the mid-latitudes, temperature variation throughout the year is more pronounced, with low temperatures prevailing during the winter period, when there is greater penetration of cold air masses from high latitudes (Brazil, 2020).

Variations in large-scale and regional circulation patterns that affect Brazil can significantly impact the regional climate, leading to heavy rainfall, droughts, heatwaves, or cold spells. These changes in circulation can trigger episodes of heavy rain and flooding, or rainfall deficits that can lead to droughts, which in some regions can increase the risk of forest fires. Droughts have affected all of Brazil, including the periods of 2010-2023 in southern Brazil, 2012-2028 in the northeast, 2019-2023 in the midwest (Pantanal), and 2005, 2010, 2015-16, and 2023-2024 in the northern Amazon region. Floods and landslides are the disasters that claim the most lives. Together with droughts, these disasters are often induced by extreme rainfall events, which are a consequence of natural climate variability and the human effects associated with global warming.

The year 2024 was the hottest on record, marking the first time it exceeded 1.5°C above pre-industrial levels (1850-1900), reaching a temperature of 1.6°C. Scientists consider this 1.5°C limit to be the ceiling necessary to prevent the worst consequences of global warming, such as the disappearance of island countries. This limit is also the limit agreed upon in the Paris Agreement in 2015. However, this milestone does not mean that the planet has definitively broken the 1.5°C barrier and the Agreement's targets. To consider that the limit has been definitively violated, it would take several years with temperatures above this threshold. Each of the last 10 years, from 2015 to 2024, is among the 10 warmest years on record. High global temperatures, coupled with record global levels of water vapor in the atmosphere in 2024, triggered unprecedented heat waves, droughts, fires, and heavy rains, causing significant impacts and misery for millions of people.

In this chapter, we present a review of the state of the art in climate and climate variability studies, with an emphasis on weather and climate extremes and the disasters they cause in Brazil. We also present developments in climate modeling in Brazil and the generation of climate change scenarios, as well as a review of the sectoral impacts of climate change.

CLIMATE EXTREMES IN BRAZIL AND THEIR IMPACTS

Brazil is a continental country. Some studies refer to an event as "extreme" if it is unprecedented; others refer to events that occur several times a year as moderate extreme events. The rarity of an event with a fixed magnitude can also change under human-induced climate change, making events that were previously unprecedented quite likely under current conditions, but unique in the observational record—and therefore often considered "surprises" (Seneviratne et al. 2021).

Extreme weather events directly affect human and natural systems in Brazil, South America, and the world. A meteorological extreme, such as heavy rainfall, is not a disaster. In this case, the disaster is the impacts caused by the rain on a population vulnerable to this extreme phenomenon. Heavy rainfall leads to floods, flash floods, and landslides, and droughts increase the risk of wildfires, as well as impacts on agriculture and hydrology. South America has experienced in recent decades floods (such as in Rio Grande do Sul in May 2024 - Marengo et al 2024a, 2025a Reboita et al 2024), landslides as happened in Petrópolis and Recife in 2022 and in São Sebastião in 2023 - Marengo et al 2022, 2024b, Alcântara et al 2023), periods of droughts such as the Northeast Drought of 2012-2018, in Southeast Brazil in 2013-15, in the Amazon and Pantanal in 2020 and in 2023, 2024 - Marengo et al 2017, Alvalá et al 2017, Marengo et al 2021, 2024, 2022, et al 2024), heat waves (Marengo et al 2025b) and forest fires affecting the Amazon and Pantanal biomes (WMO 2024, 2025).

Between 1948 and 2023, around 11 million people were affected by hydro-meteorological events in the country, highlighting the need for preventive action. Climate disasters have underscored the importance of early warning systems as a crucial means to minimize fatalities, while also enhancing disaster risk perception among the population and decision-makers, to inform individuals about the necessary actions to take when a disaster risk warning is issued. Although extreme weather can be accurately predicted, each country needs to implement, test, and continually improve early warning systems to ensure people's safety and increase the population's resilience.

Heavy rainfall

Extreme precipitation triggers floods, flash floods, and landslides. Extreme drought and heat events amplify drought and its impacts, increasing the risk of forest fires. It is essential to distinguish between a forecast of heavy rain, which represents a weather warning, and a disaster risk warning forecast, which indicates the impact of heavy rain on vulnerable and exposed areas, directly affecting the population residing in those areas. The IPCC AR5 and AR6 reports (IPCC 2013, 2021, 2022) show that the frequency and intensity of heavy rainfall events have likely increased on a global scale in most terrestrial regions with good observational coverage. The volume and intensity of precipitation have increased on a continental scale and in southern Brazil over the past 50-60 years, (Figure 1), and the natural climate variability associated with El Niño, La Niña, and the warming of the tropical North and South Atlantic, as well as human influence, particularly greenhouse gas emissions, is the primary driver of this increase (IPCC 2021, Dunn et al 2024).

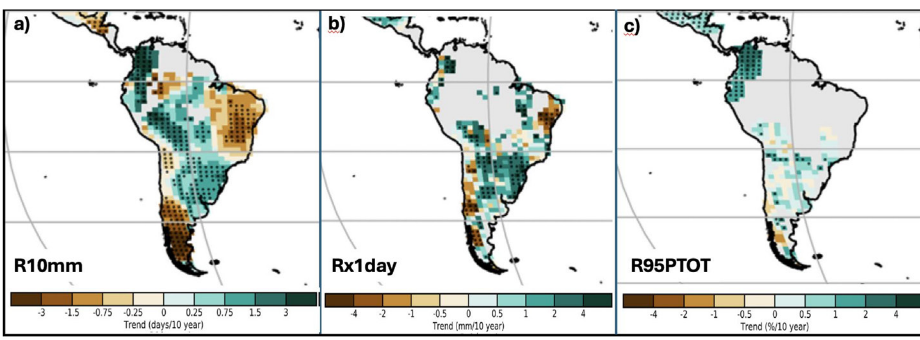


Figure 1: Linear trends in annual series of extreme precipitation indices for South America: (a) R10mm (days/decade); (b) R95pTOT (%/decade) and (c) Rx1day (mm/decade) during 1950–2018). Trends were calculated only for grid cells with sufficient data (at least 66% of years with data and the last year of the series being 2009 or later). Significant trends are indicated with dotted lines. All panels use a reference period from 1961 to 1990, with maps presented on a 1.875° x 1.25° longitude-latitude grid. Adapted from Dunn et al. 2020.

For Brazil, the assessment of extremes and their impacts has been discussed in published literature, including reports by the Brazilian Panel on Climate Change (PBMC 2013, 2014, 2016), the results of Brazil's Fourth National Communication to the UNFCCC (Brazil 2020), the National Adaptation Plan (Brazil 2016), and CEMADEN's Climate and Disasters Report for 2024 (CEMADEN 2025). The IPCC AR5 and AR6 reports (IPCC 2013, 2021, 2022), the WMO State of Climate for Latin America and the Caribbean since 2019 (WMO 2020, 2021, 2022, 2023, 2024, 2025) and the IPCC Special Report on SREX Extremes (IPCC, 2012) discuss past extremes and projections for changes in extreme heavy rainfall for Brazil. Since the IPCC AR5 (IPCC, 2013), there have been significant new developments and advances in knowledge regarding changes in climate and weather extremes, as well as human influence on individual extreme events that lead to hydro-geo-meteorological disasters.

In South America, observed trends indicate an increase in the intensity and frequency of extreme rainfall in the southeastern part of the continent. In Brazil, some of these intense rainfall events were considered “unusual and unprecedented” in 2023 and 2024. In February 2023, heavy rainfall and landslides killed 65 people in São Sebastião/São Paulo, and 683 mm accumulated in 15 hours, the highest volume of rainfall ever observed in Brazilian history in such a short period. In May 2024, heavy rainfall of more than 200 mm/24 hours in the Taquari River valley triggered floods that affected the city of Porto Alegre, capital of the state of Rio Grande do Sul, in what is considered Brazil’s worst climate disaster, leaving 183 dead and nearly $7 billion in economic losses (Marengo et al., 2024a; WMO, 2025). Disasters such as floods, flash floods, and landslides, caused by extreme rainfall events, trigger disasters that kill hundreds of people every year in Brazil and South America.

In Brazil, climate disasters have increased by 460% between 1991 and 2023. In the 32 years analyzed by the Brazilian Alliance for Ocean Culture (2025), 64,280 climate disasters were recorded in 5,117 Brazilian municipalities (almost 92% of the total). Half of the recorded disasters are droughts; floods, flash floods, and flooding account for 27%, and storms account for 19%. More than 219 million people were affected, including deaths, displaced persons, homeless persons, and sick persons, with 78 million in the last four years alone. Economic losses have also increased over the decades, totaling R$547.2 billion between 1995 (the first year for which data are available) and 2023. The average annual loss since 2020 is R$47 billion per year, more than double the annual average for the previous decade, which was R$22 billion per year. Table 1 lists precipitation extremes associated with the above systems that generated precipitation extremes and triggered disasters, resulting in fatalities in the region.

Table 1: Examples of extreme precipitation from 2022 to 2024 and subsequent hydro-geo-meteorological disasters in Brazil. The information includes location, date, extreme precipitation values, and hydrological event, if any, and reference (Source: CEMADEN 2024)

DATA E LUGAR	CHUVAS EXTREMAS E IMPACTOS	REFERÊNCIA
Petrópolis/ Rio de Janeiro, February 15 2022	258 mm/3 hours, February climatology 200mm, landslides and flash floods, 231 deads	Alcantara *et al* (2023)
Recife/Pernambuco, May 25-20 2022	551 mm/5 days, May climatology: 411 mm, landslides and flash floods, 130 deads	Marengo *et al* (2023)
Gravatai, Maquiné/ Rio Grande do Sul, June 16 2023	300 mm/24 hours, 11 deads, 18 missing due to floods.	Floodlist (2023)
São Sebastião/ São Paulo, Brasil, February 18-19 2023	683 mm/15 hours, February climatology: 120 mm, landslides left 65 deads	Marengo *et al* (2024b)
Vale do Taquari/ Rio Grande do Sul, September 3-5 2023	100 mm/24 hours, rise in the levels of the Taquari River in 12 m, September 6-7, floods left 48 deads	WMO (2024), Alvala *et al* (2024)
Rio de Janeiro/ Rio de Janeiro, February 21-22 2024	42.8 mm/1 hour, landslides in the municipalities of Piraí, Japeri, Mendes and Nova Iguaçu, 8 deads	Floodlist (2024a)
Mimoso do Sul/ Espírito Santos, Brasil, March 22-23 2024	Rainfall accumulated between 300 and 600 mm/48 hours, 20 deads consequence of floods and flashfloods. Economical losses of about US$ 200 million in coffee production	INMET (www.inmet.gov.br)
Taquari River Valley and Porto Alegre Metropolitan Region/ Rio Grande do Sul, May 1-6 2024	Floods in Porto Alegre was triggered by heavy rainfall in the Guaiba lake basin, with accumulated rainfall above 500 mm/5 hours, rising the levels of the Guaiba lake in 5.35 m on May 6, higher tat the previous flood of 1941. 183 deads.	Marengo *et al* (2024 a, 2025b), Reboita ela al (2024), Floodlist (2024b)

According to Table 1, in 2023, the accumulated rainfall of 683 mm in 15 hours during the landslide and flash flood events in São Sebastião, São Paulo state, between February 18 and 19, 2023, resulted in the deaths of 65 people (Marengo et al., 2024). The rains of March 22 and 23 had a significant impact on the Southeast, with four deaths in Petrópolis, 20 in Mimoso do Sul, and 183 deaths in Rio Grande do Sul in May 2024. Heavy rains affected the states of Rio de Janeiro in southeastern Brazil and Bahia in northeastern Brazil, causing flooding, casualties, and damage. Flooding along the Acre River in the western Amazon region caused widespread damage and displacement in riverside communities in Peru, Brazil, and Bolivia in February 2024, where the Acre River rose by 6-7 m in a matter of days. In Bolivia, in Cobija, the Acre River levels reached 15.83 m. Heavy rains affected the states of Espírito Santo and Rio de Janeiro, causing flooding and triggering landslides, killing 27 people (INMET).

In a week of rain, Rio Grande do Sul experienced flooding in most of its cities, including the capital itself. Buildings were destroyed, people died, others went missing, and tens of thousands were left homeless. The storm caused the tributaries of Lake Guaíba (the Taquari, Caí, Pardo, Jacuí, Sinos, and Gravataí) to overflow, reaching record levels of 5.35 m on May 5, higher than the previous flood in 1941, contributing to flooding in vulnerable areas of the Porto Alegre Metropolitan Region and nearby municipalities. The rains began in the early hours of April 26, with several days of uninterrupted rain and daily accumulation above 200 mm between April 29 and May 3, returning on May 11 (Marengo et al, 2024a, 2025a) (Figure 2). ENSO was considered important in explaining the variability in the observed rainfall, and the cold front that brought the rains remained stationary in southern Brazil, as it was unable to move to central Brazil due to an atmospheric block. This was the most extensive and one of the most devastating climate disasters in Brazil's recent history. The estimated cost of cleanup is $3.7 billion (Debone et al., 2024), and the economic impact of this disaster was approximately $16 billion (1.8% of the state's GDP in 2024).

The population living in vulnerable and exposed areas was promptly warned and evacuated. However, the number of fatalities was still high. There is a need to implement preventive actions for the most vulnerable population and to conduct environmental education activities for society. It is necessary to increase the population's and public authorities' perception of disaster risk. It is necessary to improve weather forecasting and disaster risk warning systems caused by climate extremes, thereby saving lives and protecting populations in risk areas. The primary concern of this case is the heightened risk of extremes and vulnerability, as well as inadequate or deficient land management, urban planning, and lingering governance issues at the federal, state, and local levels. Brazil is an example of this complex combination.

Figure 2: shows some of the impacts of extreme rainfall and flooding in the state of Rio Grande do Sul in May 2024.

a)

b)

c)

d)

e)

f)

g)

h)

Figure 2: Photos of the flood in Porto Alegre, May 5, 2024. Photo: Gustavo Mansur/ Piratini Palace (Fonte: https://www.flickr.com/photos/governo_rs/53704427222/ in/album-72177720316727998/.

Water déficit and drought

Severe droughts are the most costly natural disasters, surpassing other natural disasters such as floods, hurricanes, earthquakes, and tsunamis. Figure 3 illustrates the temporal evolution of drought in the country, with blue bars representing wetter periods and red bars indicating periods of drought. Since the 1990s, drought conditions have become more frequent and severe, culminating in a more critical period in recent years. The most intense drought appears in 2024.

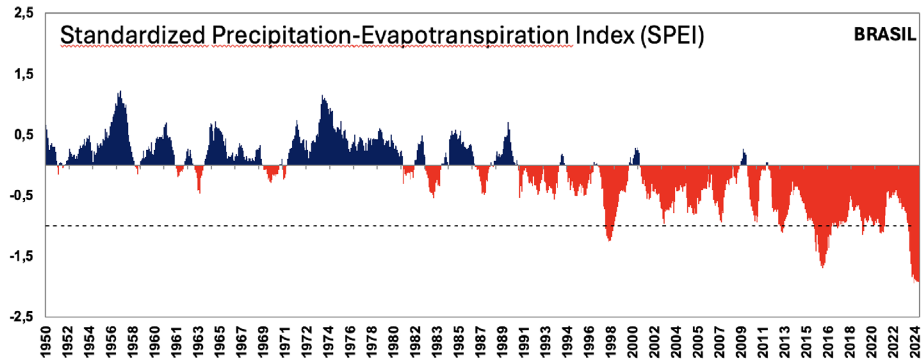


Figure 3: Temporal evolution of droughts in Brazil, as indicated by the SPEI (Standard Precipitation Evapotranspiration Index). Source: CEMADEN.

The São Paulo Metropolitan Region (RMSP) experienced one of the worst droughts in its history. The combination of low rainfall during the summers of 2014 and 2015 and a significant increase in water demand, as well as the lack of adequate planning for water resource management (not to mention the share of blame that can be attributed to Brazilian consumers' lack of collective awareness of the need for rational water use), has led to what we call a "water crisis," a crisis that was already anticipated, as we faced a similar situation during the "blackout crisis" during the 2001-2002 drought. The low accumulated rainfall totals over the Cantareira region, northeast of the RMSP, significantly affected the water availability of the Cantareira System reservoirs, located on the border between the states of São Paulo and Minas Gerais. Cantareira is São Paulo's primary water supply system, serving the water needs of 6 million inhabitants in the metropolitan region. The system is also responsible for supplying water to a population of 5 million people in the Piracicaba, Capivari, and Jundiaí river basins. As a serious consequence, the population has been suffering from water shortages in much of the RMSP and several cities in the state of São Paulo, with water rationing now part of everyday life for São Paulo residents (Marengo & Alves, 2014). According to CEMADEN, in 2024, Brazil experienced the worst drought in 70 years, characterized by both its extent and intensity. In September, 4,748 cities in Brazil—more than 80% of the country's total municipalities—faced some degree of drought, with 1,349 experiencing severe and extreme levels.

In the Amazon Basin, the severe drought is partly attributed to the impact of El Niño, a climate pattern that was present during the second half of 2023 and the first half of 2024 (Espinoza et al., 2024; Marengo et al., 2024b; Toreti et al., 2024). In the Brazilian state of Amazonas, by the end of September 2024, of the 745,000 people affected by the drought, about 330,000, including approximately 115,000 children and adolescents living in 2,200 indigenous villages and riverside communities, were isolated or at risk of isolation, with severe impacts on health, nutrition, access to water, protection, and education. The level of the Negro River in Manaus registered 12.11 m on October 10 (Figure 4), the lowest level ever observed since measurements began in 1902. Figure 5 shows some of the impacts of the drought in the Amazon region.

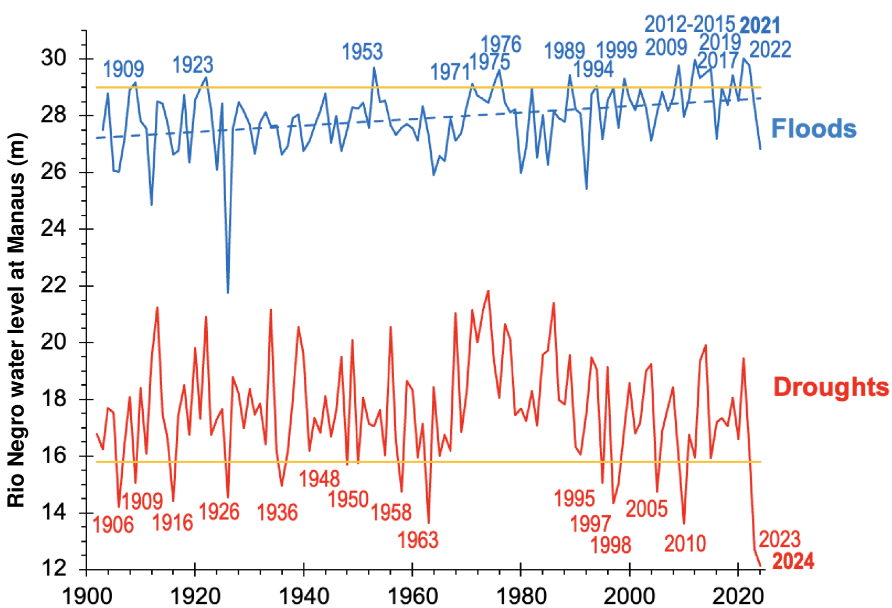


Figure 4: Maximum (blue lines) and minimum (red lines) levels of the Negro River at the Port of Manaus, 1902 to November 2024. The blue and red numbers indicate years of record floods and droughts, respectively. The orange lines represent the highest (29.0 m) and lowest (15.8 m) thresholds for defining floods and droughts, respectively. The values are in meters. Source: J. Schongart, National Institute for Amazonian Research (INPA), Brazil. (Marengo et al 2024).

Figure 5: a) Riverine communities carry gallons of water as they cross sandbanks on the Madeira River, Paraizinho community, Humaitá/Amazonas. Photo: Bruno Kelly/Reuters; b) In addition to serious environmental damage, the drought also causes significant losses to the local population and economy. Photo: Jacqueline Lisboa/WWF-Brazil; c) Image of the drought in Tabatinga, in the Alto Solimões region/AM. Photo: Civil Defense; d) The Amazon River basin faces a scenario of severe drought in 2024. Photo: Disclosure/SGB.

The Paraguay River in Asunción (Paraguay) reached record lows in September, with water levels depleted by severe drought upstream in Brazil, hampering navigation along the Paraná-Paraguay waterway. In a critical situation, the Paraguay River reached its lowest historical level on October 8, at 62 cm, according to IMASUL. The record situation surpassed that of 1964, being the worst index since monitoring began in 1900. In 2024, the Paraná River, used as a waterway to transport approximately 80% of Argentina's grains and oilseeds for export, was at its second-lowest level for this time of year since 1970, behind only a significant decline observed in 2021 due to severe drought upstream in Brazil. As a result, large grain ships carrying soybeans and corn in Argentina's main river ports around Rosario carried less cargo due to reduced draft. Also in 2024, the lowest levels of the Paraguay River since 1981 were recorded. Figure 6 illustrates the effects of the 2024 drought on the Pantanal.

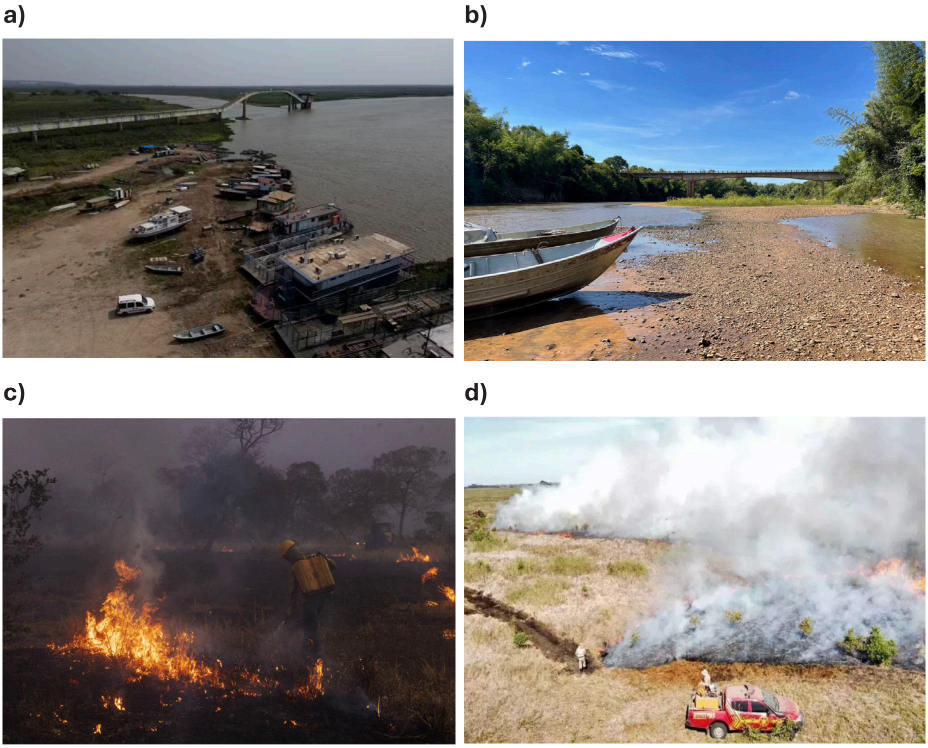


Figure 6: a) Bank of the Paraguay River, the main river in the Pantanal, showing historic drought and low water levels in MS. Photo: Marcia Foletto; b) Dry stretch of the Miranda River, in the district of Águas de Miranda, in Bonito/MS, March 30, 2024. Photo: Gustavo Figueroa/SOS Pantanal; c) Prevfogo firefighters battle a blaze on a farm in the Miranda/MS region. Photo: Lalo de Almeida, March 8, 2024 /Folhapress; d) Firefighters in action battling fires in the Abobral region in 2024. Photo: Disclosure/CBMMS.

CLIMATE MODELING IN BRAZIL

The Earth's climate is constantly changing over time, from hours to centuries. Numerical modeling is essential for enhancing knowledge about the components of the climate system (atmosphere, land surface, ocean, sea ice etc.), as well as for identifying the potential impacts of climate change on various key sectors of a country (such as water resources, energy, agriculture etc.). The results of this modeling are a key component in climate vulnerability studies and the development of measures and strategies for adapting to current and future climate change, serving as a basis for risk and vulnerability analyses and, thus, for proposing state policies for adaptation and mitigation. Climate models are essential tools for investigating the climate system's response to various forcings, such as sea ice concentrations, land-use change, and sea surface temperature, among others. In this sense, they allow projections to be made not only of how the average global temperature may increase in the 21st century, but also of how these changes may affect the climate worldwide (Flato et al., 2013).

For a better understanding of how climate change occurs at the regional level, it is essential to have access to more detailed information about the study region, such as topography, watersheds, and coastlines. This makes it important to increase the spatial resolution of global climate models (GCMs), which generally have low spatial resolution (on the order of one to two hundred kilometers) due to the high computational cost required to perform simulations on a global scale, and/or to use regionalization techniques (known as downscaling) to translate the information provided by GCMs into a more refined spatial scale (Ambrizzi et al., 2019; Chou et al., 2014; Flato et al., 2013; Marengo et al., 2012).

A weather forecast, which covers a period of a few days (up to about 10 days), provides information such as temperature and rainfall for a specific date and even time of day. On the other hand, in a climate forecast that covers months ahead, the level of accuracy is no longer the same; information is provided on temperature and rainfall anomalies for a limited number of months ahead. Climate forecasts do not provide specific dates or times for events. However, they can provide information on climate patterns and statistics, such as averages, anomalies, and extremes, for the coming months. Climate forecasting is possible due to the presence of forcings (or constraints) that can drive the climate system to a specific state. Sea surface temperature anomalies in equatorial regions are typical climate forcings that lead to anomalies in some areas of the planet (Shukla, 1983). Soil moisture conditions, significant volcanic eruptions, and anomalies in the stratosphere are examples of forcings on the climate scale

Weather prediction models are simpler than climate models. To initiate a climate prediction, a global model is required, as meteorological phenomena can circle the planet within months. This global model must have an ocean coupled to predict changes in ocean circulation and, above all, changes in sea surface temperature anomalies. To model the climate decades ahead, it is necessary to assume changes in greenhouse gas concentrations and changes in land use. The model then includes dynamic vegetation processes, the carbon cycle, and biogeochemical processes, transitioning from the category of coupled model to the category of Earth System Model.

Climate models are essential tools for investigating the climate system's response to various changes, such as changes in greenhouse gas concentrations, changes in ice cover concentrations, changes in land use, or changes in ocean circulation (Flato et al., 2013). In this sense, they allow projections to be made not only of how the average global air temperature may increase in the 21st century, but mainly of how the climate pattern of various variables such as rainfall, humidity, winds, solar and terrestrial radiation, and evaporation in different regions of the Earth will change.

Another category of models is regional models. These models provide a "zoom" on a specific region of the global model. Regional models, because they operate in a smaller area, use smaller grid sizes (approximately tens of kilometers) than global models (hundreds of kilometers), resulting in a lower computational cost compared to increasing the resolution of the global model. This is known as the technique of dynamic downscaling, also referred to as regionalization. The smaller grid of the regional model allows for better detailing of topography, capturing valleys and mountain peaks, coastlines, vegetation cover, and land use, among other features. The smaller grid of the regional model enables a more accurate capture of intense horizontal gradients and, consequently, a better representation of extreme events. This detail makes the results of the regional model more suitable for studying the local impact of global climate change.

Evolution of climate modeling in Brazil

In Brazil, numerical climate modeling began with the operational activities of CPTEC/INPE in 1995. Initially, the models were used only for numerical weather forecasts (days) and seasonal climate forecasts (seasons) (Cavalcanti et al., 2002; Marengo et al., 2003, 2012). However, with technological advances and the development of powerful supercomputers, it has become possible to make climate projections for South America. The first climate change projections for South America were made using regional climate models (Ambrizzi et al., 2007; Marengo & Ambrizzi, 2006; Marengo et al., 2009). These early studies were based on the results of the regional models RegCM3 (Giorgi; Mearns, 1999; PAL et al., 2007), HadRMP3 (Jones et al., 2004), and Eta-CCS for the period 2070-2100, with high horizontal resolution (50 km) and forced by the HadAM3P global atmospheric model from the UK Met Office Hadley Centre (MOHC), based on GHG emission scenarios (A2 and B2).

In recent decades, both GCMs and regional climate models (RCMs) have made great strides in representing the components of the climate system, mainly due to better representation of physical processes and associated phenomena and their interactions (Marengo et al., 2012). GCMs are run using horizontal resolution of the order of one to two hundred kilometers. Improvements in model resolution and physical parameterizations have allowed for a more detailed representation of landscape features such as mountain ranges, lakes, vegetation types, and soil characteristics, leading to a better characterization of the hydrological cycle and associated extreme events, as well as a more realistic representation of regional/local climate compared to models with lower resolutions (100 km – 200 km) (Ambrizzi et al., 2019; Chou et al., 2014; Flato et al., 2013; Naumann et al., 2018).

Para obter maior detalhamento das previsões de tempo e clima sazonal, considerando a heterogeneidade da cobertura vegetal, a presença de cadeia topográficas complexas na América do Sul, foi instalado o modelo regional Eta (Mesinger et al. 1988) proveniente da versão operacional do NCEP (Black, 1994). O modelo entrou em operação no CPTEC/INPE em 1996 (Chou, 1996) gerando previsões inicialmente na resolução de 40 km e horizonte de 60 horas. Hoje este modelo, com modificações nos processos dinâmicos e físicos (Mesinger et al. 2012), produz previsões de tempo para até 11 dias, na resolução de 8 km sobre toda América do Sul, e até 3 dias na resolução de 1 km cobrindo região entre Rio de Janeiro e São Paulo. Outros dois modelos regionais entraram em operação no CPTEC/INPE, o modelo BRAMS e o WRF, o primeiro com foco na previsão da qualidade do ar, e o segundo por ser usado em várias instituições e universidades visto que possui uma interface amigável para uso. Outros centros também adquiriam modelos regionais como o MBAR e o COSMO no INMET e o COSMO na Marinha. Entretanto, modelo global operacional somente foi executado no INPE.

The extension of the Eta regional model forecast period to months ahead began with the work of Chou et al. (2000 and Chou et al. (2002. The seasonal climate version of the Eta Model became operational in 2001 (Chou et al., 2002), with a resolution of 40 km and a 4-month forecast horizon, using CPTEC/INPE MCGA forecasts to feed the regional model at the lateral boundaries. Pilotto et al. (2012) demonstrated that utilizing CPTEC/INPE CGCM as boundary conditions yields more accurate forecasts than using CPTEC/INPE MCGA.

However, with the government demanding higher spatial resolution projections for South America, the first climate change projections for the region were made using regional climate models (Ambrizzi et al., 2007; Marengo et al., 2009). These early studies were based on the results of the regional models RegCM3 (Giorgi; Mearns, 1999; PAL et al., 2007), HadRMP3 (JONES et al., 2004), and Eta-CCS for the period 2070-2100, at a horizontal resolution of 50 km and forced by the HadAM3P global atmospheric model from the UK Met Office Hadley Centre (MOHC). These regional models generated climate change projections based on the A2 and B2 greenhouse gas (GHG) emission scenarios used by CMIP3 and supported the IPCC's AR4.

Future climate change projectiomns in Brazil

On the subject of climate change in international politics, discussions have been ongoing since the mid-1990s regarding the establishment of targets to limit global warming to a predefined temperature threshold relative to pre-industrial levels (WBGU, 1995). In 2015, the Paris Agreement resulted in the formalization of a series of agreements, such as limiting global warming to a maximum of 1.5°C, thereby strengthening the global response to the threat of climate change and reinforcing countries' capacity to deal with the impacts of these changes, such as flooding, if temperature changes exceed 2°C, compared to global warming of 1.5°C.

Following the example of these studies, in Brazil, climate projections produced by the Eta-Cptec regional model (Chou et al., 2014a; Chou et al., 2014b), aligned with the HadGEM2-ES and MIROC5 global models (CMIP5) models, were adjusted to GWLs of 1.5°C, 2°C, and 4°C in order to support studies of climate vulnerability and adaptation measures related to water, energy, food, and socio-environmental security in the country within the scope of Brazil's Fourth National Communication (4CN) to the UNFCCC (Brazil 2020).

For climate change studies, most global models begin their run in the pre-industrial period, around 1850, and end at the end of the 21st century, in 2099. To cover this long time horizon, it is necessary to use supercomputers and grid boxes measuring a few hundred kilometers. Unlike seasonal climate horizons, climate models for climate change studies are run for decades and centuries ahead, following scenarios of changes in greenhouse gas concentrations and simulating changes in sea surface temperature anomalies. Therefore, models for climate change studies have additional complexity, requiring the refinement of physical processes, such as those in a sea ice model, a forest growth and death model, and carbon, nitrogen, and sulfur cycle models, among others. Physical processes such as cloud and rain formation, radiative transfer, ocean-atmosphere interactions, and atmospheric turbulence are standard processes in models used for weather forecasting or simulating climate change.

The effort to model climate change due to changes in GHG concentrations began in Brazil with the SRES family of emission scenarios: A2, A1, A1B, and B2, which were produced by CMIP3 and used in AR4. This was part of the GEF/MMA PRIOBIO project, which generated the first climate change scenarios for Brazil in 2007. The outputs of the HadAM3 model, organized in the CREAS project (Marengo et al, 2009), were used. The SRES scenarios are based on stories constructed along a timeline, in which different socioeconomic developments occur in more globalized or regionalized worlds. A2 is the most pessimistic scenario in terms of emissions, treated as "business-as-usual" (BAU). Next, the Representative Concentration Pathways (RCP) scenarios were constructed and used by the CMIP5 models, which generated results for the AR5. The RCP scenarios are inverse, providing levels of radiative forcing at the end of the century, i.e., they provide levels of change in the radiative balance due to the insertion of more GHGs into the atmosphere. Socioeconomic models (Integrated Assessment Model) construct the trajectory of gas increases in order to reach a level of GHG emissions that corresponds to the radiative forcing prescribed for the end of the 21st century. The radiative forcings adopted were 2.6, 4.5, 6.0, and 8.5 W m-2, which generated scenarios called RCP2.6, RCP4.5, RCP6.0, and RCP8.5 (Nakicenovic et al., 2000).

The scenarios used by the CMIP6 models combined the concept of radiative forcings with the construction of narratives of worlds in which mitigation is more or less challenging, and worlds in which adaptation is more or less challenging. There are five scenarios, known as SSP (Shared Socioeconomic Pathways) (O'Neil et al., 2014). Of these scenarios, SSP1 is the scenario in which the world grows with equality and a focus on sustainability, using radiative forcings of 1.9 and 2.6 W m-2. SSP2 is the moderate scenario for adaptation and mitigation challenges and is accompanied by a forcing of 4.5 W m-2. SSP3 represents a fragmented world with regional rivalries. SSP4 represents a world with even greater inequalities. SSP5 is the scenario of a world of fossil fuels and economic growth at all costs and, therefore, a radiative forcing of 8.5Wm-2. These scenarios are therefore referred to as SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-6.0, SSP4-7.0, and SSP5-8.5 (O'Neil et al., 2014).

Climate change is a global phenomenon of predominantly anthropogenic origin, whose effects are already being observed in different physical and socioeconomic systems. Understanding of these dynamics has been consolidated through the Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC), which summarize the state of the art in climate science and guide the formulation of public policies at the global, regional, and national levels. Below, we will discuss the scientific advances in these assessment reports, with an emphasis on the results relevant to Brazil.

The Fifth Assessment Report (AR5) of the IPCC (2013) represented a consolidation of observational evidence of global warming, stating with extremely high confidence that "warming of the climate system is unequivocal" and attributing with high confidence more than half of the increase in global average temperature to human influence, primarily through the emission of greenhouse gases (GHGs). AR5 also advanced in quantifying the radiative forcing of different climate agents, with special attention to CO_2, CH_4, and aerosols.

About climate projections, AR5 used Representative Concentration Pathways (RCPs), which indicated average temperature increases of up to 4.8°C by 2100 in the worst-case scenario (RCP8.5). The CMIP5 global climate models (GCMs), although robust for continental scales, had limitations in capturing regional characteristics, especially in tropical regions such as South America.

The Sixth Assessment Report (AR6) significantly expanded and refined this basis. In the Working Group I volume (WGI-IPCC 2021), the estimate of global temperature increase since the pre-industrial period was updated to 1.2°C, and the attribution of warming to human activities was considered unequivocal. This represents an even higher degree of certainty than in AR5. AR6 incorporated the new Shared Socioeconomic Pathways (SSPs) scenarios, which provide an integrated framework for socioeconomic evolution, emissions, and climate policies.

The use of the CMIP6 model suite, which provides a better representation of atmospheric, oceanic, and terrestrial processes, has enabled advances in the regionalization of projections and the understanding of extreme events. In addition, AR6 introduced a more sophisticated assessment approach, comprising three complementary lines of evidence: model simulations, observational data, and a physical understanding of the processes.

One of the most relevant advances of AR6 was the consolidation of more detailed regional diagnoses, systematized in the Interactive Atlas (https://interactive-atlas.ipcc.ch/) and the regional chapters. For Brazil, the report pointed to high confidence in an increase in the frequency and intensity of temperature extremes, a trend toward reduced precipitation in northeastern and south-central Brazil, and an increased risk of agricultural and ecological drought, particularly in the transition zone between the Amazon and the Cerrado.

3.3 Climate Change projections and impacts in Brazil

Brazil has shown that it is particularly vulnerable to climate change due to its physical characteristics (extensive tropical area, high natural climate variability), ecological characteristics (incredible biodiversity and biomes such as the Amazon, the Cerrado, and the Semi-Arid region), and social characteristics (significant regional and population inequalities). Based on the AR6 SSP scenarios, it is estimated that by 2100 (Figure 7):

- The average annual temperature may increase between 2.5 and 4.5°C in most of the national territory under the SSP5-8.5 scenario.
- Areas such as the northeastern Semi-Arid region and southern Amazon may experience prolonged and severe droughts, with impacts on agricultural production, water resources, and public health.
- Extreme composite events, such as heat waves simultaneous with drought, tend to intensify, requiring integrated adaptation strategies.
- In addition, recent observations point to a weakening of the monsoon regime in South America, delays in the onset of the rainy season in the Cerrado, and intensification of dry extremes in the Paraná River basin.

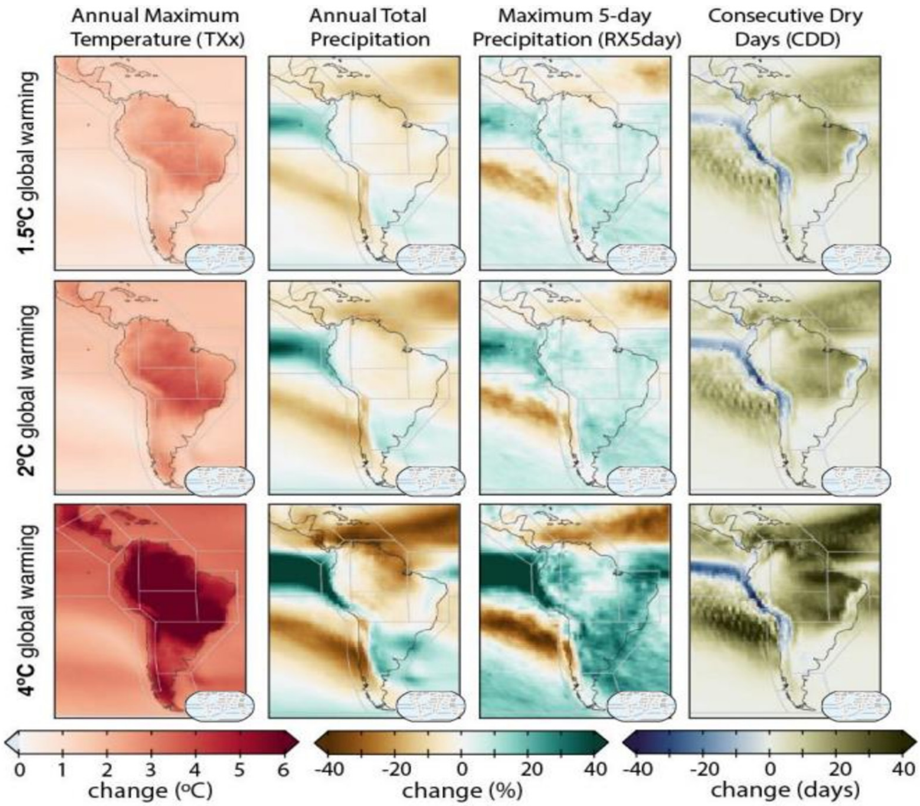


Figure 7: Projected changes in annual maximum temperature (TXx), total annual precipitation, maximum precipitation in 5 days (RX5day), and annual number of consecutive dry days (CDD) under global warming of 1.5°C, 2°C, and 4°C (in the lines), relative to the period 1850–1900. The results are based on simulations from the CMIP6 multi-model ensemble (32 models). °C, and 4°C (in the lines), relative to the period 1850–1900. The results are based on simulations from the CMIP6 multi-model ensemble (32 global climate models), using the SSP5-8.5 scenario to calculate warming levels. Source: IPCC Interactive Atlas. Available at http://interactive-atlas.ipcc.ch/.

CLIMATE CHANGE PROJECTIONS DERIVED FROM REGIONAL MODELS

The impacts of climate change on various socioeconomic sectors are generally local in scale, which usually requires more detailed climate information. The downscaling (or regionalization) of global model projections to the local scale, i.e., moving from global model grids of approximately 100 to 200 km to sizes of 20 km, 5 km, or 1 km, is performed using dynamic regional models, statistical models, or machine learning models. The combination of dynamic downscaling and bias correction can generate the best results (Tavares et al., 2022).

Climate change projections from the Eta regional model were generated at 20 km resolutions using outputs from the global models BESM, CanESM2, HadGEM2-ES, and MIROC5 (Chou et al., 2014b) and at 5 km resolutions using outputs from the HadGEM2-ES (Lyra et al., 2017) and BESM (Sondermann et al., 2023) models for the Southeast and 5 km Eta-HadGEM2-ES for Southern Brazil (Ferreira et al., 2023; Tavares & Chou, 2022). To consider the uncertainty of greenhouse gas emissions, two concentration levels were used in Chou et al. (2014b): RCP4.5 moderate emissions and RCP8.5 intense emissions. Thus, the set results in eight possibilities for future climate projections.

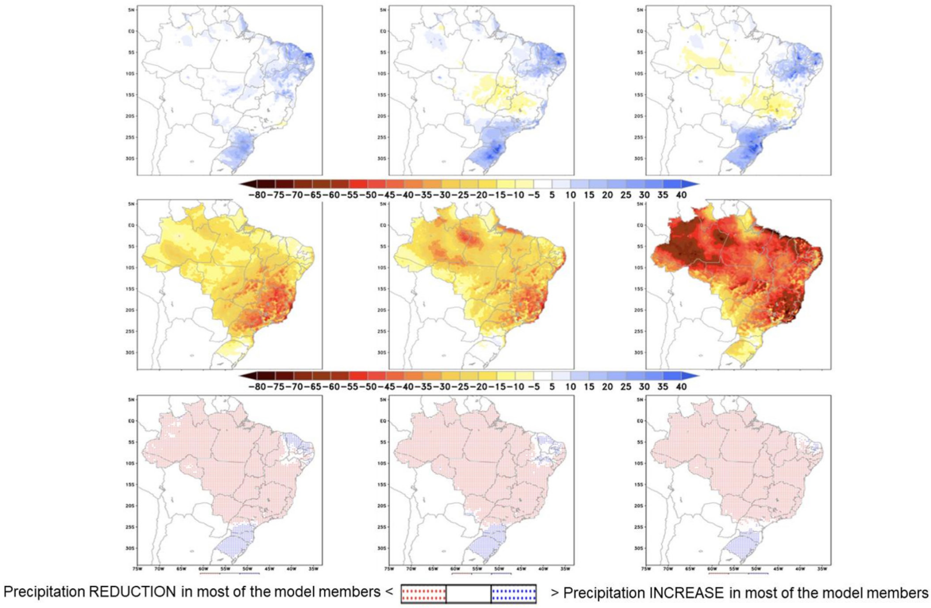


Figure 8: Projections of precipitation changes in three future periods: 2011–2040 (left), 2041–2070 (center), and 2071–2100 (right). Upper (first row) and lower (second row) limits of changes. Sign of change for most members.

Figure 8 shows the projections of precipitation changes for the three future climate periods, generated from eight model projections (four global models and two emission scenarios). The range of changes resulting from the eight climate projections, or eight members, is indicated by the upper and lower limits of the changes. This range partly reflects the uncertainty of the projections. In the Northeast, for example, projections indicate a range of outcomes, from a reduction in rainfall to an increase in rainfall, with the predominant signal being an increase in rainfall, primarily in the northern part of the Brazilian Northeast. In the central part of the country, projections indicate a range from a sharp reduction in rainfall to a slight reduction or increase, with the predominant signal being a decrease in rainfall in much of the North, Central-West, and Southeast of the country. On the other hand, in the South, projections indicate a range from a slight reduction in rainfall to a sharp increase, with the predominant signal being an increase in rainfall.

Another way of presenting climate change projections is based on the warming limits adopted by the Paris Agreement. Tavares et al. (2023)

demonstrated that with an average global warming of 1.5 °C, the precipitation pattern in the country exhibits a reduction in rainfall from the Southeast to the North, an increase in rainfall in the northern part of the Northeast, and a sharp increase in rainfall in the South.

Regarding climate extremes in the country, high-resolution projections indicate an increase in intense rainfall in the South (Chou et al., 2014b; Reboita et al., 2022), while on the other hand, there will be an increase in the dry season in the Amazon (Brito et al., 2023; Reboita et al., 2022) and the Northeast (Chou et al., 2014b).

The use of even higher resolutions, around 4 to 5 km, allows for the capture of phenomena dependent on local physiography, such as mountains, land use, and/or changes in land use. Projections for metropolitan areas in the Southeast, at a resolution of 5 km, show even more intense changes in annual rainfall reduction and the intensification of extremes (Lyra et al., 2018). The spatial resolution generally employed by global models does not allow for the distinction between urban areas, croplands, mountainous regions, or small watersheds. In addition to physiography, greater detail allows climate model equations to reproduce more extreme events. In the work of Tavares and Chou (2022), it was demonstrated that intense rainfall, combined with strong winds from cold fronts, may increase in frequency in the winter months in the future, particularly in the Itajaí Valley.

When constructing climate change projections, scenarios generally assume a global increase in greenhouse gases. On the other hand, in addition to this global effect, local changes in land use occur, which, when combined with global effects, can result in distinct impacts. These scenarios of land use change are local and require the use of models with higher spatial resolutions than those provided by global models.

Brito et al. (2022) demonstrated that projections of global climate change, combined with the conversion of the Amazon rainforest to pasture, yield even more severe impacts compared to projections that exclude deforestation. With local effects, dry seasons are further prolonged, and total annual rainfall is further reduced. The impacts of deforestation patterns in the Amazon from 1983 to 1988 were captured at a resolution of 1 km by Pilotto et al. (2023). Deforestation growth was included year by year, and based on the inclusion of river routing, the effects of El Niño and La Niña, as well as the impact of deforestation on the flow of the Ji-Paraná

River, were compared. It was found that deforestation caused an additional reduction in river flow during the dry season.

On the other hand, considering positive actions, Lopes (2023) included areas of reforestation of the Atlantic Forest, assuming changes in land use, then simulated the future climate in the Southeast in RCP8.5 scenarios and evaluated the long-term effects on water resource planning in the Paraíba do Sul, Grande, and Doce river basins. The inclusion of reforestation patches resulted in temperatures dropping by up to 2°C. The increase in the Atlantic Forest area also reduced the amplitude of flow extremes, providing better sustainability indices. Studies addressing local problems require greater computational power. However, they are more suitable for specific local issues that need to be addressed.

CONCLUSIONS

Brazil has regions that are more susceptible to climate-related disasters than others. The main ones are Serra do Mar, Serra da Mantiqueira, and Serra Geral, in the area that includes Rio de Janeiro, São Paulo, Paraná, and Santa Catarina. It is an area whose terrain is well known, where we have a concentration of landslides, debris flows, and floods. With the climate crisis and increased rainfall, the trend is for areas susceptible to landslides and floods to experience events of even greater magnitude. Any municipality within these mountain ranges will continue to experience movements such as landslides. This is part of the nature of that geological compartment. Future scenarios of extreme rainfall may further aggravate the threat and increase the risk of disasters in vulnerable and exposed areas.

Climate science in Brazil has evolved significantly, with the strengthening of institutional capacity for modeling, observation, and impact analysis. Initiatives such as the Climate Projections Portal (http://pclima.inpe.br/), the AdaptaBrasil MCTI Platform (https://adaptabrasil.mcti.gov.br/), the CORDEX-CORE project, the Climate Network Rede-Clima, and the use of high-resolution regional models have contributed to a more refined diagnosis of climate risks. However, scientific and technical challenges remain, such as:

- Reducing regional uncertainties: Interannual and decadal climate variability in the Tropical Atlantic and Pacific strongly influences rainfall patterns in Brazil, but its interaction with global warming is not yet fully understood.
- Integration of multiple data sources: The combination of climate models, reanalyses, observed series, and artificial intelligence is essential to improve predictability and regionalization.
- Analysis of composite events: The identification and prediction of simultaneous events (such as heat + drought) require statistical and physical approaches that are under development

In addition, the ability to attribute extreme events to global warming, a scientific methodology that assesses the extent to which an event has become more likely or intense due to climate change, has gained ground in Brazil but lacks ongoing investment.

The scientific implications of the IPCC reports and the work of Rede Clima, CEMADEN, and INPE of the MCTI and state and federal universities have motivated institutional advances in Brazil, including the updating of the NDC (Nationally Determined Contribution), the formulation of national adaptation strategies, and the commitment to climate federalism and disaster risk assessment in the present and future. However, the application of climate science in the formulation of public policies still faces barriers: difficulty in translating climate scenarios into sectoral impacts; lack of integration between decision-making levels (federal, state, municipal); low local technical capacity to interpret and use climate and disaster risk information.

It is important to highlight that the science presented should be considered not only as a warning, but as a strategic planning tool. The incorporation of climate scenarios into land use planning, water security, and energy transition policies can significantly reduce social and economic risks in various regions of Brazil.

REFERENCES

Aliança Brasileira pela Cultura Oceânica (2025) 2024: O Ano Mais Quente da História, Brasil em Transformação: O IMPACTO DA CRISE CLIMÁTICA, Caderno Técnico 1, São Paulo, 21 pp.

Alcântara E., Marengo, J. Mantovani, J., Londe, L.R., San, L. Y., Park, E., Lin, Y. N. Wang, J., Mendes, T., Cunha, A. P., Pampuch, L., Seluchi, M. E.. Simões, S. , Cuartas, L. A., Gon=çalves, D., Massi, K., Alvalá, R. C. S., Moraes, O. L., Souza Filho, C., Mendes, R., and Nobre, C.A. (2023) Deadly disasters in southeastern South America: flash floods and landslides of February 2022 in Petrópolis, Rio de Janeiro, Nat. Hazards Earth Syst. Sci., 23, 1–19, https://doi.org/10.5194/nhess-23-1-2023.

Alvalá RCS, Ribeiro DF, Marengo JÁ, Seluchi ME, Gonçalves DM, da Silva LA, Cuartas Pineda LA, Saito S, (2024) Analysis of the hydrological disaster occurred in the state of Rio Grande do Sul, Brazil in September 2023: Vulnerabilities and risk management capabilities, International Journal of Disaster Risk Reduction 110 (2024) 104645, https://doi.org/10.1016/j.ijdrr.2024.104645

Alvalá RC et al (2017) Drought monitoring in the Brazilian semiarid region, in press, Annais da Academia Brasilieira de Ciencias do Brasil. http://dx.doi.org/10.1590/0001-3765201720170209

Bazzanela, A.C., Dereczynski, C., Luiz-Silva, W. *et al.* Performance of CMIP6 models over South America. Clim Dyn 62, 1501–1516 (2024). https://doi.org/10.1007/s00382-023-06979-1

Brasil 2016. Plano Nacional de Adaptação à Mudança do Clima.Sumário Executivo, Ministério do Meio Ambiente, Brasília, 2016, Secretaria de Mudanças Climáticas e Qualidade Ambiental, 16 pp.

Brasil 2020. Quarta Comunicação Nacional do Brasil a UNFCCC, Sumário Executivo, Brasil 20-20, Ministério da Ciência, Tecnologia e Inovações, Brasília, 33 p.

Brêda, J.P.L. Filho; De Paiva, R.C.D.; Chou, S.C.; Collischonn, W. Assessing extreme precipitation from a regional climate model in different spatial-temporal scales: A hydrological perspective in South America. International Journal of Climatology. , 42, 1 - 15, 2022.

Brito, A. L., Veiga, J. A. P., Correia, F. S., Michiles, A. A., Capistrano, V. B., Chou, S. C., Lyra, A., & Medeiros, G. (2023). Impacts of increasing greenhouse gas concentrations and deforestation on extreme rainfall events in the Amazon basin: A multi-model ensemble-based study. International Journal of Climatology, 1–24. https://doi.org/10.1002/joc.8158

Cavalcanti, I. F. A. ; Marengo, J. ; Satyamurty, P. ; Nobre, C. N. ; Trosnikov, I. ; Bonatti, J. P. ; Manzi, A. O. ; Tarasova, T. ; Pezzi, L. P. ; Dalmeida, C. . Global Climatological features in a Simulation Using the CPTEC/COLA AGCM. Journal of Climate, v. 15, n.21, p. 2965-2988, 2002. https://doi.org/10.1175/1520-0442(2002)015<2965:GCFIAS>2.0.CO;2

CEMADEN (2025) Estado do clima, extremos de clima e desastres no Brasil em 2024, CEMADEN, São Jose dos Campos, SP, 2025, 37 pp, disponível em https://inctmc2.cemaden.gov.br/

Chou, Sin Chan, Justi da Silva, M. G. A. Objective evaluation of Eta Model precipitation forecasts over South America. Climanálise (São José dos Campos). , v.14, 1999 ISSN 0103-0019

Chou, Sin Chan. Modelo Regional Eta. Climanálise (São José dos Campos), Cachoeira Paulista, SP, v. 1, p. 27- 29,, 1996, http://climanalise.cptec.inpe.br/~rclimanl/boletim/cliesp10a/27.html

Chou, S. C.; Nunes, A. M. B.; Cavalcanti, I. F. A., 2000. Extended range forecasts over South America using the regional Eta model. Journal of Geophysical Research, v. 105, n. D8, p. 10147-10160

Chou, S. C.; Tanajura, C. A. S. ; Xue, Y. ; Nobre, C. A., 2002. Validation of the Coupled Eta/SSiB Model over South America. Journal of Geophysical Research, Estados Unidos, v. 107, n. D20, pp. LBA 56-1, doi: 10.1029/2000JD000270

Chou SC, Marengo JA, Lyra A, Sueiro G, Pesquero J, Alves LM, Kay G, Betts R, Chagas D, Gomes JL, Bustamante J, Tavares P (2012) Downscaling of South America present climate driven by 4-member HadCM3 runs. Climate Dynamics. Vol. 38 n. 3-4, 635-653. DOI 10.1007/s00382-011-1002-8

Chou, S.C , Lyra, A. , Mourão, C. , Dereczynski, C. , Pilotto, I. , Gomes, J. , Bustamante, J. , Tavares, P. , Silva, A. , Rodrigues, D. , Campos, D. , Chagas, D. , Sueiro, G. , Siqueira, G. , Nobre, P. and Marengo, J. (2014a) Evaluation of the Eta Simulations Nested in Three Global Climate Models. American Journal of Climate Change, 3, 438-454. doi:10.4236/ajcc.2014.35039.

Chou, S.C, Lyra, A., Mourão, C., Dereczynski, C., Pilotto, I., Gomes, J., Bustamante, J., Tavares, P., Silva, A., Rodrigues, D., Campos, D., Chagas, D., Sueiro, G., Siqueira, G. and Marengo, J. (2014b) Assessment of Climate Change over South America under RCP 4.5 and 8.5 Downscaling Scenarios. American Journal of Climate Change,3, 512-527. doi: 10.4236/ajcc.2014.35043

Chou, S.C., de Arruda Lyra, A., Gomes, J.L., Rodriguez, D.A, Martins, M., Resende, N., Tavares, P., Dereczynski, C.P., Pilotto, I., Martins, A.M., Carvalho, L.F.A., Onofre, J.L.L., Major, I., Penhor, M., Santana, A.. 2020b. Downscaling projections of climate change in Sao Tome and Principe Islands, Africa. Clim Dyn (2020). 54:4021–4042https://doi.org/10.1007/s00382-020-05212-7

Dereczynski, C., Chou, S.C., Lyra, A., Sondermann, M., Regoto, P., Tavares, P.,Chagas, D., Gomes, J.L., Rodrigues, D.C., Skansi, M.M.. Downscaling of climate extremes over South America – Part I: Model evaluation in the reference climate. Weather and Climate Extremes. p. 100273, 2020. DOI: 10.1016/j.wace.2020.100273

Debone, D.; Tavella, R. A.; Colombo, A. L.; Gales, A. C.; da Silva Júnior, F. M. R.; Miraglia, S. G. E. K. Is It Time to Build an Ark? The Reality of Climate Change in One of the Worst Climate Tragedies in Brazil. Preprints 2024, 2024061702. https://doi.org/10.20944/preprints202406.1702.v1

Dunn, R. J. H., Alexander, L. V., Donat, M. G., Zhang, X., Bador,M., Herold, N., *et al.* (2020). Development of an updated global land in situ‐based data set of temperature and precipitation extremes: HadEX3. Journal of Geophysical Research: Atmospheres, 125, e2019JD032263. https://doi.org/10.1029/2019JD032263

Dunn, R. J. H., Herold, N., Alexander, L. V., Donat, M. G., Allan, R., Bador, M., *et al.* (2024). Observed global changes in sector‐relevant climate extremes indices— An extension to HadEX3. Earth and Space Science, 11, e2023EA003279. https://doi.org/10.1029/2023EA003279

Espinoza, J., Marengo, J. A., Schongart, J., & Jimenez, J. C. (2022). The New Historical Flood of 2021 in the Amazon River Compared to Major Floods of the 21st Century: Atmospheric Features in the Context of the Intensification of Floods. Weather and Climate Extremes, 35, Article ID: 100406. https://doi.org/10.1016/j.wace.2021.100406

Espinoza, J., Jimenez, J. C., Marengo, J. A., Schongart, J., Ronchail, J., Lavado-Casimiro, W., *et al.* (2024). The New Record of Drought and Warmth in the Amazon in 2023 Related to Regional and Global Climatic Features. Scientific Reports, 14, Article No. 8107. https://doi.org/10.1038/s41598-024-58782-5

Ferreira, N. C. R., Tavares, P. S., Medeiros, G. S., Ferreira, L. N., Borges, P., Chou, S. C., & Rodrigues, M. L. (2023). Projeções de tempo severo e impactos em torres de linhas de transmissão em Santa Catarina, Brasil, sob cenários futuros de mudanças climáticas globais. Derbyana, 44. https://doi.org/10.14295/derb.v44.808

Floodlist (2023) https://floodlist.com/america/floods-tarija-bolivia-february-2022

Floodlist (2024b) https://floodlist.com/america/argentina-flood-buenos-aires-march-2024

Floodlist (2024c) https://floodlist.com/america/brazil-floods-rio-de-janeiro-february-2024

Gorenstein, I.; Prado, L.F.; Bianchini, P.R.; Wainer, I.; Griffiths, M.L.; Pausata, F.S.R.; Yokoyama, E. 2022. A fully calibrated and updated mid-Holocene climate reconstruction for Eastern South America. Quaternary Science Reviews, 292: 107646. https://doi.org/10.1016/j.quascirev.2022.107646

Grimm A, Tedeschi R, (2009) ENSO and Extreme Rainfall Events in South America, J of Climate, 22, 1589–1609, https://doi.org/10.1175/2008JCLI2429.1

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2021) Summary for Policymakers. In: Climate Change (2021) The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Reitzel, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32, doi:10.1017/9781009157896.001.

IPCC (2022) Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, p. 3056. https://doi.org/10.1017/ 9781009325844, 2022

IPCC 2012: Summary for Policymakers. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 3-21.

Lopes, L.G. Sustentabilidade hídrica sob cenários de mudanças climáticas, restauração florestal e de demanda de água em sistemas hídricos no Sudeste brasileiro. Tese de Doutorado em Ciência do Sistema Terrestre. Instituto Nacional de Pesquisas Espaciais, São José dos Campos, 2023.

Lyra, A., Tavares, P., Chou, S.C., Sueiro, G., Dereczynski, C.P., Sondermann, M., Silva, A., Marengo, J., Giarolla, A. 2018. Climate change projections over three metropolitan regions in Southeast Brazil using the non-hydrostatic Eta regional climate model at 5-km resolution. Theor Appl Climatol 132, 663–682 (2018). https://doi.org/10.1007/S00704-017-2110-0

Marchi, A. C. de, Melo, M. L. D. de, Lyra, A. de A., Kubota, P. Y. ., Chou, S. C., & Rosas, P. (2022). Simulações climáticas do Holoceno Médio para o Brasil utilizando o modelo regional paleoclimático Eta. Derbyana, 43, e775. https://doi.org/10.14295/derb.v43.775

Marengo, J. A.; Alves, L. M. Crise hídrica em São Paulo em 2014: seca e desmatamento. Geousp – Espaço e Tempo (Online), v. 19, n. 3, p. 485-494, mês. 2016. ISSN 2179-0892.

Marengo JA, Torres RR, Alves LM (2017) Drought in Northeast Brazil—past, present, and future. Theor Appl Climatol 20:1–12. https ://doi.org/10.1007/s0070 4-016-1840-8

Marengo JA, Alves LM, Alvala RCS et al (2018) Climatic characteristics of the 2010–2016 drought in the semiarid northeast Brazil region. An Acad Bras Cienc. https ://doi.org/10.1590/0001-37652 01720 17020 6

Marengo JA, Cunha AP, Nobre CA, Ribeiro Neto G, Magalhaes AR, Torres RR, Sampaio G, Alexandre F., Alves LM, Cuartas LA, Leal K, Alvalá RCS, (2020) Assessing drought in the drylands of northeast Brazil under regional warming exceeding 4 °C, Natural Hazards (2020) 103:2589–2611, https://doi.org/10.1007/s11069-020-04097-3

Marengo JA, Cunha AP, Cuartas LA, Deusdará Leal KR, Broedel E, Seluchi ME, Michelin CM, De Praga, Baião CF, Chuchón Ângulo E, Almeida EK, Kazmierczak ML, Mateus NPA, Silva RC and Bender F (2021) Extreme Drought in the Brazilian Pantanal in 2019–2020: Characterization, Causes, and Impacts. Front. Water 3:639204. doi: 10.3389/frwa.2021.639204

Marengo, J. A., Alcantara, E., Cunha, A. P., Seluchi, M. E., Nobre, C.A., Dolif, G., Goncalves, D., Assis Dias, M., Cuartas, L. A., Bender, F., Ramos, A. M., Mantovani, J. R., Alvalá, R.C.S., and Moraes, O.L. (2023) Flash floods and landslides in the city of Recife, Northeast Brazil after heavy rain on May 25–28, 2022: Causes, impacts, and disaster preparedness, Weather and Climate Extremes, 39, 100545, doi: https://doi.org/10.1016/j.wace.2022.100545

Marengo, J., Dolif, G., Cuartas, A., Camarinha, P., Gonçalves, D., Luiz, R., Silva, L., Alvala, R., Seluchi, M., Moraes, O., Soares, W., Nobre, C. (2024 a) O Maior Desastre Climático do Brasil: Chuvas e Inundações no estado do Rio Grande do Sul em abril-maio 2024. Estudos Avançados (online). v.38, p.203 - 228, 2024.

Marengo, J., Cunha, A., P., Espinoza, J. C., Fu, R., Schöngart, J., Jimenez, J.C., Costa, M. C., Ribeiro, J. M., Wongchuig, S., Zhao, S., (2024b) The Drought of Amazonia in 2023-2024. American Journal of Climate Change. v.13, p.567 - 597, 2024.

Marengo, J.A., Alcantara, E., Moraes, O. L., Martinez, R., Seluchi, M., Alvala, R., Dolif, G., Goncalves D (2025 a) Early warning services for disaster risk reduction in Brazil: The experience of CEMADEN during the floods of Rio Grande do Sul of May 2024, International Journal of Disaster Risk Reduction, 126, August 2025, 105645, https://doi.org/10.1016/j.ijdrr.2025.105645

Marengo JA, Costa MC, Cunha AP, Espinoza J-C, Jimenez JC, Libonati R, Miranda V, Trigo IF, Sierra JP, Geirinhas JL, Ramos AM, Skansi M, Molina-Carpio J and Salinas R (2025b) Climatological patterns of heatwaves during winter and spring 2023 and trends for the period 1979–2023 in central South America. Front. Clim. 7:1529082. doi: 10.3389/fclim.2025.1529082

Marques, V.S.; Dereczynski, C.P. Weather Forecasting in Brazil: A Concise Historical Review. Anuário do Instituto de Geociências - UFRJ, v. 44, p. 1-14, 2021. doi:10.11137/1982-3908_2021_44_45358

Melo, M.L.D.; Marengo, J.A. 2007. The influence of changes in orbital parameters over South American climate using the CPTEC AGCM: simulation of climate during the mid-Holocene. The Holocene, 18(4): 501-516. https://doi.org/10.1177/0959683608089205

Mesinger F, Chou SC, Gomes JL, Jovic D, Bastos P, Bustamante JF, Lazic L, Lyra AA, Morelli S, Ristic I, Veljovic K. (2012) An upgraded version of the Eta model. Meteorology and Atmospheric Physics. Vol 116 (3), 63-79. DOI: 10.1007/s00703-012-0182-z

Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenham J, Gaffin S, Gregory K, Gruebler A, Jung TY, Kram T, La Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner H-H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooijen S, Victor N, Dadi Z (2000) Special report on emissions scenarios. Cambridge University Press, New York.

Nobre, P., and Coauthors, 2013: Climate Simulation and Change in the Brazilian Climate Model. J. Climate, 26, 6716–6732, https://doi.org/10.1175/JCLI-D-12-00580.1.

O'Neill BC, Kriegler E, Riahi K, Ebi KL, Hallegatte S, Carter TR, *et al.* A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim. Change (2014) 122(3):387–400. doi: 10.1007/s10584-013-0905-2

Pesquero, J.F., Chou, S.C., Nobre, C.A., Marengo, J.A., 2010: Climate downscaling over South America for 1961-1970 using the Eta Model. Theoretical and Applied Climatology. Vol 99, 1-2, p.75-93. DOI: 10.1007/s00704-009-0123-z

Pilotto ID, Chou SC, Nobre P. Seasonal climate hindcasts with Eta model nested in CPTEC coupled ocean-atmosphere general circulation model. Theoretical and Applied Climatology. Vol.110, no. 3, pp. 437-456. 2012. DOI:10.1007/s00704-012-0633-y.

Pilotto, I.L., Rodriguez, D.A., Chou, S.C., Garofolo, L., Gomes, J.L. Impacts of the land use and land-cover changes on local hydroclimate in southwestern Amazon. Clim Dyn 61, 5597–5612 (2023). https://doi.org/10.1007/s00382-023-06872-x

Reboita, M.S., Kuki, C.A.C., Marrafon, V.H. *et al.* South America climate change revealed through climate indices projected by GCMs and Eta-RCM ensembles. Clim Dyn 58, 459–485 (2022). https://doi.org/10.1007/s00382-021-05918-2

Reboita, M.S.; Mattos, E.V.; Capucin, B.C.; Souza, D.O.d.; Ferreira, G.W.d.S. A Multi-Scale Analysis of the Extreme Precipitation in Southern Brazil in April/May 2024. Atmosphere 2024, 15, 1123. https://doi.org/ 10.3390/atmos15091123

Seluchi, M. E., Chou, S. C. Evaluation of two eta Model versions for weather forecast over South America. Geofísica Internacional. Mexico, v.40, p.219 - 237, 2001

Seneviratne, S.I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., Ghosh, S., Iskander, I., Kossin, J., Lewis, S., Otto, F., Pinto, I., Satoh, M., Vicente-Serrano, S.M., Wehner, M., & Zhou, B. (2021). Weather and Climate Extreme Events in a Changing Climate (Chapter 11). In: IPCC 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Eds. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., *et al.*, pp. 1513-1766 Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. 10.1017/9781009157896.013.

Sondermann, M.; Chou, S.C.; Tavares, P.; Lyra, A.; Marengo, J.A.; Souza, C.R.d.G. Projections of Changes in Atmospheric Conditions Leading to Storm Surges along the Coast of Santos, Brazil. Climate 2023, 11, 176. https://doi.org/10.3390/cli11090176

Tavares, P.S., Chou, S.C. Passagens de frentes frias extremas no Vale do Itajaí no clima futuro. Anais do XIX Simpósio Brasileiro de Geografia Física Aplicada. 2022. Rio de Janeiro, RJ.

Tavares, P.S., Acosta, R., Nobre, P., Resende, N.C., Chou, S.C., Lyra, A.A. Water balance components and climate extremes over Brazil under 1.5 °C and 2.0 °C of global warming scenarios. Reg Environ Change 23(1), 40 (2023). https://doi.org/10.1007/s10113-023-02042-1

Toreti, A., Bavera, D., Acosta Navarro, J., Acquafresca, L., Barbosa, P., de Jager, A., Ficchì, A., Fioravanti, G., Grimaldi, S., Hrast Essenfelder, A., Magni, D., Mazzeschi, M., McCormick, N., Salamon, P., Santos Nunes, S., Volpi, D. (2024) Drought in the Amazon and the La Plata basins - December 2024, GDO Analytical Report, JRC140741, doi:10.2760/9524487, Luxembourg: Publications Office of the European Union, 2024 European Union, 2024,. 30 pp.

Veiga SF, Nobre P, Giarolla E, Capistrano V, Baptista J et al (2019) The Brazilian Earth System Model ocean–atmosphere (BESM-OA) version 2.5: evaluation of its CMIP5 historical simulation. Geosci Model Dev 12:1613–1642. https://doi.org/10.5194/gmd-12-1613-2019

World Meteorological Organization (WMO) (2020) State of Climate for Latin America and Caribbean 2019. WMO, Geneva, Switzerland.

World Meteorological Organization (WMO) (2021) State of Climate for Latin America and Caribbean 2020. WMO, Geneva, Switzerland.

World Meteorological Organization (WMO) (2022) State of Climate for Latin America and Caribbean 2021. WMO, Geneva, Switzerland.

World Meteorological Organization (WMO) (2023) State of Climate for Latin America and Caribbean 2022. WMO, Geneva, Switzerland.

World Meteorological Organization (WMO) (2024) State of Climate for Latin America and Caribbean 2023. WMO, Geneva, Switzerland.

World Meteorological Organization (WMO) (2025) State of Climate for Latin America and Caribbean 2024. WMO, Geneva, Switzerland.

2. THE AMAZON RAINFOREST IS CHANGING DUE TO DEFORESTATION, FIRES, AND GLOBAL CLIMATE CHANGE

Luciana V. Gatti[3], Camilla L. Cunha[3], Jose A. Marengo[4], Ben-Hur Marimon[5], Beatriz S. Marimon[5], Julia Arieira[6], Carlos Nobre[7]

INTRODUCTION

Over the past five decades, significant progress has been made in displacing the Amazon rainforest through grazing, logging, soy and corn plantations, mining, urban growth, and more. According to PRODES (INPE), 21.6% of the Brazilian Amazon has been deforested since monitoring began (Figure 1). Between 2005 and 2012, a significant decrease in deforestation was observed, due to the implementation of the PPCDAm (Action Plan for the Prevention and Control of Deforestation in the Legal Amazon). Since 2012, when the Forest Code was reformed by the National Congress, an amnesty was granted for 58% of illegal deforestation prior to 2008, environmental penalties were suspended, and landowners were given 20 years to comply with the Forest Code. Since then, deforestation in the Brazilian Amazon has slowly resumed. From 2015 to 2018, deforestation increased by 28% compared to the period 2009 to 2014. From 2019,

---

3 National Institute of Space Research, INPE, São José dos Campos, Brazil.

4 National Center for Monitoring and Alerting of Natural Disasters, CEMADEN, São Jose dos Campos, Brazil.

5 State University of Mato Grosso, UNEMAT, Nova Xavantina, Brazil.

6 Science Panel for the Amazon, SPA, São José dos Campos, Brazil.

corresponding author: luciana.gatti@inpe.br

a period of intensified deforestation began, that had not been observed since 2008. If we compare the period 2019 to 2022 with the period 2009 to 2014, the increase is 119%. In 2023 and 2024, a decrease of 47% was observed compared to the previous period.

When analyzing the Amazon states, the state of Pará accounts for an average of 42% of annual deforestation, with a significant decrease between 2022 and 2024 (Figure 2). The state of Mato Grosso accounts for an average of 19% of the total, and the states of Amazonas and Rondônia for 14% and 13%, respectively. The state of Amazonas recorded a significant increase in 2021 and 2022, which declined again in 2023 and 2024, while the state of Mato Grosso is again the second largest state with the highest deforestation rate in the biome.

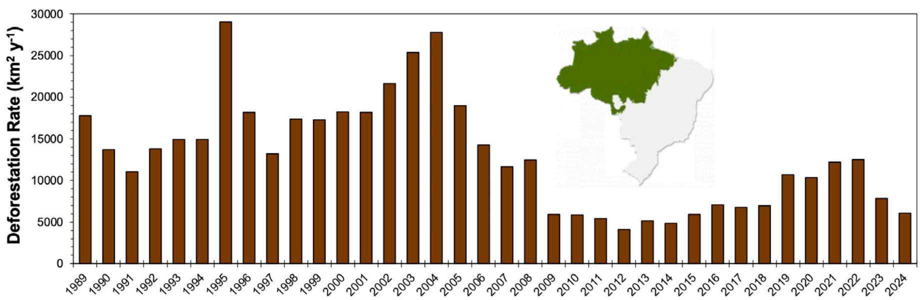


Figure 1: Historical deforestation rate from PRODES (INPE) in the Legal Amazon.

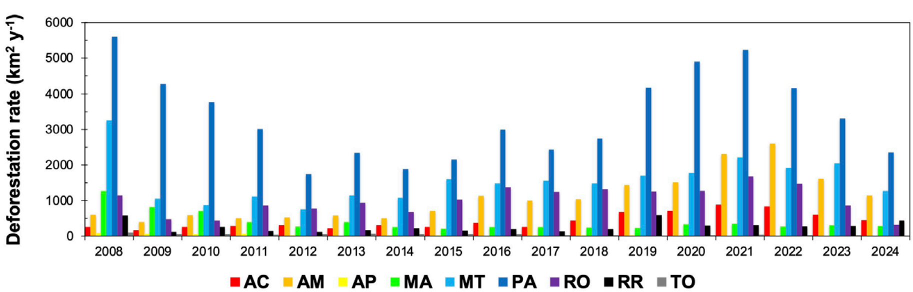


Figure 2: Historical deforestation rate by state in the Legal Amazon from PRODES (INPE).

A link has been established between deforestation, the decrease in precipitation, and the increase in temperatures, mainly during the dry season[4-9]. According to Gatti et al. (2021, 2023)[4,6], the most deforested region, presented highest decrease in precipitation and increase in temperature. Figure 3 shows three Amazon sub-regions. Region 1 is located in the eastern part of the Amazon part of the states of Pará and Mato Grosso), is already 28% deforestation until 2018, and presented decrease in precipitation of 28% and an increase in temperature of 2.3°C in the months of August, September, and October in the last 40 years (1979-2018). Region 2, with an accumulated deforestation of 8% up to 2018, a reduction in precipitation of 20% and a temperature increase of 1.6°C were observed, showing once again the relationship between deforestation, reduction in precipitation and increase in temperature, that is, less deforested areas show less precipitation losses and less increase in temperature When compared with regions more deforested (eastern region of the Amazon).

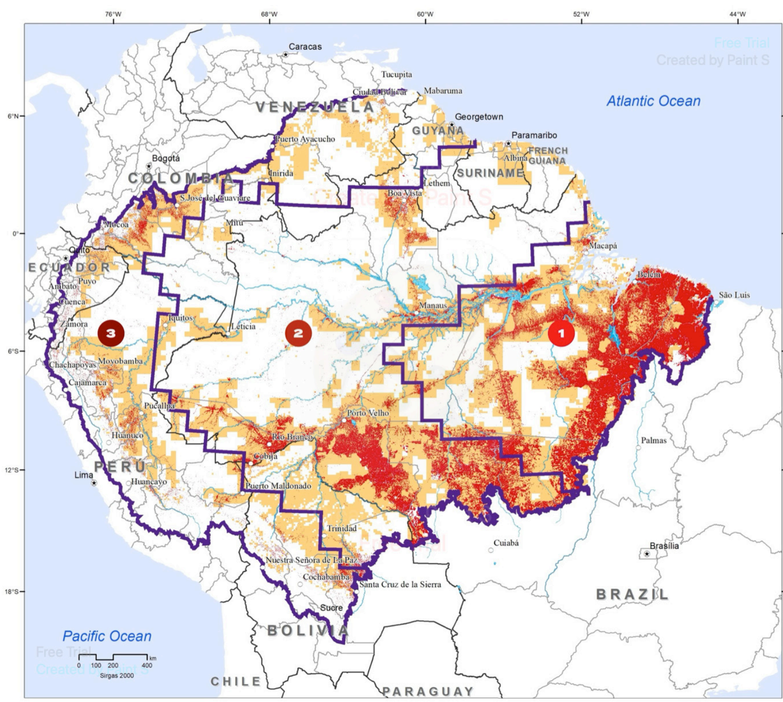


Figure 3: Amazonia was divided into three sub-regions, based on the areas of influence formed from vertical profile sites, using small aircraft for the sampling in the Amazon as part of the CARBAM Project[4,6]. Region 1 integrates two sites in the eastearn side of the Amazon. Region 2 integrates two sites on the central-western side and Region 3 represents uncovered area. Deforested areas determined by PRODES[1] are represented in red on the map, and degradated areas are represented in orange[10]. Fonte: SPA, 2023[5].

The reduction of forest inside Amazonia occurs mainly from deforestation (legal and illegal), land grabbing, land sales (legal and illegal), expansion of pastures, soy and corn plantations, mining, etc. According to Mapbiomas[11], pasture areas grew from 12.7 million hectares in 1985 to 59.1 million hectares in 2023, an increase of 365% (Figure 4). Compared to 2010, the increase represents 19% enhancement, which represents a worrying expansion of cattle ranching in the Brazilian Amazon. In 2023, the cattle population in the Amazon was 80.3 million, which corresponds to approximately 3 cattle per Amazonian inhabitant. The conversion of the Amazon forest to soybean plantation areas is even more intensive. In 1985, the soybean area was 0.0015 million hectares, and increased to 5.89 million hectares in 2023. The growth rate, based on an area of 2.03 million hectares in 2010, increased 190% related to 2023. Considering that Amazonia has been officially under a moratorium for soybean plantation areas since 2006, the enhancement became evident that, in practice, the moratorium is not effectively enforced. Nowadays, 19 years after its introduction, the sector faces no government resistance to its intensive expansion in the Amazon. Soybean exportation from the Amazon increased by 257% between 2010 and 2023. The largely illegal logging and timber exportation is the first stage of forest destruction. 98.1% of exported timber comes from native forests, while exports from planted forests account for only 1.9%. Brazil is one of the world's leading exporters, suggesting that this is also a significant source of destruction of forest in Amazonia. Controlling the sale of these three commodities would be an important tool to curb deforestation.

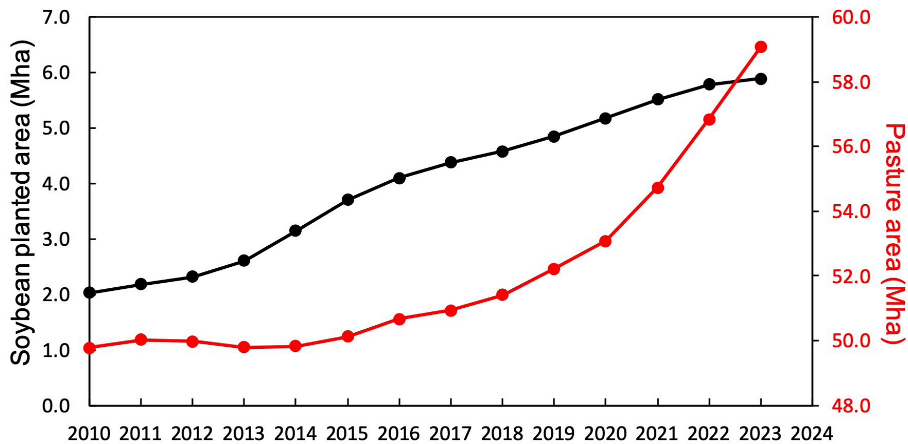


Figure 4: Evolution of soybean planted area (black line) and pasture area (red line) in the Brazilian Amazon[11].

GLOBAL WARMING AND EXTREME EVENTS AFFECTING AMAZON CLIMATE

Temperature increases in the Amazon, caused by deforestation and global climate change, is promoting a significant impact on the region, including more severe droughts and floods, increasing forest fires, and changes in the hydrological cycle. Marengo et al. (2024)[13] re-evaluate studies that analyzed temperature trends over different time periods and data sets. All of these studies show that, despite the differences in trends estimated from different datasets, the last two decades have been the warmest. The warming trend has been most pronounced since 1980 and intensified since 2000, when three exceptional droughts occurred in 2005, 2010, and 2015/2016 (Figure 5), and 2023-24. On the other hand, severe floods were observed in 2009, 2012, 2021, and 2022. In drought and flood years in the Amazon region, the geographical distribution of positive and negative precipitation anomalies was different. For example, during the 2005 drought, negative precipitation anomalies were observed in the southwestern Amazon, and during the 2015-16 drought, negative precipitation anomalies were concentrated in the central and eastern Amazon.

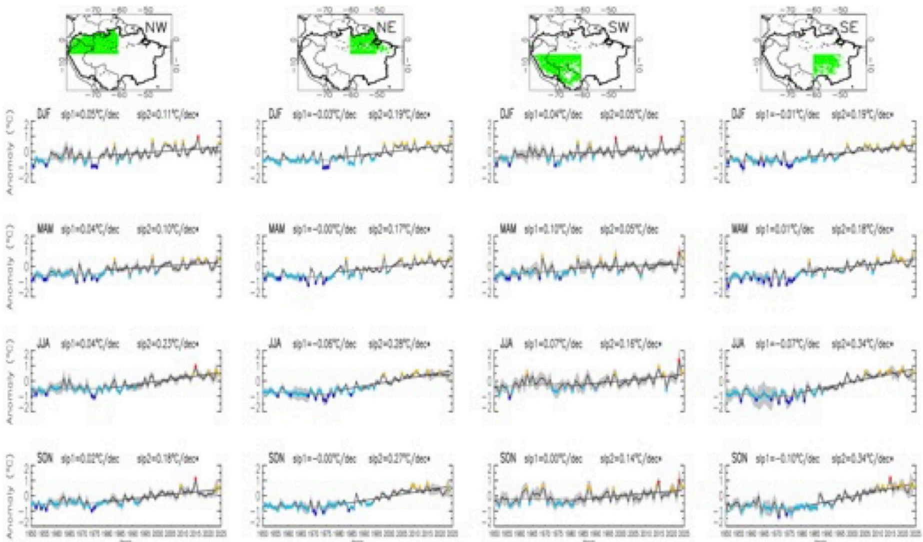


Figure 5: Temporal series of air temperature seasonal anomalies (DJF, MAM, JJA, SON) in the four Amazon regions (NO, NE, SO, SE) using Climate Research Unit CRU Version 4 (CRUTS4)[17] data related to the period of 1981-2010. Orande and red dots are related to temperature anomalies trat exceed 1σ and 2σ, respectively. Light and dark blue represent temperature anomalies lower than -1σ and -2σ, respectively. The linear trends for the periods of 1950-1979 and 1980-2021 are represented by dashed and solid line, respectively. The slope values for these two periods (slp1, slp2) are also included. DJF: December, January, February; MAM: March, April, May; JJA: June, July, August; SON: September, October, November. NW: northwest; NE: northeast; SW: southeast; SE: southeast[13].

Analysis of CRU air temperature data showed that 2016 (an El Niño year) was the warmest year since 1850, with a warming of up to +1°C above the average annual temperature for the reference period 1961-1990, and some monthly temperature anomalies exceeded +1.5°C in the same year. The historical records show an increasing trend for all seasons, with the warming being strongest from June to November (Figure 2.1). A contrasting west-east pattern can also be observed, with warming rates in the eastern Amazon being almost twice as high as in the western Amazon. The eastern Amazon-Cerrado transition zone has shown a widespread and significant warming trend (0.38°C + 0.15°C/decade) during the dry-wet transition period from July to October (JASO) over the last four decades[15]. The higher warming rates in the eastern Amazon are attributed to changes in land cover and the resulting shift in the energy balance[16].

The interannual variability of droughts and floods is linked to the substantial warming of the tropical Atlantic and to El Niño phenomena, which have played a central role in the intensification of the hydrological cycle in the Amazon region since the 1990s. [18] The warming of the tropical South Atlantic increases the atmospheric water vapor, that is imported into the northern Amazon basin by the trade winds. This increases rainfall and river runoff, especially during the rainy season[18-20]. Several studies have observed an intensification of the hydrological cycle in the region[18-21], which is reflected in the recent increase in extreme hydroclimatic events[22-24]. In addition, several studies over the last four decades, have demonstrated increased convective activity and an increase in precipitation and river flow in the northern Amazon, and a decrease in these hydroclimatic variables in the southern Amazon[25], creating a precipitation "dipole" in the Amazon. The last decades have been the warmest ever recorded in the Amazon, with four severe droughts and heat waves since 2000.

Rising temperatures and the increasing intensity of extreme weather events, such as droughts, heatwaves and floods, are causing devastating damage to ecosystems[13-26]. The 2023-24 drought was characterized by exceptionally low rainfall and seven heatwaves during the dry season and the pre-rainy season, ranging from dry to wet. River levels are low, and fires have increased[13-27]. Deficits in soil moisture have led to high temperatures and more frequent and severe heatwaves in summer, according to climate models and observations[28,29] These drought- and heat-induced changes have led to increased mortality of fish and aquatic mammals, lack of safe water and food for riparian communities, disruption of river transport, increased risk of waterborne diseases, and severe defoliation of riparian vegetation, that could signal vegetation dieback and increase the risk of fires. These impacts on Amazonian aquatic fauna, which have not been observed in previous droughts, demonstrate the severity of the unprecedented drought in the Amazon in 2023-24. In 2023, high mortality of fish, pink river dolphins, and other mammals occurred in Amazonian lakes due to higher water temperatures and lower oxygen concentrations[30-32]

According to Fleischmann et al. (2024)[32] the warming of Amazonian waters is widespread. Since 1990, an average warming trend of 0.6°C per decade has been observed in Amazonian lakes. The peak was reached during the dry season in 2023, when the water temperature of Lake Tefé, measured in the entire water column at a depth of 2 meters (m), reached over 40°C. As a result of the drought, the level of the Negro River in Manaus dropped to 12.11 m on October 10, 2024, the lowest level in 122 years of records. It turns out that six droughts and nine floods have occurred in the Amazon region in the last 40 years, indicating a greater frequency of dry and rainy seasons compared to previous decades.

The most extreme heat waves in the Amazon have occurred simultaneously with extreme drought signals,[29,33,34] creating a "perfect storm" for biodiversity, connectivity, and ecosystem functioning in the Amazon. Compound drought and heat events significantly increase the incidence of fires in the Amazon, as reported in 2005, 2010, 2015, and 2023. This leads to a positive feedback loop between fires and droughts.[26,35] The increased frequency of compound drought and heat wave events also increases the risk of the Amazon rainforest approaching critical thermal thresholds, beyond which the photosynthetic machinery of these trees begins to fail, followed by irreversible damage and, consequently, leaf loss.[36–38] Areas that rarely experienced heat waves in the 1980s, such as the Amazon and northeastern Brazil, have been experiencing increasingly severe heat wave conditions since the 2000s. Feron et al. (2024)[39] and Marengo et al. (2025, submitted) assessed the progression of simultaneous heat, drought, and high fire risk conditions since 1971. They found that these composite extremes have increased in the recent decade in key regions of South America, including the northern Amazon and the Brazilian Pantanal

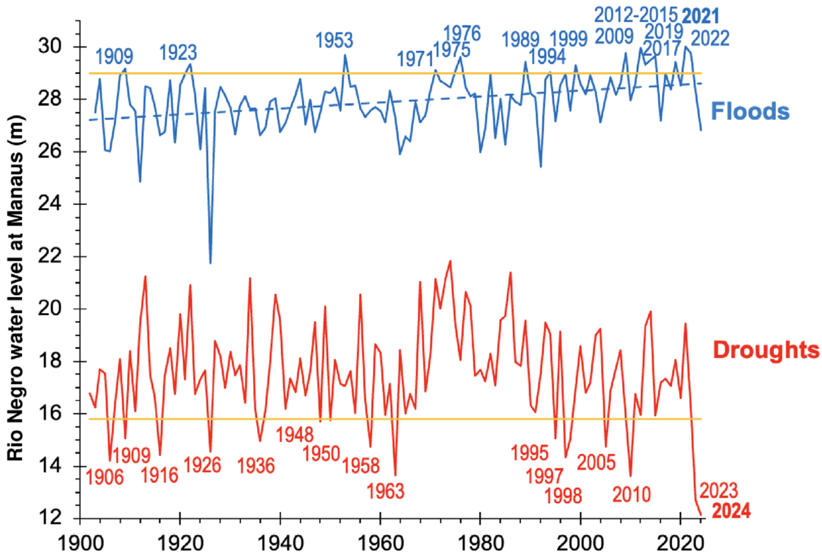


Figure 6 - Maximum (blue lines) and minimum (red lines) water levels of the Negro River at the Port of Manaus, from 1902 to November 2024. The blue and red values indicate when the flood and drought records were broken, respectively. The orange lines represent the upper (29.0 m) and lower (15.8 m) limits used to declare flood and drought episodes, respectively. Values are expressed in meters (WMO 2025)[27].

Above- and belowground productivity in the Amazon under a rapidly changing climate

Net primary productivity (NPP) is the fraction of carbon fixed by photosynthesis (gross primary production) that remains in the ecosystem after autotrophic respiration is deducted, and it can be partitioned into aboveground NPP (NPPa) and belowground NPP (NPPs). NPPa expresses the rate of formation of new biomass aboveground, estimated by the sum of woody increment of live trees (including recruitment) and litterfall production, whereas NPPs expresses the belowground rate, estimated by the production of fine and coarse roots.

NPP can indicatate the CO_2 balance of the ecosystem carbon cycle, since heterotrophic respiration is linked to the decomposition of dead biomass (litter and dead trees), a process by which the ecosystem emits CO_2. Estimates of NPP, such as the difference between tree recruitment and mortality, can reveal whether the forest is a CO_2 sink or source. Thus, when recruitment exceeds mortality, the forest acts as a sink of atmospheric carbon; when mortality exceeds recruitment, the forest acts as an emitting source of CO_2. Both processes represent CO_2 flux when the carbon cycle is in a removal or emission phase of atmospheric carbon, a condition that can vary with the climatic year in the Amazon (Figure 7). For example, in El Niño years, when the Amazon climate is warmer and drier, NPPa enters a CO_2 emission phase [40], an effect that can be measured by tree mortality surpassing recruitment.

In the Amazon, we still do not know exactly how aboveground NPP (NPPa) will respond to climate change and forest degradation. aboveground NPP (NPPa) in the Amazon will behave in response to climate change and forest degradation. However, converging evidence indicates that the productivity and carbon balance of Amazonian forests are under growing pressure due to more frequent and intense droughts, fire degradation, edge effects, and selective logging. Atmospheric profiles showed that southeastern Amazon acted as a net carbon source from 2010 to 2018 (carbon emission phase), condition associated with frequent fires, increased temperatures and reduced precipitation (e.g., in El Niño years), resulting in an atmospheric vapor pressure deficit (VDP), suggesting a decline in assimilation (photosynthesis) relative to respiration (mortality).

The Amazon is a continental-scale carbon sink, as first demonstrated by Phillips & Gentry (1994)[41] using calculations with field data from forest inventory plots. Nevertheless, long-term trends indicate a decline in this sink capacity due to increased mortality and reduced carbon residence time in the ecosystem, even where forest growth has been maintained, weakening aboveground biomass accumulation[42], indicating a downward trend in the Amazon's NPPa. This results from two conditions operating simultaneously: (1) a decline in the tree growth trend from atmospheric CO_2 fertilization, and (2) increased environmental stress due to climatic factors, a growing condition in eastern and southeastern Amazonia. At the global scale, higher VPD reduces vegetation growth and suppresses photosynthesis via stomatal closure, a mechanism particularly relevant during longer and warmer dry seasons[43], a phenomenon that has been intensifying in the Amazon.

Throughfall-exclusion experiments in Caxiuanã show persistent declines in woody growth, increases in autotrophic respiration, and reductions in carbon use efficiency under chronic water deficit; after two decades, the system stabilizes at a new NPPa equilibrium state with lower biomass and carbon stocks[44]. In parallel, forest degradation already affects ~38% of the remaining Amazon forest and can reduce dry-season evapotranspiration by up to ~34%, with carbon losses comparable to deforestation, which depresses NPPa by opening the canopy, increasing microclimatic aridity, and elevating fire recurrence[10].

Other evidence reveals that aboveground biomass accumulation has decreased in recent decades because rising mortality is outpacing growth gains and shortening arboreal carbon residence time[42]. In regions already warmer and more deforested in the southeastern Amazon, the net balance shifted to a source, reinforcing that climatic and anthropogenic stress limits NPPa4. This effect is intensified by increasing wind intensity in the Amazon, which leads to an abnormal rise in tree breakage and death[45].

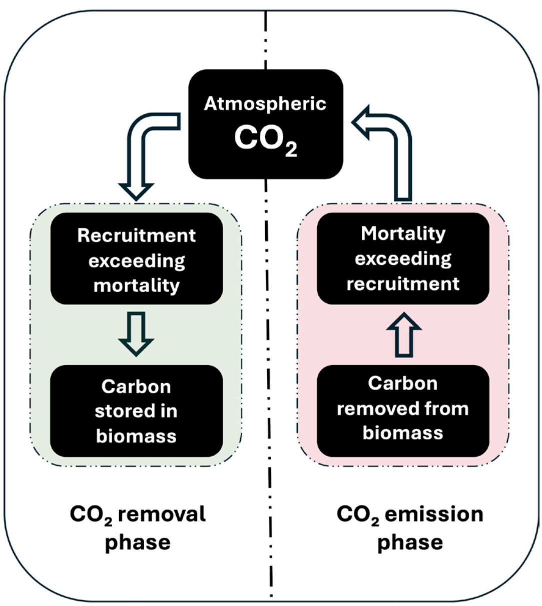


Figure 7: CO_2 exchange between the atmosphere and vegetation in different phases of the carbon cycle. In green, on the left, the carbon flux during the CO_2 removal phase by the forest, and in red, on the right, the carbon flux during the emissions phase. In very dry and hot climate years in the Amazon, the system tends to emit CO_2, as during El Niño events.

Regarding biomass allocation by vegetation, meta-analyses in tropical forests suggest, on average, partitioning of ~34% of NPP to canopy,

~39% to stems, and ~27% to fine roots, but with strong spatial and environmental variation[46]. Under water deficit, throughfall-exclusion (TFE) experiments record declines in woody NPP and physiological shifts (e.g., higher leaf/litter respiration), reducing carbon use efficiency; root studies show morphological adjustments (greater area/specific surface) in drier soils, consistent with relatively higher investment to sustain water and nutrient uptake[47]. Studies also indicate that sandier and/or poorer soils in the phosphorus/nitrogen (P/N) relationship increase the fraction of NPP allocated to fine roots, an allocation condition important for explaining regional contrasts in the Amazon as a function of edaphic factors[48].

Variations in the hydrological cycle and temperature affect forest productivity. NPP and belowground carbon fluxes (NPPs) are strongly modulated by moisture. In the Amazon, soil respiration responds more to short-term water limitation than to warming alone, with temperature sensitivity attenuated under drought[49]. In turn, warming associated with drought tends to make older fractions of soil carbon (e.g., pyrogenic carbon) more vulnerable to decomposition, implying a risk of soil organic matter (SOM) losses under warmer and drier scenarios[50], which leads to a reduction in NPPs. In this case, subsurface hydrology is key, since deep roots (>8 m) sustain transpiration and the maintenance of Amazon forests during prolonged dry seasons, when the water table is deeper and less accessible[51]. Precipitation and the water table modulate the forest in distinct ways: shallow water tables (<5 m) are associated with ~18% lower NPPs and ~23% lower biomass than deep water tables, and under drier conditions (maximum cumulative water deficit < −160 mm) there is ~21% lower NPP and ~24% lower biomass than under wetter conditions. There is also an interaction: in dry conditions, a shallow water table penalizes productivity more than a deep one; in humid climates, this disadvantage is limited to very shallow tables. Finally, the observed/projected increase in atmospheric VPD and the lengthening of the dry season in southern/southeastern Amazonia (≈ +6.5 ± 2.5 days per decade since 1979) intensify these hydro-thermal limitations, with negative repercussions for belowground fluxes[23,43,52,53].

Despite the many available studies, data gaps still limit our understanding. For example, the subsurface is an ecosystem compartment that remains insufficiently observed. There are few standardized records of fine-root production/turnover, exudates, and mycorrhizae in the Amazon, especially at depths >1 m and in low-fertility sandy soils; the spatial variability of allocation to roots still exceeds the predictive capacity of simple climate[48,54].

Another problem is scale integration. We lack long time series of NPP measurements and their partitioning. Today, the only long-term field NPP measurement program is GEM/Plots[55], but it does not cover most of the Amazon. CO_2 flux towers are also rare, and few operate long-term, limiting more accurate outcomes. We also lack accurate satellite biomass monitoring to close carbon balances above and belowground and to link allocation changes to climatic anomalies (e.g., El Niño/VPD).

We also lack a better spatial representation of degradation in the Amazon region. Forest degradation is extensive and ongoing, but still underrepresented in inventories and models (DETER/INPE will start monitoring in 2026); uncertainties in classification (e.g., fire intensity/age, selective deforestation and edge effects) affect estimates of emissions and productivity. For example, western and northwestern Amazonia and remote areas lack instrumentation for large-scale profiles of soil moisture, water-table depth, and soil temperature, hindering attributions of forest degradation effects in these compartments.

Another pressing need is more rainfall-manipulation experiments in the field. Beyond Caxiuanã, there is only one chronic-drought experiment simultaneously tracking NPP, ecosystem biomass partitioning, deep roots, and soil organic matter for more than 10–20 years (Projeto Seca Limite / Dry-Limit Project). Seca Limite is investigating drought effects in southern Amazonia—the region most sensitive to climate change due to high rainfall seasonality—but results are still preliminary

The combination of drier air (higher VPD), longer and warmer dry seasons, and degradation is reducing woody growth, raising respiration, and, in many contexts, shifting biomass allocation toward root structures at the expense of aboveground biomass. These vegetation responses to environmental stressors help maintain water uptake and immediate canopy function, but they weaken aboveground biomass accumulation and may increase the vulnerability of soil carbon. This is why recent evidence reveals a strong relationship between extreme climate and atmospheric carbon emissions from the Amazon, indicating that the forest may be transitioning to a more continuous CO-emission phase from vegetation.

Research/monitoring priorities should include: networks of soil profiles (moisture/temperature/water table), harmonized time series of NPP and partitioning (including roots >1 m), manipulation experiments in multiple soil types, and the explicit incorporation of degradation into models and inventories. These actions are essential to reduce uncertainties and to project the future of Amazon productivity under warming and more severe droughts.

THE CHANGES IN THE FOREST AND THEIR IMPACT ON AMAZON CARBON EMISSIONS

The Amazon forests are among the most productive natural ecosystems in the world. They store carbon in the order of 123 ± 23 billion tons in soil and vegetation [56,57], a stock equivalent to 14–18 years of global carbon emissions. As they grow, these forests also contribute to reducing atmospheric carbon dioxide levels, by absorbing 1.2 billion tons of CO_2 per year in primary and secondary forests58. This contribution to reducing atmospheric CO_2 levels may seem modest when compared to total human emissions (40 billion tons of CO_2 per year over the last 10 years[59]), but it accounts for 25% of all global sources associated with land-use change (5 billion tons of CO_2 per year[59]). This carbon sink has decreased in recent decades, with a significant increase in tree mortality[42,60,61] (Table 1). The increase in mortality is most likely related to climatic conditions changing, such as increasing stress in the Amazon, especially during dry season, which is becoming increasingly dry, hot, and long due to factors such as deforestation, degradation, and climate change[4,6,58]. This process in the Amazon rainforest can transform it into a positive feedback loop, potentially releasing a huge amount of carbon into the atmosphere[4,62].

In addition to their role in the global carbon balance, forests also contribute to the regulation of the water cycle in the Amazon region, in Latin America, and even worldwide. Forest evapotranspiration accounts for up to 50% of precipitation formation and actively sustains atmospheric rivers that supply the continent with essential precipitation and help regulate regional temperatures and water availability in rivers and streams throughout the year[63-64]. The loss of forests leads to lower precipitation and higher surface temperatures on Earth, particularly in the most deforested areas, during the dry season, reinforcing the feedback loop in which reduced transpiration leads to lower atmospheric water content and a further decline in precipitation[4,6-9,63,64].

Table 1: Measurements of carbon sequestration in primary forests from long-term studies of approximately 300 one-hectare plots monitored for carbon stored in the stem, leaf litter (leaf litter and other), mortality, etc., normalized to 7.25 x 106 km².

Area normalizada 7.25 x 10^6 km^2	Periodo	absorção de C (PgC ano^{-1})
Phillips and Brienen, 2017	1990-00	-0.54 ±0.18
	2000-10	-0.38 ±0.20
	2010-20	-0.20*
Brienen et al, 2015	1990-00	-0.62 ±0.09
	2000-10	-0.44 ±0.10
	2010-20	-0.23*
Hubau et al, 2020	1990-00	-0.68 ±0.15
	2000-10	-0.45 ±0.13
	2010-20	-0.25 ±0.30

*Extrapolated value considering the tendency related to the early two decades.

These processes accelerate regional warming and increase the likelihood of extreme weather events, which over time contribute to forest degradation and impoverishment. The cumulative effects of these disturbances exacerbate the risk of irreversible forest degradation, undermining carbon sinks and making the forest an even greater source of emissions in the long term[66]. Ultimately, these processes could bring tropical forest regions to a critical threshold and eventual ecological collapse, preventing effective management measures to mitigate these impacts. With the El Niño event of 2023 and the North Atlantic Ocean temperature anomaly (TNA) in 2023 and 2024 (Figure 8), the Amazon is again threatened by large fires, leading to a disaster scenario due to intense drought and rising air temperatures, combined with high deforestation rates and the use of fire to manage pasture and agricultural land and promoting new deforestation. Such events have already affected the Amazon in other years, such as the 2015/2016 El Niño[67], which led to the degradation of millions of hectares.

Figure 8 shows that precipitation has steadily decreased since 2021, while temperatures have risen over the same period. In line with this trend, the total area of the Brazilian Amazon reached 22% of deforestation (PRODES[1]), with increasing degradation of the Amazon forest, and increasing areas for logging, cattle ranching, and soy and corn cultivation, as shown in the introduction of this chapter. We have continued to monitor the two global phenomena El Niño (ONI) and the North Atlantic Temperature Anomaly (TNA), and have concluded that since 2010 North

Atlantic temperatures affect the Amazon more than El Niño. The latter was negative from 2020 to 2022, while the TNA has only increased since 2020, especially in 2023 and 2024, when an extreme drought was observed in the Amazon, causing rivers to dry up and more than 200 dolphins to die in the Tefé region.

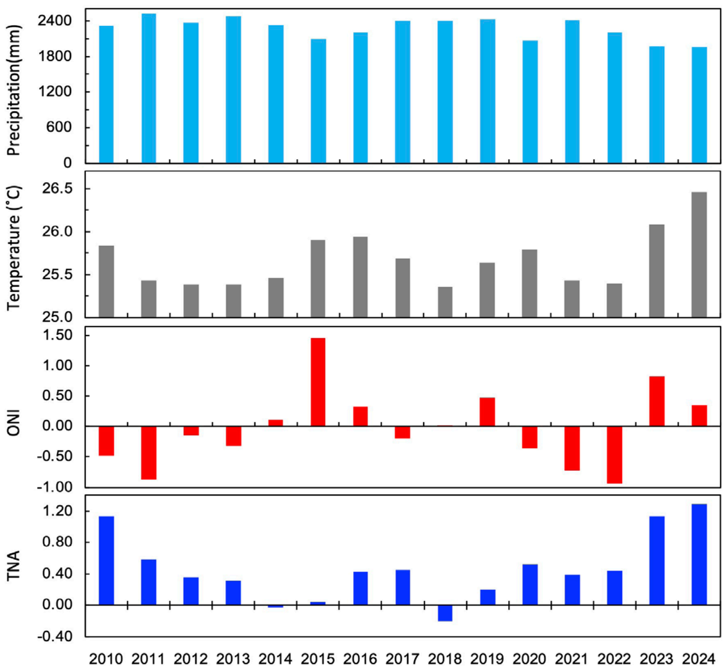


Figure 8: Amazon annual accumulated precipitation (GPCP[68]), Mean Temperature 2 m above surface in the Amazon (ERA5[69]), Oceanic Niño Index[70] (ONI) and North Atlantic Temperature Anomaly (TNA) for latitudes from 23.5N - 5.5N, and longitudes 57.5W - 15.0W, related to the period 1971-2000[69,71].

Amazon Carbon balance estimates for the last decade (2010-2020), in a review based on bottom-up and top-down studies, indicate that the Amazon as a whole, including all absorption and loss processes, taking into account all emissions and absorptions, both natural and human, represents a carbon source of about 1.10 ± 0.73 Pg CO_2 year-1 and 0.84 ± 0.73 Pg CO_2 year-1, respectively[6,58]. It is important to recognize and understand the assumptions behind these two approaches, and further research is needed to understand and reduce the differences between them. These results encompass all processes in the Amazon, including sinks in mature and secondary forests, recovery of disturbed forests, and carbon emissions from deforestation, degradation, logging, decomposition, fires, fossil fuels, and agriculture (pastures and plantations).

Gatti et al. (2023)[6] presented the Amazon CO_2 balance for the last decade (2010-2020), where a large interannual variability was observed. The interannual variability is related both to fluctuations in annual climate conditions and to human actions, which also change annually. The average Amazon CO_2 balance for this period (2010-2020) was 1.15 ± 0.11 billion tonnes per year (Figure 4.2). This study found a notable increase in the Amazon's net carbon budget between 2019 and 20206, with deforestation increasing by 80% and biomass burning by 40% compared to 2010-2018. Carbon emissions more than doubled during this period, increasing from 0.92 to 1.91 billion tons of CO_2 per year. Consequently, in these two years, the Amazon stopped being a carbon sink and became a significant carbon source, largely due to the dismantling of deforestation control measures and law enforcement in the Brazilian Amazon during this period. Emissions from biomass burning represent the largest source of CO_2 emissions to the atmosphere, and –were responsible for the emission of 1.47 ± 0.11 billion tons of CO_2 per year in the last decade (2010-2020) (Figure 9).

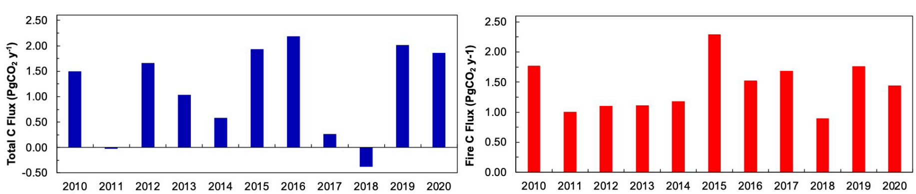


Figure 9: Annual carbon balance of the Amazon (blue bars) and annual carbon emissions from biomass burning (red bars).

Carbon emissions vary from region to region within the Amazon, influenced by different climatic conditions due to the extent of historically accumulated deforestation and forest degradation4,6. After a decrease in deforestation of around 80% between 2004 and 2012, there was a gradual increase until 2018 and a sharp increase starting at 2019. In 2023, there was a significant decrease in deforestation, followed by a further decrease in 2024. The observed decreases were 37% and 51%, respectively, compared to the 2022 rate (Figure 1). Deforestation rates in the Amazon region have increased, particularly in the "arc of deforestation", contributing to significant warming in these regions[4,6]. The southern region of the states of Amazonas and Acre recorded a significant increase in deforestation. The state of Amazonas had the second largest deforested area in 2021 and 2022 (Figure 2). Although the implementation of environmental public policies protection in Brazil was responsible for an 84% decrease in deforestation between 2004 and 2012, between 2013 and 2018 there was an increase of 44% compared to 2012 (the lowest rate on record), and between 2019 and 2022, the reduction in government policies caused an increase of 150% compared to 2012. Deforestation is always associated with forest fires, which increase the impact on the forest.

In the Figure 3, showing three sub-regions in Amazonia, Region 1, which by 2018 experienced a cumulative deforestation of 28%, presented a decrease of 28% in precipitation, and a increase in temperature of 2.3°C (for the months August, September, and October), and increase in 16% of burned area, and had the highest CO_2 emissions in the Amazon, presenting emissions over the last decade of 0.72 billion tons of CO_2 per year. The Fire emissions were 0.59 billion tons of CO_2 per year. In the Region 2, which the cumulative deforestation up to 2018 was 8%, the observed decrease in precipitation was 20% and the temperature increased by 1.6°C. There were also average total emissions of 0.13 billion tonnes of CO_2 per year and 0.44 billion tonnes of CO_2 per year from forest fires. During this period it was observed 6% of the area burned[5,6].

The Amazon as a whole warmed by an annual average of 1.0°C, and during the main dry season (August–October) the warming was 1.4°C, considering the period 1979–2018. The effects are particularly acute in heavily deforested regions. In the southeastern Amazon, which more than 28% was deforested until 2018 (~ 33% by 2023), temperatures rose by 3.1°C in the most acute months of the dry season: August and September. In the northeastern Amazon (38% deforested), annual precipitation decreased by 11%, including dry season losses of 35%, showing that the impact of forest loss on the hydrological cycle can be as significant as its contribution to carbon emissions[4-6,58]. In addition, the intensification and longer duration of the dry season means an increase in climate stress on the forest, which increases carbon losses, particularly through fires, as forests become drier due to reduced precipitation and rising temperatures, making them more flammable[72].

REFERENCES

1. PRODES. Amazon Deforestation Monitoring Project (PRODES / INPE). (2022). Available at: http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes.

2. MMA GOV BR. PPCDAm. (2017). Available at: http://redd.mma.gov.br/pt/acompanhamento-e-a-analise-de-impacto-das-politicas-publicas/ppcdam.

3. Soares-Filho, B. et al. Cracking Brazil's Forest Code. *Science* (80-.). 344, 363–364 (2014).

4. Gatti, L. V. *et al*. Amazonia as a carbon source linked to deforestation and climate change. *Nature* 595, 388–393 (2021).

5. Gatti, L. V. *et al*. *Human Impacts on Carbon Emissions and Losses in Ecosystems services*. (2023). doi:10.55161/HUYE3394

6. Gatti, L. V. *et al*. Increased Amazon carbon emissions mainly from decline in law enforcement. *Nature* 621, 318–323 (2023).

7. Leite-Filho, A. T., Soares-Filho, B. S., Davis, J. L., Abrahão, G. M. & Börner, J. Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. *Nat. Commun.* 12, 2591 (2021).

8. Leite-Filho, A. T., de Sousa Pontes, V. Y. & Costa, M. H. Effects of Deforestation on the Onset of the Rainy Season and the Duration of Dry Spells in Southern Amazonia. *J. Geophys. Res. Atmos.* 124, 5268–5281 (2019).

9. Leite-Filho, A. T., Costa, M. H. & Fu, R. The southern Amazon rainy season: The role of deforestation and its interactions with large-scale mechanisms. *Int. J. Climatol*. 40, 2328–2341 (2020).

10. Lapola, D. M. *et al*. The drivers and impacts of Amazon forest degradation. *Science* (80-.). 379, eabp8622 (2023).

11. Mapbiomas_Amazonia. The MapBiomas Amazon Collection 9.0 includes annual land use and land cover data for the period 1985-2023. (2025). Available at: https://plataforma.brasil.mapbiomas.org/. (Accessed: 11th August 2025)

12. Ministry of Development, Industry, C. and S.-B. G. Comexstat. wood exportation (2025). Available at: http://comexstat.mdic.gov.br/pt/comex-vis. (Accessed: 9th July 2025)

13. MARENGO, J. A. *et al*. Long-term variability, extremes and changes in temperature and hydrometeorology in the Amazon region: A review. Acta Amaz. 54, (2024).

14. Jiménez-Muñoz, J. C. *et al*. Record-breaking warming and extreme drought in the Amazon rainforest during the course of El Niño 2015–2016. *Sci. Rep.* 6, 33130 (2016).

15. Marengo, J. A., Jimenez, J. C., Espinoza, J.-C., Cunha, A. P. & Aragão, L. E. O. Increased climate pressure on the agricultural frontier in the Eastern Amazonia–Cerrado transition zone. *Sci. Rep.* 12, 457 (2022).

16. Davidson, E. A. *et al*. The Amazon basin in transition. *Nature* 481, 321–328 (2012).

17. Harris, I., Osborn, T. J., Jones, P. & Lister, D. Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Sci. Data* 7, 109 (2020).

18. Gloor, M. *et al*. Intensification of the Amazon hydrological cycle over the last two decades. Geophys. Res. Lett. 40, 1729–1733 (2013).

19. Gloor, M. *et al*. Recent Amazon climate as background for possible ongoing and future changes of Amazon humid forests. Global Biogeochem. Cycles 29, 1384–1399 (2015).

20. Heerspink, B. P., Kendall, A. D., Coe, M. T. & Hyndman, D. W. Trends in streamflow, evapotranspiration, and groundwater storage across the Amazon Basin linked to changing precipitation and land cover. *J. Hydrol. Reg. Stud.* 32, 100755 (2020).

21. Barichivich, J. *et al*. Recent intensification of Amazon flooding extremes driven by strengthened Walker circulation. *Sci. Adv*. 4, (2018).

22. Marengo, J. A. & Espinoza, J. C. Extreme seasonal droughts and floods in Amazonia: causes, trends and impacts. Int. J. Climatol. 36, 1033–1050 (2016).

23. Marengo, J. A. *et al*. Changes in Climate and Land Use Over the Amazon Region: Current and Future Variability and Trends. *Front. Earth Sci.* (2018). doi:10.3389/feart.2018.00228

24. Espinoza, J.-C., Marengo, J. A., Schongart, J. & Jimenez, J. C. The new historical flood of 2021 in the Amazon River compared to major floods of the 21st century: Atmospheric features in the context of the intensification of floods. *Weather Clim. Extrem.* 35, 100406 (2022).

25. Paca, V. H. da M., Espinoza-Dávalos, G., Moreira, D. & Comair, G. Variability of Trends in Precipitation across the Amazon River Basin Determined from the CHIRPS Precipitation Product and from Station Records. *Water* 12, 1244 (2020).

26. Espinoza, J.-C. *et al*. The new record of drought and warmth in the Amazon in 2023 related to regional and global climatic features. *Sci. Rep.* 14, 8107 (2024).

27. WMO. State of the Climate in Latin America and the Caribbean 2024. (2025).

28. Lorenz, R., Jaeger, E. B. & Seneviratne, S. I. Persistence of heat waves and its link to soil moisture memory. *Geophys. Res. Lett.* 37, (2010).

29. Marengo, J. A. *et al*. Climatological patterns of heatwaves during winter and spring 2023 and trends for the period 1979–2023 in central South America. *Front. Clim.* 7, (2025).

30. Ratier, R. Agua a 38 ˚ C, peixe podre e jacar. morto: Cientistas mostram colapso no AM. (2023). Available at: https://www.uol.com.br/ecoa/colunas/rodrigo-ratier/2023/10/17/agua-a-38-oc-peixe-p%0D%0Aodre-e-jacare-morto-cientistas-mostram-colapso-no-am.htm. (Accessed: 19th November 2023)

31. Marmontel, M., Fleischmann, A., Val, A. & Forsberg, B. Safeguard Amazon's aquatic fauna against climate change. *Nature* 625, 450–450 (2024).

32. Fleischmann, A. *et al*. *Extreme warming of Amazon waters in a changing climate*. (2024). doi:10.31223/X56D9T

33. Costa, D. F., Gomes, H. B., Silva, M. C. L. & Zhou, L. The most extreme heat waves in Amazonia happened under extreme dryness. *Clim. Dyn.* 59, 281–295 (2022).

34. Libonati, R. *et al*. Drought–heatwave nexus in Brazil and related impacts on health and fires: A comprehensive review. *Ann. N. Y. Acad. Sci.* 1517, 44–62 (2022).

35. Aragão, L. E. O. C. *et al*. 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. *Nat. Commun.* 9, (2018).

36. Docherty, E. M. *et al*. Long‐term drought effects on the thermal sensitivity of Amazon forest trees. *Plant. Cell Environ.* 46, 185–198 (2023).

37. Doughty, C. E. *et al*. Tropical forests are approaching critical temperature thresholds. *Nature* 621, 105–111 (2023).

38. Slot, M. *et al*. Leaf heat tolerance of 147 tropical forest species varies with elevation and leaf functional traits, but not with phylogeny. *Plant. Cell Environ.* 44, 2414–2427 (2021).

39. Feron, S. *et al*. South America is becoming warmer, drier, and more flammable. *Commun. Earth Environ.* 5, 501 (2024).

40. Matias Reis, S. *et al*. Sensitivity of tropical woodland savannas to El Niño droughts. *Biogeosciences* 22, 3949–3964 (2025).

41. Phillips, O. L. & Gentry, A. H. Increasing Turnover Through Time in Tropical Forests. *Science* (80-.). 263, 954–958 (1994).

42. Brienen, R. J. W. *et al*. Long-term decline of the Amazon carbon sink. *Nature* 519, 344–348 (2015).

43. Barkhordarian, A., Saatchi, S. S., Behrangi, A., Loikith, P. C. & Mechoso, C. R. A Recent Systematic Increase in Vapor Pressure Deficit over Tropical South America. *Sci. Rep.* 9, 1–12 (2019).

44. Sanchez-Martinez, P. *et al*. Amazon rainforest adjusts to long-term experimental drought. *Nat. Ecol. Evol.* 9, 970–979 (2025).

45. Reis, S. M. *et al*. Climate and crown damage drive tree mortality in southern Amazonian edge forests. *J. Ecol.* 110, 876–888 (2022).

46. Malhi, Y., Doughty, C. & Galbraith, D. The allocation of ecosystem net primary productivity in tropical forests. *Philos. Trans. R. Soc. B Biol. Sci.* 366, 3225–3245 (2011).

47. Metcalfe, D. B. *et al*. Shifts in plant respiration and carbon use efficiency at a large-scale drought experiment in the eastern Amazon. *New Phytol.* 187, 608–621 (2010).

48. Huaraca Huasco, W. *et al*. Fine root dynamics across pantropical rainforest ecosystems. *Glob. Chang. Biol.* 27, 3657–3680 (2021).

49. Meir, P., Metcalfe, D. ., Costa, A. C. . & Fisher, R. . The fate of assimilated carbon during drought: impacts on respiration in Amazon rainforests. *Philos. Trans. R. Soc. B Biol. Sci.* 363, 1849–1855 (2008).

50. McFarlane, K. J. *et al*. Experimental warming and drying increase older carbon contributions to soil respiration in lowland tropical forests. *Nat. Commun.* 15, 7084 (2024).

51. Nepstad, D. C. *et al*. The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. *Nature* 372, 666–669 (1994).

52. Brando, P. M. *et al*. Drought effects on litterfall, wood production and belowground carbon cycling in an Amazon forest: results of a throughfall reduction experiment. *Philos. Trans. R. Soc. B Biol. Sci.* 363, 1839–1848 (2008).

53. Meir, P., Mencuccini, M. & Dewar, R. C. Drought-related tree mortality: addressing the gaps in understanding and prediction. *New Phytol.* 207, 28–33 (2015).

54. Cordeiro, A. L. *et al*. Fine‐root dynamics vary with soil depth and precipitation in a low‐nutrient tropical forest in the Central Amazonia. *Plant-Environment Interact.* 1, 3–16 (2020).

55. Malhi, Y. *et al*. The Global Ecosystems Monitoring network: Monitoring ecosystem productivity and carbon cycling across the tropics. *Biol. Conserv.* 253, 108889 (2021).

56. MALHI, Y. *et al*. Comprehensive assessment of carbon productivity, allocation and storage in three Amazonian forests. *Glob. Chang. Biol.* 15, 1255–1274 (2009).

57. MALHI, Y. *et al*. The regional variation of aboveground live biomass in old-growth Amazonian forests. *Glob. Chang. Biol.* 12, 1107–1138 (2006).

58. Gatti, L. V *et al*. Cross Chapter 1: The Amazon Carbon Budget. in *Amazon Assessment Report 2021* (UN Sustainable Development Solutions Network (SDSN), 2021). doi:10.55161/VNBV7494

59. Friedlingstein, P. *et al*. Global Carbon Budget 2022. *Earth Syst. Sci. Data* 14, 4811–4900 (2022).

60. Phillips, O. L. & Brienen, R. J. W. Carbon uptake by mature Amazon forests has mitigated Amazon nations' carbon emissions. *Carbon Balance Manag.* 12, 1 (2017).

61. Hubau, W. *et al*. Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature* 579, 80–87 (2020).

62. Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A. & Totterdell, I. J. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature* 408, 184–187 (2000).

63. Costa, M. H. *et al*. Chapter 5: The Physical hydroclimate system of the Amazon. in *Amazon Assessment Report 2021* (UN Sustainable Development Solutions Network (SDSN), 2021). doi:10.55161/HTSD9250

64. Costa, M. H. *et al*. Chapter 7: Biogeophysical Cycles: Water Recycling, Climate Regulation. in *Amazon Assessment Report 2021* (UN Sustainable Development Solutions Network (SDSN), 2021). doi:10.55161/KKHX1998

65. Uribe, M. del R. *et al*. Net loss of biomass predicted for tropical biomes in a changing climate. *Nat. Clim. Chang.* 13, 274–281 (2023).

66. Read, D. *et al*. *The role of land carbon sinks in mitigating global climate change.* (2001).

67. Berenguer, E. *et al*. Tracking the impacts of El Niño drought and fire in human-modified Amazonian forests. *Proc. Natl. Acad. Sci.* 118, (2021).

68. Adler, R. *et al*. The Global Precipitation Climatology Project (GPCP) Monthly Analysis (New Version 2.3) and a Review of 2017 Global Precipitation. *Atmosphere (Basel).* 9, 138 (2018).

69. Hersbach, H. *et al*. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). *ERA5 hourly data on single levels from 1940 to present* (2023). doi:10.24381/cds.adbb2d47

70. Climate Prediction Center, N. Oceanic Nino Index. (2025). Available at: https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php. (Accessed: 21st May 2025)

71. Enfield, D. B., Mestas-Nuñez, A. M., Mayer, D. A. & Cid-Serrano, L. How ubiquitous is the dipole relationship in tropical Atlantic sea surface temperatures? *J. Geophys. Res. Ocean.* 104, 7841–7848 (1999).

72. Brando, P. *et al*. Amazon wildfires: Scenes from a foreseeable disaster. *Flora* 268, 151609 (2020).

Marengo JA, Calim Costa M, Cunha AP, Espinoza, JC, Jimenez JC, Libonati R, Geirinhas J., Miranda V, Trigo IF, Sierra JP, Maria TO, Meeiros O (2025b) Characterization of the exceptional heatwave conditions observed in Brazil during the record-hot years of 2024 and 2025, submitted, Int. J. Climatol

3. BRAZIL'S CONTINENTAL BIOMES AND BIODIVERSITY IN FACE OF CLIMATE CHANGE

Adalberto L. Val[7], Ima C.G. Vieira[8], Mariana M. Vale[9], Sérgio Lucena Mendes[10], Tiago da Mota e Silva[7]

INTRODUCTION: THE BRAZILIAN BIOMES

Brazil is home to six continental biomes — the Amazon, the Cerrado, the Atlantic Forest, the Caatinga, the Pantanal, and the Pampa — which together represent one of the largest reserves of biodiversity on the planet. These natural systems play an important ecological, climatic, and socio-economic role that transcends national boundaries, influencing everything from the South American water balance to the stability of the global climate.

All of these biomes (Figure 1) are subject to increasing anthropogenic pressures associated with the effects of climate change, leading to biodiversity loss, habitat degradation, and a growing risk of ecological collapse. The term climate change refers to the definition of the United Nations Framework Convention on Climate Change (UNFCCC), signed in Rio de Janeiro in 1992: a change in climate directly or indirectly attributable to human activity, that alters the composition of the atmosphere and adds to the natural variations in the Earth's climate that have been observed for centuries. In other words, these are changes caused by hu-

7 Instituto Nacional de Pesquisas da Amazônia, INPA, Manaus, AM
8 Museu Paraense Emílio Goeldi, MPEG, Belém, PA
9 Universidade Federal do Rio de Janeiro, UFRJ, Rio de Janeiro, RJ
10 Instituto Nacional da Mata Atlântica, INMA, Santa Teresa, ES.
corresponding author: dalval.inpa@gmail.com

man activity, such as the emission of greenhouse gasses into the atmosphere. Although the rise in global average temperature is one of the best known manifestations of these changes, the Intergovernmental Panel on Climate Change (IPCC) clarifies that they include a wide range of changes, such as: a) changing precipitation patterns; b) more frequent and intense extreme weather events (heat waves, hurricanes, floods, fires, and droughts); c) melting glaciers; d) ocean acidification and warming and, consequently, d) changes in ecosystems and biodiversity, as already observed in Brazilian biomes.

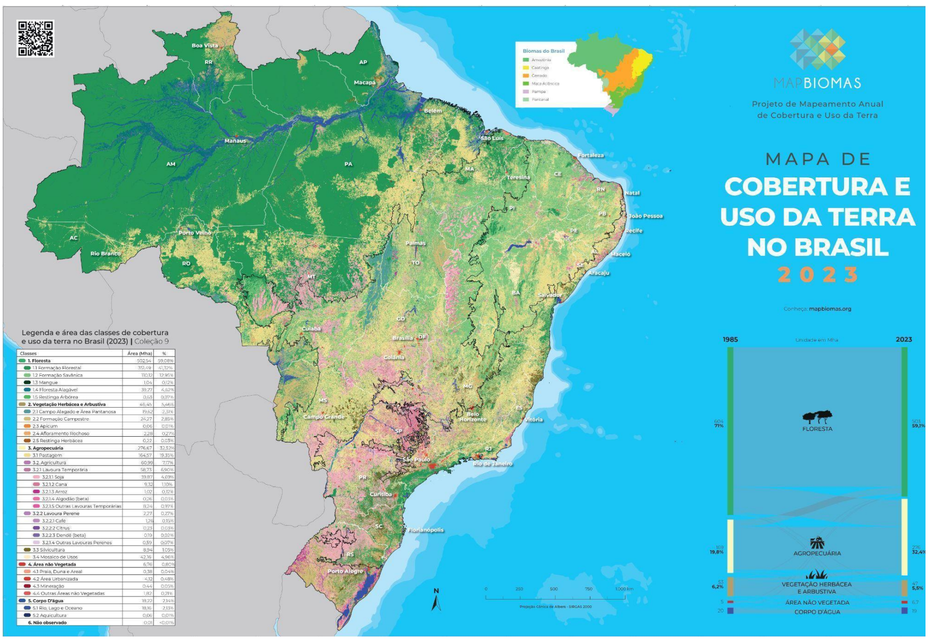


Figure 1: Map of Land Cover and Use in Brazil, by biome (2023). On the right, the change in land use, with a reduction of forests of around 71% in 1985 to 59.1% in 2023. Agriculture accounts for the main change in land use in the historical series. Source: Mapbiomas (2023). Map of Land Cover and Use in Brazil. Collection 9.

Climate change often interacts with other stressors such as deforestation, fires, overexploitation, agricultural expansion, and pollution, including plastics and microplastics (Lucas et al., 2023; Souza et al., 2023). Reducing these non-climatic stressors is therefore crucial to increase the resilience of biodiversity to climate change (IPCC, 2022). For example, studies indicate that targeted measures, such as the expansion of protected areas in regions with high climate risk, can reduce the expected climate impacts on Brazilian biodiversity by up to 21% (Vale et al., 2018; Malecha et al., 2023).

Studies such as Urban's (2024) show that the risk of species extinction increases exponentially with global warming: a scenario with higher emissions would threaten around a third of the planet's species. In Brazil, these effects will be particularly severe in transitional regions and fragmented ecosystems, such as the Atlantic Forest, the Cerrado, and the Caatinga. Ecological and climatic modeling has concluded that certain transitions in vegetation cover can be irreversible if they exceed critical temperature and humidity thresholds. The study by Boit et al. (2016) indicates that, even under optimistic scenarios for mitigating these temperature and moisture changes, the combination of climate change and land use change can lead to forest degradation, replacing biodiverse tropical ecosystems with systems that are poor in species and ecological functionality. These tipping points, once reached, jeopardize regional climate resilience, alter the hydrological system and increase net carbon emissions, ultimately affecting the livelihoods of people in all parts of the world.

On the other hand, work by Warren et al. (2018) shows that limiting warming to 2°C, as envisioned in the Paris Agreement, can double the ability of protected areas to act as climate refuges. This finding is particularly relevant for Brazil, which has a growing network of protected areas, but is still characterized by regional gaps and connectivity deficits (Encalada et al., 2024). Studies conducted in Brazil indicate that the current network of protected areas is insufficient to ensure biodiversity conservation in the face of climate change (Malecha et al., 2023).

Despite the challenges posed by this converging crisis, Brazil has the capacity to provide innovative responses. The country has developed a robust institutional architecture for environmental governance, as demonstrated by the historic success of the Plan for the Prevention and Control of Deforestation in the Amazon (PPCDAm), which reduced deforestation by 32.4% from 2023 to 2024 (MapBiomas, 2025). Many are the conditions that position Brazil as a potential leader in nature-based solutions, such as: a) National conservation programs, b) satellite monitoring systems such as the Legal Amazon Deforestation Monitoring Project (PRODES) and the Real-Time Deforestation Detection System (DETER), c) land use and land cover mapping in the legal Amazon through the TerraClass program, d) established scientific networks such as the Long-Term Ecological Program

(PELD) and the Biodiversity Research Program (PPBio), e) and the national commitment to restore 12 million hectares of forest by 2050. In addition, the rich diversity of traditional knowledge held by indigenous peoples and local communities offers conservation and sustainable management strategies that can be integrated into climate adaptation policies.

This chapter attempts to organize and analyze the current state of scientific knowledge on the impacts of climate change on Brazilian biomes. It identifies specific weaknesses, knowledge gaps, and opportunities for integrated conservation and adaptation strategies. The section "Climate Impacts on Brazilian Biomes" explains the scenarios of climate change in Brazil and how each of these biomes would respond to the challenges of climate change. The section "Science, technology and innovation for conservation in the face of climate change" disPasses promising scientific developments to address these challenges. The section "Public Policy, Governance, and Economic Instruments" presents policy and governance initiatives, based on the best available science that would help avoid the most damaging climate change scenarios for Brazil. Finally, the section "Integrated climate change mitigation strategies" discusses priorities and ways to implement solutions based on the main findings addressed in the chapter.

CLIMATE IMPACTS ON BRAZILIAN BIOMES

The climate projections for Brazil show worrying scenarios. According to estimates, the country could experience an average temperature rise of 3 to 6°C by the end of the 21st century, depending on how greenhouse gas emissions develop (IPCC, 2021). The climate projections, resulting from the global and regional development models made by the IPCC and the National Institute for Space Research (INPE), show that temperature and precipitation patterns vary greatly in the different regions of the country. The study by Malhi et al. (2020) highlights that the northern and central-western regions, where large parts of the Amazon and Cerrado are located, will face a significant increase in temperature, a decrease in annual precipitation and a greater frequency of severe drought events.

In the south, the scenarios also point to an increase in temperature, but with an expected increase in precipitation. This combination could increase flooding, especially in areas such as the Pampas and the Atlantic

Forest. Research by Braga and Laurini (2024) suggests that these extreme weather events will have a negative impact on biodiversity and agricultural productivity, exacerbating economic and social challenges. According to the authors, significant differences in warming patterns were observed in different regions of the country between 1961 and 2023. Particularly striking is an upward trend in temperatures in the Amazon biome, with an increase of 1.12°C over this period, and in the Cerrado biome, which recorded an increase of 0.85°C — biomes that have also been the most affected by deforestation over the last 40 years. In the Pantanal and the Pampa, on the other hand, the warming was rather modest at 0.17°C and 0.37°C, respectively.

Projected climate scenarios imply significant transformations in the vegetation distributions and water regimes of Brazilian biomes. Simulations conducted by Malecha et al. (2023) indicate that, under a scenario of high greenhouse gas emissions (SSP5-8.5), there will be a drastic reduction in areas suitable for key species in the Atlantic Forest and Cerrado. Furthermore, progressive forest degradation along the eastern edge of the Amazon could intensify, threatening the region's already threatened biodiversity (Santos et al., 2023). These projected climate changes result in a potential loss of 20% to 30% of Brazilian biodiversity by 2100, with more severe consequences for biomes already facing fragmentation or prior degradation, such as the Caatinga and the Pantanal (Santos et al., 2023). This is an alarming situation, jeopardizing the biomes' ability to provide essential ecosystem services, such as water regulation and carbon capture.

Recent climate projections indicate that, under high-emissions scenarios (SSP5-8.5), the Amazon could experience a 4.5 to 5.2°C increase in average temperature by the end of the century, accompanied by a reduction of up to 20% in annual precipitation, especially in the eastern portion of the forest (IPCC, 2021; Malhi et al., 2020). In the Cerrado, warming of up to 5°C and a decrease of up to 15% in annual rainfall are expected (IPCC, 2021; Marengo et al., 2022). For the Atlantic Forest, estimates indicate an increase of up to 4.5°C in average temperature and a reduction of nearly 10% in precipitation (Ribeiro et al., 2011). In the Caatinga, the scenario is for warming of up to 4.5°C and a decrease in rainfall of up to 50%, worsening the biome's water deficit (PBMC, 2013). In the Pantanal, projections indicate warming of up to 4.5°C and a reduction in rainfall of up to 45% (PBMC, 2013). The Pampa, in turn, could face an increase of up to 3.8°C in average temperature, but with a significant increase in both precipitation and the frequency of extreme rainfall events (Castellanos et al., 2022) (Figure 2).

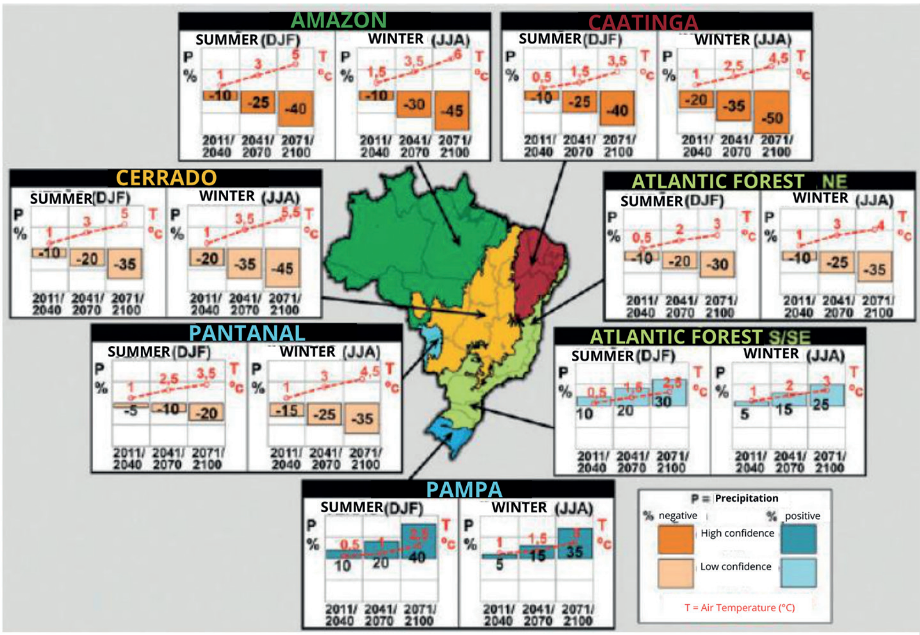


Figure 2: Regionalized climate projections for the Brazilian biomes of Amazonia, Cerrado, Caatinga, Pantanal, Atlantic Forest, and Pampa for the early (2011-2040), mid- (2041-2070), and late (2071-2100) periods, based on scientific results from global and regional climate modeling. Regions with different colors on the map indicate the geographic domain of the biomes. Source: Brazilian Panel on Climate Change – PBMC. 2013. Scientific basis of climate change: Contribution of Working Group 1 to the First National Assessment Report of the Brazilian Panel on Climate Change – Executive Summary. Rio de Janeiro: PBMC. ISBN: 978-85-285-0208-4

To summarize, the climate scenarios projected for Brazil indicate a warmer future, with less predictable rainfall and more intense and frequent extreme weather events. Each biome will respond differently to climate pressures, so it is important to advance specific ecological modeling and integrate different socio-economic scenarios into public conservation and adaptation policies. Understanding these patterns is crucial for the development of adaptation and mitigation strategies that take into account regional specificities and the feedback mechanisms between climate change and land use in Brazil.

The observed changes in temperature and precipitation patterns are already affecting the functioning of ecosystems in virtually all Brazilian regions. Recent studies have identified specific vulnerabilities in the individual biomes, which are explained in more detail below:

Impacts on the Amazon

Climate change is leading to increased tree mortality, reduced forest biomass, and more frequent fires, resulting in a loss of biodiversity and a decline in ecosystem services (Pinho et al., 2020). The forested areas in the central-eastern and south-eastern Amazon basin show lower resilience, which coincides with increasing human activities in the area of deforestation (Hirota et al., 2011) (Figure 3).

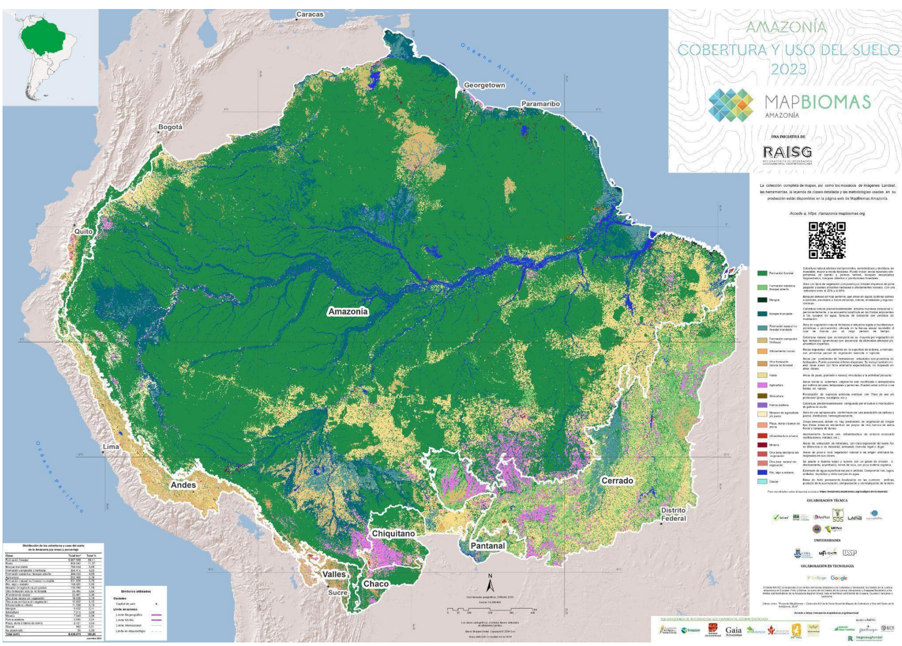


Figure 3: Map of Land Cover and Use in the Pan-Amazon (2023) shows the transition of a broad swath, from Rondônia through southern Amazonas to Pará, to pastureland. Known as the "Arc of Deforestation" this region demonstrates reduced ecosystem resilience to the climate emergency. Source: Mapbiomas (2023). Map of Land Cover and Use in Brazil. Collection 9.

The combination of warming and reduced water resources favors a process of forest degradation, in which the humid forest loses its tree structure and diversity, and evolves into a more open landscape, losing species that require wetter conditions, resulting in a reduced water recycling capacity of the biome (Nobre et al., 2016). This risk is exacerbated by human-induced degradation, as accelerated deforestation has triggered changes in the hydrological cycle and increased regional temperatures. According to Silva Junior et al. (2021), the deforestation rate in 2020 was the highest in a decade, at over 10,000 km^2. The impacts go beyond the loss of vegetation: these cumulative disturbances are already impairing the forest's ability to act as a carbon sink and climate regulator.

The combination of deforestation, wildfires, and forest fragmentation reduces ecological resilience and could lead to the so-called Amazon tipping point, a threshold beyond which the forests would no longer be able to regenerate, permanently altering its functional balance and leading to hydrological collapse. It is estimated that this tipping point would be reached with a 20 to 25% deforestation of the Amazon, combined with an increase in global average temperature of 2 to 2.5°C compared to pre-industrial times (Nobre & Borma, 2009; Lovejoy & Nobre, 2018). This point could be within reach: around 19% of the Amazon rainforest has already been deforested, according to MapBiomas data (1985-2022), and the global average temperature has already risen by around 1.47°C above pre-industrial levels (NASA, 2025).

Ecological niche modeling shows that up to 43% of plant species in the Amazon could lose at least 30% of their range by 2070 (Esquivel-Muelbert et al., 2019). Of the approximately 8,000 species assessed in the Amazon, including thousands of plant species and hundreds of vertebrate (mainly mammals and birds) and invertebrate (bees) species, 26% could be threatened with extinction due to climate change if pessimistic scenarios for greenhouse gas emissions are applied. In a scenario in which the goals of the Paris Agreement are achieved, this figure could be as low as 14% (Malecha et al., 2024).

Another critical aspect of these scenarios is the loss of the role of the forest as a carbon sink. Long-term studies show that the carbon balance of the Amazon has weakened. In other words, the biotope has lost its ability to absorb carbon released into the atmosphere, which hinders the mitigation of climate change associated with greenhouse gasses. In some degraded areas, the forest already emits more carbon than it absorbs, especially in fragmented forest edges that are prone to fires (Gatti et al., 2021). This reversal poses a risk not only to regional biodiversity, but also to global efforts to mitigate climate change.

Even in areas with intact forests, fauna is vulnerable to climate change, as demonstrated by the decline in bird survival rates due to harsher dry seasons in the Amazon over the past 27 years (Wolfe et al., 2025). The study predicts that a 1°C increase in average dry season temperature will reduce the average survival rate of the understory bird community by 63%.

Rising temperatures, combined with pollution, oxygen depletion and acidification of the water, are seriously affecting the health of fish in the Amazon. Studies such as those by Campos et al. (2019) and Braz-Mota & Val (2024) show that chronic heat stress impairs the aerobic metabolism of fish, reduces their energy efficiency and increases the production of reactive oxygen species (ROS), i.e. molecules that are harmful to the body. These stresses activate cellular and hormonal defense mechanisms that are designed to protect the animal, but consume a lot of energy and impair essential functions such as growth, reproduction, and immunity (Pörtner, 2010). These disturbances can be linked to the mass fish mortality during the extreme droughts in the Amazon region between 2023 and 2024 (Braz-Mota & Val, 2024).

Amazon's vulnerability is not evenly distributed. Regions such as the arc of deforestation (southern and eastern Amazon) concentrate the highest rates of degradation and are therefore more vulnerable (Rorato et al., 2022). Areas with contiguous forests in the northwest still show greater relative resilience to climate. However, these areas are also exposed to extreme events, such as historic droughts and record floods, which are exacerbated by changes in atmospheric circulation patterns.

Impacts on the Cerrado

Warming in the Cerrado will increase dry spells, directly affecting the ecological functioning of the biome, including natural regeneration, pollination cycles, and aquifer dynamics (Martinelli et al., 2021). Progressive aridification could transform large parts of the biome into semi-arid landscapes or even degraded steppes (Colman et al., 2024). This process of biome transformation carries a high risk of species extinction (Muniz, Lemos-Filho & Lovato, 2024). Ecological modeling studies indicate that up to 35% of the Cerrado's plant species could be at risk of regional extinction by the middle of the 21st century (Poteau & Birnbaum, 2016). The loss of key species, such as pollinators and dispersers, also jeopardizes the sustainability of regional agriculture, highlighting the interdependence of nature conservation and production.

According to Castro (2023), 91.6 % of Cerrado protected areas are at high or moderate climate risk, mainly due to their fragmentation, their location in areas of high agricultural pressure, and their limited management effectiveness (Figure 4). The extent of protected areas remains disproportionately small: only about 8.5% of the territory is formally protected, most of which is concentrated in sustainable use categories that are often exposed to vulnerabilities in regulation.

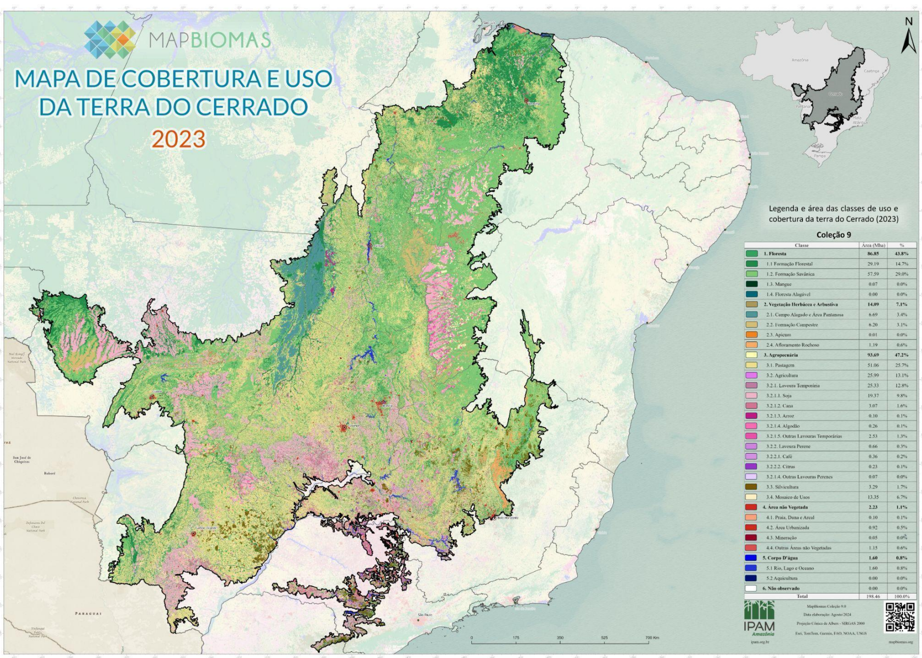


Figure 4: Map of Land Cover and Use in the Cerrado (2023). Agriculture accounts for 47.2% of land use in the biome. Source: Mapbiomas (2023). Map of Land Cover and Use in Brazil. Collection 9.

Another aggravating factor in this biotope is the frequent fires that are traditionally used as an instrument of agricultural management. Although the Cerrado is a fire-dependent habitat, in the current context of climate change, these fires are assuming destructive proportions, disrupting soil nutrient cycling, degrading seed banks, and endangering plant species adapted to less intense fire regimes (Pivello, 2011). In addition, persistent fires reduce the Cerrado's ability to act as a carbon sink, potentially making it a net source of emissions.

Impacts on the Atlantic Forest

Of the approximately 1,300 species assessed in the Atlantic Forest, including dozens of plant species and hundreds of vertebrate (mammal, amphibian, and bird) and invertebrate (especially moths), 31% could be threatened with extinction due to climate change if pessimistic greenhouse gas emission scenarios, are applied. In a scenario where the goals of the Paris Agreement are achieved, this figure drops to 20% (Malecha et al., 2024). The strong fragmentation of the Atlantic Forest exacerbates this scenario (Figure 5). This is because it represents an ecological obstacle to the spread of species, and reduces their ability to adapt to environmental changes. Most flora and fauna populations are currently restricted to forest remnants of less than 50 hectares, which impairs gene flow and facilitates the colonization of invasive alien species (Ribeiro et al., 2009).

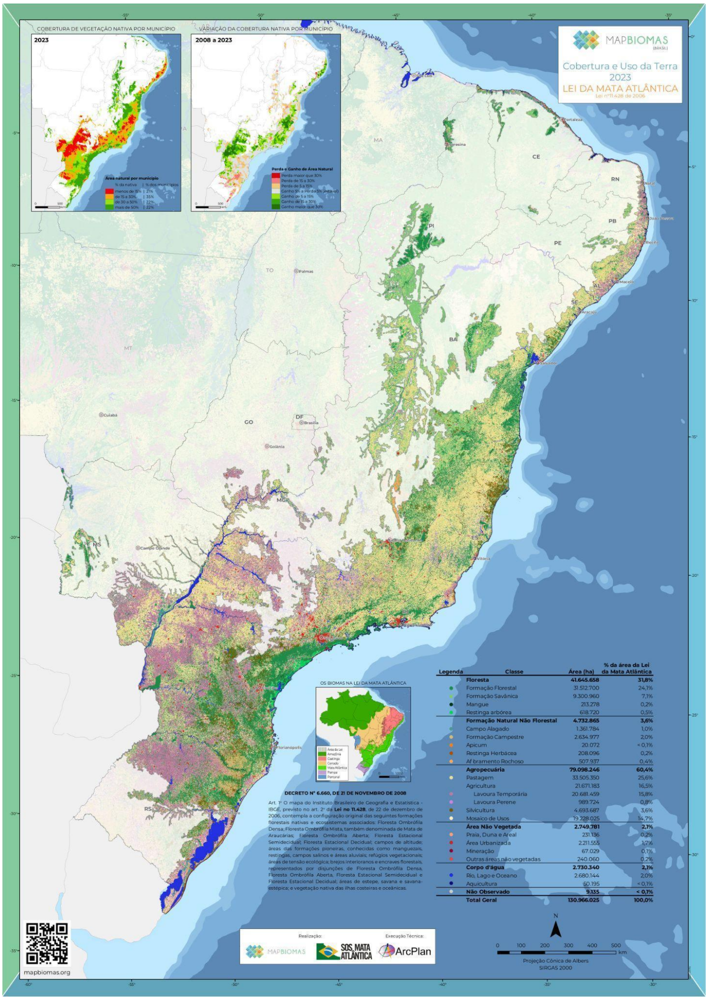


Figure 5: Map of Land Cover and Use in the Atlantic Forest (2023). Only 31.8% of the territory corresponds to areas of native vegetation. Source: Mapbiomas (2023). Map of Land Cover and Use in Brazil. Collection 9.

Species distribution modeling studies show that temperature increases can force species to move up to 300 meters in elevation, which can lead to isolation or local extinction in fragmented mountain regions due to low mobility or ecological constraints (Elith & Leathwick, 2009). In a long-term ecological study conducted in the state of Santa Catarina, 27% of tree communities showed upward shifts in elevation, while 15% showed downward shifts (Bergamin et al. 2024). Upward shifts occurred mainly in montane forest areas, where a temperature increase of 0.34°C was recorded. Downward shifts occurred mainly in lowland forests, where a decrease of 0.36°C was recorded. This is the first evidence of altitudinal shifts in response to climate change in Brazil.

Rapid urbanization in the Atlantic Forest areas, especially along the Rio-São Paulo axis, is putting pressure on springs, wells and slopes, threatening not only biodiversity but also regional water security. Diffuse pollution and impermeable soils contribute to erosion and geotechnical instability, leading to increasing socio-environmental risks, such as landslides or flooding in heavily populated areas (Ribeiro et al. 2011).

Impacts on the Caatinga

The Caatinga is one of the biomes most vulnerable to climate change, particularly due to the combination of unfavorable climatic factors, anthropogenic degradation, and regional socio-economic vulnerability (Figure 6). Projections of global warming and precipitation decline indicate prolonged and intense droughts that increase desertification and jeopardize the hydrological balance of catchments such as the São Francisco River (Beuchle et al., 2015; IPCC, 2021). In fact, an increase in the duration of droughts associated with climate change is already being observed (Castellanos et al., 2022).

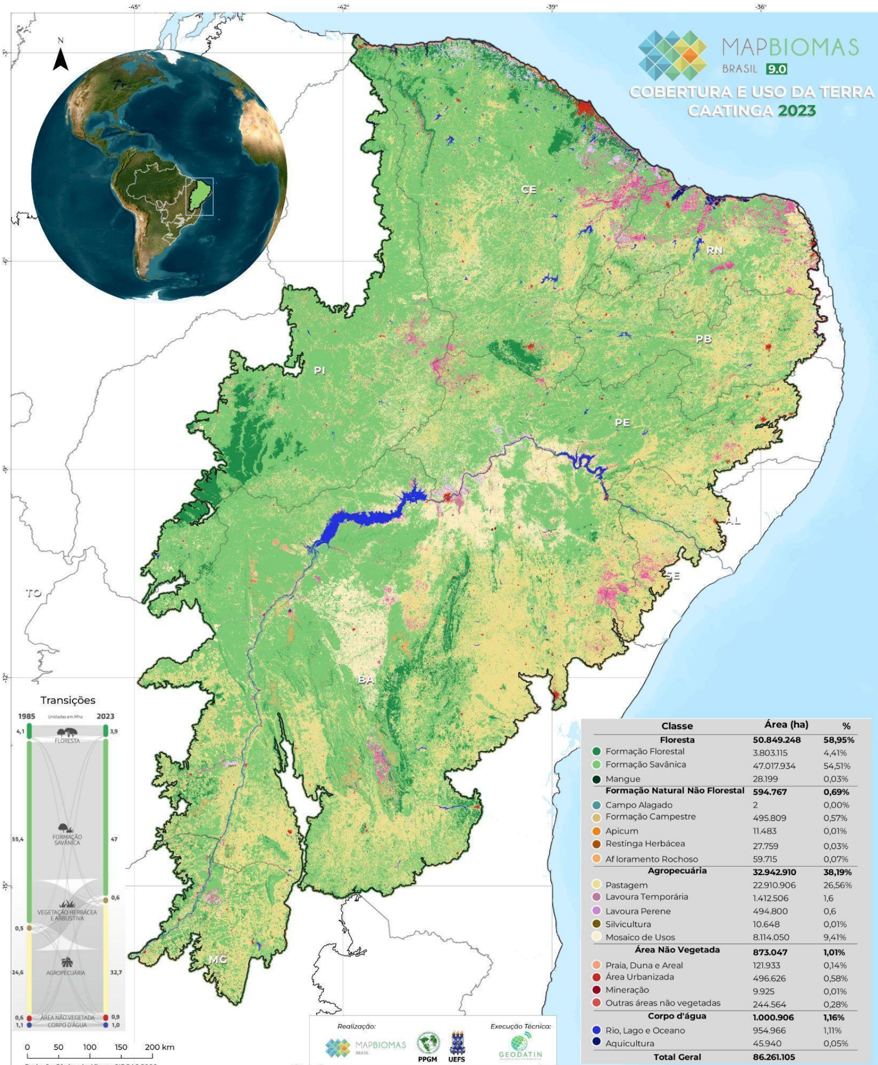


Figure 6: Map of Land Cover and Use in the Caatinga (2023). Between 1985 and 2023, forest areas, savanna formations and shrub vegetation gave way to the expansion of agriculture, which corresponded to 32.7% of land use in 2023. Source: Mapbiomas (2023). Map of Land Cover and Use in Brazil. Collection 9.

Water scarcity, which is already chronic in the region, is exacerbated by ongoing environmental degradation, such as deforestation for firewood and charcoal, overgrazing, and unsustainable land use. It is estimated that more than 45% of the Caatinga is in an advanced stage of soil degradation and loss of vegetation cover (Beuchle et al., 2015). This scenario reduces the soil's ability to retain moisture and recycle nutrients, impairs natural regeneration and jeopardizes the food security of the local population.

Plant and animal species adapted to a dry climate, such as the Brazilian pepper tree (Myracrodruon urundeuva) and the three-banded armadillo (Tolypeutes tricinctus), are facing unprecedented survival problems due to rising temperatures and the collapse of water cycles. Many of these species have a low dispersal capacity, which limits their ability to adapt to displacement from their climatic comfort zones (Braga & Laurini, 2024). Modeling suggests that, under extreme scenarios, up to 99% of the Caatinga's vegetation could be lost to species by mid-century, indicating a high risk of regional extinction (Moura et al., 2023).

Impacts on the Pantanal

In recent years, extreme drought events and megafires have had a serious ecological impact on the Pantanal. Between 2019 and 2020, the Pantanal experienced the worst drought in 60 years, resulting in a drastic reduction in flooded areas and affecting fauna and flora adapted to the seasonal water cycle (Marengo et al., 2021). In addition to reduced rainfall, rising temperatures and the lengthening of the dry season contribute to conditions that favor the spread of fires, many of which are triggered by human activities (Figure 7). The lack of integrated land use planning and the expansion of agriculture and livestock farming on the edges of the biome exacerbate this situation.

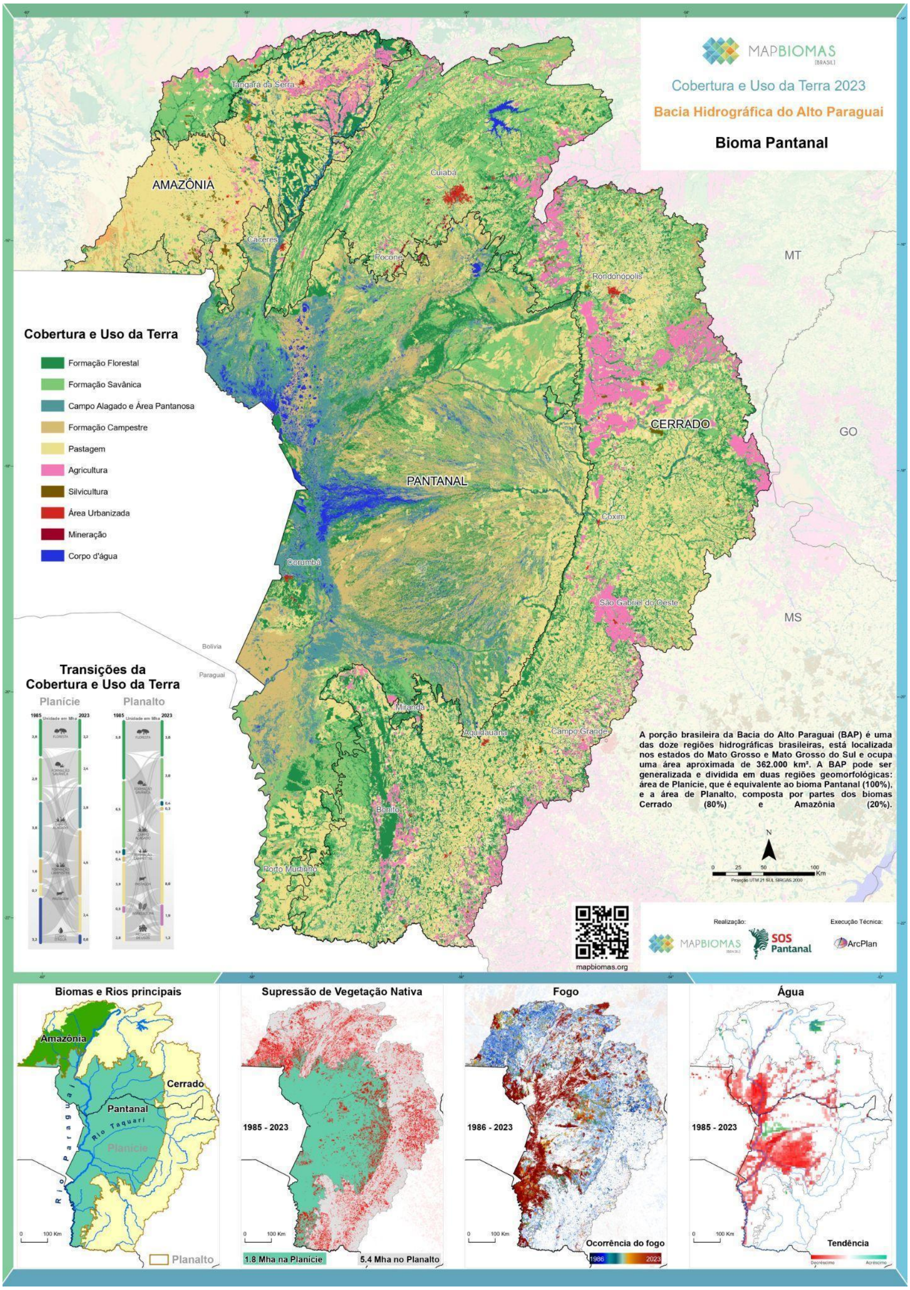


Figure 7: Map of Land Cover and Use in the Pantanal (2023), highlighting the increased incidence of fire and the loss of water surface in the biome between 1985 and 2023. Source: Mapbiomas (2023). Map of Land Cover and Use in Brazil. Collection 9.

The highly specialized biodiversity of the Pantanal is suffering from the loss of aquatic and terrestrial habitats. Species such as the giant otter (Pteronura brasiliensis), the swamp deer (Blastocerus dichotomus), and the tuiuiú (Jabiru mycteria) are among the most affected species. Harris et al. (2005) emphasize that the fragmentation of natural habitats, predatory fishing and invasive species are the greatest threats to the ecological resilience of the biome, alongside the effects of climate change.

Impacts on the Pampa

In some regions of the Pampa biome, increased precipitation rates (up to 12%) have already been observed, which has led to increased erosion, soil degradation, and altered water regimes (Overbeck et al., 2007). A higher frequency of extratropical cyclones is observed in the region, which is likely to intensify in the future (Castellanos et al., 2021). In addition, the resilience of the biome is severely impaired by the displacement of native vegetation by monocultures of soybeans, rice, and exotic pastures. More than 50% of the original vegetation has already been converted to agricultural land, and less than 2.5% of the area is officially protected by nature reserves — the lowest proportion among Brazilian biomes (Roesch et al., 2009)(Figure 8). This conversion promotes soil erosion and biodiversity decline, which in turn leads to the loss of ecosystem services such as hydrological regulation and carbon sequestration (Roberti et al., 2024).

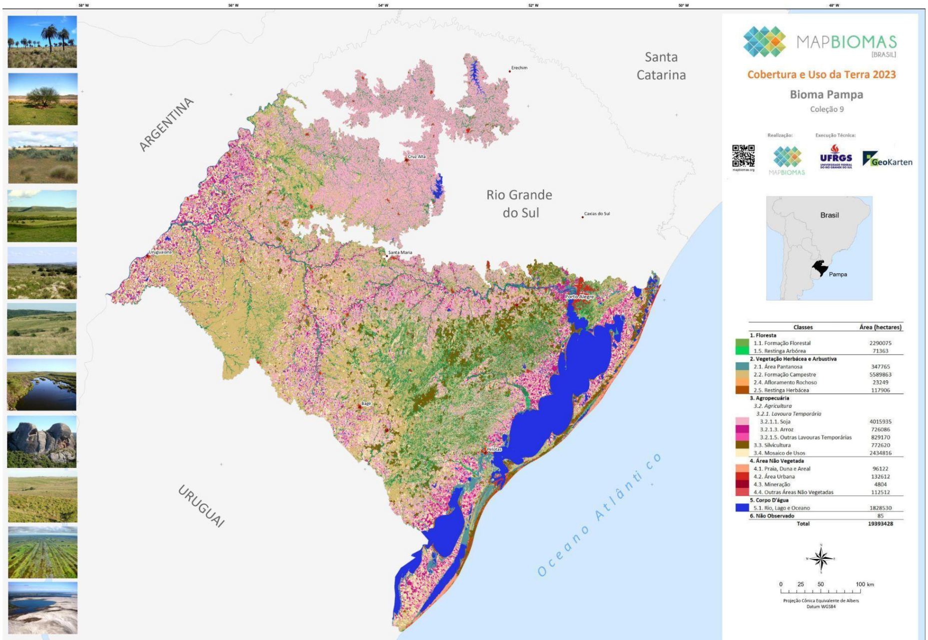


Figure 8: Map of Land Cover and Use in the Pampas (2023). Only 3% of the biome is protected in a region where agriculture is predominant as a land use. Source: Mapbiomas (2023). Map of Land Cover and Use in Brazil. Collection 9.

Advances and Gaps in Current Scientific Knowledge

Scientific knowledge about the impacts of climate change on Brazilian biomes has evolved considerably in the last decade. This is a result of advancements in biological databases, open science, new regional climate models, ecological monitoring networks, and the increasing integration of remote sensing systems and biodiversity data. In fact, Brazil is currently one of the countries with the most studies on the potential impacts of climate change on its biodiversity (Manes et al., 2021; Manes & Vale, 2022). However, this progress is characterized by an uneven distribution of scientific efforts, with a strong geographical and taxonomic bias, which limits the country's ability to provide a systemic and territorially equitable response to the climate crisis (Malecha et al., 2025).

Thus, the concrete risks identified by scientific research still reflect a partial reality, anchored in the best-studied biomes — the Amazon, the Cerrado, and the Atlantic Forest — and in more visible biological groups, such as mammals, amphibians, birds, and vascular plants. Biomes such as the Pantanal, the Caatinga, and the Pampa remain underrepresented in the databases, and are only sparsely covered scientifically. A notable example is the recent synthesis of studies on climate change and biodiversity in Brazil, where only 8% of the studies were conducted in the Caatinga, 3% in the Pampa, and 1% in the Pantanal (Malecha et al. 2024). Although the Pantanal is known for its hydrological importance and rich aquatic fauna, there is a lack of integrated modeling that simultaneously considers climate scenarios, flooding patterns, and the vulnerability of the local population. The Caatinga, on the other hand, despite being the only exclusively Brazilian biome, is neglected in global and national analyses, especially with regard to its microbiota, native pollinators, and regeneration dynamics under water stress.

The gaps are not only spatial, but also taxonomic, functional, and conceptual. In the summary by Malecha et al. (2024), 40% of studies foPas on vascular plants, 43% on terrestrial vertebrates, and 13% on arthropods, most of which are moths and bees. Other invertebrates, fungi, microorganisms, soil organisms, and aquatic species are not included in most climate risk assessments. Coastal ecosystems, such as mangroves, reefs, and estuaries, are also systematically excluded from terrestrial climate assessment agendas, although they are functionally linked to the most important biomes. In addition, there are few studies in Brazil that investigate systemic ecological responses, such as trophic collapses, synchronization of phenological events, or loss of functional connectivity (Encalada et al., 2024) under global warming scenarios (Artaxo, 2020).

Another gap is the limited number of studies that combine climate modeling with socio-economic variables and policy scenarios. Most current models work with idealized environmental parameters, that are far from the Brazilian territorial reality, which is characterized by unequal access to environmental policies, social vulnerability, and the lack of adaptive planning at the subnational level. As Milhorance et al. (2018) emphasize, effective adaptation to climate change in Brazil requires not only technical expertise, but also inter-institutional coordination and the integration of cross-sectoral public policies in the territories.

SCIENCE, TECHNOLOGY AND INNOVATION FOR CONSERVATION IN THE FACE OF CLIMATE CHANGE

Addressing the challenges that climate change poses to Brazilian biodiversity requires a transformation in the way we mobilize Science, Technology, and Innovation (STI). The complexity of socio-ecological systems requires integrated, evidence-based, multi-scalar, and interdisciplinary approaches capable of anticipating risks, making decisions, and promoting environmental and social resilience. High-resolution environmental and climate models, satellite remote sensing, molecular bioindicators, conservation genetics, artificial intelligence in environmental monitoring, and restoration strategies in functionally degraded landscapes are currently at the core of a new and urgent scientific agenda.

The convergence of science and technological innovation not only expands our ability to observe and understand environmental impacts in real time, but also supports the translation of data into strategic decisions, the transformation of knowledge into adaptive public policies, and the transformation of knowledge into concrete hope for reversing collapse scenarios. In this context, Brazil has the opportunity — and the responsibility — to be at the forefront of innovative, science-based solutions that combine the richness of its biodiversity with the transformative power of technology and collaborative governance. Below, we disPass the areas of science, technology, and innovation that support effective, evidence-based climate action.

Integrating Climate Change Impact Modeling with Public Policies

Understanding the impacts of climate change on Brazilian biomes depends on the consolidation of environmental monitoring systems capable of integrating multiple spatial and temporal scales, and combining ecological, climate, and land use data. Advances in multi-biome modeling, based on artificial intelligence, predictive algorithms, and scenario-based simulations, have allowed us to anticipate critical trajectories of ecological transition, functional collapse, and ecosystem reorganization.

The integration of modeling data into public policy is one of the most promising avenues for climate protection. In the Atlantic forest biome, for example, studies such as those by Ribeiro et al. (2009) and Rezende et al. (2018) show that the restoration of 5.2 million hectares of legally protected areas could increase forest cover from 28% to 35%, which exceeds the minimum ecological threshold required to maintain functional connectivity (Encalada et al., 2024). These projections, based on spatial modeling and multi-criteria analysis, allow the identification of priority areas for the connection of forest fragments and the establishment of ecological corridors.

Advances in multi-biome modeling have also improved the predictive capacity for extreme events, such as prolonged droughts, floods, and fires, enabling the development of early warning systems and territorial risk assessment mechanisms. By integrating biodiversity data with climate and socio-economic variables, these models become key tools in the formulation of adaptation and mitigation strategies under different governance scenarios.

Innovation in Ecophysiology and Bioindicators

The use of physiological and molecular bioindicators, such as the activation of antioxidant mechanisms in organisms to prevent cell damage from high temperatures, has emerged as one of the most effective approaches to assess ecological risk in tropical aquatic ecosystems, particularly in the Amazon. When integrated with environmental and climate models, these biomarkers provide ecological early warning systems and support adaptive public policies based on actual biological risks (Dalzochio et al., 2016). Their application makes it possible to prioritize endangered regions and species, and to strengthen the resilience of aquatic systems in the Amazon in the face of rapid environmental change (Souza et al., 2025).

Nature based solutions

The conservation of Brazilian biodiversity in the face of climate change is not limited to mitigation strategies. In the Brazilian case, nature-based solutions can mitigate about 80% of the net emissions target by 2050 (Soterroni et al., 2023). These conditions put Brazil in a strategic position to take a leading role in global climate change mitigation and adaptation policies that go hand in hand with biodiversity conservation.

There is solid evidence that nature-based solutions promote climate adaptation by protecting ecosystem services that increase our resilience

(Manes et al., 2022). Coastal habitats reduce climate change-related risks to the Brazilian coast by 2.5 times, such as extratropical cyclones, coastal erosion, and flooding associated with sea level rise (Manes et al., 2023). In the city of Rio de Janeiro, forests in protected areas reduce temperatures by 4°C and flood risk by 20%, two factors that are likely to be exacerbated with climate change (Martins et al., 2024; Malecha et al., 2024). The ecosystem services that increase our resilience are provided not only by vegetation, but also by our rich wildlife. In Brazil, 82% of mammals provide at least one ecosystem service (Vale et al. 2023). 575 species provide services such as pollination, pest, disease, and rodent control, and ecotourism, contributing to the economy, food security, and health of the population.

In addition to the expansion and consolidation of protected areas, there are other nature-based mitigation strategies: (i) the restoration of ecologically functional landscapes, that foPas on ecological corridors, habitat reconnection, and the provision of ecosystem services; (ii) payments for environmental services (PES), that reward sustainable production practices; (iii) the adoption of agroforestry systems and regenerative agriculture, that combine food production with soil conservation and carbon sequestration; and (iv) the valorization of traditional and indigenous knowledge that historically manages natural resources with low impact and high resilience.

High-resolution remote sensing

Satellite monitoring has become an important instrument of environmental policy in Brazil. The country has developed the PRODES and DETER programs, and the TerraClass project, which provide annual deforestation rates and real-time alerts to combat illegal activities such as illegal mining and selective logging (Kintisch, 2007; Cortinhas Ferreira Neto et al., 2024), detecting deforestation even in cloudy conditions (Doblas et al., 2022).

Another positive example is the MapBiomas platform. Using time series of Landsat imagery, machine learning algorithms, and validation with local data, MapBiomas has accurately revealed the conversion of vast areas of native vegetation into fragmented agroecosystems, and identified the main causes of degradation in all Brazilian biomes (MapBiomas, 2023).

However, access to very high-resolution images (<1 meter) is a challenge for the national scientific community. Commercial images of this type (such as PlanetScope and WorldView) are expensive, and limit research in independent laboratories. Therefore, there is a need to create a repository of images purchased with public research funds while investing in the development of national, high-resolution, publicly available sensors (Prizibisczki, 2020).

Biotechnology for Conservation and Restauration

Biotechnology is a valuable ally in the conservation of biodiversity and the restoration of ecosystems in the face of climate change. One of the most important research fronts for this purpose is the identification of plant genotypes that are more resistant to some of the effects of climate change, such as water stress or high temperatures. The Brazilian Agricultural Research Corporation, Embrapa, is an example of research into the genetic variability of forestry and agricultural species, as in the development of drought-tolerant bean and soybean varieties through gene editing (Embrapa, 2023). In ecosystem restoration, biotechnological techniques help to increase the survival of plants reintroduced into degraded areas, by identifying those populations that show greater tolerance to unfavorable climate or soil conditions.

Genomics Tools and Environmental DNA (e-DNA)

e-DNA is a novel tool that enables non-invasive monitoring of biodiversity based on traces of genetic material in samples such as water or soil. It enables the identification of species present in an ecosystem, including rare or unidentified species, as well as invasive species (Heinrichs-Caldas et al., 2024). In addition to species detection, e-DNA helps in early warning of microorganisms harmful to humans and animals, pollution, tracking and improving decision making by mapping ecological relationships. As it is a non-invasive method, it can also be used as a strategy to reduce field costs or to obtain data on areas that are difficult to access. However, the technology still lacks strategic investment in digital infrastructure and open-access platforms to realize its full potential.

Ecological niche modeling integrating Big Data and AI

Ecological niche modeling is a technique for predicting the distribution of species by relating environmental data (such as temperature, rainfall, etc.) to the presence or absence of a species, in order to estimate its potential abundance. In Brazilian research, species occurrence datasets from databases such as GBIF and speciesLink, have been used and combined with climate projections to estimate changes in species distribution and potential local extinction, as in the case of the study that identified the risk of loss of amphibian diversity due to climate change (Alves-Ferreira et al. 2025). Big data and artificial intelligence (AI) tools have been combined to integrate data on occurrence, functional traits, and phylogenetic relationships, enabling more complex studies with predictions on the impact of climate change. Brazil is among the world leaders in publications using this tool, and linking climate and biodiversity (Giannini et al., 2012). This technology is of great importance for environmental policy, as it anticipates species extinction and displacement and even identifies climate refugia and priority areas for protection.

Citizen Science Platforms and Open Data

Citizen science is evolving into a participatory method of monitoring environmental impacts, with greater emphasis on the social dimension of science and the importance of public engagement in research (Albagli & Rocha, 2021). In Brazil, individuals can report observations of extreme weather events (flood warnings, drought monitoring, etc.) and monitor biodiversity through citizen science projects. Traditional and local communities complement and validate climate models and align the scientific agenda with local needs, making the impact of research more tangible (Pereira et al., 2023). Citizen Science platforms, such as iNaturalist and eBird, , have established themselves as biodiversity monitoring tools. The Monitora program, led by ICMBio, involves volunteers and local communities in several phases, from planning to data collection, strengthening the links between citizens, researchers, and managers in the monitoring of protected areas in a qualified way.

In-the-field sensors (IoT)

Networks of environmental sensors on site as part of the concept of the Internet of Things (IoT) are expanding the climatic-ecological monitoring options in Brazil. Examples include automatic weather stations, humidity sensors, networks of rain gauges, river level sensors, and others.

The National Center for Monitoring and Warning of Natural Disasters (CEMADEN) is a prime example, with over 4,000 automatic rain gauges and hundreds of hydrological sensors distributed throughout the country. The AmazonFACE and Large-Scale Biosphere-Atmosphere Experiment (LBA) projects have deployed an arsenal of sensors to measure carbon fluxes, leaf moisture, tree growth, and atmospheric composition in the Amazon rainforest. This enables rapid responses to climate shocks, and increases the resilience of ecosystems and communities.

Technologies for Adding Value in Sociobiodiversity Chains

An important front in the fight against climate change is the development of technologies that add value to the products of socio-biodiverse agriculture and promote sustainable production chains that generate local income and replace extractive practices. Many examples have recently come to light. One such approach is the use of intelligent solar dryers for the processing of fruits, nuts, wood, and other products, developed by researchers at Embrapa Amazônia Oriental (Embrapa, 2010). The Brazilian solar dryer is 53% more economical than conventional drying methods. There are also promising methods for the environmentally friendly extraction of oils and bioactive compounds, such as essential oils from andiroba (Carapa guianensis) and copaiba (Copaifera langsdorffii), without the use of toxic solvents, to obtain high purity extracts without generating environmentally harmful waste. Methods to isolate and characterize bioactive compounds for pharmaceutical use have evolved and produced promising results, such as compounds with antimalarial, antibiotic, and anticancer activity (Aldana-Mejía et al., 2025).

Finally, digital traceability and certification platforms are another important part of these chains. Initiatives such as Origens Brasil provide seals and a traceable QR code for sociobiodiversity products such as honey, babassu oil, and others. Traceability gives these products a market advantage and prevents the entry of illegal products or those that violate the rights of traditional populations (Jokura, 2023).

Integration of climate and ecological data via interoperable repositories

The transdisciplinary research enabled by technology can reach its full potential if the fragmentation of data across different systems is overcome. In Brazil, there are different environmental data platforms (SiBBr, AdaptaBrasil, AdaptaClima, etc.) with meteorological information, biodiversity databases, socioeconomic data, and other data sources, that follow different standards and are managed by different agencies, with no dedicated staff. Therefore, these data do not communicate with each other, which hinders integrated analysis and the formulation of policies at multiple levels and in multiple biomes. In Latin America as a whole, the lack of open and integrated data repositories (compliant with FAIR principles) has delayed climate change adaptation strategies (Cavazos et al., 2024). Interoperability is key to overcoming this challenge, by introducing standardized formats (e.g., DarwinCore for biological data, netCDF for climate data), open APIs, and web services that enable automatic cross-referencing. Only with standardized data repositories is it possible to efficiently monitor ecosystem protection and climate resilience goals, and improve the quality of public policy.

PUBLIC POLICIES, GOVERNANCE AND ECONOMICAL INSTRUMENTS

The response to the challenges posed by climate change and the loss of biodiversity in Brazilian biomes goes beyond the limits of ecological science or technological innovation. Above all, it is anchored in the ability to build and maintain sound public policies, multi-scalar environmental governance mechanisms, and effective economic instruments. This is a deeply political issue, involving distributional choices, territorial priorities, and development models.

In a country characterized by regional inequalities, social vulnerability and strong pressure on natural resources, climate change mitigation strategies require coordination between different levels of government, economic sectors, and parts of civil society. Command and control mechanisms, economic incentives, and federal and community alliances form the institutional basis for addressing today's socio-environmental challenges with scale, legitimacy, and efficiency.

Climate change interacts with land use and socio-economic factors. The increase in forest fires in the Pantanal and Cerrado, for example, can be attributed to both changes in precipitation and the expansion of inappropriate agricultural practices (Pimentel et al., 2024). These complex interactions require an integrated approach to address the environmental challenges, taking into account the socio-economic impacts and livelihoods of the local population. Several national programs have sought to support research projects that enable more robust measures in Brazil's different biomes.

This section examines the main axes of this climate governance applied to biodiversity: the advances and setbacks in environmental monitoring and control mechanisms; the development and limitations of economic instruments such as PES and carbon markets; the interplay between the federal government, states, and municipalities; the challenges of the classic territorial strategy based on conservation units; and the irreplaceable role of local actors and traditional knowledge in promoting sustainable and equitable solutions.

Command and Control: Between Advances and Stepbacks

In recent decades, Brazil has had an ambivalent history with regard to the use of environmental control instruments. On the one hand, it has demonstrated its institutional capacity to curb deforestation through coordinated public policies, remote monitoring, and targeted repression of environmental crimes. On the other hand, it has experienced cycles of regulatory weakening and legal setbacks that have significantly affected environmental governance, especially since 2019. For example, according to a survey by the Climate Observatory (Freitas, 2025), 44 proposals are pending in the National Congress that weaken Brazilian environmental legislation.

A paradigmatic example of the effectiveness of command and control was the 2004 Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm), which integrated real-time satellite monitoring with enforcement and land use planning, among other measures, to curb deforestation in the region. The plan was successful, and led to a 70% reduction in deforestation between 2004 and 2012 (Nepstad et al., 2014). However, with the weakening of the program, rates rose again by 2021 (Silva Junior, 2021), and fell again in 2022 (Mataveli et al., 2024).

These data underscore the fundamental role of political will in controlling deforestation in the Amazon.

The Amazon deforestation arc has become the focus of restoration as part of Brazil's new commitment to the Paris Agreement. In its new nationally determined contribution, Brazil commits to restore 6 million hectares of forest in the so-called "Amazon Restoration Arc" by 2030 and 42 million hectares by 2050 (Ministry of Economy, 2024), which should attract new reforestation projects to the region.

It is also important to recognize the significant advances in Brazilian environmental policies aimed at preserving the Atlantic Forest. The approval of the Atlantic Forest Law (Law No. 11.428/2006) was a groundbreaking legal milestone that ensures specific rules for the protection and sustainable use of a biome. Initiatives such as the National Policy for the Restoration of Native Vegetation (ProVeg) and the Payment for Environmental Services (such as Floresta+) have promoted ecological restoration with native species and compensated rural landowners who maintain vegetation cover. The expansion of protected areas, such as the creation of private natural heritage reserves (RPPNs), also contributes to the conservation of strategic fragments and functional ecological corridors (Crouzeilles et al., 2013). In addition, the effectiveness of Atlantic Forest conservation still relies heavily on coordination between local governments, the private sector, and traditional communities, who have strategic knowledge on the sustainable use of the landscape.

In response to the critical situation of the Pantanal, the Brazilian government has adopted a series of structural initiatives to protect the biome. Of particular note is the Action Plan for the Prevention and Control of Deforestation and Fires in the Pantanal (PPCPantanal), which is coordinated by the Ministry of the Environment (MMA), and aims to coordinate public policies with the states and municipalities of the region. ICMBio, in turn, manages strategic protected areas such as the Pantanal Matogrossense National Park and the Taiamã Ecological Station, and invests in fire departments and aquatic fauna monitoring. The government has also integrated the Pantanal into the Ecological-Economic Zoning (ZEE) guidelines, which foPas on conservation-friendly land use. Lastly, it is also promoting the Pró Pantanal project, which is supported with funding from the Climate Fund, with measures for ecological restoration and strengthening the local bioeconomy.

The Cerrado, Caatinga, and Pampa biomes lack a solid public policy for their conservation or restoration, which exacerbates the impacts in these regions. Unlike the Amazon and the Atlantic Forest, the Cerrado is not officially recognized as a national heritage site in the federal constitution, which limits the legal mechanisms for protection and funding. Initiatives such as the PPCerrado (Plan for the Prevention and Control of Deforestation and Fires in the Cerrado), are promising, but face chronic budgetary and institutional challenges. The environmental and socio-economic vulnerability of the Caatinga requires policy measures to combat desertification, such as the National Plan to Combat Desertification and Mitigate the Effects of Droughts (Law 13.153/2015), which is currently being implemented. Efforts to conserve and restore the pampa are led by research institutions, non-governmental organizations and universities in Rio Grande do Sul, but they lack the coordination of a specific national plan for the biome.

Institutional setbacks in recent years have undone some of the socio-ecological successes. Budget cuts and the institutional weakening of agencies such as IBAMA and ICMBio, combined with the abolition of participatory councils and the relaxation of licensing requirements, have compromised the effectiveness of the state's environmental oversight apparatus. According to Silva Junior et al. (2021), deforestation in the legal Amazon in 2020 was the highest of the decade, at more than 11,000 km^2. This reflects not only the increase in illegal activities, but also the loss of state capacity to monitor and prevent violations.

Recently, Bill 2.159/2021, which deals with environmental licenses, was approved by the National Congress. It brings "a significant disruption to the existing regulations on the subject and poses a risk to the environmental and social security of the country" (Climate Observatory, 2025) According to the Ministry of Environment and Climate Change, this is the biggest setback in Brazilian environmental legislation since the amendments to the old Forest Code in 2012. As announced in a technical note by the Climate Observatory (2025), serious setbacks were identified in at least 42 of the 66 articles in the proposal. According to the note, "the proposed text created a scenario of regulatory chaos, and weakened environmental impact assessments, risk analysis, public participation, and environmental control." Among the most critical points were the exemption from licensing for several activities with potential environmental impacts, such as mining, the introduction of self-licensing without prior technical analysis, and the possibility of legalizing illegal companies through amnesties. The bill also excludes indigenous and quilombola territories that are still in the process of being recognized from protection, thus endangering the lives of the people living in these territories.

As this chapter went to press, the President of the Republic had vetoed 63 of the 400 provisions of the General Licensing Law. Among the provisions vetoed are the possibility of a special environmental authorization (LAE), intended for projects and works classified as “strategic” and carried out in a single phase, and the possibility of a simplified authorization for projects with medium pollution potential, which includes the new authorization modality based on self-declarations. The presidential vetoes may mitigate the negative effects of the law on environmental management. It remains to be seen whether they will be confirmed or overturned by Congress.

The survey conducted for this chapter identified 102 legislative proposals, or Bills, currently under consideration related to environmental issues or the climate emergency. Among the proposals with potentially positive impacts (Table 1), criminal law proposals that increase penalties for environmental crimes stand out — particularly in response to the significant increase in fires in the period 2023-2024 — as well as initiatives to mitigate climate disasters triggered by the floods in Rio Grande do Sul and the severe drought in the Amazon, (both in 2024). These are largely reactive projects that respond to specific crises. Nevertheless, the draft laws show a scenario characterized by setbacks and the dismantling of protection and mitigation measures. Furthermore, not enough attention is paid to the specificities of each biome: only the Amazon has been specifically addressed, with the Bill 3443/2025, which establishes the national policy for the integrated protection of the Brazilian Amazon.

Table 1: Bills (PLs) in progress with positive potential for conservation, adaptation and/or mitigation in the face of the climate emergency.

BILLS	WHAT IS IT?	CURRENT SITUATION
Bill 3443/2025	Establishes the National Policy for Integrated Protection of the Brazilian Amazon, foPasing on the defense of traditional peoples and territories, combating environmental and organized crime, and valuing local socio-environmental knowledge.	Waiting for the Seal and Publication of the Order.
Bill 2900/2025	Establishes the National Campaign to Encourage the Acquisition of Agroecological and Organic Products and Ingredients from Family Farming.	Waiting for Designation of Rapporteur.
Bill 1530/2025	Establishes the Fund to Support Agrosilvopastoral, Extractive and Artisanal Production carried out by Indigenous Peoples, Quilombolas and Traditional Communities (FUNAP-TRADICIONAIS), to finance and support research and actions aimed at enhancing, assisting and encouraging the development of sustainable and agroecological production for national and international commercialization purposes.	Waiting for Designation of Rapporteur.
Bill 1879/2025	Amends Law No. 11,445/2007 to establish measures aimed at maintaining and regulating water supply in areas susceptible to shortages due to drought.	Waiting for the Rapporteur's Advice.

BILLS	WHAT IS IT?	CURRENT SITUATION
Bill 1525/2025	Institutes the National Program for the Enhancement of Sustainable Sugarcane (PROCANAS) and establishes incentives for regenerative agricultural practices in sugarcane production in Brazil.	Waiting for Designation of Rapporteur.
Bill 2177/2025	Provides guidelines for mitigating the effects of climate change in public buildings and public or private spaces where people circulate or gather.	Waiting for the Rapporteur's Advice.
Bill 1286/2025	Determines the creation of a credit line by the National Bank for Economic and Social Development (BNDES) for renewable energy projects for family farming.	Waiting for the Rapporteur's Advice.
Bill 3444/2025	Establishes the Sustainable Infrastructure Program for Amazonian Island Communities, foPasing on basic sanitation, access to drinking water and environmental management.	Waiting for the Seal and Publication of the Order.
Bill 1725/2025	It prohibits the offering of new oil and gas exploration blocks in the Amazon and requires environmental restoration in areas where these hydrocarbons are produced in the region.	Ready for Agenda.
Bill 3540/2025	Establishes the National System for Mapping Vectors of Deforestation and provides other measures.	Waiting for the Seal and Publication of the Order.

BILLS	WHAT IS IT?	CURRENT SITUATION
Bill 3512/2025	Provides for the establishment of targets, guidelines and instruments for the reduction of methane emissions in Brazil, and contains other provisions.	Waiting for the Seal and Publication of the Order.
Bill 456/2025	It establishes guidelines and standards for sustainable urban mobility and orderly urban expansion, aiming to prevent disasters in urban areas, reduce social inequalities and encourage sustainable practices in urban development.	Ready for Agenda.
Bill 3652/2024	Attached of projects that provide guidelines and bases for national education to include material on climate change in teaching materials.	Waiting for Designation of Rapporteur.
Bill 157/2025	Amends Law No. 14,902/2024 to include guidelines for mitigating pollutant emissions caused by motor vehicles.	Waiting for the Rapporteur's Advice.
Bill 367/2025	Authorizes the Union to participate in a fund whose purpose is to support the requalification and recovery of infrastructure in areas affected by extreme climate events and to support infrastructure projects related to mitigation and adaptation to climate change.	Waiting for Designation of Rapporteur.

BILLS	WHAT IS IT?	CURRENT SITUATION
Bill 3130/2025	Amends Law No. 12,114/2009 to allocate resources from the National Climate Change Fund to actions aimed at reconstruction, strengthening the public education system and promoting School Climate Resilience in territories affected by extreme climate events.	Waiting for Designation of Rapporteur.
Bill 3218/2025	Establishes the National Program to Encourage the Formation of Ecological Corridors in Rural Properties, Reforestation and the Adoption of Soil and Water Conservation Practices, with the creation of the AgroBio Seal of Environmental Quality.	Waiting for Designation of Rapporteur.
Bill 2634/2025	Establishes the National Program to Encourage the Creation and Strengthening of Municipal Climate and Environment Councils and provides other measures.	Waiting for Designation of Rapporteur.
Bill 2401/2025	Establishes the Legal Framework for the Decarbonization of Brazilian Industry, establishing guidelines, targets, regulatory mechanisms and incentives to promote carbon neutrality in the industrial sector by 2050.	Waiting for Designation of Rapporteur.

BILLS	WHAT IS IT?	CURRENT SITUATION
Bill 2402/2025	Institutes the National Policy to Incentive the Circular Economy and Reverse Logistics, establishing obligations for manufacturers, importers, distributors and traders.	Waiting for the Rapporteur's Advice.
Bill 3658/2024	Amends Law No. 12,114/2009 to allow the allocation of resources from the National Climate Change Fund to combat deforestation, burning, forest fires, desertification and natural disasters.	Waiting for the Rapporteur's Advice.
Bill 3025/2024	Amends Law No. 11,445/2007 to prioritize the application of federal public resources in basic sanitation actions in municipalities that have their territory partially or fully located in Conservation Units.	Waiting for the Rapporteur's Advice.
Bill 3904/2023	Establishes the National Policy on Agroecology and Organic Production.	Ready for Agenda.
Bill 4816/2024	Provides for the protection and preservation of springs and watercourses, establishes monitoring mechanisms, recovery of degraded areas and stricter penalties for polluters.	Waiting for the Rapporteur's Advice.
Bill 4947/2024	Establishes the National Policy on Payments for Environmental Services (PNPSA) and provides for financial incentives for environmental conservation.	Waiting for Designation of Rapporteur.

BILLS	WHAT IS IT?	CURRENT SITUATION
Bill 3187/2024	Amends Law No. 11,484/2007, which provides for the Program to Support Technological Development of the Semiconductor Industry (PADIS), and includes incentives for technologies to promote emission reduction and energy transition.	Ready for Agenda.
Bill 3144/2024	Establishes a contribution for intervention in the economic domain (CIDE-Pecuária) intended to fund the Clean Livestock Fund (FUNPECLIMP), for the financing of programs and actions aimed at the adoption of low-carbon agriculture techniques.	Waiting for the Rapporteur's Advice.
Bill 4946/2024	Establishes the National Policy for Sustainable Ecotourism.	Waiting for the Rapporteur's Advice.
Bill 3604/2024	Amends the National Climate Change Fund to allow for the investment of resources in the development of information technology (IT) and artificial intelligence (AI) in the prevention and containment of fires in natural environments, and provides other measures.	Waiting for the Rapporteur's Advice.
Bill 4364/2023	Amends the National Policy on Climate Change to include rules for consolidating and encouraging the adoption of measures to mitigate and remove greenhouse gases.	Waiting for the Rapporteur's Advice.

BILLS	WHAT IS IT?	CURRENT SITUATION
Bill 2860/2022	Creates the Climate Change Combat Financing Program.	Waiting for the Rapporteur's Advice.
Bills 2085/2025, 3643/2024, 3299/2024, 2968/2024, 3321/2024, 3339/2024, 1703/2020, 10457/2018	Laws that expand monitoring and penalties for crimes involving burning, deforestation and/ or significant environmental degradation.	Diverse Situations.
PL 3899/2012	Establishes the National Policy to Stimulate Sustainable Production and Consumption.	Awaiting Deliberation in the Plenary.

Economical Instruments, Carbon Market and Biodiversity Credits

Conserving biodiversity and tackling climate change require not only environmental oversight, but also effective economic mechanisms that incentivize the conservation of existing forests, the restoration of ecosystems, and the transition to sustainable production models. Economic instruments are capable of reconciling environmental and financial interests, and transforming environmental liabilities into assets of strategic value for development.

In Brazil, this movement has gained momentum with the inclusion of Payments for Environmental Services (PES) in the new Forest Code (Law No. 12.651/2012) and, more recently, with Federal Law No. 14.119/2021, which establishes the national PES policy. These mechanisms allow rural producers, traditional communities, and indigenous territories to receive payments for services they provide to society, such as the conservation of water, soil, biodiversity, and climate stability.

Another important recent regulatory milestone is Law No. 15.042/2024, which establishes the Brazilian System of Greenhouse Gas Emissions Trading (SBCE), laying the foundation for a regulated carbon market in the country. The Brazilian legislation was enacted shortly after the formalization of the global UN-supervised mechanism for carbon credits at COP29 in Baku, as provided for in Article 6.4 of the Paris Agreement. Permanent Preservation Areas (APPs) and Legal Reserves (RLs) to be restored, representing an environmental footprint of about 20 million hectares, open space for an ecological restoration agenda through measures such as Green Rural Credit, CRAs (Environmental Reserve Quotas), and the use of restored land as carbon assets.

Despite these regulatory advances in Brazil, the consolidation of "avoided deforestation" as an asset in carbon markets still faces resistance intarnationally, which affects the economic valuation of standing forests. REDD+ projects (acronym for Reducing Emissions from Deforestation and Forest Degradation) are part of carbon market strategies. It is a multilateral, voluntary mechanism that rewards emission reductions related to combating deforestation and forest degradation. The mechanism was launched in 2005 at the Conference of the Parties (COP), but has not yet been formally consolidated, and only exists in the voluntary market. As Brazil is one of the countries with the highest emissions related to deforestation and degradation, it quickly became one of the largest REDD+ beneficiaries in the world (Cerbu et al. 2011). According to the international REDD+ project database (reddprojectsdatabase.org), there are currently more than 700 such projects in 57 countries, 91 of which are in Brazil, . Although these voluntary projects are triggering a wave of optimism, their effectiveness remains limited: a study of 40 projects found that the 47% reduction in deforestation in the first five years of implementation is less significant than the reduction achieved by Conservation Units, for example (Guizar-Coutiño et al., 2022). In addition, the average compensation from REDD+ is still not competitive with extractive activities, underlining that purely financial mechanisms may not be sufficient to solve such a complex problem (Kill, 2020).

In addition to carbon credits, biodiversity credits are an instrument that is being discussed in the international market. In contrast to carbon credits, which foPas on the reduction or elimination of greenhouse gasses, biodiversity credits focus on the protection of habitats, species, and ecosystem services that are important for the stability of the environment.

However, their implementation faces significant technical challenges, such as the difficulty of accurately measuring and quantifying these benefits, the need for robust methodologies for valuation and monitoring, ensuring additionality and avoiding double counting of credits (Vardon & Lindenmayer, 2023). It is also impossible to imagine successful implementation scenarios without addressing the serious issues of transparency, equity, and social justice in the commercialization of credits (Swift, 2024). So far, there has not been enough time for studies to prove the effectiveness of biodiversity credits.

The consolidation of economic instruments therefore requires an integrated strategy that includes: i) legal certainty for PES projects and contracts; ii) integration between voluntary and regulated carbon markets; iii) environmental traceability of products and production chains; iv) inclusion of farming families and traditional peoples in payment and decision-making processes.

Multilevel Governance and Federative Articulation

The conservation of biodiversity in a country with the size, territorial complexity, and socio-ecological diversity of Brazil requires environmental governance at multiple levels, i.e. the development of public policies coordinated between the federal government, states, municipalities, and civil society. The decentralization of environmental management, enshrined in the 1988 Constitution, has the potential to increase the scope of action and adapt it to local realities. However, its effectiveness depends on vertical integration, federal cooperation, and the equitable distribution of responsibilities and resources. Initiatives such as the Legal Amazon Consortium, formed by nine states in the region, show that subnational institutions are capable of formulating integrated responses to the climate crisis. However, such initiatives still operate with uncertain funding, weak links to federal policy, and limited replicability in other biomes. At the municipal level, inter-municipal environmental management consortia are increasingly emerging, particularly in frontier agricultural areas such as Matopiba and southeastern Pará. These agreements have the potential to form regional pacts for sustainable land use, but they lack the technical and financial instruments to ensure their sustainability.

Coordination across scales also requires integration between sectors. Brazilian climate policy, as reflected in the Nationally Determined

Contributions (NDCs), needs to work with policies in land use planning, land regulation, transportation, energy, and rural development. As Warren et al. (2018) point out, even if international commitments are met, the benefits for biodiversity will be limited if they are not accompanied by strategic spatial planning, ecological connectivity, and the protection of functional areas for species migration. Therefore, effective climate governance requires that federal instruments are anchored in legitimate territorial pacts, with decentralized funding, transparent data sharing, and intergovernmental coordination mechanisms. Otherwise, environmental governance tends to fragment and loses its capacity for systemic transformation.

Protected Areas and the Limits of the Classical Territorial Strategy

Protected areas (PAs), or Conservation Units, are the backbone of biodiversity conservation policy in Brazil. The National System of Protected Areas (SNUC), which covers about 30% of the national territory, including terrestrial and marine areas, is a well-established institutional framework. However, the worsening climate crisis poses new challenges to traditional territorial strategies, and highlights the limits of the distribution of Pas among the different biomes and their capacity to adapt to ongoing environmental changes.

Recent studies show that the effectiveness of PAs in protecting species could decrease significantly under global warming scenarios. According to Malecha et al. (2023), most Brazilian PAs will not maintain suitable climate conditions for the species they protect. Many currently protected populations could migrate to areas outside their boundaries in the coming decades, so there is an urgent need to develop dynamic conservation strategies based on landscape planning.

Another structural problem is the geographical bias in the allocation of PAs between biomes. While the Amazon and, to a lesser extent, the Atlantic Forest account for most strictly PAs, biomes such as the Pampas and the Caatinga remain unprotected, with less than 1% of their areas covered by this type of unit (Jenkins et al. 2015). This asymmetry affects the representation of ecosystems in the SNUC and weakens the system's ability to function as a network of national climate change mitigation areas.

In addition to territorial coverage, there are also challenges to management effectiveness, including lack of management plans, staff shortages, insufficient budgets, land conflicts, and external pressures such as mining, land grabbing, and illegal hunting. These weaknesses reduce the institutional resilience of protected areas to climate change and hinder the implementation of adaptation measures, such as connectivity management, the use of buffer zones, and integration with private and collective use areas.

Given this scenario, it is essential to rethink protected area policy based on a more dynamic approach, that takes into account changes in the potential distribution of species, incorporates tools such as climate-related ecological corridors, and integrates instruments such as payments for environmental services, conservation mosaics, and private reserves. The future effectiveness of the SNUC will depend on its ability to respond to a rapidly changing environmental reality.

Local actors and Traditional Knowledge

Climate and environmental policy in Brazil will not be effective without the recognition and active appreciation of local actors and traditional knowledge. Indigenous peoples, quilombola communities, extractivists, riverside communities, and family farmers are not only potential beneficiaries of environmental policies, but above all, historical and current actors of conservation. Their territorial practices, based on adaptive management and accumulated ecological knowledge, have ensured the conservation of large areas of native vegetation, even under increasing external pressure.

Indigenous territories have the lowest deforestation rates in the legal Amazon, even in regions experiencing strong agricultural and mining expansion (Qin et al., 2023) (Figure 9). This is the result of territorial governance systems based on reciprocity, intergenerational care, and sophisticated knowledge of local ecosystems. These territories act as effective barriers against environmental degradation, and also serve as zones of ecological connectivity and climatic resilience (Halla, 2020).

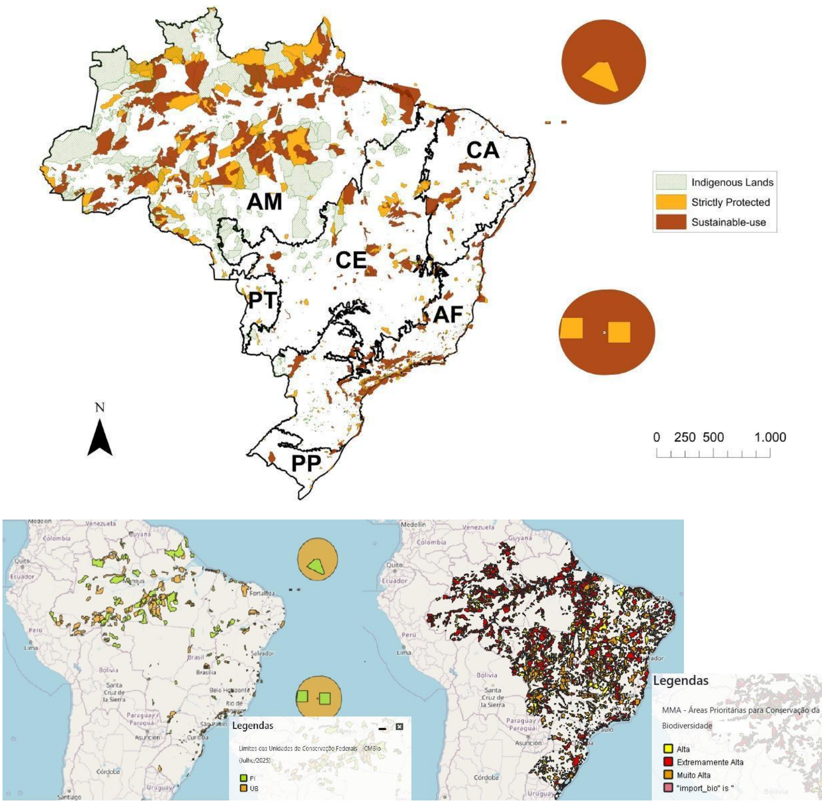


Figure 9: Distribution of Indigenous Territories, Conservation Units, Sustainable Use Reserves, and Priority Areas for Biodiversity Conservation in Brazil. Sources: Malecha, A., Vale, M. M., & Manes, S. (2023). Increasing Brazilian protected areas network is vital in a changing climate. Biological Conservation, 288, Article 110360. https://doi.org/10.1016/j.biocon.2023.110360/ ICMBIO.

The inclusion of traditional ecological knowledge in conservation and climate adaptation policies is, therefore, not only an ethical and constitutional imperative, but also an efficient environmental management strategy. In the Cerrado and Caatinga, for example, practices such as community fire management, indigenous seed management, traditional beekeeping, and the use of medicinal plants represent resilient ways of coping with water scarcity, fire, and changing rainfall patterns (Welch & Coimbra Jr., 2021). Ignoring these systems means missing opportunities for innovation and adaptability.

Social mapping initiatives, community protocols for free and informed consultation, and integration into co-management networks have progressed in several regions of the country, but still face institutional and political barriers. Formal recognition of territories, regularization of land, protection against invasions, and inclusion in public environmental programs are essential steps to consolidate the presence of traditional groups in climate governance.

In addition, programs such as Floresta+ Comunidades, Payment for Environmental Services on Indigenous Lands (PSATI), and the strengthening of community organizations are promising ways to ensure fair benefit sharing, respect for collective rights, and synergy between public policies and local knowledge. Involving these actors not only expands the scope of conservation, but also its social and political legitimacy.

INTEGRATED STRATEGIES FOR CLIMATE CONSERVATION

Building a strategic agenda for biodiversity conservation in times of climate change requires coordinated, multiscalar and multisectoral action based on sound science, territorial planning, and environmental justice. Although Brazil has technical and scientific knowledge, legal instruments, and sound environmental technologies, the effectiveness of these instruments is still limited by institutional distortions, regional asymmetries, and deficits in socio-environmental governance.

To overcome these obstacles, efforts in the areas of prevention, restoration, adaptive management, and social inclusion need to be coordinated through strategies that integrate predictive models, functional spatial planning, local community participation, and the appreciation of traditional knowledge. This integration should not only be thematic but also operational, promoting synergies between conservation, climate, agriculture, infrastructure, and regional development policies.

This section presents the main pillars of an integrated climate change mitigation strategy for the Brazilian biomes, based on the scientific evidence collected in this work. The proposal aims to guide public and societal actions that respond to the climate emergency in a territorially equitable, environmentally effective, and institutionally sustainable manner.

Table 2: Matrix of Change: Promoting Climate Conservation in Brazilian Biomes

PROBLEM	GOAL (SHORT TERM)	GOAL (LONG TERM)
1. Deforestation and degradation threaten ecological resilience.	Reduce deforestation and degradation in all biomes.	End illegal deforestation and restore 6 million hectares by 2030.
2. Poorly distributed and climate-vulnerable PAs	Review the network of PAs based on climate risk criteria.	Expand network with a focus on connectivity and climate refuges by 2035.
3. Caatinga, Pantanal e Pampa with insufficient scientific coverage.	Launch calls for proposals aimed at these biomes.	Balance research efforts across biomes by 2030.
4. Fragmented environmental governance.	Consolidate interfederative committees in all states.	Implement territorial pacts in all biomes by 2035.
5. Disintegrated environmental data platforms.	Consolidate interoperable repositories with FAIR & CARE principles.	Establish a unified national system by 2035.

IMPLEMENTATION MECHANISMS	ACTORS INVOLVED	INDICATORS AND METRICS
Institutional strengthening (IBAMA/ICMBio), resumption of PPCs, PSA and encouragement of sustainable production, active and passive restoration methods, allocation of public lands for conservation and/or indigenous territories.	MMA, IBAMA, ICMBio, state governments, MPF, rural producers, local communities, universities, research institutes and INCTs.	- km2 deforested/ year by biome - Area restored (ha) - Number of effective inspections - Amount paid in PES - Sustainable value chains structured based on sociobiodiversity products - km^2 of public lands designated for conservation and/or indigenous territories..
Systematic conservation planning, creation of ecological corridors and agroforestry mosaics, integration with PSA and RPPNs.	ICMBio, SNUC, NGOs, UC managers, states, municipalities, local communities.	- % of territory protected by biome. - Ecological Connectivity Indexes. - PAs created/redesigned. - Updated management plans.
Gap-oriented funding, support for scientific networks such as PPBio, inclusion of research groups, integration with INCTs.	MCTI, CNPq, Capes, universities, research institutes, INCTs and FAPs.	- Scientific production by biome - Consolidation of scientific networks by biome - Funding proportion for each biome
Intermunicipal consortia, multisectoral coordination and integrated policies.	MMA, MDA, states, intermunicipal consortia, councils, civil society.	- Active interfederative committees - Integrated territorial plans - Social participation in councils - Territorial pacts implemented
Coordination between MCTI/MMA, formation of a dedicated team, maintenance and public accessibility.	MCTI, INPE, IBGE, MMA, universities, research institutes and public developers.	- Number of interoperable databases - Access to public platforms - Degree of adherence to FAIR & CARE standards

PROBLEM	GOAL (SHORT TERM)	GOAL (LONG TERM)
6. Incipient economic instruments.	Regulate economic instruments in an evidence-based manner, with a focus on social justice and equity (e.g. biodiversity credits).	Consolidate a green economy with socio-productive inclusion by 2035.
7. The discontinuity and underfunding of science compromise the response to the climate emergency.	Ensure stable, multi-year funding for ST&I and expand public participation in environmental policies.	Consolidate a robust scientific and citizen base to inform adaptive policies by 2030.
8. Marginalized traditional knowledge.	Integrate leaders and formalize consultation protocols.	Consolidate adaptive co-management of territories and co-participation in research projects by 2030.

IMPLEMENTATION MECHANISMS	ACTORS INVOLVED	INDICATORS AND METRICS
Legal security, traceability, regulation, program expansion.	MMA, MRE, MAPA, private sector, public banks, traditional and local communities.	- Number of active PES contracts - Volume of carbon/ biodiversity credits traded - Participation of traditional people and communities in payment flows - Results of avoided deforestation/conserved biodiversity
Restructure the S&T budget, create permanent lines of support for climate science and green innovation, utilize government procurement and tax benefits, expand citizen science calls for proposals, and ensure the institutionalization of participatory councils.	MCTI, CNPq, Capes, FAPs, universities and research institutes, social movements, traditional and local communities.	- Annual volume of federal investment in ST&I focused on climate, biodiversity, and environmental change - Number of multidisciplinary or interdisciplinary projects supported per year - Number of active councils with representation from traditional communities and organized civil society.
Land recognition, indigenous PSA, participation in councils, research calls that require co-participation of traditional communities, valorization of local practices.	FUNAI, INCRA, MMA, MCTI, CNPq, Capes, indigenous, quilombola and riverside organizations, MDS, MDA, universities and research institutes.	- Number of territories with formal consultation protocols - Number of communities benefiting from PSA or conservation projects - Proportion of protected areas with formal participation of traditional peoples - Proportion of research projects with participation of traditional peoples.

Maintain the commitment to end deforestation by 2030

Preventing the degradation and loss of natural habitats is the first and most cost-effective axis of an integrated climate change mitigation strategy. In many cases, it is both ecologically and economically more efficient to avoid the conversion of ecosystems than to restore them later. In the context of the Brazilian biomes, this logic gains urgency given the current rate of deforestation, especially in the Amazon, Cerrado, and Caatinga.

Therefore, halting the progression of deforestation is indispensable to prevent the functional collapse of ecosystems (Vieira & Silva, 2024; Vieira, 2023). This requires: I) the rebuilding of institutional environmental oversight capacity, especially in federal agencies such as IBAMA and ICMBio; II) the strengthening of the PPCDAm and its equivalents in other biomes, such as the PPCerrado; III) zero tolerance for land grabbing, illegal deforestation, and environmental impunity, that fuel the cycle of land speculation and systemic destruction; and IV) the recognition and valuation of already conserved areas through payment for environmental services (PES) mechanisms, the promotion of sustainable production, and the legal protection of traditional communities and indigenous peoples. Preventing loss is not just about protecting what is left. It is also about ensuring ecological continuity, climate security, the rights of indigenous peoples and traditional communities, and sovereignty over the country's strategic natural assets

Restore 6 million hectares of forests by 2030

Ecological restoration is emerging as one of the most effective and cost-efficient strategies to simultaneously tackle the climate crisis and biodiversity loss. Restoring just 15% of land converted to strategic points can prevent up to 60% of projected global species extinctions and also contribute up to 30% of the carbon sequestration needed to keep global warming below 2°C (Strassburg et al., 2020). In the Brazilian context, this strategy takes on added value, as it integrates the legal obligations under the Forest Code, such as the restoration of permanent protected areas (APPs) and legal reserves.

In the Atlantic Forest, for example, the restoration of 5.2 million hectares of legally protected areas can not only increase forest cover from 28% to over 35%, as suggested by Ribeiro et al. (2009), but also reconnect isolated fragments, overcome critical thresholds of functional connectivity, and strengthen ecosystem resilience to global warming. In addition, MapBiomas (2023) data show that most of these areas are privately owned, highlighting the need for economic incentives and cooperative agreements between the public and private sectors.

Commitment to international goals such as the UN Decade of Restoration (2021–2030) and Goal 2 of the Kunming-Montreal Global Biodiversity Framework, which aims to restore at least 30% of degraded ecosystems by 2030, can help position Brazil as a global leader in nature-based solutions. Passive restoration strategies, combined with nucleation and adaptive models, have proven successful in regenerating biodiversity and restoring ecosystem services, even in anthropogenic landscapes (Brancalion et al., 2019).

For an active restoration process, a restoration-oriented supply chain is crucial to ensure the quantity and diversity of seeds and seedlings needed. This chain is characterized by three main links: (a) seed collection and processing, (b) seedling production and marketing, and (c) restoration services and monitoring. An expansion of restoration therefore requires an expansion of production, marketing, and service provision, which would also lead to more opportunities and income for the local population (Jacovak et al., 2024).

Expand and Redesign the Protected Areas Network

According to Malecha et al.(2023), a significant proportion of the species currently protected in Brazil could lose their ideal climatic conditions by the end of the century. This means that, without spatial adaptations, protected areas could become "obsolete ecological islands", unable to keep pace with the shifts in biodiversity caused by environmental change. It is therefore crucial that new climatic refugia are taken into account when expanding the network, especially in less protected biomes such as the Pampa and Caatinga, which make up less than 1% of fully protected areas.

In addition to the creation of new units, it is necessary to reconfigure the network and promote its functionality, : a) the formation of ecological-climatic corridors that ensure genetic and adaptive mobility; b) the integration of public and private lands, including RPPNs, indigenous lands, traditionally used areas and OMECs (other effective spatial mechanisms); c) the conversion of undesignated public lands— - approx. 600.000 km^2

currently at risk from land grabbing and illegal deforestation (Vieira & Silva, 2024) — into protected areas or indigenous lands; d) the use of systematic conservation planning to guide land allocation decisions. The redesign of the UC network should not be done in isolation, but in conjunction with ecological restoration strategies, regularization of land tenure , and adaptive landscape management.

Finally, most PAs still lack management plans, a deficiency that needs to be urgently addressed by incorporating long-term climate change adaptation perspectives into these plans. The inclusion of participatory governance tools, such as strengthened management councils and territorial conservation pacts, is also crucial to ensure legitimacy and long-term effectiveness.

Mantain and expand ecological connectivity

Landscape fragmentation and the isolation of natural habitats are among the most important risk factors for biodiversity in climate change scenarios. Disconnected ecosystems impair gene flow, impede species dispersal in response to climate change, and reduce ecological resilience, especially in the face of extreme events and changing climate regimes. Therefore, the maintenance and expansion of ecological connectivity should be considered as a structuring axis of Brazilian spatial planning (Encalada et al., 2024).

The study by Ribeiro et al. (2009) shows that the creation of ecological corridors, agroforestry mosaics, and management of the landscape matrix are fundamental strategies to allow the movement of species in altitudinal and latitudinal ranges when their distribution areas shift due to climate change. The functional integration of forest fragments, wetlands, and savannas is particularly urgent in highly degraded biomes such as the Atlantic Forest, the Cerrado, and the Pantanal.

It is important that ecological planning is integrated into the processes that: I) urban expansion, II) the construction of transportation and energy infrastructures, III) ecological-economic zoning, IV) land regulation and rural planning, and V) the efficient use of already deforested areas, the reduction of low productivity pastures and their transformation into diversified production systems.

The creation and strengthening of buffer zones, ecological corridors and conservation mosaics enables the integration of areas with different degrees of protection, and expands connectivity without compromising production. Initiatives such as the Ministry of Environment's Ecological Corridors project are promising, but still lack a national dimension and coordination with sectoral policies. In addition, the introduction of geospatial tools and connectivity models should be included in territorial governance, such as ecological cycles, landscape resistance analysis and the identification of functional bottlenecks.

Funding and Strengthening Science, Innovation and Participation

The transition to a new era of climate change mitigation requires a revolution in the role of science and technology, anchored in the generation of applied knowledge, high-resolution monitoring, and the integration of academic, traditional, and local knowledge. Above all, Brazil cannot rely on solutions developed in other countries, even if they are more scientifically advanced, because they were not developed for the specific needs of our biomes.

Given the complexity and speed of climatic and environmental changes, it is increasingly necessary to invest in dynamic observation, modeling, and adaptation systems that are supported by a broad social and territorial base. The platforms AdaptaBrasil (https://sistema.adaptabrasil.mcti.gov.br) of the Ministry of Science, Technology, and Innovation and AdaptaClima (http://adaptaclima.mma.gov.br/plataforma) of the Ministry of Environment and Climate Change are good examples of this. Tools such as physiological and molecular bioindicators, spatial ecological modeling, big data, on biodiversity and multitemporal remote sensing are being consolidated as essential instruments for understanding and predicting climate impacts on Brazilian biodiversity.

At the same time, traditional ecological knowledge, collected from indigenous peoples, quilombola communities, and traditional populations, provides interpretive keys and resilient practices for biodiversity management in extreme contexts. Their rightful inclusion in public policies is crucial not only for epistemic justice, but also for territorial efficiency and socio-environmental adaptive capacity.

The role of the state is crucial in building institutional arrangements aimed at financing such solutions, not only through direct investment in research through ministries such as the Ministry of Science, Technology, and Innovation, but also through inductive instruments such as public procurement, subsidies, and tax incentives for companies that invest in research and development. Although Brazil already has a legal framework that enables these types of measures, their implementation remains limited, fragmented, and poorly coordinated across different levels of government (Rauen & Paiva, 2023; WEF, 2018).

Scientific governance of climate change mitigation must therefore be based on the following: I) public and decentralized scientific infrastructure, II) long-term funding for applied research, III) integration of ecological, climate, and social data networks, and IV) full involvement of local communities in the production and use of knowledge.

CONCLUSIONS

The moment is crucial: Brazil is in a unique position to lead a new global agenda, based on nature-based solutions, traditional knowledge, and technological innovation. Climate protection of Brazil's biomes is no longer just an environmental policy, but is becoming a national security policy — with direct implications for water, food, energy, and social security—, - and a national economic project, capable of creating value chains supported by products of the socio-biodiverse economy.

This chapter emphasizes that Brazil has proven scientific and technological capabilities for monitoring and conservation, as well as advanced legal frameworks for the implementation of economic instruments. The successful experience of the PPCDAm shows that coordinated public policies can quickly reverse degradation trends, while the traditional knowledge of indigenous peoples and local communities provides sustainable management strategies that can be integrated into national climate adaptation policies.

With their unique characteristics, all Brazilian biomes will be affected by climate change, albeit in different ways. In the most extreme scenarios, which are getting closer to our immediate reality every day, the impending collapse of biomes also impacts the human communities that depend on their ecosystem services, jeopardizing the well-being of the population.

Tackling the climate and environmental crisis requires overcoming structural challenges that fall into three categories: the fragmentation of scientific knowledge, which results in entire biomes being inadequately protected due to a lack of adequate data; the institutional disorganization that results in an artificial separation of the climate, biodiversity, and development agendas; and the limited implementation of economic instruments already provided for by law.

Despite the worrying outlook, there are solutions based on science and dialog with local and traditional knowledge that can be applied to find quick answers to the country's challenges. Therefore, rethinking Brazil's institutional arrangements to address the climate emergency becomes a priority, whether to mobilize resources to finance these solutions or to integrate existing information and knowledge that can benefit governance and public policy making. Brazil is experiencing a historical paradox: it is simultaneously one of the most biodiverse countries on the planet and one of the most threatened by the convergence of climate change and environmental degradation. "To do its homework," i.e. update its climate policies, expand protected areas, invest in restoration, and integrate science into public management, a national decision is needed to face the political and economic pressures that are leading to the loss of its ecosystems.

Despite the obstacles, the country has concrete ways to lead a new agenda based on transparency, climate justice, ecological sovereignty, and the dialogue of scientific and territorial knowledge. It is not just a technical challenge, but Brazil's ability to redefine its role in the world - not as a supplier of raw materials, but as an environmental and climate power.

BRAZILIAN BIOMES: CHARACTERISTICS AND CHALLENGES

The Amazon is a dense tropical forest, including terra firme forests, floodplains, and igapós, home to over 10% of the world's biodiversity. In addition to its rich biodiversity, the biome plays an important role in global climate regulation, storing up to 64 tons of carbon per hectare aboveground in intact forests (Longo et al., 2016). Furthermore, 10 to 23 billion liters of water evaporated from the Amazon vegetation is transported southward (Arraut et al., 2012), contributing to rainfall in other regions of Brazil, acting as a source of freshwater on a continental scale. Approximately 27 million people live in the Brazilian Legal Amazon (IBGE, 2023), of which approximately 250,000 are Indigenous. Land use includes plant and mineral extraction as traditional pillars of the regional economy, but in recent decades, the expansion of extensive livestock farming and commercial agriculture into deforested areas has become predominant, undermining the provision of forest ecosystem services (Qin et al., 2022). Indigenous, riverine, and quilombola communities depend on sustainable forest use for their subsistence.

BRAZILIAN BIOMES: CHARACTERISTICS AND CHALLENGES
The Cerrado is characterized by herbaceous vegetation, including grass and shrubs, interspersed with medium-sized trees, and plants adapted to fire and drought. The Brazilian Cerrado, classified as the most biodiverse savanna on the planet and one of two biodiversity hotspots in Brazil, is home to more than 12,000 plant species, of which approximately 40% are endemic (Myers et al., 2000). It is also Brazil's main water recharge region, feeding large river basins such as the São Francisco, Tocantins-Araguaia, Paraná-Paraguay, and Amazon rivers. However, the biome is facing unprecedented pressure: it is estimated that more than 50% of its native vegetation has already been lost, primarily due to agricultural expansion, particularly agribusiness focused on soybeans, corn, and extensive livestock farming (Strassburg et al., 2017). More than 20 million people live in Cerrado areas, many of them with income linked to the agricultural expansion front (IBGE, 2004).
The Atlantic Forest is a biome predominantly influenced by a humid tropical climate, thanks to its proximity to the Atlantic Ocean. The combination of rugged terrain and forest cover creates locally cooler environments with high rainfall. It encompasses various types of forest formations and associated ecosystems, such as mangroves, restingas, and high-altitude grasslands. Classified as a global biodiversity hotspot, it is home to approximately 20,000 species of vascular plants and over 2,000 species of vertebrates, with a high degree of endemism (Myers et al., 2000). The biome encompasses approximately 65% of the Brazilian population (Resende et al., 2024), encompassing a variety of land uses, from agricultural to urban-industrial, and also encompasses diverse traditional peoples and communities, such as Indigenous peoples (Guarani, Tupiniquim, Pataxó, among others), Quilombolas, Caiçaras, and riverine communities. The Atlantic Forest provides essential environmental services to millions of people, especially maintaining fertile soils, water conservation, agricultural pollination, and climate stabilization. However, it is a highly impacted and fragmented biome, with an estimated total native vegetation coverage of around 28% (MapBiomas, 2023) — only about half of which is mature forest — dispersed across small forest fragments on private properties and larger remnants in Conservation Units.

BRAZILIAN BIOMES: CHARACTERISTICS AND CHALLENGES
The Caatinga is characterized by a hot, dry, semiarid climate with sparse and irregular rainfall and high average annual temperatures. Due to the strong sunlight, vegetation evapotranspiration exceeds precipitation over the biome, making the region prone to desertification, especially in degraded areas. The predominant vegetation consists of shrubs, small trees with deep roots, various succulents, and annual herbs that take advantage of the short rainy season — all adapted to the rocky soil and low humidity. Although less lush than other biomes, the Caatinga is still one of the most biodiverse semiarid biomes in the world, with unique fauna and flora, with approximately 33% of the flora and 15% of the fauna being endemic, that is, exclusive to the Caatinga (Silva, Leal & Tabarelli, 2017). Its vegetation protects the soil from erosion and maintains fertility through nutrient cycling, even in semi-arid conditions. It also influences local rainfall patterns, preventing complete desertification. Approximately 30 million people live in the semi-arid region, including sertanejos (sertanejos), indigenous peoples (Pankararú, Xukuru, among others), and quilombola communities (IBGE, 2017). Much of its rural population faces vulnerable conditions and depends on extensive goat and sheep farming, as well as subsistence agriculture and extractive activities.
The Pantanal is a confluence of neighboring biomes, combining species from the Amazon, the Cerrado, and the Bolivian/Paraguayan Chaco. With hot, rainy summers and dry, mild winters, the biome is characterized by extensive seasonal flooding, with up to 80% of the Pantanal plain flooded during peak rainy seasons (Alho & Silva, 2012). In the permanently flooded areas, there is an abundance of aquatic plants, while near the rivers, there are dense gallery forests with large trees, and grasses and shrubs in the higher, non-flooded fields (Alho & Silva, 2012). These characteristics contribute to high aquatic and bird biodiversity, as well as mammals and reptiles, all adapted to the flood cycle (Junk, Bayley & Sparks, 1989). Its floodplains regulate the regional hydrological cycle, preventing flooding during high water periods and maintaining river flow during dry periods (Lázaro & Oliveira Jr., 2020). Furthermore, the Pantanal's aquatic vegetation promotes water purification, removing sediments and pollutants, and ensuring habitat and migratory routes for several species (de Groot, Brander & Max Finlayson, 2018). Approximately 3 million people live in areas defined as the Pantanal, many living in rural settlements, farms, and small traditional communities. The main economic activity in the biome is extensive cattle ranching. However, in recent years, there has been a critical reduction in water mass and a change in the biome's hydrology due to significant vegetation loss and an increase in fires (Mapbiomas, 2024).

BRAZILIAN BIOMES: CHARACTERISTICS AND CHALLENGES

The Pampas consist of native grasslands, primarily composed of grasses and other herbaceous plants, shaped by a climate with no dry season, hot summers, and cold winters. The climate favors the formation of perennial vegetation, but it is also highly vulnerable to extremes, such as droughts or very intense cold snaps (Zheng et al., 2024). Despite its homogeneous appearance, the Pampas present endemic species of plants, birds, and small animals, forming a reserve of genetic resources for species adapted to the temperate climate (Rolim & Overbeck, 2025). Occupying only 2% of the national territory, the biome is heavily used for agriculture, and in recent decades, extensive areas have been converted to crops (soybean, rice, wheat, and corn). This intense occupation makes the Pampas one of the least protected biomes in the country, with only 3% of the territory protected by parks, reserves, and environmental protection areas (APA) (Santos, 2023).

REFERENCES

Albagli, S., Rocha, L. 2021. Ciência cidadã no Brasil: um estudo exploratório. In M. M. Borges & E. S. Casado (Orgs.), Sob a lente da ciência aberta: olhares de Portugal, Espanha e Brasil (pp. 489–511). ISBN 978-989-26-2022-0.

Aldana-Mejía, J. A., *et al.* 2025. Bioactive metabolites of Brazilian red propolis: Cytotoxic, antiplasmodial, and antimicrobial properties. Fitoterapia, Volume 181, 106351. https://doi.org/10.1016/j.fitote.2024.106351

Alho, C. J. R., Silva, J. S. V. 2012. Effects of severe floods and droughts on wildlife of the Pantanal wetland (Brazil)—A review. Animals, 2(4), 591–610. https://doi.org/10.3390/ani2040591

Alves-Ferreira, G., Heming, N. M., Talora, D., Keitt, T. H., Solé, M., & Zamudio, K. R. 2025. Climate change is projected to shrink phylogenetic endemism of Neotropical frogs. Nature Communications, 16(1), 3713. https://doi.org/10.1038/s41467-025-59036-2

Arraut, J.M; Nobre, C.; Barbosa, H.M.J; Obregon, g.; Marengo, J. 2012. Aerial rivers and Lakes: Looking at Large-Scale Moisture Transport and Its relation to Amazonia and to Subtropical rainfall in South America. J. Climate, 25, 543–556.

Artaxo, P., 2020. As três emergências que nossa sociedade enfrenta: saúde, biodiversidade e mudanças climáticas. Estudos Avançados 34, 53-66. 10.1590/s0103-4014.2020.34100.005

Bergamin, R.S., Bastazini, V.A.G., Esquivel-Muelbert, A., Bordin, K.M., Klipel, J., Debastiani, V. J., Vibrans, A.C., Loyola, R., Müller, S.C. 2024. Elevational shifts in tree community composition in the Brazilian Atlantic Forest related to climate change. Journal of Vegetation Science 35, e13289. 10.1111/jvs.13289

Beuchle, R., Grecchi, R.C., Shimabukuro, Y.E., Seliger, R., Eva, H.D., Sano, E., Achard, F. 2015. Land cover changes in the Brazilian Cerrado and Caatinga biomes from 1990 to 2010 based on a systematic remote sensing sampling approach. Applied Geography 58, 116-127. https://doi.org/10.1016/j.apgeog.2015.01.017

Boit, A., Sakschewski, B., Boysen, L., Cano-Crespo, A., Clement, J., Garcia-Alaniz, N., Kok, K., Kolb, M., Langerwisch, F., Rammig, A., Sachse, R., vanEupen, M., vonBloh, W., Zemp, D.C., Thonicke, K. 2016. Large-scale impact of climate change vs. land-use change on future biome shifts in Latin America. Global Change Biology 22, 3689-3701. 10.1111/gcb.13355

Braga, A., Laurini, M. 2024. Spatial heterogeneity in climate change effects across Brazilian biomes. Scientific Reports 14, 16414. 10.1038/s41598-024-67244-x

Brancalion, P.H.S., Niamir, A., Broadbent, E., Crouzeilles, R., Barros, F.S.M., AlmeydaZambrano, A.M., Baccini, A., Aronson, J., Goetz, S., Reid, J.L., Strassburg, B.B.N., Wilson, S., Chazdon, R.L. 2019. Global restoration opportunities in tropicalrainforest landscapes. Science Advances 5, eaav3223. 10.1126/sciadv.aav3223

Braz-Mota, S., Val, A.L. 2024. Fish mortality in the Amazonian drought of 2023: the role of experimental biology in our response to climate change. J. Exp. Biol. 227, jeb247255. 10.1242/jeb.247255

Campos, D., Braz-Mota, S., Val, A.L., Almeida-Val, V.M.F. 2019. Predicting thermal sensitivity of three Amazon fishes exposed to climate change scenarios. Ecological Indicators 101, 533-540. 10.1016/j.ecolind.2019.01.051

Castellanos, E., Lemos, M.F., Astigarraga, L., Chacón, N. , Cuvi, N., Huggel, C., Miranda, L. Vale, M.M., Ometto, J.P. , Peri, P.L. , Postigo, J.C. , Ramajo, L. , Roco, L, Rusticucci, M., 2022. Central and South America. In: Pörtner, H.O., Roberts, D.C., Tignor, M., Poloczanska, E.S. , Mintenbeck, K., Alegría, A. , Craig, M. , Langsdorf, S. , Löschke, S. , Möller, V. , Okem, A., Rama B. (eds.). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1689–1816. 10.1017/9781009325844.014

Castro, M. P. 2023. Áreas protegidas do Cerrado: vulnerabilidade e adaptação às mudanças climáticas (Dissertação de mestrado, Universidade Federal de Viçosa). Universidade Federal de Viçosa.

Cavazos, T., Bettolli, M. L., Campbell, D., Sánchez Rodríguez, R. A., Mycoo, M., Arias, P. A., Rivera, J., Reboita, M. S., Gulizia, C., Hidalgo, H. G., Alfaro, E. J., Sörensson, A. A., Cerezo-Mota, R., Stephenson, T. S., Ley, D., & Mahon, R. 2024. Challenges for climate change adaptation in Latin America and the Caribbean region. Frontiers in Climate, 6. https://doi.org/10.3389/fclim.2024.1392033

Cerbu, G. A., Swallow, B., Thompson, D. Y. 2011. Locating REDD: A global survey and analysis of REDD readiness and demonstration activities. Environ. Sci. Pol, Volume 14, issue 2, pages 168-180. https://doi.org/10.1016/j.envsci.2010.09.007

Colman, C. B. *et al.* 2024. Modeling the Brazilian Cerrado land use change highlights potential tipping points. Scientific Reports, 14, Article 1304.

Cortinhas Ferreira Neto, L., Diniz, C.G., Maretto, R.V. *et al.* (2024). Uncontrolled Illegal Mining and Garimpo in the Brazilian Amazon. Nat Commun 15, 9847. https://doi.org/10.1038/s41467-024-54220-2

Crouzeilles, R., Vale, M.M., Cerqueira, R., Grelle, C.E.V. 2013.. Increasing strict protection through protected areas on Brazilian private lands. Environmental Conservation 40, 209-210. 10.1017/S0376892912000367

Dalzochio, T., Rodrigues, G. Z. P., Petry, I. E., & Silva, L. B. 2016. The use of biomarkers to assess the health of aquatic ecosystems in Brazil: a review. International Aquatic Research, 8, 283–298.

de Groot, D.; Brander, L.; Max Finlayson, C. 2018. Wetland ecosystem services. Wetl. B. I Struct. Funct. Manag. Methods, 13, 323–333.

Doblas, J., Reis, M. S., Belluzzo, A. P., Quadros, C. B., Moraes, D. R. V., Almeida, C. A., Maurano, L. E. P., Carvalho, A. F. A., Sant'Anna, S. J. S., & Shimabukuro, Y. E. (2022). DETER-R: An Operational Near-Real Time Tropical Forest Disturbance Warning System Based on Sentinel-1 Time Series Analysis. Remote Sensing, 14(15), 3658. https://doi.org/10.3390/rs14153658

Elith, J., Leathwick, J.R. 2009. Species Distribution Models: Ecological Explanation and Prediction Across Space and Time. Annual Revew of Ecology. Evolution and Systematics 40, 677-697. 10.1146/annurev.ecolsys.110308.120159

Embrapa. 2010, 24 de junho. Secador solar é tema de palestra para estudantes e produtores do setor madeireiro. Embrapa. Recuperado de https://www.embrapa.br/busca-de-noticias/-/noticia/18127207/secador-solar--e-tema-de-palestra-para-estudantes-e-produtores-do-setor-madeireiro.

Embrapa. 2023, 20 de março. Soja com genoma editado para tolerância à seca é aprovada pela CTNBio. Embrapa. Recuperado de https://www.embrapa.br/.../soja-com-genoma-editado-para-tolerancia-a-seca-e-aprovada-pela-ctnbio

Encalada, A.C., Val, A.L., Athayde, S., Espinoza, J.C., Macedo, M., Marmontel, M., Miranda, G., Piedade, M.T.F., Silva, T.M., Arieira, J. 2024. Conserving the Amazon's freshwater ecosystems' health and connectivity, Policy Brief. SDSN-UN, Washington, DC, 24.

Esquivel-Muelbert, A., Baker, T.R., Dexter, K.G., Lewis, S.L., Brienen, R.J.W., Feldpausch, T.R., Lloyd, J., Monteagudo-Mendoza, A., Arroyo, L., Álvarez-Dávila, E., Higuchi, N., Marimon, B.S., Marimon-Junior, B.H., Silveira, M., Vilanova, E., Gloor, E., Malhi, Y., Chave, J., Barlow, J., Bonal, D., Davila Cardozo, N., Erwin, T., Fauset, S., Hérault, B., Laurance, S., Poorter, L., Qie, L., Stahl, C., Sullivan, M.J.P., ter Steege, H., Vos, V.A., Zuidema, P.A., Almeida, E., Almeida de Oliveira, E., Andrade, A., Vieira, S.A., Aragão, L., Araujo-Murakami, A., Arets, E., Aymard C, G.A., Baraloto, C., Camargo, P.B., Barroso, J.G., Bongers, F., Boot, R., Camargo, J.L., Castro, W., Chama Moscoso, V., Comiskey, J., Cornejo Valverde, F., Lola da Costa, A.C., del Aguila Pasquel, J., Di Fiore, A., Fernanda Duque, L., Elias, F., Engel, J., Flores Llampazo, G., Galbraith, D., Herrera Fernández, R., Honorio Coronado, E., Hubau, W., Jimenez-Rojas, E., Lima, A.J.N., Umetsu, R.K., Laurance, W., Lopez-Gonzalez, G., Lovejoy, T., Aurelio Melo Cruz, O., Morandi, P.S., Neill, D., Núñez Vargas, P., Pallqui Camacho, N.C., Parada Gutierrez, A., Pardo, G., Peacock, J., Peña-Claros, M., Peñuela-Mora, M.C., Petronelli, P., Pickavance, G.C., Pitman, N., Prieto, A., Quesada, C., Ramírez-Angulo, H., Réjou-Méchain, M., Restrepo Correa, Z., Roopsind, A., Rudas, A., Salomão, R., Silva, N., Silva Espejo, J., Singh, J., Stropp, J., Terborgh, J., Thomas, R., Toledo, M., Torres-Lezama, A., Valenzuela Gamarra, L., van de Meer, P.J., van der Heijden, G., van der Hout, P., Vasquez Martinez, R., Vela, C., Vieira, I.C.G., Phillips, O.L. 2019. Compositional response of Amazon forests to climate change. Global Change Biology 25, 39-56. https://doi.org/10.1111/gcb.14413

Gatti, L.V., Basso, L.S., Miller, J.B., Gloor, M., Domingues, L.G., Cassol, H.L.G., Tejada, G., Aragão, L.E.O.C., Nobre, C., Peters, W., Marani, L., Arai, E., Sanches, A.H., Corrêa, S.M., Anderson, L., Von Randow, C., Correia, C.S.C., Crispim, S.P., Neves, R.A.L. 2021. Amazonia as a carbon source linked to deforestation and climate change. Nature 595, 388-393. https://doi.org/10.1038/s41586-021-03629-6

Freitas, A. 2025, 27 de julho. Em ano de COP, Congresso tem 44 projetos que mexem em políticas ambientais. UOL Notícias. Recuperado de https://noticias.uol.com.br/politica/ultimas-noticias/2025/07/27/em-ano-de-cop-congresso-tem-44-projetos-que-afrouxam-politicas-ambientais.htm

Giannini, T. C., Siqueira, M. F., Acosta, A. L., Barreto, F. C. C., Saraiva, A. M., & Alves-dos-Santos, I. 2012. Desafios atuais da modelagem preditiva de distribuição de espécies. Rodriguésia, 63(3), 651–655. https://doi.org/10.1590/S2175-78602012000300017

Guizar-Coutiño, A., Jones, J. P. G., Balmford, A., Carmenta, R., Coomes, D. A. 2022. A global evaluation of the effectiveness of voluntary REDD+ projects at reducing deforestation and degradation in the moist tropics. Conservation Biology, 36(6), Article e13970. https://doi.org/10.1111/cobi.13970

Halla, M. (Org.). 2020. Governança territorial indígena na América Latina. Forest Trends. Repositório ACERVA Digital da Socioambiental. Recuperado de https://acervo.socioambiental.org/sites/default/files/documents/c2l00003.pdf

Harris, M.B., Tomas, W., Mourão, G., Silva, C.J., Guimarães, E.T., Sonoda, F., Fachim, E. 2005. Safeguarding the Pantanal wetlands: Threats and conservation initiatives. Conservation Biology 19, 714-720.

Heinrichs-Caldas, W. *et al.* 2024. Environmental Nucleic Acids: A Toolkit for Monitoring Diversity, Conservation, and Environmental/Population Health. In: de Souza, S.S., Braz-Mota, S., Val, A.L. (eds) The Future of Amazonian Aquatic Biota. Springer, Cham. https://doi.org/10.1007/978-3-031-66822-7_13

Hirota, M., Holmgren, M., van Nes, E. H., & Scheffer, M. 2011. Global resilience of tropical forest and savanna to critical transitions. Science, 334(6053), 232–235. https://doi.org/10.1126/science.1210657

IBGE - Instituto Brasileiro de Geografia e Estatística. 2004. Mapa de Biomas do Brasil – Primeira aproximação. Disponível em < https://brasilemsintese.ibge.gov.br/territorio.html>.

IBGE - Instituto Brasileiro de Geografia e Estatística. 2017. População residente e características gerais — Censo Demográfico. Disponível em: https://censo.ibge.gov.br/

IBGE - Instituto Brasileiro de Geografia e Estatística. 2023. Censo demográfico 2022: resultados. IBGE. https://www.ibge.gov.br/censos/censo-demografico-2022

IPCC. 2021. Summary for Policymakers. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, in: V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, ..., B. Zhou (Eds.), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, 2391. 10.1017/9781009157896.

IPCC. 2022. Summary for Policymakers. In: Pörtner, H.O., Roberts, D.C., Tignor, M., Poloczanska, E.S. , Mintenbeck, K., Alegría, A. , Craig, M. , Langsdorf, S. , Löschke, S. , Möller, V. , Okem, A., Rama B. (eds.). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3-33. 10.1017/9781009325844.001.

Jakovac C.C., Nascimento, N., Gallegos, S.C., Celentano, D., Vieira D.L.M., Fernandes, C.C., Brienza Junior, S., & Pellicciotti, A.S. 2024. Strategies for implementing and scaling up forest restoration in the Amazon, Policy Brief. Science Panel for the Amazon, United Nations Sustainable Development Solutions Network, New York, USA. Available from https://www.theamazonwewant.org/spa-reports/. doi: 10.55161/donQ675.

Jenkins, C.N., Alves, M.A.S., Uezu. A., Vale, M.M. 2015. Patterns of Vertebrate Diversity and Protection in Brazil. PLoS ONE 10, e0145064. 10.1371/journal.pone.0145064

Jokura, T. 2023, junho. Novas ferramentas para rastrear produtos florestais. Revista Pesquisa FAPESP. Recuperado de https://revistapesquisa.fapesp.br/novas-ferramentas-para-rastrear-produtos-florestais/

Junk, W. J., Bayley, P. B., Sparks, R. E. 1989. The flood pulse concept in river–floodplain systems. In D. P. Dodge (Ed.), Proceedings of the International Large River Symposium. Canadian Special Publication of Fisheries and Aquatic Sciences, 106, 110–127.

Kill, J. 2020, 28 de agosto. REDD: The pitfalls of market-compliant forest conservation. Heinrich-Böll-Stiftung. Recuperado de https://www.boell.de/en/2020/08/28/redd-pitfalls-market-compliant-forest-conservation

Kintisch, E. 2007. Improved monitoring of rainforests helps pierce haze of deforestation. Science, 316(5824), pp.536-537.

Lázaro, W. L., Oliveira-Júnior, E. S. 2020. Climate change reflected in one of the largest wetlands in the world: an overview of the Northern Pantanal water regime. Acta Limnologica Brasiliensia, 32, e104. https://doi.org/10.1590/S2179-975X7619

Longo, M., Keller, M., dos-Santos, M. N., Leitold, V., Pinagé, E. R., Baccini, A., Morton, D. C., Frolking, S. 2016. Aboveground biomass variability across intact and degraded forests in the Brazilian Amazon. Global Biogeochemical Cycles, 30(11), 1639–1660. https://doi.org/10.1002/2016GB005465

Lovejoy, T.E., Nobre, C.A., 2018. Amazon Tipping Point. Science Advances 4, eaat2340. 10.1126/sciadv.aat2340

Lucas, K.R.G., Caldarelli, C.E., Ventura, M.U., 2023. Agriculture and biodiversity damage: A prospective evaluation of the impact of Brazilian agriculture on its ecoregions through life cycle assessment methodology. Science of the Total Environment 899, 165762. 10.1016/j.scitotenv.2023.165762

Malecha, A., Vale, M.M., Manes, S., 2023. Increasing Brazilian protected areas network is vital in a changing climate. Biological Conservation 288, 110360. 10.1016/j.biocon.2023.110360

Malecha, A., Mendes, C.B., Melo, Y., Manes, S., Vale.M.M. 2024. O Papel das Unidades de Conservação e do Reflorestamento na Redução do Risco de Enchentes na Cidade do Rio de Janeiro. In: Peixoto, S.L., Vale, M.M., Mesquita, C.A.B., Mendes, C.B. (Org.). A Floresta da Janela. Rio de Janeiro: Lumen Juris, p. 305-317. 0.17655/lumens.9788551932216.12

Malecha, A., Manes, S., Vale, M.M. 2025. Climate change and biodiversity in Brazil: What we know, what we don't, and Paris Agreement's risk reduction potential. Perspectives in Ecology and Conservation, XXX. 10.1016/j.pecon.2025.03.004

Malhi, Y., Franklin, J., Seddon, N., Solan, M., Turner, M.G., Field, C.B., Knowlton, N., 2020. Climate change and ecosystems: threats,opportunities and solutions.

Philosophical Transaction of the Royal Society B Biological Sciences B 375, 20190104. 10.1098/rstb.2019.0104

Manes, S., Costello, M.J., Beckett, H., Debnath, A., Devenish-Nelson, E., Grey, K.A., Jenkins, R., Khan, T.M., Kiessling, W., Krause. C., Maharaj., S.S., Midgley, G.F., Price, J., Talukdar, G. Vale, M.M. 2021. Endemism increases species' climate change risk in areas of global biodiversity importance. Biological Conservation 257, 109070. 10.1016/j.biocon.2021.109070

Manes, S., Vale, M.M. 2022. Achieving the Paris agreement would substantially reduce climate change risks to biodiversity in central and South America. Regional Environmental Change 22, 60. 10.1007/s10113-022-01904-4

Manes, S., Vale, M.M., Malecha, A., & Pires, A.P. 2022. Nature-based solutions promote climate change adaptation safeguarding ecosystem services. Ecosystem Service, 55, 101439. 10.1016/j.ecoser.2022.101439

Manes, S., Gama-Maia, D., Vaz, S., Pires, A. P., Tardin, R. H., Maricato, G., Bezerra, D.S., Vale, M. M. 2023. Nature as a solution for shoreline protection against coastal risks associated with ongoing sea-level rise. Ocean & Coastal Management 235, 106487. 10.1016/j.ocecoaman.2023.106487

MapBiomas. 2023. Coleções Anuais de Uso e Cobertura da Terra no Brasil. Projeto MapBiomas, https://mapbiomas.org.

MapBiomas. 2024, 12 de novembro. Redução de superfície de água no Pantanal favorece incêndios. MapBiomas. Recuperado de https://brasil.mapbiomas.org/2024/11/12/reducao-de-superficie-de-agua-no-pantanal-favorece-incendios/

MapBiomas. 2025. Desmatamento caiu em todos os biomas brasileiros em 2024. MapBiomas Brasil. Recuperado de https://brasil.mapbiomas.org/2025/05/15/mapbiomas-desmatamento-caiu-em-todos-os-biomas-brasileiros-em-2024/

Martins, G., Mendes, C.B., Malecha, A., Lyra, G.B., Dias, A.T.C., Vale, M.M. 2024. O Papel das Unidades de Conservação e do Reflorestamento na Atenuação das Ilhas de Calor na Cidade do Rio de Janeiro. In: Peixoto, S.L., Vale, M.M., Mesquita, C.A.B., Mendes, C.B. (Org.). A Floresta da Janela. Rio de Janeiro: Lumen Juris, p. 319-335. 10.17655/lumens.9788551932216.13

Marengo, J.A., Cunha, A.P., Cuartas, L.A., Leal, K.R.D., Broedel, E., Seluchi, M.E., Michelin, C.M., Baião, C.F.P., Angulo, E.C., Almeida, E.K., Kasmierczak, M.L., Mateus, N.P.A., Silva, R.C., Bender, F. 2021. Extreme Drought in the Brazilian Pantanal in 2019–2020: Characterization, Causes, and Impacts. Frontiers Water 3, 639204. 10.3389/frwa.2021.639204

Marengo, J.A., Jimenez, J.C., Espinoza, J.C., Cunha, A.P., Aragão, L.E.O.C. 2022. Increased climate pressure on the agricultural frontier in the Eastern Amazonia–Cerrado transition zone. Scientific Reports 12, 457. 10.1038/s41598-021-04241-4

Martinelli, L. A., Filoso, S. 2021. The Brazilian Cerrado is becoming hotter and drier. Regional Environmental Change, 21, 101.

Mataveli, G., Jones, M.W., Carmenta, R., Sanchez, A., Dutra, D.J., Chaves, M., Oliveira, G., Anderson, L.O., Aragão, L.E. 2024. Deforestation falls but rise of wildfires continues degrading Brazilian Amazon forests. Global change biology 30, e17202. 10.1111/gcb.17202

Milhorance, C., Sabourin, E., Chechi, L. 2018. Adaptação às mudanças climáticas e integração de políticas públicas no semiárido pernambucano. Artmix/Odisseia INCT, Brasília, DF, 39 pages.

Ministério da Economia (Brasil). 2024. Brazil's second nationally determined contribution (NDC): National determination to contribute and transform. UNFCCC. Recuperado de https://unfccc.int/sites/default/files/2024-11/Brazil_Second%20Nationally%20Determined%20Contribution%20%28NDC%29_November2024.pdf

Moura, M. R., do Nascimento, F. A. O., Paolucci, L. N., Silva, D. P., & Santos, B. A. 2023. Pervasive impacts of climate change on the woodiness and ecological generalism of dry forest plant assemblages. Journal of Ecology, 111(8), 1762–1776. https://doi.org/10.1111/1365-2745.14139

Muniz, A. C., Lemos-Filho, J. P. de, Lovato, M. B. 2024. Non-adaptedness and vulnerability to climate change threaten Plathymenia trees (Fabaceae) from the Cerrado and Atlantic Forest. Scientific Reports, 14, Article 25611. https://doi.org/10.1038/s41598-024-75664-y

Myers, N., Mittermeier, R.A., Mittermeier, C. G., Da Fonseca, G. A., Kent, J., 2000. Biodiversity hotspots for conservation priorities. Nature, 403, 853-858. 10.1038/35002501

NASA. 2025. Vital signs: Global temperature. NASA. Recuperado em 7 de agosto de 2025, de https://climate.nasa.gov/vital-signs/global-temperature/?intent=121

Nepstad, D. *et al.* 2014. Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. Science 344, 1118-112. DOI:10.1126/science.1248525

Nobre, C.A., Borma, L.D.S. 2009. 'Tipping points' for the Amazon forest. Current Opinion in Environmental Sustainability, 28-36. 10.1016/j.cosust.2009.07.003

Nobre, C., Sampaio, G., Borma, L., Castilla-Rubio, J., Silva, J., Cardoso, M. 2016. Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. Proceedings of the National Academy of Sciences 113, 10759-10768. https://doi.org/10.1073/pnas.1605516113

Observatório do Clima. 2025, 24 de julho. Análise técnica defende veto integral do PL 2159: “inconstitucional e incompatível com o interesse público”. Observatório do Clima. Recuperado de https://www.oc.eco.br/analise-tecnica-defende-veto-integral-do-pl-2159-inconstitucional-e-incompativel-com-o-interesse-publico/

Overbeck, G.E., Müller, S.C., Fidelis, A., Pfadenhauer, J., Pillar, V.D., Blanco, C.C., Boldrini, I.I., Both, R., Forneck, E.D. 2007. Brazil's neglected biome: The South Brazilian Campos. Perspectives in Plant Ecology, Evolution and Systematics 9, 101-116. https://doi.org/10.1016/j.ppees.2007.07.005

PBMC - Painel Brasileiro de Mudanças Climáticas. 2013. Base científica das mudanças climáticas: Contribuição do Grupo de Trabalho 1 ao Primeiro Relatório de Avaliação Nacional do Painel Brasileiro de Mudanças Climáticas – Sumário Executivo. Rio de Janeiro: PBMC. ISBN: 978-85-285-0208-4.

Pereira, R. D., Brazílio, L. de P., Trejo-Rangel, M. A., Santos, M. D., Silva, L. M. B., Souza, L. F., Barbosa, A. C. S., Oliveira, M. R., Santos, R., Sato, D. P., & Iwama, A. Y. (2023). Traditional and local communities as key actors to identify climate-related disaster impacts: A citizen science approach in Southeast Brazilian coastal areas. Frontiers in Climate, 5. https://doi.org/10.3389/fclim.2023.1243008

Pimentel, J.S., Bulhões, R.S., Rodrigues, P.C. 2024. Bayesian spatio-temporal modeling of the Brazilian fire spots between 2011 and 2022. Scientific Reports 14, 21616. 10.1038/s41598-024-70082-6

Pinho, P. F., Anjos, L. J. S., Rodrigues-Filho, S., Santos, D. V., & Toledo, P. M. 2020. Projections of Brazilian biomes resilience and socio-environmental risks to climate change. Sustainability in Debate, 11(3), 225–241. https://doi.org/10.18472/SustDeb.v11n3.2020.33918

Pivello, V.R. 2011. The Use of Fire in the Cerrado and Amazonian Rainforests of Brazil: Past and Present. Fire Ecology 7, 24-39. 10.4996/fireecology.0701024

Pörtner, H.O. 2010. Oxygen- and capacity-limitation of thermal tolerance: a matrix integrating climate-related stressor effects in marine ecosystems. J. exp. Biol. 213, 881-893. https://doi.org/10.1242/jeb.037523

Pouteau, R., Birnbaum, P. 2016. Island biodiversity hotspots are getting hotter: vulnerability and shifts in species richness in New Caledonia. Biological Conservation, 204, 322–332. https://doi.org/10.1016/j.biocon.2016.10.020

Prizibisczki, C. 2020, 30 de setembro. Brasil precisa comprar imagens privadas de satélite? Entenda a polêmica. ((o))eco.

Qin, Y., Xiao, X., & Fearnside, P. M. 2022. Carbon loss from forest degradation exceeds that from deforestation in the Brazilian Amazon. Nature Communications, 13, 5145. https://doi.org/10.1038/s41467-022-32169-0

Qin, Y., Xiao, X., Liu, F., de Sa e Silva, F., Shimabukuro, Y., Arai, E., & Fearnside, P. M. (2023). Forest conservation in Indigenous territories and protected areas in the Brazilian Amazon. Nature Sustainability, 6(3), 295–305. https://doi.org/10.1038/s41893-022-01018-z

Rauen, A. T. & Paiva, V. P. 2020. Buying to develop: The experience of Brazil and China in using public procurement to drive innovation. International Journal on Management of Innovation & Technology, 17, 2050021

Resende, A. F., *et al.* 2024. How to enhance Atlantic Forest protection? Dealing with restoration plantings that use a small, biased, and homogeneous set of tree species. Journal of Environmental Management, 372, 118732. https://doi.org/10.1016/j.jenvman.2024.118732

Rezende, C.L., Scarano, F.R., Assad, E.D., Joly, C.A., Metzger, J.P., Strassburg, B.B.N., Tabarelli, M., Fonseca, G.A., Mittermeier, R.A. 2018. From hotspot to hopespot: An opportunity for the Brazilian Atlantic Forest. Perspectives in Ecology and Conservation 16, 208-214. https://doi.org/10.1016/j.pecon.2018.10.002

Ribeiro, M.C., Metzger, J.P., Martensen, A.C., Ponzoni, F.J., Hirota, M.M. 2009. The Brazilian Atlantic Forest: How much is left, and how is the remaining forest distributed? Implications for conservation. Biological Conservation 142, 1141-1153. https://doi.org/10.1016/j.biocon.2009.02.021

Ribeiro, M.C., Martensen, A.C., Metzger, J.P., Tabarelli, M., Scarano, F., Fortin, M.-J. 2011. The Brazilian Atlantic Forest: A Shrinking Biodiversity Hotspot, in: F.E. Zachos, J.C. Habel (Eds.), Biodiversity Hotspots: Distribution and Protection of Conservation Priority Areas. Springer Berlin Heidelberg, Berlin, Heidelberg, 405-434. 10.1007/978-3-642-20992-5_21

Roberti, D. R., Mergen, A., Gotuzzo, R. A., Veeck, G. P., Bremm, T., Marin, L., de Quadros, F. L. F., & Jacques, R. J. S. 2024. Sustainability in natural grassland in the Brazilian Pampa biome: Livestock production with CO_2 absorption. Sustainability, 16(9), 3672. https://doi.org/10.3390/su16093672

Roesch, L.F.W., Vieira, F.C.B., Pereira, V.A., Schünemann, A.L., Teixeira, I.F., Senna, A.J.T., Stefenon, V.M. 2009. The Brazilian Pampa: A Fragile Biome. Diversity 1, 182-198. 10.3390/d1020182

Rolim, R. G., Müller, S. C., Overbeck, G. E. 2025, 9 de janeiro. Plantas características de campos conservados: um parâmetro para subsidiar a conservação do bioma Pampa. Bio Diverso, 4(1), artigo eletrônico 4e4, 1–20. Disponível em https://seer.ufrgs.br/index.php/biodiverso/article/view/140760.

Rorato, A. C., Escada, M. I. S., Camara, G., Picoli, M. C. A., Verstegen, J. A. 2022. Environmental vulnerability assessment of Brazilian Amazon Indigenous Lands. Environmental Science and Policy, 129, 19–36. https://doi.org/10.1016/j.envsci.2021.12.005

Santos, E.A., Fortini, R.M., Cardoso, L.C.B., Zanuncio, J.C. 2023. Climate change in Brazilian agriculture: vulnerability and adaptation assessment. International Journal of Environmental Science and Technology 20, s13762-13022-04730-13767. 10.1007/s13762-022-04730-7

Santos, J. V. 2023, 7 de dezembro. Patinho feio da conservação no Brasil, Pampa perde área equivalente a cinco cidades de Porto Alegre. Entrevista especial com Eduardo Vélez Martin. IHU — Instituto Humanitas Unisinos. Disponível em https://www.ihu.unisinos.br/categorias/159-entrevistas/634990-patinho-feio-da-conservacao-no-brasil-pampa-perde-area-equivalente-a-cinco-cidades-de-porto-alegre-entrevista-especial-com-eduardo-velez-martin

Silva, J. M. C., Leal, I. R., & Tabarelli, M. (Eds.). 2017. Caatinga: The largest tropical dry forest region in South America (1ª ed.). Springer Cham. https://doi.org/10.1007/978-3-319-68339-3

Silva Junior, C.H.L., Pessôa, A.C.M., Carvalho, N.S., Reis, J.B.C., Anderson, L.O., Aragão, L.E.O.C. 2021. The Brazilian Amazon deforestation rate in 2020 is the greatest of the decade. Nature Ecology & Evolution 5, 144-145. 10.1038/s41559-020-01368-x

Soterroni, A. C., Império, M., Scarabello, M. C., Seddon, N., Obersteiner, M., Rochedo, P. R. R., Schaeffer, R., Andrade, P. R., Ramos, F. M., Azevedo, T. R., Ometto, J. P. H. B., Havlík, P., & Alencar, A. A. C. 2023. Nature-based solutions are critical for putting Brazil on track towards net-zero emissions by 2050. Global Change Biology, 29(24), 7085–7101. https://doi.org/10.1111/gcb.16984

Souza, M.T.V., Sales-Shimomoto, V., Silva, G.S., Val, A.L. 2023. Microplastics and the Amazon: From the rivers to the estuary. Quimica Nova 46, 655-667. 10.21577/0100-4042.20230066

Souza, S. S., Braz-Mota, S., Val, A. L. 2025. Introduction. In The future of Amazonian aquatic biota, 590 pp., Cham, Switzerland, Springer.

Strassburg, B.B.N., Brooks, T., Feltran-Barbieri, R., Iribarrem, A., Crouzeilles, R., Loyola, R., Latawiec, A.E., Oliveira Filho, F.J.B., Scaramuzza, C.A.d.M., Scarano, F.R., Soares-Filho, B., Balmford, A., 2017. Moment of truth for the Cerrado hotspot. Nature Ecology & Evolution 1, 0099. 10.1038/s41559-017-0099

Strassburg, B.B.N., Iribarrem, A., Beyer, H.L., Cordeiro, C.L., Crouzeilles, R., Jakovac, C.C., Braga Junqueira, A., Lacerda, E., Latawiec, A.E., Balmford, A., Brooks, T.M., Butchart, S.H.M., Chazdon, R.L., Erb, K.-H., Brancalion, P., Buchanan, G., Cooper, D., Díaz, S., Donald, P.F., Kapos, V., Leclère, D., Miles, L., Obersteiner, M., Plutzar, C., de M. Scaramuzza, C.A., Scarano, F.R., Visconti, P., 2020. Global priority areas for ecosystem restoration. Nature 586, 724-729. 10.1038/s41586-020-2784-9

Swift, B. 2024, 14 de outubro. Why biodiversity credits cannot work (commentary). Mongabay. Recuperado de https://news.mongabay.com/2024/10/why-biodiversity-credits-cannot-work-commentary/

Urban, M.C. 2024. Climate change extinctions. Science 386, 1123-1128. 10.1126/science.adp4461

Vale, M.M., Souza, T.V., Alves, M.A.S., Crouzeilles, R. 2018. Planning protected areas network that are relevant today and under future climate change is possible: the case of Atlantic Forest endemic birds. PeerJ 6, e4689. 10.7717/peerj.4689

Vale, M.M., Vieira, M.V., Grelle, C.E.V., Manes, S., Pires, A.P., Tardin, R.H., Weber, M.M., Menezes, M.A., O'Connor, L., Thuiller, W., Tourinho, L. 2023. Ecosystem services delivered by Brazilian mammals: spatial and taxonomic patterns and comprehensive list of species. Perspectives in Ecology and Conservation 21, 302-310. 10.1016/j.pecon.2023.10.003

Vardon, M.J., Lindenmayer, D.B. 2023. Biodiversity market doublespeak. Science 382, 491-491. 10.1126/science.adg6823

Vieira, I. C. G. 2023. Desafios para o enfrentamento da crise ambiental da Amazônia: região é peça-chave no equilíbrio climático global e na conservação de parte relevante da biodiversidade mundial. Cienc. Cult. vol 75 no. 4. São Paulo Out./Dez. http://dx.doi.org/10.5935/2317-6660.20230046

Vieira, I. C. G., Silva, J. M. C. 2024. Zero deforestation and degradation in the Brazilian Amazon. Trends in Ecology & Evolution, 39(5), 413–416. https://doi.org/10.1016/j.tree.2024.03.004

Warren, R., Price, J., Graham, E., Forstenhaeusler, N., VanDerWal, J. 2018. The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5°C rather than 2°C. Science 360, 791-795. 10.1126/science.aar3646

Welch, J. R., & Coimbra Jr., C. E. A. 2021. Indigenous fire ecologies, restoration, and territorial sovereignty in the Brazilian Cerrado: The case of two Xavante reserves. Land Use Policy, 104, Article 104055. https://doi.org/10.1016/j.landusepol.2019.104055

Wolfe, J.D., Luther, D.A., Jirinec, V., Collings, J., Johnson, E.I., Bierregaard, R.O., Stouffer, P.C., 2025. Climate change aggravates bird mortality in pristine tropical forests. Science Advances 11, eadq8086. 10.1126/sciadv.adq8086

WEF - World Economic Forum. 2018. The Global Competitiveness Report 2017–2018: Brazil Competitiveness and Inclusive Growth Lab Report [Supplemento]. World Economic Forum.

Zheng, W,. Askari, K.; Song, C.; Shi, P.; Ge, W.; Shi, S.; Chu, J.; Chen, H.; Wang, F. 2024. Increasing vulnerability of vegetation to Meterological and Groundwater drought: A case study in Argentina. Journal of Hydrology: Regional Studies, Vol. 55, 101931. https://doi.org/10.1016/j.ejrh.2024.101931

4. FOREST DEGRADATION IN BRAZIL AND THE CLIMATE CRISIS

Liana O. Anderson[11], Luiz E.O.C. Aragão[11]

INTRODUCTION

The functioning of tropical forests is crucial for maintaining climate stability, regulating mass and energy flows, and preserving biodiversity, thereby contributing to the provision of critical ecosystem services essential for the national economy. These services include maintaining rainfall for large-scale and subsistence agriculture, as well as ensuring water and energy security. These services guarantee the resources necessary for human well-being and the protection of the Earth's diverse forms of life, and tropical forests can be considered a common and vital good for all humanity. According to data from the Brazilian Forest Service's National Forest Information System (SNIF, 2025), in 2022, 58.3% of Brazil's territory was covered by forests, with an estimated area of 495,834,867 ha, using 1990 as a reference. The largest expanse of our forests is found in the Amazon biome, with the most common phytophysiognomy being the Dense Ombrophilous Forest, representing 67.45% of the total forests, followed by the forest formations of the Cerrado, Caatinga, and Atlantic Forest, which cover, respectively,15.75%, 8.92% and 6% of the national territory. Of the total forests, only 1.9% are considered planted forests.

In addition to the direct benefits to society, tropical forests, especially those in Brazil, which account for about half of these forests globally, are essential components of the Earth system for mitigating and alleviat-

11 Instituto Nacional de Pesquisas Espaciais, INPE, São José dos Campos, Brasil
corresponding author: liana.anderson@inpe.br

ing the effects of climate change. The Brazilian Amazon, for example, is a significant carbon sink, storing approximately 0.30 (0.22 to 0.37) Pg C year−1 in its undisturbed Terra Firme forests (Aragão et al., 2018). This flux ensures a total storage of 150-200 Pg C in its biomass, equivalent to 15–20 years of global CO_2 emissions (Flores et al., 2024). However, due to deforestation and other anthropogenic disturbances that cause forest degradation, these forests also contribute significantly to CO_2 emissions into the atmosphere. According to data from the National Emissions Registry System (SIRENE, 2025), which is the official instrument of the Ministry of Science, Technology and Innovation (MCTI) for the disclosure of greenhouse gas emissions results in the country [access link], in 2022, it was estimated that total gross emissions of all greenhouse gases for all economic sectors in the country amounted to approximately 2,040 Tg CO2eq. Of this total, the land use change and forestry (LULCC) sector was responsible for almost 40% of emissions, standing out as the sector with the most considerable contribution. Considering CO_2 emissions separately, the contribution of the LULCC sector reaches almost 60% of national emissions.

Most analyses of changes in land use and land cover, however, focus solely on the causes and impacts of forest loss through deforestation, obscuring the significant impact of forest degradation. According to data from the MapBiomas project (Souza et al., 2020), in 1985, there were approximately 604 million hectares of forests in Brazil (71% of the country's land cover), of which 114 million hectares were converted to areas dedicated to agriculture and livestock by 2023. Despite the obvious pressure exerted by the deforestation process, which is defined by the total removal of native vegetation cover, anthropogenic disturbances represent a growing threat to the stability of natural ecosystems in Brazil, mainly in forested areas. This concern is based on the fact that anthropogenic disturbances cause forest degradation, resulting in significant losses of carbon stocks, biodiversity, and ecosystem services (Costa et al., 2023, Pessôa et al., 2023, Barbosa et al., 2022, Mataveli et al., 2021). Degradation can be defined, according to the methodology proposed by the Intergovernmental Panel on Climate Change (IPCC), as a direct, human-induced, long-term (persisting for X years or more) loss of at least Y% of forest carbon stocks (and other forest attributes) since time T and not qualifying as deforestation (Penman et al., 2003). Degradation caused by anthropogenic disturbances is therefore related to edge effects, illegal logging, and forest fires.

It is estimated that between 2001 and 2018, approximately 3.6 million hectares of the Amazon basin were affected by some form of degradation associated with human activity. Considering the area of forests affected by fires, timber extraction and edge effects, and the overlaps between these processes, Lapola et al. (2023) estimated that the area degraded due to these factors affected at least 364,748 km^2 (5.5% of all remaining Amazonian forests) between 2001 and 2018, equivalent to an area 12% larger than the total area deforested during the same period (325,975 km^2). Degradation directly and negatively impacts forest functions and services such as, but not limited to, carbon storage, biological productivity, species composition, forest structure, local and regional atmospheric humidity, and the uses and values of the forest for humans (Lapola et al., 2023).

The long-term impacts of forest degradation and its extent in Brazilian forests differ from those caused by deforestation, both in terms of changes in ecosystem functioning and in relation to the provision of livelihoods for local populations. The different vectors of degradation often occur simultaneously and repeatedly, considerably increasing their pressure on the conditions of forests and other native vegetation. Many of the effects of these disturbances also occur over longer time scales. For example, the continued mortality of trees after a fire or extreme drought means that forests can continue to emit more carbon for decades after the event (Silva et al., 2020). Thus, recent estimates suggest that the total carbon loss linked to forest degradation processes is comparable, if not greater, to the carbon loss caused by deforestation.

Furthermore, it is estimated that only 14% of degraded Amazonian forests were subsequently deforested over a 22-year period (Bullock et al., 2020), suggesting that these processes are partially independent. A pan-Amazonian estimate between 1995 and 2017 indicates that an area of 103 million ha (± 2.4 million ha) was impacted by human and natural disturbances, corresponding to 17% of the total forest area in 2017 (Bullock et al., 2020). In another study, between 2001 and 2018 (Lapola et al., 2023), the estimate of the total degraded area increases to 2,542,593 km^2, representing 38% of the remaining Amazon forests, considering timber extraction, edge effects, fire, and droughts, as well as all possible overlaps between these factors. This total degraded area includes 628,909 km^2 of forest where two or more of the four disturbances overlap.

The degradation of Brazilian forests, particularly those in the Amazon, undermines the ecological, climatic, social, economic, cultural, and spiritual values deeply rooted in traditional and indigenous communities (Camilotti et al., 2020; Whyte, 2020). Depending on the scale and intensity of the process, this degradation can undermine much of the socio-economic fabric that has evolved intertwined with the forest ecosystem over millennia (Pereira et al., 2023). The complexity and irreplaceability of these biocultural relationships underscore the urgent need for land allocation to these groups, in accordance with the rights related to territory and as provided for in the Brazilian Constitution, as this indirectly contributes to the conservation of these forests. Therefore, understanding, monitoring, and exploring alternative ways to prevent forest degradation are of unique importance in understanding not only the context of greenhouse gas emissions, but also the entire potential socio-bioeconomic value that this environmental asset offers the country.

The results of the studies presented in this chapter primarily represent research led by or with significant participation from Brazilian researchers. Due to the importance of the Amazon region and the availability of large-scale studies published on the topic of degradation in this region, many of the results presented here will focus on current established knowledge about the world's largest tropical forest, the Amazon. It is worth noting that Brazilian researchers, whether at institutions in Brazil or abroad, led more than 50% of the references cited. Among the other references, most of the studies have Brazilian authors participating. Approximately one-third of the studies were published in the journals Science and Nature, highlighting the exceptionally high quality of Brazilian science. The remaining works are primarily published in journals with a high impact factor. This assessment highlights the leading role of Brazilian science, as well as the importance of knowledge flow and the consolidation of international collaborations in advancing the understanding of relevant and complex issues of national and global interest.

In this chapter, we will address two types of pressures facing our forests: climatic and anthropogenic. First, we discuss the threats posed by extreme droughts and temperatures to the functioning of forests. Then, human stressors are explored, focusing on forest fragmentation, edge effect and forest fires. Finally, we explore ways to mitigate the emissions from deforestation and forest degradation, discussing the benefits of forest restoration and the critical needs of science and technology to support efficient public policies implementation

EXTREME DROUGHTS AND TEMPERATURES AS VECTORS OF DEGRADATION

Some of the main interannual climate processes that modulate drought events in the Amazon include sea surface temperature (SST) anomalies in the North and tropical Pacific and North and tropical Atlantic oceans (Aragão et al., 2018; Marengo, 2004). These oscillations are measured by climate indices, which are: South Atlantic Tropical Oscillation (TSA) index, ENSO multivariate index (MEI V2), Pacific Decadal Oscillation (PDO) index, and Atlantic Decadal Oscillation index. Studies suggest that extreme droughts have been intensified by human-induced climate change. For example, in the Amazon region, it is estimated that anthropogenic forcings altered the intensity of the 2015-2016 drought and increased the risk of this event by about four times, with a confidence interval ranging from 2.7 times to 4.7 times (Ribeiro et al., 2020). Since the beginning of the 21st century, four intense droughts (2005, 2010, 2015-2016, and 2023-24) were classified as ‘once in a hundred years’ events when they occurred. However, each of these was surpassed in magnitude by the following event (Barichivich et al., 2018; Papastefanou et al., 2022; Espinoza et al., 2024). Spatially, depending on the pattern of ocean warming, droughts affect different regions. For example, areas affected by reductions in precipitation due to positive ENSO events and warm phases of the PDO are predominantly located in the north and northeast of the Amazon, as well as on the western edge of the Amazon, encompassing Ecuador and Peru. Areas affected by abnormally high SSTs in the North Atlantic occur predominantly in the central-western Amazon, and those affected by abnormally high SSTs in the eastern tropical South Atlantic predominantly affect the southern Bolivian Amazon and northern Venezuelan Amazon (Marengo et al., 2011). Using the Integrated Drought Index (IDI) (Cunha et al., 2019), the years 2023 and 2024 rank first in terms of the extent of areas affected by drought, covering approximately 5 million km^2, which corresponds to about 59% of Brazil’s territory. In second place, the 2015-2016 drought affected approximately 4.6 million square kilometres (approximately 54% of the country). The 1997-1998 drought affected around 3.6 million km^2, equivalent to 42% of the national territory (CEMADEN, 2024).

The exposure and vulnerability of Brazilian forests to extreme droughts and temperatures have become increasingly evident. For example, droughts have affected Amazonian forests approximately every five years (Anderson et al., 2018). The first documented event of widespread tree mortality in terra firme forests resulting from a drought was recorded in 2005 (Phillips et al., 2009). This event caused persistent impacts on tree crowns, which lasted at least 4 to 5 years after the drought (Saatchi et al., 2013). Although there is no evidence of compound impacts between drought recurrences, based on field data, it was estimated that during the 2010 drought, terra firme forests did not gain biomass, there was an increase in tree mortality, and a decline in forest productivity. These impacts covered a significant fraction of the Amazon basin during the 2010 drought and were related to the intensity of the water deficit (Feuldspatch et al., 2016). However, the evaluation of satellite data on the photosynthetic capacity of the forest revealed that the impacts of droughts seem to exacerbate over time with the recurrence of events (Anderson et al., 2018). In this study, researchers observed a reduction in photosynthetic capacity, as evidenced by satellite data monitoring vegetation, affecting more than 400,000 km^2 of forests in the Brazilian Amazon. This reduction was accompanied by an increase in intensity and the ever-larger areas of forest affected in years of extreme drought.

A study assessing the impact of the 2015–2016 El Niño on South American tropical forests, focusing on the Amazon and Atlantic Forest, showed that all data collection sites experienced extreme temperatures and greater water deficits (WD) during the 2015-2016 El Niño census interval than in the pre-El Niño monitoring period (Bennett et al., 2023).WD serves as an indicator of water stress in forests, based on the logic that the forest enters stress when evapotranspiration exceeds rainfall, without considering the soil's water storage capacity and the physiological adaptations of plants (Aragão et al., 2007). The results of the study by Bennett et al. (2023) revealed that during the high temperatures and drought induced by the 2015-2016 El Niño phenomenon, the 123 monitored forest plots were unable to act as a significant carbon sink in biomass, contrasting with their long-term behavior before the El Niño event. The authors estimated that the net change in carbon was driven by a significant increase in losses due to tree mortality, from 1.96 to 2.41 Mg C ha^{-1} per year ($P = 0.02$). In comparison, there was no change in carbon gains from tree growth and recruitment of new trees (2.40 Mg C ha^{-1} per year before El Niño and 2.43 Mg C ha^{-1} per year during El Niño, $P = 0.7$) (Bennett et al., 2023).

The impacts of droughts on forests are clear, but how often have these droughts affected the Amazon rainforest? An analysis of historical data from 2003 to 2020 reveals that certain years have a significant impact on extensive forested areas, accounting for ≥20% of the region's total area, and are characterised by severe precipitation anomalies (annual precipitation below the long-term local average). These years (affected area) were as follows: 2015 (54%), 2010 (35%), 2020 (26%), 2003 (21%), and 2005 (20%). However, substantial reductions in precipitation do not necessarily lead to water deficits in forest soils, as precipitation in the Amazon region is usually well above the water demand of vegetation, which is approximately 100 mm per month (Aragão et al., 2007). Thus, the calculation of the maximum cumulative water deficit (MCWD, Aragão et al. 2007) is considered a more appropriate indicator for analysing the impact of droughts in forested areas. Evaluating this indicator as an alternative to precipitation anomalies reveals a slight change in the years and area affected in terms of the extent of MCWD anomalies, with the years (affected area) of 2015 (34%), 2010 (33%), 2016 (33%), 2005 (24%), and 2007 (21%) standing out. In addition, a recent analysis of the accumulated water deficit, derived from rainfall data (Lapola et al., 2023), showed that between 2001 and 2018, 2,740,647 km^2 of the forest area of the Pan-Amazon biome was affected by droughts, corresponding to 41.1% of the remaining Amazonian forest cover (6,673,908 km^2). Although the cumulative effects of droughts on forests are not yet fully understood, it is known that droughts induce increased mortality and decreased tree growth, potentially exacerbating this impact in areas affected multiple times. It is known that more than one-third of the area affected by extreme droughts was affected by two (26%) or more (10%) events over an 18-year period (Lapola et al., 2023).

Increasingly, more severe and complex impacts of Amazonian droughts are being observed. Recently, the 2023–24 drought was characterised by exceptionally sparse rainfall and seven heatwaves during the dry season (Espinoza et al., 2024). River levels reached record lows, and fires increased (Jiménez et al., 2024), resulting in a series of negative impacts on the entire Amazonian population and ecosystems. During 2023-2024, there was a reduction of more than 8% in the area of open water extent (OWE) in the central Amazon when compared to the average OWE for November and December. A reduction of 4,458 km^2 was observed for December 2023 compared to the average OWE for December, and a comparative analysis highlighted the transition from previously flooded areas to dry zones during the 2023 drought, highlighting a substantial difference of up to 80% in both percentage and area (Maciel et al., 2024). The total loss of surface water in 2023, compared to the same period in 2022, reached 3.3 million hectares, with the most affected locations being the state of Amazonas, with a loss of 1.96 million hectares (59.4%) of surface water, followed by Pará (841,000 hectares; 25.5%) and Roraima (333,000 hectares; 10.1%) (Souza Jr et al., 2024).

Variations in river levels have significant impacts on forests. Householder et al. (2024) demonstrated that one-sixth of the trees in the Amazon floodplains are ecologically specialised in floodplain habitats, highlighting the importance of these freshwater environments for biodiversity conservation. The availability of water in the soil, which determines plants' perception of water deficit or excess, is primarily controlled by local edaphic and hydrological conditions, the latter being significantly influenced by topography. Thus, trees exposed to the same macroclimate may be in direct contact with groundwater (as in lowlands and valleys, with more humid soils where there is a shallow water table - SWT) or far from this source (as on slopes and plateaus), suffering higher water deficits and being more dependent on precipitation (Esteban et al., 2020). Evidence from the central Amazon region suggests that species associated with shallow-water table forests were significantly less affected by periods of severe drought than those associated with forests in locations with deeper groundwater. Nevertheless, extreme periods of both drought and rainfall reduced diameter growth rates by between 11% and 42% and increased mortality by between 88% and 146%, respectively, indicating that both climate extremes can have adverse effects on the forest (Esteban et al., 2020). However, species associated with SWTs do not show a decrease in growth or an increase in mortality as drought becomes more severe, and could, at least based on limited evidence to date and theoretically, function in drought conditions as hydrological refuges, i.e., places in the landscape that sustain populations of a species while surrounding climatic conditions become unsuitable (Costa et al., 2023).

The multitude of results from long-term data, measured in the field through forest inventories or satellite imagery, leads us to two clear conclusions. First, drought events increase tree mortality and reduce the carbon absorption capacity of these forests. Similar impacts were recorded during droughts in other tropical forests in the country. Secondly, the frequency and intensity of these droughts are increasing, with global climate change contributing to this trend. Therefore, increasingly larger areas of forest will be exposed to repeated drought events with high temperatures, thereby increasing the risk of disruption to the provision of essential ecosystem services, including the loss of stability in carbon stocks, biodiversity, and the hydrological cycle. Furthermore, droughts can increase the vulnerability of forests to other degradation vectors, such as fire, and exacerbate the negative impacts of other events, such as fragmentation, as discussed in the following sections.

FOREST FRAGMENTATION AND EDGE EFFECTS

It is estimated that in the tropical belt of Latin America, between 2001 and 2018, approximately 11.72% (702,954 km^2) of existing forest cover since 2000 (702,954 km^2) was lost, at an average rate of 39,053±11,677 km^2 per year (Silva Júnior et al., 2022). Deforestation inevitably leads to habitat loss, altering the spatial distribution and size of remaining forests through forest fragmentation (Villard & Metzger, 2014). Analysing the forests of seven states in the Brazilian Amazon between 2001 and 2010, Numata and Cochrane (2012) estimated that the total number of fragments doubled in the period analysed, from 76,866 fragments in 2001 to 143,572 fragments in 2010, considering forest edges with a length of 1,000 m, quantifying an increase from 467,237 km^2 in 2001 to 543,393 km^2 in 2010. For 2014, an assessment covering the total forest area of the nine states in the Brazilian Amazon and defining edges with an estimated extension of 1,020 m, resulted in a total forest area of 3,177,238 km^2, of which 28.1% were classified into some fragmentation class. Of this total, 3.2% of the remaining forests fell into the category of isolated fragments, known as forest islands, which are relatively more isolated forests within the landscape and are susceptible to degradation (Vedovato et al., 2016). In comparative terms, adding up the types of forest fragmentation for the year 2014, in the order of 891,593 km^2 of forests and considering that the edge effects extend up to 1020 m within the forest, we have an affected area that is 17% larger than the total accumulated deforestation to date (Vedovato et al., 2016).

On the scale of the Amazon basin involving nine countries, Silva Júnior et al. (2020) estimated that forest edge areas, defined as 120 m wide towards the interior of the forest from a given land use, increased from 16,212 km^2 in 2001 to 176,555 km^2 in 2015, representing 65% of the total deforested area during this period. This figure provides an average estimate of 11,770 ± 3,546 km^2 of new forest edges formed annually in the Amazon. For the year 2009, in this region, a total of 77,038 fragments with an average area of 83.76 km^2 and 321,135 km^2 of total edge area (1,000 m wide) were estimated (Putz et al., 2014). Regarding the Atlantic Forest, in 2005, the same authors identified a total of 245,173 forest fragments with an average area of 0.63 km^2 and a total edge length of 73,476 km^2, considering a threshold of 1,000 m in width. An assessment of the age of forest edges in the Amazon basin revealed that in 2015, 23% of forest edges were between 1 and 3 years old, 21% between 4 and 6 years old, 19% between 7 and 9 years, 20% between 10 and 12 years, and 16% between 13 and 15 years, giving an average age of 7 ± 3 years (Silva Júnior et al., 2020). These results indicate that forest fragmentation in tropical America has had a significant impact on native forests. Depending on the history of deforestation frontiers, edges of different ages can be observed, which consequently lead to spatial and temporal variation in the impacts of this edge effect on forest structure, especially on biomass stocks (Silva Júnior et al., 2020).

The study of the edge effect on biomass has broadened our understanding of the negative impact of this process on forest carbon stocks, both in terms of increased tree mortality due to microclimate change and the increased incidence of fires at forest edges. Forest edges experience significant carbon losses, at least in the first 100 m towards their interior, over the course of their formation, induced by microclimatic changes in their interior, leading to increased tree mortality rates (Laurance et al., 2011; Magnago et al., 2015; Meza-Elizalde et al., 2021; Nunes et al., 2023). Hissa et al. (2018) reported a small contribution by this disturbance to total carbon losses in relation to deforestation, with an average of 1.88% and 3.7% for 100 and 300 metres of edges, respectively, during the period from 1985 to 2012, assessed over a 700 km stretch along the BR-163 highway between the states of Pará and Mato Grosso. In another study, Numata et al. (2010) estimated that the carbon loss due to the edge effect represented 3.6% of the total loss attributed to all carbon flows derived from deforestation between 1985 and 2008 in a region of the state of Rondônia. On the scale of the Brazilian Amazon, Numata et al. (2011) assessed the carbon released by forest edges between 2001 and 2010, representing 2.6–4.5% of carbon emissions related to deforestation, but its relative importance increased from 1.7–3.0% to 3.3–5.6% between periods of low and high deforestation rates, respectively. The authors had already warned of the growing increase in emissions due to the creation of new forest edges. However, Silva-Júnior et al. (2020) quantified that for forests in the Pan-Amazonian region, between 2001 and 2015, average carbon losses associated with the edge effect corresponded to one-third of the losses resulting from deforestation. This study demonstrated a total gross carbon loss due to the edge effect of approximately 947 Tg C (0.95 Pg C), with an average of 63 ± 8 Tg C per year. To compare the order of magnitude of these losses with those due to deforestation, a total gross loss of 2592 Tg C (2.59 Pg C) was estimated for the same period, with an average of 173 ± 46 Tg C per year. The temporal analysis of this contribution reveals a carbon loss at forest edges estimated at 25% in relation to the loss caused by deforestation in 2001, with an increase to 48% in 2015. It is important to note that above-ground forest carbon stocks decrease progressively at the edges of the Amazon Forest due to their age, with the most critical period being the first five years after the creation of the forest edge (Silva Júnior et al., 2022). Similarly, Laurance (1997) found a significant loss of biomass, ranging from 8% to 14%, in the first 100 metres of forest edges during the first 10 years after fragmentation, with the most pronounced loss occurring in the first four years.

At the initial stage of edge formation, mortality rates increase significantly among large trees, which are responsible for most of the carbon stored in the forest (Laurance et al., 2000; Brando et al., 2024). Subsequently, as the edges age, renewal rates, the number of woody lianas, and pioneer species increase as a result of the succession process (Laurance et al., 2011; Numata et al., 2017). After this process, the plant community established at the forest edge tends to adapt better to the new microclimatic conditions, reducing the loss of biomass due to tree mortality. Although the growth of new trees increases over time, renewal rates also increase (Esquivel-Muelbert et al., 2019) as a consequence of increased mortality, leading to a tendency for forest edges to remain in an alternative state of post-fragmentation equilibrium. This alternative state, which stabilises between 6 and 15 years after the edge is created, is characterised by forests with lower above-ground biomass (AGB) than adjacent central areas. This occurs because most Amazonian edges are constantly exposed to fires, which in the Brazilian Amazon can lead to a reduction in forest AGB of 24.8±6.9% after 31 years (Silva et al., 2018; Silva et al., 2020). Barni et al. (2025) assessed the impacts of forest edge effects between 2007 and 2023 in the municipality of Rorainópolis, located in the southern part of the state of Roraima, and quantified a biomass loss of 19 Mg C ha−1. The authors also assessed the loss of carbon in biomass in a location exposed to three degradation vectors, totalling a loss of 36.4% of carbon in the exposed biomass, weighted by the areas of occurrence and considering the percentages of loss of 22.15% due to fires, a value similar to that estimated by Silva et al. (2018) and Silva et al. (2020), and 8.20% due to selective logging and 8.75% due to the edge effect.

The impacts of this forest fragmentation process and the resulting edge effect extend far beyond the carbon stored in forest biomass. It is known that in fragmented landscapes, the area of the forest fragment is an important determinant of species persistence. It has been suggested that the conservation of forest bird diversity is negatively impacted by fragment size, with a minimum area of more than 10,000 ha being suggested for maintaining diversity in well-preserved forests (Lees et al., 2006; Morante-Filho et al., 2015). The impacts of forest disturbances extend to all biodiversity, including fauna and flora. A study focusing on the Atlantic Forest revealed that forest fragments may have 25-32% less biomass, 23-31% fewer species, and 33, 36, and 42% fewer individuals of endemic, large-seeded, and late-successional species, respectively (Lima et al., 2020).

These results indicate that, despite a decrease in deforestation rates, new forest edges are still being created. These will contribute significantly to the increase in national greenhouse gas emissions. In addition, the observed effect on the biodiversity of fauna and flora jeopardises bioeconomic assets and critical ecosystem functions, such as pollination processes. Ending illegal deforestation and reducing the expansion of forest edges are essential for the success of efforts to reduce emissions from deforestation and forest degradation in Brazil, as well as for compliance with international agreements aimed at mitigating the climate crisis.

FOREST FIRES

The severity, extent, and recurrence of forest fires are increasing worldwide. In Brazil, in particular, this increase is due to human activities related to land use change, deforestation and forest degradation, with people being the main cause of ignitions and their impacts amplified by climate change, with increased frequency and intensity of droughts and temperature extremes (Lapola et al., 2023, Jones et al., 2024, Kelley et al., 2025).

In Brazil, there is an average record of 219,811 fire detections per year between 1998 and 2025 (INPE/Queimadas, 2025), reaching maximum and minimum values in 2007 (393,915 detections) and 2000 (101,530 detections), respectively. Among the months with the highest numbers, a change in seasonal patterns has been observed throughout this century. Historical peaks in fire occurrences typically occur between June and December. The years between 2003 and 2007 exhibited the highest values in the entire historical series since 1998, coinciding with a period of high deforestation rates. Annually, between February and May, there is also a peak in the occurrence of fires, about 10 times lower than those observed between June and December. This peak is related to fire events detected above the equator during the dry season in this region. The maximum values recorded in the entire historical series for this region occurred in the last five years (INPE/Queimadas, 2025). Changes in the pattern of fires in the national territory, such as those reported above, have been observed throughout the country. For example, an assessment of the average monthly values for May throughout the historical series (1998-2025) revealed that, since 2020, that month has had more than 4,000 fire outbreaks, a threshold previously exceeded only between 2003 and 2007 and then again in 2010, with the historical record being set in 2022. There was also a 25% increase in the number of fire outbreaks for the average month of February over the last five years, compared to the historical average between 1999 and 2019. The increase in fire outbreak detections in the first months of the year did not occur at the expense of a decrease in occurrences in the most critical months. The average values for September and October, in relation to the long-term averages, were within a 10% variation, which is considered high. This increase in fires at the beginning of the year indicates an intensification of fire patterns associated with land use, deforestation, and recent droughts, particularly in the State of Roraima.

The impact of fire outbreaks is usually revealed by analysing data on burned areas. The burned area product produced by MapBiomas (Alencar et al., 2020) indicates the extent of the area affected by fire events. Based on this data, it is estimated that approximately 24% of the national territory has been affected by fire at least once in the last 40 years, with an average of 18.5 million hectares burned per year (MapBiomas fire, 2025). Between 1985 and 2024, it is estimated that 69.5% of the burned area occurred in regions occupied by native vegetation, with approximately 11% in forests. Therefore, these fires can be directly categorised as anthropogenic forest fires, as fires in this type of land cover are practically non-existent or rare in these ecosystems.

In the Amazon, forest fires are amplified in years of extreme drought and temperatures, and the extent of forests affected by fire has been increasing with each drought event. Silva Júnior et al. (2019) estimated a total of 41,378 km^2 of burned area during the 2010 Amazon drought, dominated by fires on productive land (68%; 28,161 km^2), with 12% (5,032 km^2) of fires occurring in forest areas. These figures represented a simultaneous increase in the burned area of 168% on productive land, 73% in non-forest vegetation, and 91% in forest cover compared to the average between 2006 and 2016. During the droughts of 2015 and 2016, burned areas of 20,049 km^2 and 16,994 km^2 were observed, respectively. Of this total, 55% (10,944 km^2) and 39% (6,568 km^2) of the burned area was recorded on productive land in these two years, respectively. However, the forest areas affected by fire represented 20% (3,993 km^2) and 31% (5,253 km^2) in 2015 and 2016, respectively, surpassing the percentages in all other years analysed. These figures represent a simultaneous 51% and 99% increase in burned forests in 2015 and 2016, respectively, compared to the average for the period.

The drought of 2023 and 2024, which affected approximately 59% of the national territory (CEMADEN 2024), brought new records for burned forests. A diagnosis provided by MapBiomas Fogo (Mapbiomas, 2025) revealed that, in 2024, 30 million hectares were affected by fire, representing a 62% increase over the annual average, considering estimates since 1985. The Amazon and Atlantic Forest biomes set historical records in these years, with increases of 117% and 261% in the affected areas, respectively. The Pantanal and Cerrado biomes also experienced a high incidence of fire: an increase of 157% and 10%, respectively, was observed. The situation was only mild in the Pampa and Caatinga biomes, with a 48% and 16% reduction in the area affected by fire, respectively (Mapbiomas, 2025). Still referring to MapBiomas data, in 2024, 72.7% of the burned area occurred in native vegetation, comprising 25.9% forest formations, 20.7% savanna formations, 13.9% floodplains, and 12.2% grassland formations. Forest formations were the land cover class most affected by fire, with 7.7 million hectares (Mha), 287% above the historical average.

The report on forest fires, covering the period from January 2023 to February 2024 (Jones et al., 2024), showed that this period was quite intense when evaluating different metrics associated with fires in Brazil. The states of Amapá and Amazonas had the largest and second-largest areas burned since 2002, respectively. The states of Roraima and Amazonas had the second- and third-worst years in terms of carbon emissions, respectively. The states of Amazonas, Roraima, and Amapá had the first, second, and third highest number of fires, with Amapá and Rondônia having the first and second highest fire spread rates in the entire historical series, respectively. A causal attribution analysis revealed that the anomalies in the area burned in the western Amazon during the 2023-2024 fire season were 50% higher than expected due to anthropogenic climate change. The new report on forest fires covering the period from March 2024 to February 2025 (Kelly et al., 2025) paints an even more critical picture. The states of Pará and Amazonas have had a historic record of burned areas since 2002. Mato Grosso do Sul had the second-largest area burned in the series, Rondônia had the third-largest, and Mato Grosso and São Paulo had the fourth-largest area burned in the historical series evaluated. In terms of C emissions from fires, Amazonas, São Paulo, and Mato Grosso do Sul had record values in the 2024-2025 period in relation to the entire data series analysed. Paraná had the second-worst year in terms of emissions, and Pará had the fourth-worst year. In terms of fire intensity, this period was the most extreme in the states of São Paulo, Mato Grosso do Sul, Paraná, Rio de Janeiro, and Roraima, and the second-worst year for the states of Amazonas and Goiás. All of these states were also among the five worst years in terms of the extent and spread rates of fire events. These metrics related to the occurrence of fire send a clear message: In the most recent periods of the historical series, it can be observed that fires are producing a larger burned area, with hotter fire events and faster spread in several states of the national territory, compared to the first 18 years of this century.

In the Brazilian Amazon, it was calculated that approximately one-third of active fire detections between 2003 and 2019 occurred within 1 km of areas deforested in the same year, and one-third of the areas deforested in a given year were located within 500 m of areas deforested in the previous year (Silveira et al., 2020). Furthermore, on the scale of the Amazon basin, 25% of forest fires occur within the first 120 metres of the forest in relation to the area of contact with other land uses, a region known as the forest edge, resulting in approximately 17% of forest edges being affected by fire (Lapola et al., 2023). According to this study, 69% of the burned forest area in the basin was affected by a single forest fire. These fires have a number of negative impacts, ranging from reduced biodiversity of fauna and flora and carbon stocks, altered forest functioning, increased emissions of air pollutants and greenhouse gases, to increased vulnerability of populations that depend on these forest resources for subsistence, economic, spiritual, or well-being purposes (Lapola et al., 2023). Quantifying the magnitude of the negative impacts of fires is somewhat complex, as fire severity measures, which are directly measured in the field, are restricted to specific locations and may not be representative of all forests, which vary in terms of carbon stocks, species diversity, climate, landscape structure, soils, and land uses.

Tree mortality in the understory after fires varies spatially: the highest levels of tree mortality and the greatest biomass losses were recorded in the Brazilian state of Pará (Cochrane et al., 1999; Barlow et al., 2023). Minor effects were recorded in drier Amazonian regions (Brando et al., 2020), where trees are protected by thicker bark (Staver et al., 2020) and in less seasonal regions, where fire intensity may be limited by high fuel moisture content (Pontes et al., 2021). For the southeastern Amazon region, it was found that the frequency and intensity of fires significantly increased mortality, particularly among small trees, but the impacts on forest structure and productivity were more subtle. For example, above-ground biomass decreased by about 13% in forests exposed to two fires in 2013 and 2016 (Maracahipes-Santos et al., 2025). It is also known that the time elapsed since the disturbance can be considered an important determinant of above-ground carbon stocks. When forests are burned, the recovery of carbon stocks from tree recruitment and growth is offset by high rates of ongoing tree mortality (Berenguer et al., 2021, Barlow et al., 2003), so that the burned forest can be a net source of carbon emissions for up to 7 years after the fire and contain about 25% less carbon after 30 years (Aragão et al., 2018, Silva et al., 2018). The negative impacts of fire are even more critical when fire occurs two or more times in the same location. This characteristic of fires is called recurrence and can be assessed quantitatively. For example, Barlow et al. (2008) demonstrated that areas with high recurrence can suffer losses of more than 80% of above-ground carbon (Barlow et al., 2008). It is estimated that in the Amazon, almost one-third of the burned area was burned twice (18%) or three or more times (13%) (Mapbiomas fogo, 2025). Fire has a direct effect on species richness and composition. The upper canopy cover is more affected over time after the fire than the forest understory. These structural changes also tend to influence the composition of bird species, which, even after a period of 38 years, has not shown a full recovery of the bird community (Valentim et al., 2025).

However, generalisations about the negative impacts of fire on the diversity of forest physiognomies and their habitats are limited. For example, Schöngart et al. (2024) specify that, in addition to the ombrophilous forests, where most fire impact studies are conducted, there are areas of floodplain forests in the Amazon basin. These are divided into two large groups: várzea, covering an area of approximately 456,000 km^2, and igapó, covering an area of 302,000 km^2. Among the igapó forests, there are two forest types: those exposed to black waters (~140,000 km^2) and those exposed to clear waters (162,000 km^2). Currently, the little that is known about the impacts of fires on floodplain vegetation is predominantly related to events that affected blackwater igapó forests, which represent about 15% of Amazonian floodplains. Most studies have focused on the central Amazon region. Flores et al. (2014) found that blackwater igapó forests are extremely sensitive to fire, with tree mortality reaching 91% (75-100%) and a relatively low recovery rate for this forest type. Resende et al. (2014) observed milder effects, yet they were still significant. The blackwater igapó forests affected by fire in this study exhibited a 59% (±13 %) loss of trees. For other Amazonian floodplain forests, there is a lack of scientific evidence on vulnerability to fire, but the magnitude of the impacts is expected to be similar to those reported so far.

Furthermore, few studies have been conducted on the impact of fire in the Campinaranas, which are plant formations that develop on white sand substrates in the Amazon and cover an area of approximately 87,500 km^2 in the region, with unique characteristics and peculiarities depending on their location. In the north of the state of Acre, where various species of campinaranas are traditionally used, it was quantified that the density of individuals with timber potential in the unburned area of the campinarana forest type was 70 ± 25 individuals ha−1, and with the impact of a forest fire, there was a 23% reduction in the density of these individuals. For species with non-timber potential, in areas where there were no fires, a density of 67 ± 58 individuals ha−1 was quantified, and a 93% reduction in the density of these individuals after the fire (Costa et al., 2023). These results indicate an exacerbated vulnerability of campinarnas to fires, given that large areas of this vegetation have no legal protection (Acre, 2017).

In general, among the various negative impacts of forest fires, carbon emissions into the atmosphere are considered the most critical in terms of contributing to the worsening climate crisis. Although there are still several limitations, the scientific knowledge framework allows for assessments of this impact to be made, especially in Terra Firme forests. With the reduction in deforestation, there has been a corresponding decrease in emissions resulting from deforestation. However, it has been shown that, even with the pattern of deforestation, during years of drought, the incidence of fires and their respective carbon emissions into the atmosphere tend to increase. In 2010, a dry year, gross C emissions due to fires were 1.7 times higher (0.51 ± 0.12 Pg C year-1) than during the subsequent year without drought. This corresponded to 57% of global emissions in 2010, resulting from land-use change (0.9 ± 0.7 Pg C) (Gatti et al., 2014; Gatti et al., 2023). It is estimated that forest fires in the Brazilian Amazon contribute to an average gross annual emission of 454 ± 496 Tg CO2 year-1 (2003-2015), or 31 ± 21% of the estimated emission from deforestation (Aragão et al., 2018). These studies suggest that the Amazon region is entering a new phase of land use and land cover change, in which a decoupling between carbon emissions related to fire and deforestation, driven by recurrent droughts in the 21st century, may jeopardise national achievements in reducing emissions from deforestation.

THE IMPORTANCE OF SECONDARY FORESTS FOR THE MITIGATION OF DEGRADATION IMPACTS

Despite ongoing forest loss in Brazil at varying rates, secondary forests are regrowing in areas where old-growth forests have been completely removed by human activities. Secondary forests are distinct from old-growth primary forests and differ greatly in terms of successional stage, species composition, structure, and functionality. These forests are essential for mitigating carbon emissions from deforestation and degradation, alleviating climate change impacts, and for restoring ecosystems' diversity and functions. Secondary forests are highly productive, with an average net carbon absorption rate, for neotropical regions in forests less than 20 years old, ranging from 2.95 ± 0.4 to 3.05 ± 0.5 Mg C ha-1 year-1, which are 11 to 20 times higher than old-growth primary forests (Heinrich et al., 2020). An analysis of 1,500 plots in South and Central America revealed that, in general, secondary tropical forests took an average of 66 years to reach 90% of the AGC of old-growth forests (Poorter et al., 2016).

The growth of these secondary forests across the fragmented and degraded landscapes can minimise biodiversity loss by allowing species to move along forest corridors, and thereby maintain genetic flow across the landscape. The species richness and compositional similarity of secondary forests reach, on average, 88% and 85%, respectively, of the values found in old-growth forests after 40 years (Lennox et al., 2018). In fragments of the Atlantic Forest, the growth of secondary forest recovered approximately 76% of taxonomic diversity, 84% of phylogenetic diversity, and 96% of functional diversity over a 30-year period following abandonment. In addition, the recovery of these forests, when compared to primary forests, allowed for the recovery of 65% and 30% of threatened and endemic species, respectively (Matos et al., 2020). Considering these benefits, natural regeneration management may be the most effective strategy for promoting large-scale forest restoration (Crouzelles et al., 2017, 2020). Between 1986 and 2018, an estimated total of 262,791 km^2 of secondary forests recovered in Brazil (Silva Júnior et al., 2020b). This area corresponds to 59% of the old-growth forest area deforested in the Brazilian Amazon between 1988 and 2019. The spatial distribution by biome of these regenerating forests occurs in greater proportion, approximately 57% (148,764 km^2) in the Amazon biome, followed by the Atlantic Forest, contributing 26.72% (70,218 km^2), Cerrado with 12.98% (34,115 km^2), the Caatinga with about 2.32% (6,106 km^2), the Pampa with 0.94% (2,469 km^2) and the Pantanal, contributing 0.43% (1,120 km^2). Based on 2018 data, it was estimated that the age distribution of secondary forests in the Caatinga and Atlantic Forest biomes showed younger secondary forests, with more than 50% of forests aged between 1 and 6 years, and older forests, with more than 50% of forests aged between 1 and 12 years, respectively. The age stratification of secondary forests for the Amazon for the year 2023 indicates that most of these forests are young, with about 50% under 11 years old and 90% under 29 years old (Silva Júnior et al., 2020b).

In the context of the climate emergency, where secondary forests are considered a nature-based solution, their most important characteristic is their potential to sequester carbon. Between 1986 and 2018, Silva Junior et al. (2020b) estimated that secondary forests were responsible for absorbing 835 Tg C during the 33 years analysed, or 25.30 Tg C year−1. While the Pantanal biome had the smallest contribution, accounting for 0.42% of Brazil's carbon absorption and storing 3 Tg C in its secondary forests between 1986 and 2018, the Amazon biome had the largest contribution, accounting for 52.21% of the absorption of Brazilian secondary forests. This estimate was based on a linear net carbon absorption rate of 3.05 ± 0.19 Mg C ha-1 year-1, which, despite being a methodological simplification, is based on an average value for neotropical secondary forests during the first 20 years of forest succession (Pooter et al., 2016; Fearnside et al., 1996; Heinrich et al., 2023). Based on this estimate by Silva-Júnior et al. (2020b) and considering the period between 1988 and 2018, the estimated absorption by secondary forests in Brazil (784 Tg C) offsets only 12% of carbon emissions from deforestation in the Brazilian Amazon alone (6,740 Tg C). It is worth noting that there is considerable spatial variability in the rates of growth and permanence of stored carbon between regions, due to differences in climate, soil, previous land use, and exposure to disturbances such as fires. Heinrich et al. (2021) demonstrated that, in general, secondary forests in the north-western Amazon regenerate up to twice as fast (3.0 ± 1.0 Mg C ha-1 year-1) compared to regions in the east of the basin (1.3 ± 0.3 Mg C ha-1 year-1). The impacts of disturbances such as fires and repeated deforestation before regrowth begins reduce the growth of these forests by 20% in the northwestern Amazon (2.4 ± 0.8 Mg C ha-1 year-1) compared to 55% in the southeast (0.8 ± 0.8 Mg C ha-1 year-1) of the basin. Focusing solely on 2017, the authors found that the total carbon stored in the secondary forests of the Amazon that year was 293.7 Tg C. If these forests had regenerated without any disturbance, they could have reached 319.7 Tg C in 2017. However, disturbances caused an 8% reduction in total potential amount of carbon that could be restored since 1985. Considering a scenario in which all secondary forests existing in 2017 had been preserved, it was estimated that by 2030, ~19.0 ± 2.4 Tg C year-1 could be removed from the atmosphere, a value that corresponds to approximately 5.5% of Brazil's net emission reduction target for 2030. Therefore, promoting the growth of secondary forest areas and ensuring their permanence is an efficient nature-based solution to mitigate climate change, contributing to the neutralisation of emissions from deforestation and degradation, and providing ecosystem services (Silva Júnior et al., 2020b; Matos et al., 2020; Heinrich et al., 2021; Baker et al., 2025).

The restoration and reforestation of 12 million hectares of secondary forests was one of the main mitigation strategies to reduce carbon emissions within Brazil's Nationally Determined Contribution (NDC) (MMA, 2016). This instrument needs to be accompanied by political and economic incentives, which are necessary to drive the transition from the current production model based on extensive environmental degradation and exploitation to an alternative model that promotes the emergence of new secondary forests, as well as, and above all, the conservation and maintenance of remaining forests. This challenge is unique to Brazil, as there are currently no economic development models from developed countries that have successfully developed in line with environmental integrity. However, with the knowledge currently available, both regarding the climate crisis and the importance of forests and their biodiversity for the country's economy and the global climate, a new path awaits us to be discovered and implemented. Increasing the area of natural regeneration at a large scale, on deforested areas, can efficiently revert, in part, the losses of carbon, biodiversity and ecosystem services due to the continuous deforestation and degradation of Brazilian native vegetation. These results reinforce the need to restore large areas of secondary forest across Brazilian biomes, however, restoration does not substitute the conservation of native vegetation.

SCIENCE AND TECHNOLOGY IN BRAZIL TO SUPPORT ACTIONS FOR REDUCING DEGRADATION

The scientific and technological basis for large-scale monitoring of environmental impacts has evolved since the 1970s, with the expansion of the activities of INPE's Remote Sensing Project (SERE). Brazil was the third country in the world to receive images from the Landsat-1 satellite, which enabled progress in training specialised human resources for scientific development and the construction of the environmental monitoring systems currently in operation. In the 1980s, the consolidation of experience in satellite data analysis, known as remote sensing, became evident when INPE launched the Fire Detection project, which utilised images from polar-orbiting satellites of the NOAA/Advanced Tiros-N series, and the Amazon Forest Cover Assessment project, using data from 1988 onwards. While the fire detection system openly provides various data on fires in Brazil and South America, the Legal Amazon Deforestation Project (PRODES), which uses images from Earth observation satellites, provides an annual inventory of clear-cutting in the forest, where trees are completely removed, consolidating deforestation. A significant advance in the systems occurred in 2004, when INPE launched the Near Real-Time Deforestation Detection System (DETER) to produce daily alerts of changes in forest cover. These not only indicate areas undergoing forest cover removal through clear-cutting, using the same concept of deforestation employed by PRODES, but also map areas undergoing degradation (logging, mining, burning, and other forms of degradation of the forest canopy). These alerts aim to assist enforcement agencies in planning actions during the process in question, thereby preventing environmental damage from becoming permanent and increasing the likelihood of holding those associated with such crimes accountable. The DETER system has evolved to a spatial resolution of 64m, compared to the previously used 250m, thanks to the successful operation of the CBERS-4 satellites in 2014, CBERS-4A in 2019, and Amazônia-1 in 2021, when INPE began to rely on images from the WFI sensor. All information generated by these platforms is available on the Terra Brasilis platform (access link) to the entire society, which has access to all data in ‘near real-time’. This information forms the Georeferenced Information Base (BIG), also led by INPE, which is advancing in the structuring of a unified base for the dissemination of satellite products through freely accessible platforms for society.

Satellites have been instrumental for decades in combating deforestation, forest degradation, and forest fires. In 2025, new satellites from international partners, such as the European Space Agency’s BIOMASS and NASA’s NISAR, were successfully launched and will add important information to the data already produced in Brazil, increasing the accuracy of quantifying the multiple negative impacts to which forests are exposed. Specifically, these will enable a detailed assessment of vegetation structure, as well as the quantification of disturbance vectors such as fire, selective cutting, and others. Advances are expected in the field of artificial intelligence, which will improve the accuracy of mapping and predictive modelling of the risk of deforestation and degradation by fire and selective logging in our ecosystems at different time scales. In addition, climate modelling through the development of Earth system models, specifically MONAN, led by INPE, will allow for more consistent projections, both temporally and spatially, which will not only improve assessments of how climate will amplify risks to Brazilian forests, but also serve as a starting point for mitigation and adaptation strategies in various sectors of society and the national economy.

The solution to the problem of forest degradation, especially that caused by fires, is not a matter exclusively for the development of national science and technology. It is clear that science and technology must be used in conjunction with effective public policies. This need is even more relevant in view of the upcoming 30th Conference of the Parties (COP), to be held in Brazil. At the last Conference of the Parties (COP29), Brazil presented its nationally determined contributions (NDC) for reducing greenhouse gas emissions. The progress in reducing deforestation (INPE-PRODES) to 6,000 km^2 per year is an achievement for the NDC target, as it contributes to almost 50% of national emissions (SEEG, 2024) (access link). This milestone exemplifies the integration of technology with a policy aimed at reducing deforestation, as outlined in the Plan for Prevention and Control of Deforestation (PPCDAm), which was re-established in 2023 by Decree No. 11,367/2023. However, the INPE/DETER programme (INPE-DETER) quantified an area of forest degraded by fire of 40,000 km^2 in 2024. Fire degradation increases emissions from deforestation by an average of 30% to 50% (Aragão et al., 2018), potentially compromising the achievement of NDC targets. Certainly, this situation can be reversed with technologies combined with urgent public policies, since the potential increase in the frequency and intensity of future droughts associated with climate change and continuous changes in land cover are likely to catalyse an increase in the incidence of forest fires if the management and accountability of the different aspects that contribute to their occurrence do not advance. This future climate-land cover arrangement, already observed during the last four major droughts, will increase the direct negative impacts on ecosystem services and, consequently, on water, food, and energy security, with direct effects on the national economy.

The sustainable management of forest degradation vectors in Brazil should be based on a solid scientific foundation to quantify and predict the magnitude, extent, and impacts of degradation, and propose solutions to the problem. The success of this action depends on the flow of information between science and society, such as supporting the implementation of the National Policy for Integrated Fire Management (Law 14944/2024), where the alignment of programs implemented by the government, private initiatives, society, and communities is fundamental to mitigating forest fires. The scientific information generated in the country should also support the effective application and monitoring of the National Policies on the Environment (Law 6938/1981), Climate Change (Law 12187/2009), Biodiversity (Decree 4339/2002), the National Policy on Environmental Education (Law 9795/1999) and Payment for Environmental Services (Law 14119/2021), in addition to ensuring the efficiency of actions to reduce greenhouse gas emissions, in the context of Brazil's nationally determined contributions (NDCs) and national sustainable development.

CONCLUSIONS

In this chapter, we present the primary climatic and anthropogenic causes of forest degradation, which threaten the integrity of Brazilian forests. We also explored data that demonstrate the country's technical and scientific capacity to support and lead mitigation and adaptation actions in the global fight against climate change. Investments in native vegetation conservation, through Reducing Emissions from Deforestation and Degradation (REDD+) and carbon credits initiatives, allied with initiatives to promote natural regeneration and forest restoration actions, within the context of payment for environmental services, are real opportunities to be implemented as climate change mitigation strategies. To this end, it is crucial to utilise cutting-edge science and technology to consolidate the scientific basis and the science-policy-society interface, as well as to support the processes involved in the environmental management of Brazilian biomes. This challenge is one of the most important today, with significant advances in public policy and science and technology, as the country has already demonstrated with its capabilities and actions in the past.

Preventing further deforestation remains a fundamental objective for stabilising the climate system, preserving biodiversity, and ensuring sustainable development. Deforestation is, in itself, one of the primary drivers of greenhouse gas emissions and biodiversity loss and a driver of various forms of degradation, considering that the integrity of the basin depends on maintaining forest cover. Preventing forest degradation will also benefit from the conditions required to curb deforestation, such as strengthening land tenure, providing environmentally oriented credit, and providing sustainable income and livelihood alternatives that can mitigate social inequalities. However, it is clear that actions taken to prevent deforestation are not sufficient to prevent forest degradation and must be supported by other interventions, such as large-scale investments and training for a shift to fire-free agricultural production, monitoring and accountability techniques to prevent illegal logging, and promoting and supporting bioeconomy markets as one of the alternatives for sustainable development. In addition, initiatives to curb degradation and stimulate restoration originating in the private sector should be encouraged by public policies, as demonstrated by efforts to prevent deforestation in the soybean production sector of the Amazon. All of these actions will benefit from improvements in monitoring and forecasting tropical forest degradation.

REFERENCES

Acre, Governo do Estado do Acre; Secretaria de Estado de Planejamento; Secretaria de Estado de Meio Ambiente; Programa Estadual de Zoneamento Ecológico-Econômico do Acre. Acre Zoneamento Ecológico-Econômico do Estado do Acre: Fase II (Escala 1:250000), 2nd ed.; Secretaria de Estado de Meio Ambiente: Rio Branco, Brazil, 2010; ISBN 978-85-60678-00-6.

Alencar, Ane, *et al*. "Mapping three decades of changes in the Brazilian savanna native vegetation using Landsat data processed in the google earth engine platform." Remote Sensing 12.6 (2020): 924.

Anderson, Liana Oighenstein, *et al*. "Vulnerability of Amazonian forests to repeated droughts." Philosophical Transactions of the Royal Society B: Biological Sciences 373.1760 (2018): 20170411.

Aragão, Luiz Eduardo OC, *et al*. "Spatial patterns and fire response of recent Amazonian droughts." Geophysical Research Letters 34.7 (2007).

Aragão, L. E. O. C., *et al*. "Above-and below-ground net primary productivity across ten Amazonian forests on contrasting soils." Biogeosciences 6.12 (2009): 2759-2778.

Barbosa, Maria Lucia F, *et al*. "Compound impact of land use and extreme climate on the 2020 fire record of the Brazilian Pantanal." Global Ecology and Biogeography 31.10 (2022): 1960-1975.

Barichivich, Jonathan, *et al*. "Recent intensification of Amazon flooding extremes driven by strengthened Walker circulation." Science advances 4.9 (2018): eaat8785.

Barlow, Jos, *et al*. "Large tree mortality and the decline of forest biomass following Amazonian wildfires." Ecology letters 6.1 (2003): 6-8.

Barlow, Jos, and Carlos A. Peres. “Fire-mediated dieback and compositional cascade in an Amazonian forest.” Philosophical Transactions of the Royal Society B: Biological Sciences 363.1498 (2008): 1787-1794.

Barni, Paulo Eduardo, *et al*. “Edge Effects in the Amazon Rainforest in Brazil’s Roraima State.” Forests 16.8 (2025): 1322.

Bennett, Amy C., *et al*. “Sensitivity of South American tropical forests to an extreme climate anomaly.” Nature Climate Change 13.9 (2023): 967-974.

Berenguer, Erika, *et al*. “A large-scale field assessment of carbon stocks in human-modified tropical forests.” Global change biology 20.12 (2014): 3713-3726.

Berenguer, Erika, *et al*. “Tracking the impacts of El Niño drought and fire in human-modified Amazonian forests.” Proceedings of the National Academy of Sciences 118.30 (2021): e2019377118.

Brando, Paulo M., *et al*. “Legacies of multiple disturbances on fruit and seed patterns in Amazonia: Implications for forest functional traits.” Ecosphere 15.2 (2024): e4780.

Brando, Paulo M., *et al*. “The gathering firestorm in southern Amazonia.” Science advances 6.2 (2020): eaay1632.

Bullock, Eric L., *et al*. “Satellite-based estimates reveal widespread forest degradation in the Amazon.” Global Change Biology 26.5 (2020): 2956-2969.

Camilotti, Vagner Luis, *et al*. “The importance of Forest extractive resources for income generation and subsistence among Caboclos and colonists in the Brazilian Amazon.” Human Ecology 48.1 (2020): 17-31.

CEMADEN, 2024. Nota Técnica. Nº 679/2024/SEI-CEMADEN. Disponível em: https://www.gov.br/cemaden/pt-br/assuntos/noticias-cemaden/cemaden-analisa-secas-recentes-no-brasil-e-apresenta-diagnostico-e-projecoes-como-subsidio-para-a-cop-16/NotaTcnicaHistricodeSecasnoBrasileProjecoes_2024_CEMADEN_202411.pdf

Cochrane, Mark A., *et al*. “Positive feedbacks in the fire dynamic of closed canopy tropical forests.” Science 284.5421 (1999): 1832-1835.

Costa, Jessica Gomes, *et al*. “Forest Degradation in the Southwest Brazilian Amazon: Impact on Tree Species of Economic Interest and Traditional Use.” Fire 6.6 (2023): 234.

Costa, Flavia RC, *et al*. “The other side of tropical forest drought: do shallow water table regions of Amazonia act as large-scale hydrological refugia from drought?.” New Phytologist 237.3 (2023): 714-733.

Cunha, Ana Paula MA, *et al*. “Extreme drought events over Brazil from 2011 to 2019.” Atmosphere 10.11 (2019): 642.

Crouzeilles, Renato, *et al*. “Ecological restoration success is higher for natural regeneration than for active restoration in tropical forests.” Science advances 3.11 (2017): e1701345.

Crouzeilles, Renato, *et al*. “Achieving cost-effective landscape-scale forest restoration through targeted natural regeneration.” Conservation letters 13.3 (2020): e12709.

Espinoza, Jhan-Carlo, *et al*. “The new record of drought and warmth in the Amazon in 2023 related to regional and global climatic features.” Scientific Reports 14.1 (2024): 8107.

Esteban, Erick JL, *et al*. “The other side of droughts: wet extremes and topography as buffers of negative drought effects in an Amazonian forest.” New Phytologist 229.4 (2021): 1995-2006.

Esquivel-Muelbert, Adriane, *et al*. “Compositional response of Amazon forests to climate change.” Global change biology 25.1 (2019): 39-56.

Fearnside, Philip M. “Amazonian deforestation and global warming: carbon stocks in vegetation replacing Brazil’s Amazon forest.” Forest ecology and management 80.1-3 (1996): 21-34.

Feldpausch, T. R., *et al*. “Amazon forest response to repeated droughts.” Global Biogeochemical Cycles 30.7 (2016): 964-982.

Flores, Bernardo M., Maria-Teresa F. Piedade, and Bruce W. Nelson. “Fire disturbance in Amazonian blackwater floodplain forests.” Plant Ecology & Diversity 7.1-2 (2014): 319-327.

Flores, Bernardo M., *et al*. “Critical transitions in the Amazon forest system.” Nature 626.7999 (2024): 555-564.

Gatti, L. V., *et al*. “Drought sensitivity of Amazonian carbon balance revealed by atmospheric measurements.” Nature 506.7486 (2014): 76-80.

Gatti, Luciana V., *et al*. “Increased Amazon carbon emissions mainly from decline in law enforcement.” Nature 621.7978 (2023): 318-323.

Guedes, Betina J., *et al*. “Vulnerability of small forest patches to fire in the Paraiba do Sul River Valley, southeast Brazil: Implications for restoration of the Atlantic Forest biome.” Forest Ecology and Management 465 (2020): 118095.

Heinrich, Viola HA, *et al*. “Large carbon sink potential of secondary forests in the Brazilian Amazon to mitigate climate change.” Nature communications 12.1 (2021): 1785.

Heinrich, Viola HA, *et al*. “The carbon sink of secondary and degraded humid tropical forests.” Nature 615.7952 (2023): 436-442.

Hissa, Letícia de Barros Viana, *et al*. "Historical carbon fluxes in the expanding deforestation frontier of Southern Brazilian Amazonia (1985–2012)." Regional Environmental Change 18.1 (2018): 77-89.

Householder, John Ethan, *et al*. "One sixth of Amazonian tree diversity is dependent on river floodplains." Nature ecology & evolution 8.5 (2024): 901-911.

INPE-Queimadas - INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS. Banco de Dados de queimadas. Disponível em: http://www.inpe.br/queimadas/bdqueimadas. Acesso em: 22 de julho. 2025

INPE-PRODES - INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS. – Monitoramento Anual da Supressão da Vegetação Nativa – Amazônia/Cerrado/Pantanal/Caatinga/Mata Atlântica/Pampa. Disponível em: <https://terrabrasilis.dpi.inpe.br/downloads/>. Acesso em: 2 de setembro. 2025

Jiménez, Juan Carlos, *et al*. "Vegetation Warming and Greenness Decline across Amazonia during the Extreme Drought of 2023." Remote Sensing 16.14 (2024): 2519.

Jones, Matthew W., *et al*. "State of wildfires 2023–2024." Earth System Science Data 16.8 (2024): 3601-3685.

Kelley, Douglas I., *et al*. "State of Wildfires 2024–25." Earth System Science Data Discussions 2025 (2025): 1-179.

Lapola, David M., *et al*. "The drivers and impacts of Amazon forest degradation." Science 379.6630 (2023): eabp8622.

Laurance, William F., *et al*. "Biomass collapse in Amazonian forest fragments." Science 278.5340 (1997): 1117-1118.

Laurance, William F., Heraldo L. Vasconcelos, and Thomas E. Lovejoy. "Forest loss and fragmentation in the Amazon: implications for wildlife conservation." Oryx 34.1 (2000): 39-45.

Laurance, William F., *et al*. "The fate of Amazonian forest fragments: a 32-year investigation." Biological conservation 144.1 (2011): 56-67.

Lees, Alexander C., and Carlos A. Peres. "Rapid avifaunal collapse along the Amazonian deforestation frontier." Biological conservation 133.2 (2006): 198-211.

Lennox, Gareth D., *et al*. "Second rate or a second chance? Assessing biomass and biodiversity recovery in regenerating Amazonian forests." Global Change Biology 24.12 (2018): 5680-5694.

Lima, Renato AF, *et al*. "The erosion of biodiversity and biomass in the Atlantic Forest biodiversity hotspot." Nature communications 11.1 (2020): 6347.

Maciel, Daniel A., *et al*. "Sentinel-1 data reveals unprecedented reduction of open water extent due to 2023-2024 drought in the central Amazon basin." Environmental Research Letters 19.12 (2024): 124034.

Magnago, Luiz Fernando Silva, *et al*. "Microclimatic conditions at forest edges have significant impacts on vegetation structure in large Atlantic forest fragments." Biodiversity and Conservation 24.9 (2015): 2305-2318.

Malhi, Yadvinder, *et al*. "The above-ground coarse wood productivity of 104 Neotropical forest plots." Global change biology 10.5 (2004): 563-591.

Ministério do Meio Ambiente (MMA). REDD+ and Brazil's Nationally Determined Contribution. http://redd.mma.gov.br/en/redd-and-brazil-s-ndc (2016).

MapBiomas Fogo, 2025, "40 anos de fogo nos biomas brasileirs: coleção 4 do Mapbiomas (1985 a 2024)", https://doi.org/10.58053/MapBiomas/8JLX1T, MapBiomas Data, V1

Maracahipes-Santos, Leonardo, *et al*. "Amazonian forest resilience inferred from fire-induced changes in carbon stocks and tree diversity." Environmental Research Letters (2025).

Marengo, José A. "Interdecadal variability and trends of rainfall across the Amazon basin." Theoretical and applied climatology 78.1 (2004): 79-96.

Marengo, Jose A., *et al*. "The drought of 2010 in the context of historical droughts in the Amazon region." Geophysical research letters 38.12 (2011).

Mercado, Lina M., *et al*. "Variations in Amazon forest productivity correlated with foliar nutrients and modelled rates of photosynthetic carbon supply." Philosophical Transactions of the Royal Society B: Biological Sciences 366.1582 (2011): 3316-3329.

Mataveli, Guilherme AV, *et al*. "Relationship between biomass burning emissions and deforestation in Amazonia over the last two decades." Forests 12.9 (2021): 1217.

Matos, Fabio AR, *et al*. "Secondary forest fragments offer important carbon and biodiversity cobenefits." Global Change Biology 26.2 (2020): 509-522.

Meza-Elizalde, María C., and Dolors Armenteras-Pascual. "Edge influence on the microclimate and vegetation of fragments of a north Amazonian forest." Forest Ecology and Management 498 (2021): 119546.

Morante-Filho, José Carlos, *et al*. "Birds in anthropogenic landscapes: the responses of ecological groups to forest loss in the Brazilian Atlantic Forest." PLoS One 10.6 (2015): e0128923.

Numata, Izaya, *et al*. "Biomass collapse and carbon emissions from forest fragmentation in the Brazilian Amazon." Journal of Geophysical Research: Biogeosciences 115.G3 (2010).

Numata, Izaya, and Mark A. Cochrane. "Forest fragmentation and its potential implications in the Brazilian Amazon between 2001 and 2010." Open Journal of

Forestry 2.4 (2012): 265-271.Pan, Yude, *et al*. “A large and persistent carbon sink in the world’s forests.” science 333.6045 (2011): 988-993.

Numata, Izaya, *et al*. “Fire and edge effects in a fragmented tropical forest landscape in the southwestern Amazon.” Forest Ecology and Management 401 (2017): 135-146.

Nunes, Matheus Henrique, *et al*. “Edge effects on tree architecture exacerbate biomass loss of fragmented Amazonian forests.” Nature communications 14.1 (2023): 8129.

Papastefanou, Phillip, *et al*. “Recent extreme drought events in the Amazon rainforest: Assessment of different precipitation and evapotranspiration datasets and drought indicators.” Biogeosciences 19.16 (2022): 3843-3861.

Penman, Jim, *et al*. “Definitions and methodological options to inventory emissions from direct human-induced degradation of forests and devegetation of other vegetation types.” Hayama Kanagawa: IPCC National Greenhouse Gas Inventories Programme-Technical Support Unit, available at http://www. ipcc-nggip. iges. or. jp (2003): 32.

Pereira, Cássio Alves, *et al*. “Restoring fire-degraded social forests via biocultural approaches: a key strategy to safeguard the Amazon legacy.” Restoration Ecology 31.8 (2023): e13976.

Pessôa, Ana Carolina M., *et al*. “Protected areas are effective on curbing fires in the Amazon.” Ecological Economics 214 (2023): 107983.

Phillips, Oliver L., *et al*. “Drought sensitivity of the Amazon rainforest.” Science 323.5919 (2009): 1344-1347.

Pontes-Lopes, Aline, *et al*. “Drought-driven wildfire impacts on structure and dynamics in a wet Central Amazonian forest.” Proceedings of the Royal Society B 288.1951 (2021): 20210094.

Poorter, Lourens, *et al*. “Biomass resilience of Neotropical secondary forests.” Nature 530.7589 (2016): 211-214.

Pütz, Sandro, *et al*. “Long-term carbon loss in fragmented Neotropical forests.” Nature communications 5.1 (2014): 5037.

Quesada, C. A., *et al*. “Variations in chemical and physical properties of Amazon forest soils in relation to their genesis.” Biogeosciences 7.5 (2010): 1515-1541.

Resende, Angélica F., *et al*. “Fire damage in seasonally flooded and upland forests of the Central Amazon.” Biotropica 46.6 (2014): 643-646.

Ribeiro, G. G., *et al*. “Attributing the 2015/2016 Amazon basin drought to anthropogenic influence.” Climate Resilience and Sustainability 1.1 (2022): e25.

Rosan, Thais M., *et al*. “Fragmentation-driven divergent trends in burned area in Amazonia and Cerrado.” Frontiers in Forests and Global Change 5 (2022): 801408.

Saatchi, Sassan, *et al*. “Persistent effects of a severe drought on Amazonian forest canopy.” Proceedings of the National Academy of Sciences 110.2 (2013): 565-570.

Schöngart, Jochen, *et al*. “Fate of floodplain forests in a changing Amazon.” The future of Amazonian aquatic biota. Cham: Springer Nature Switzerland, 2024. 163-222.

SEEG, 2024. Sistema de Estimativa de Emissões e Remoções de Gases de Efeito Estufa, Observatório do Clima, acessado em 2 DE SETEMBRO DE 2025 – seeg.eco.br

Silva, Camila VJ, *et al*. “Drought-induced Amazonian wildfires instigate a decadal-scale disruption of forest carbon dynamics.” Philosophical Transactions of the Royal Society B: Biological Sciences 373.1760 (2018): 20180043.

Silva, Camila VJ, *et al*. “Estimating the multi-decadal carbon deficit of burned Amazonian forests.” Environmental Research Letters 15.11 (2020): 114023.

Silva Junior, Celso HL, *et al*. “Deforestation-induced fragmentation increases forest fire occurrence in central Brazilian Amazonia.” Forests 9.6 (2018): 305.

Silva Junior, Celso HL, *et al*. “Fire responses to the 2010 and 2015/2016 Amazonian droughts.” Frontiers in Earth Science 7 (2019): 97.

Silva Junior, Celso HL, *et al*. “Persistent collapse of biomass in Amazonian forest edges following deforestation leads to unaccounted carbon losses.” Science Advances 6.40 (2020): eaaz8360.

Silva Junior, Celso HL, *et al*. “Benchmark maps of 33 years of secondary forest age for Brazil.” Scientific data 7.1 (2020b): 269.

Silva-Junior, Celso HL, *et al*. “Forest fragmentation and fires in the eastern Brazilian Amazon–Maranhão State, Brazil.” Fire 5.3 (2022): 77.

Silveira, Marcus VF, *et al*. “Drivers of fire anomalies in the Brazilian Amazon: lessons learned from the 2019 fire crisis.” Land 9.12 (2020): 516.

SNIF. Sistema Nacional de Informações Florestais do Serviço Florestal Brasileiro. Disponível em: https://www.gov.br/florestal/pt-br. Acesso em: 22 de julho. 2025

SIRENE. Sistema de Registro Nacional de Emissões. Disponível em: http://sirene.mctic.gov.br. Acesso em: 22 de julho. 2025

Souza Jr, Carlos M., *et al*. “Reconstructing three decades of land use and land cover changes in Brazilian biomes with landsat archive and earth engine.” Remote Sensing 12.17 (2020): 2735.

Souza, Carlos M., *et al*. "Amazon severe drought in 2023 triggered surface water loss." Environmental Research: Climate 3.4 (2024): 041002.

Staver, Ann Carla, *et al*. "Thinner bark increases sensitivity of wetter Amazonian tropical forests to fire." Ecology letters 23.1 (2020): 99-106.

Valentim, C., *et al*. "Fire Effects on Bird Communities From Seasonally Flooded Forests Along Amazonian Black Water Rivers of the Negro River Basin." Diversity and Distributions 31.5 (2025): e70035.

Vedovato, Laura Barbosa, *et al*. "The extent of 2014 forest fragmentation in the Brazilian Amazon." Regional environmental change 16.8 (2016): 2485-2490.

Villard, Marc-André, and Jean Paul Metzger. "Beyond the fragmentation debate: a conceptual model to predict when habitat configuration really matters." Journal of Applied Ecology 51.2 (2014): 309-318.

Whyte, Kyle. "Too late for indigenous climate justice: Ecological and relational tipping points." Wiley Interdisciplinary Reviews: Climate Change 11.1 (2020): e603.

Zhao, Maosheng, and Steven W. Running. "Drought-induced reduction in global terrestrial net primary production from 2000 through 2009." science 329.5994 (2010): 940-943.

5. THE CENTRAL ROLE OF WATER IN RESILIENCE AND ADAPTATION TO CLIMATE CHANGE

Suzana Maria Gico Lima Montenegro[12], Cristovão Vicente Scapulatempo Fernandes[13], Dirceu Silveira Reis Junior[14], Eduardo Mario Mendiondo[15], Eduardo Sávio Passos Rodrigues Martins[16], Francisco de Assis Souza Filho[17], Pedro Borges Chaffe[17], Rodrigo Cauduro Dias de Paiva[18], Rosa Maria Formiga Johnsson[19], Saulo Aires de Souza[20], Walter Collischonn[19]

INTRODUCTION

The hydrological cycle is the most active dynamic mechanism of ecosystems, playing an integrative role between the atmosphere, soil, subsoil, and surface waters. Therefore, the potential impacts of climate change carry social, economic, and environmental consequences. Water,

12 Agencia Pernanbucana de Água e Clima - APAC, Recife, PE.
13 Universidade Federal do Paraná - UFPR, Curitiba, PR.
14 Universidade de Brasília - UnB, Brasilia, DF.
15 Universidade de São Paulo - USP, São Carlos, SP.
16 Fundação Cearense de Meteorologia - FUNCEME, Fortaleza, CE.
17 Universidade Federal de Santa Catarina - UFSC, Florianópolis, SC.
18 Universidade Federal do Rio Grande do Sul - UFRGS, Porto Alegre, RS.
19 Universiddade Estadual do Rio de Janeiro, Rio de Janeiro, RJ
20 Agência Nacional de Água - ANA, Brasília, DF.
corresponding author: suzana.montenegro@apac.pe.gov.br

especially rivers, serves as a true thermometer of environmental quality, and the associated impacts reach a scale that requires a new vision of planning, actions, and interactions, especially with society. It is worth noting that, while climate science calls for mitigation of greenhouse gas emissions, water science is strategically focused on promoting adaptation strategies. While effective mitigation of climate change requires a global vision and agreement, adaptation depends on local knowledge of water management.

Furthermore, hydrological variability is distinct from climate variability, although the two are naturally linked. Ecosystems balance themselves in cycles, up to the limit of anthropogenic influence, introducing impacts that add a new component to the conditions of temporal and spatial variability that characterizes hydrological processes. These changes introduce uncertainties with marked effects on the stationarity, homogeneity, independence, and randomness of observational series, with implications for water resources planning and management. Thus, while climate informs us about possible changes in precipitation and evaporation, water resources management primarily requires an understanding of how water is stored and transported after it reaches the continent. This depends on local conditions (the natural characteristics of river basins) and also on changes made by society, such as land use and the construction of hydraulic structures.

In this context, the effects of climate change and the exacerbation of extreme events, combined with inappropriate land use, unplanned deforestation for agricultural expansion, insufficient of basic sanitation, unsustainable rural activities, and environmental degradation from inappropriate mining practices, among other factors, are leading to large-scale natural disasters, with significant social, economic, and environmental impacts, such as loss of life, destruction of infrastructure, and the disruption of economic activities. The effects of climate change are already being felt at a local level, particularly through the exacerbation of drought and flooding disasters.

Brazil has approximately 12% of the world's surface freshwater (ANA, 2022), but this availability is unevenly distributed. Approximately 80% of the average annual runoff occurs in the Amazon basin, which is home to less than 5% of the country's population (ANA, 2022; IBGE, 2023). In densely populated regions, such as the southeast, per capita availability is well below the national average. In semi-arid areas, the water balance tends to be negative, as natural recharge, limited by low rainfall and high evapotranspiration, often falls short of demand, especially in areas with intensive land use. This situation has led to a reduction in ecological flows, overexploitation of aquifers, and a deterioration in water quality.

Other important problems include pollution from diffuse and point sources, the degradation of springs and riparian forests, and the low efficiency of water use. Agriculture accounts for around 70% of water abstraction in the country (ANA, 2021). Approximately 45% of wastewater is not treated appropriately (SNIS, 2022), further exacerbating water pollution. Improper land use and removal of native vegetation impair infiltration, increase surface runoff, and reduce watershed resilience.

Extreme hydrological events have also increased in frequency and intensity. Among the most serious recent drought episodes, CEMADEN (2024) highlights the prolonged drought in the Northeast (2012–2017), the events in the Southeast (2014–2015, 2017–2018, 2023–2024), in the Pantanal (2020–2024), and in southern Brazil (2020–2023). Urban water crises, such as the Cantareira system in 2014–2015, have highlighted the vulnerability of the water supply in urban areas. The Amazon has experienced severe droughts in 2005, 2010, 2015–2016, and 2023–2024 (CEMADEN, 2024). In terms of floods, examples include the mega-disaster in the mountainous region of Rio de Janeiro (2011), the floods in Petrópolis (2022) and in the metropolitan region of Recife (2022), and the historic floods in Rio Grande do Sul in 2024, which affected hundreds of communities and highlighted the increasing severity of climate change-related disasters in Brazil.

This combination of climatic, environmental, and socio-economic stresses requires adaptive water management based on monitoring, integrated planning, and risk management (ANA, 2022; PBMC, 2022). The Brazilian water resources sector has extensive experience that goes beyond the technical and scientific field and also encompasses the complex interface between hydrological processes and legal and institutional aspects. Anchored in Law No. 9.433/1997, which established the National Water Resources Policy (PNRH), the country adopted the principles of decentralization, social participation, and integrated management. Over time, this framework fostered a multidisciplinary and interdisciplinary approach that combines knowledge, management and practice. This set of competencies makes Brazil a reference in water resources planning and management focused on adaptation, sustainable development, and resilience, entrusted with the task of providing decision support and consistent input for public policies with a concrete impact on society.

This chapter provides an overview of the impacts of climate change on hydrological dynamics in Brazil, linking scientific knowledge with practices and challenges for water resources management. It highlights the implications for public policy and explores adaptation and resilience strategies aimed at the country's water security.

WATER RESOURCES MANAGEMENT IN BRAZIL AND WATER SECURITY - CONTEXTUALIZATION

The management of water resources in Brazil began in a more systematic way with the Water Law, Law 9.433/1997, which established the National Policy on Water Resources (PNRH), with guidelines, objectives, and instruments for water management in Brazil. It also created the National Water Resources Managment System (SINGREH), which is the institutional framework for implementing the **policy.** The law aims to ensure the multiple, rational, and sustainable use of water, and to guarantee its availability for present and future generations. The PNRH guidelines provide a participatory managment framework, in which the authorities, water users, and society as a whole are involved in the decision-making process.

The Water Law establishes respect for multiple use as a basis and prioritizes water supply for people and watering animals in cases of water scarcity. Progress in water resources managment at the national level is monitored through the publication of the State of Water Resources Report, which every four years takes stock of the implementation of management instruments, the institutional progress of the system and the current situation of water resources in the country. During this period, since the political foundations were laid, significant progress has been made at federal and state level. Special regional mechanisms have been created to resolve potential conflicts over water use, such as the negotiated allocation of water in the Northeast. In addition to the challenges of consolidating policy and the management system, a global agenda has also emerged in recent years to address the issue of water and climate. The 2030 Agenda for Sustainable Development published by the United Nations in September 2015, which was developed in a participatory manner based on the experience gained since the publication of the report Our Common

Future (UN, 1991), consolidates the most advanced developments in the field of sustainability, and establishes 17 Sustainable Development Goals (SDGs) to be achieved by developed and developing countries. In this context, the last 25 years of research, progress and technological tools have highlighted the impact of climate change. On another front, among several proposed definitions (Vörösmarty et al, 2018; Singh, 2017; UN, 2015, Cook and Bakker, 2012), the concept of water security goes beyond the mere balance between water availability and water demand, and has as a common denominator the availability and access to an adequate quantity and quality of water for the population and economic activities, in addition to an acceptable level of risk due to extreme hydrometeorological impacts and environmental degradation (Moura et al., 2020; Arreguin-Cortes et al., 2019; Jepson et al., 2017; Lall et al., 2017).

The concept of 'water security' is defined by UNESCO, as "the ability of a population to secure access to adequate quantities of water of acceptable quality to maintain the health of people and ecosystems in a watershed, and to ensure effective protection of life and property from water-related hazards – floods, landslides, subsidence, and droughts" (UNESCO-IHP, 2012); thus, this concept, encompasses several dimensions related to water. Another definition was introduced by Scott et al. (2013), which includes the dimension of resilience: 'Water security is the sustainable availability of water in sufficient quantity and quality for resilient societies and ecosystems in the face of uncertain global change.' By including the dimension of resilience, the interactive and coupled society-environment dynamics can reverse a situation of water insecurity and adjust any interpretation of the non-dynamic nature of the definition.

Beek and Arriens (2014) affirm that water security can be understood as the main objective of integrated water resources management, which forms the basis for adaptation strategies to cope with climate change. However, these concepts are extremely complex in their practical application, as the multiple uses and demands for water challenge the responsiveness of governance systems (Ribeiro and Formiga-Johnsson, 2018).

In Brazil, water security is a major national challenge, as it has several dimensions related to economic, social, climatic and ecosystem aspects, as well as water infrastructure.

At the national level, it is important to highlight the role of the National Plan for Water Security (PNSH), which was launched in 2019, as a result of a partnership between ANA and the then Ministry of Regional Development (MDR). The PNSH is a unique initiative in the country, inspired by international concepts on water security and aims, among other things, to “ensure “integrated and coherent planning of water infrastructure of strategic nature and regional relevance, by 2035, to reduce the impact of droughts and floods” (ANA, 2018). 2019a). The PNSH has developed the Index for Water Security (ISH) with the aim of “presenting the different dimensions of water security, in a simple and clear way and incorporating the concept of risk into water use” (ANA, 2019a).

It is also necessary to consolidate the “scientific foundations of global environmental change, impacts, adaptation, vulnerability, mitigation, and technological innovation efforts in climate system models, geosensors, and natural disaster prevention systems.” The scientific legacy has addressed the issue of extremes and their impact on priority areas such as: (i) agriculture: related to food security; (ii) health: related to the vulnerability of the environment to the spread of climate-related diseases and climate extremes; (iii) urban development: related to climate extremes and natural disasters, the human dimensions and their impact on physical infrastructure: housing, highways, railroads, water and sewage systems, ports, public transportation, developing more resilient cities, and reducing the risk of natural disasters; (iv) alternative renewable energy sources: related to energy and water security; and (v) information and communication technology: related to more effective and comprehensive communication of the issue of global change to society and government, with the aim of defining environmental policies.

In this context, a deeper reflection on water security and adaptive management is emphasized — perceptible and powerful concepts that require an appropriate scientific approach. The need for reflection is understood, to contribute to the establishment of a collaborative innovation paradigm in Brazil, promoting closer relationships between universities and public and private companies, as well as interaction between the different components of the National Science, Technology, and Innovation System (SNCTI), within the framework of the PNRH (National Water Resources Policy) and the National Water Resources Management System (SINGREH). It guides the SNCTI in the search for solutions to major social, environmental, and economic challenges, and contributes to laying the foundations for the country’s sustainable development within the framework of adaptive management.

ADVANCES IN KNOWLEDGE OF THE IMPACT OF CLIMATE CHANGE ON WATER RESOURCES IN BRAZIL

Changes in the historical period

Changes in climate and land use, as well as increased water consumption, have influenced patterns of water availability worldwide. In the Southern Hemisphere, for example, these changes have led to a 20 % decrease in average water availability over the last 20 years (Blöschl & Chaffe, 2023). To understand how changes in atmospheric availability (precipitation and evaporation) translate into changes in the terrestrial part of the cycle (storage and flow), it is necessary to analyze consistent hydrological databases and physical characteristics of river basins (e.g., CAMELS-BR; Chagas et al., 2020), in addition to modeling studies at different scales that provide indications of changes in water resources (Borges & Chaffe, 2019). In Brazil, there has been a significant decline in river flows in 40% of the territory over the last four decades, associated with the decrease in rainfall and increased consumption for human activities (Figure 1; Chagas et al., 2022a).

Changes in river flows, however, are not always linked to changes in average atmospheric water availability. In some regions, both floods and droughts have increased significantly in 30% of the territory — twice as much as would normally be expected. This intensification of the terrestrial part of the cycle is not only due to the intensification of the precipitation regime, but also to changes in water storage and runoff mechanisms and their use for various human activities (Chagas et al., 2022a). Despite recent advances in the understanding of Brazilian hydrology, we still need to better attribute the main mechanisms of changes in floods and droughts and their impacts (Paiva et al., 2020).

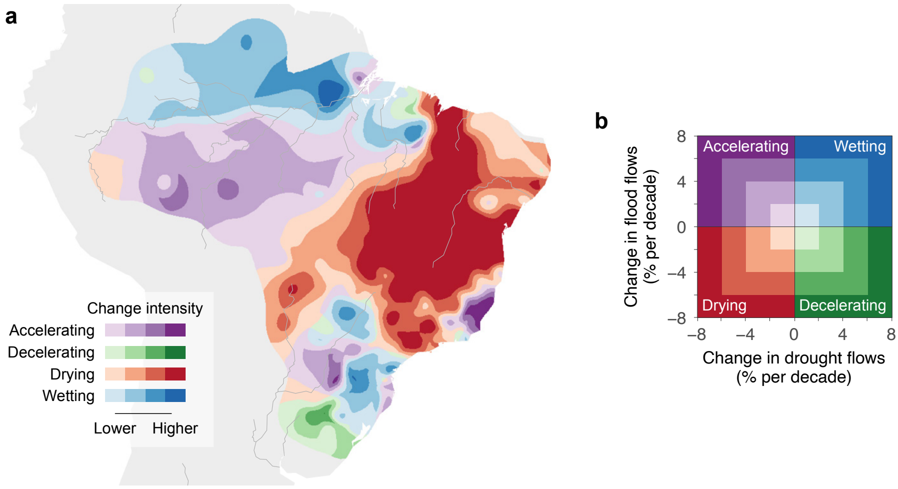


Figure 1: Four quadrants of streamflow change: accelerating, wetting, drying, decelerating. (Source: Chagas et al., 2022)

Projections of climate change impacts on water resources

Studies by the Intergovernmental Panel on Climate Change (IPCC) (Arias et al., 2021) show how anthropogenic climate change, caused by the emission of greenhouse gasses (GHG) is leading to a warming of the atmosphere and, as a consequence, to changes in precipitation patterns, water availability, and the frequency and magnitude of extreme hydrological events. Therefore, measures to improve water security, risk management, resilience to extreme hydrological events, and adaptation to climate change require the assessment of scenarios and projections of future hydrological conditions.

Climate change may lead to changes in water exchange between the atmosphere and river basins, e.g. in the total amount of precipitation and its seasonal distribution, in heavy rainfall, and potential evapotranspiration. However, the same change in these variables can have different effects on water availability, floods, and droughts, depending on hydrological processes occurring in the river basins. Therefore, it is necessary to develop regionalized projections of potential hydrological changes.

Numerous studies have been conducted to understand the impacts of climate change on Brazilian water resources (e.g., Brêda et al. 2020, Brêda et al. 2023, Sorribas et al. 2016, Borges de Amorim et al. 2020, Petry et al. 2025, Paiva et al. 2024, Miranda et al. 2025). Projections of change are generally developed on the basis of the results of global climate models (GCMs) from the Coupled Model Intercomparison Project (CMIP). Variables such as precipitation, temperature, solar radiation, air temperature, and humidity are evaluated. Possible scenarios for greenhouse gas emissions are also taken into account. These climate projections are used to drive hydrological models (e.g. *Modelo de Grandes Bacias* - MGB), which is able to computationally simulate the hydrological cycle over the basins and rivers. Finally, the projections of hydrological conditions for the coming decades up to the end of the century are compared with the historical period of recent decades.

According to current projections, precipitation will decrease in large parts of Brazil, including the Amazon, the Cerrado, and parts of the Northeast. Average precipitation is only expected to increase in the south. Due to rising air temperatures, potential evapotranspiration could increase in most parts of Brazil. As a result, water availability and mean river flow could decrease in most parts of Brazil, with changes of more than 50% in the Amazon region.

According to projections, an increase in short-term heavy rainfall (e.g., lasting one day) is expected over most of Brazil. This increase in heavy rainfall raises concerns about the intensification of flooding in small basins and urban areas.

Regarding flooding in medium- to large rivers, increases in maximum flows are projected in the southern region, including Rio Grande do Sul, Santa Catarina, Paraná, and parts of northeastern Brazil. Increases in maximum flows of more than 20% are possible. This could cause increases of approximately 3 meters in the maximum water level in rivers in mountainous regions (equivalent to one floor of a building) and 50 cm to 1 m in flat regions. The flooded area and affected population would be larger, and there could be larger destruction due to the flow of water with larger velocity and depth. This scenario also threatens the safety of water infrastructure such as reservoirs, dams, flood protection structures, drainage systems, roads, etc. Furthermore, extreme floods could become up to 5x more frequent. This means that, for example, an extreme event that currently occurs on average every 50 years could occur on average every 10 years in the future, increasing its negative impacts.

On the other hand, a reduction in flooding is expected in the major rivers of central Brazil and parts of the Amazon, caused by increased water loss through evapotranspiration and reduced soil moisture preceding the flood period. As a result, the extent and frequency of flooding in humid areas such as the Amazon and Pantanal could decrease, compromising the maintenance of important ecosystems.

Changes in droughts are expected in Brazil. Projections point to a lengthening and intensification of the dry season. In most regions of Brazil, an increase in the number of consecutive days without precipitation is expected, particularly in the Amazon, Northeast, and Central-West regions. Arid climate conditions are expected in these same regions.

Climate change is expected to impact low flows in rivers, which are responsible for maintaining water use and ecosystems during dry periods. Low flows are expected to decrease across most of Brazil, with changes reaching more than 50% in the southern Amazon and parts of the Northeast. Intermittency (completely dry rivers) may increase in the Northeast region. Furthermore, periods of water scarcity (up to two months) are expected to increase, during which available river flow is lower than that currently used as a reference for water management.

Groundwater

Groundwater is inherently more protected than surface water, and is more resilient to climate variability in general, and to climate change, as well as being better protected from pollution. However, once groundwater is degraded, both in terms of quantity and quality, it is more difficult to restore. A recent scientific article sheds light on these aspects (Schroeter et al. 2025). The study emphasizes that hydroclimatic extremes, can affect not only groundwater recharge, but also groundwater quality. Changes in recharge can affect the storage capacity of aquifers and the availability of groundwater. The potential decline in surface water availability in some regions due to climate change may also increase pressure on groundwater, which, under conditions of overexploitation and altered recharge conditions, will significantly affect usable reserves. Research conducted in Brazil highlights these issues, by considering projections of climate change scenarios for future time periods and the impact on natural groundwater recharge in different regions (Hirata et al., 2025).

In addition, aquifers in coastal regions may be affected by sea level rise, combined with overexploitation and reduced natural recharge, making them more susceptible to saltwater intrusion, as saltwater mixes with freshwater, and changes groundwater quality standards.

In addition, studies warn that due to climatic conditions and intensive agricultural activities, Brazilian rivers are at risk of carrying less water as water flows into aquifers (Uchôa et al., 2024. The study highlights the São Francisco River basin and the MATOPIBA region, which includes the states of Maranhão, Tocantins, Piauí, and Bahia, as particularly critical areas, both of which are highly dependent on groundwater for irrigation and human consumption.

NATIONAL CLIMATE PLANNING AND WATER RESOURCES

The report “Application of the Water Resilience Tracker Tool for National Climate Planning” (CEPAS et al, 2024), prepared by ANA in collaboration with AGWA, IDB and CEPAS/UFC, represents a pioneering initiative in the Brazilian context to assess in a structured way how water resilience has been integrated into the main climate and sectoral planning tools. Using an innovative content analysis method supported by artificial intelligence, eight strategic documents were analyzed: Brazil’s Nationally Determined Contribution (NDC) (the country submitted its first NDC in 2016 and updated it in 2023; both are analyzed in the report), the National Adaptation Plan (PNA) (BRAZIL/MMA, 2016), the National Water Resources Plan (PNRH) (BRAZIL/MIDR, 2022), the National Plan for Water Security (PNSH) (BRAZIL/ANA, 2019), the ABC+ Plan (Agriculture) (BRAZIL/MAPA, 2021), the PLANSAB (Sanitation) (BRAZIL/SNS-MIDR, 2019), the Ten-Year Plan for the Development of Energy Supply (PDE) (BRAZIL/MME, 2022), and the National Civil Defense Plan (PNDC). (BRAZIL/MME, 2024). The analysis was structured around four main dimensions: (i) water presence in climate plans; (ii) governance and adaptive planning; (iii) linkages with water-using sectors; and (iv) climate finance and project implementation.

The results show important progress, particularly in the PNRH and the ABC+ Plan, which are characterized by their recognition of water as a strategic element in the face of climate change. The PNRH contains climate scenarios and guidelines for water risk management, and thus occupies first place in the “Water in climate plans” dimension. The PNA also makes relevant contributions by linking water resilience to food security and human nutrition. In contrast, plans such as PLANSAB and PNDC show little integration between climate challenges and water management measures, indicating an urgent need for review and adaptation.

In the dimension of governance and adaptive planning, the PNRH again stands out, as it provides a legal framework that favors flexible and interactive approaches. The ABC+ also makes progress by proposing adaptation mechanisms in the agricultural sector. The PNSH, despite its strategic importance, hardly establishes a link between water security and climate adaptation. The Brazilian NDC, on the other hand, emphasizes international commitments but still lacks effective national instruments to integrate water into its governance.

An analysis of the links to the strategic sectors shows that, while the agricultural sector (ABC+) provides important guidelines for efficient water use, particularly in irrigation, it has weaknesses in other sectors. For example, PLANSAB and PNSH, lack clear strategies for water allocation in situations of water scarcity. At this point, the importance of guidelines that allow for dynamic adjustment of water use rights based on seasonal fluctuations and climate projections is emphasized.

The analysis of the energy sector, presented by the Ten-Year Energy Development Plan (PDE), shows concrete but still insufficient progress. Although the PDE recognizes the climate risks to energy security and mentions the need to diversify the energy matrix, it lacks a more structured approach to integrating water resilience into power sector planning. Reliance on the hydroelectric matrix requires greater coordination between hydrological and energy scenarios, especially given the increasing variability of water flows. This gap limits the ability of PDE to anticipate and respond to critical events, such as prolonged droughts and severe dry spells, which directly impact power generation and system security.

In terms of climate finance, the report finds a significant gap in most plans. Only the ABC+ and PNRH mention, sources such as the Green Climate Fund and resource mobilization strategies through public-private partnerships, albeit only rudimentarily. The other plans do not mention financing mechanisms or technical criteria that are compatible with the requirements of international financial institutions. This lack of support affects the feasibility of the proposed measures and hinders access to available resources for climate adaptation. The analysis therefore underlines the need to develop more robust financial strategies that are adapted to the realities of different sectors and regions.

Overall, the report highlights the fragmentation of public policy, poor coordination between levels of government, and insufficient integration of agendas — such as water, agriculture, energy, sanitation, and civil protection. The Water Resilience Tracker also highlights the importance of incorporating evidence-based tools, such as hydro-climatic projections, early warning systems, and vulnerability indicators, in a more systematic and standardized way. Only a few documents, such as the PNRH and the PNA, show progress in this regard. Most still lack robust methods for dealing with uncertainty and decision-making in environments of increasing risk.

Finally, the report highlights the potential of the Water Resilience Tracker as a replicable methodology for future assessment cycles and continuous improvement of public policy. Experience shows the importance of positioning water as a structuring axis of national climate planning, and strengthening governance focused on resilience and sustainable adaptation. The study provides a valuable diagnosis and strategic recommendations for Brazil to move forward in developing more integrated, effective climate and water policies that respond to the challenges of the 21st century.

CHALLENGES OF WATER RESOURCES MANAGEMENT IN BRAZIL FOR AN ADAPTATION AND RESILIENCE AGENDA

Climate change exacerbates droughts, floods, thereby impacting on water quality and availability in Brazil, and increasing social and territorial vulnerability. Addressing these challenges requires overcoming dependence on purely infrastructural solutions and moving towards integrated strategies that combine governance, science, innovation, and social participation. This chapter discusses the main water resource management challenges for an adaptation and resilience agenda, organized into five areas: droughts, heavy rainfall, groundwater, water quality, and disaster risk management.

Disaster risk management

Disaster risk management (DRM) is a systematic process that includes the identification, analysis, assessment, treatment, and monitoring of risks. DRM aims to reduce the negative impact of hazards and the likelihood of disasters occurring. It is an ongoing effort to protect people, property, and the environment. According to the UNDRR, DRM comprises several stages and measures: (i) prevention (to prevent disasters), (ii) mitigation (to reduce the intensity of the impact of a disaster), (iii) preparedness (to ensure that the community is ready to respond to a disaster), (iv) response (measures taken during and immediately after a disaster to save lives and protect property), and (v) recovery (measures to restore a new "normal" after a disaster).

In addition, Brazil has signed the Sendai Framework for Disaster Risk Reduction, adopted in 2015, which aims to guide global efforts to prevent and reduce disaster risk by 2030. It sets out global goals and priorities for action to strengthen the resilience of communities and reduce the negative impacts of disasters. These priorities are: a) understanding disaster risk; b) strengthening disaster risk management; c) investing in disaster risk reduction to strengthen resilience; and d) improving disaster risk reduction, including response and recovery.

The objectives of the Sendai Framework include: i) reducing mortality; ii) reducing the number of people affected; iii) reducing economic losses; iv) reducing damage to critical infrastructure; v) increasing the number of countries with risk reduction strategies; vi) promoting international cooperation; and vii) providing early warning systems. The "Early Warnings for All" initiative of the United Nations and the World Meteorological Organization "(WMO, 2023) aims to ensure that all people are protected by these systems by 2027. To reduce risks, it is essential to create scales of action, such as early warning systems for short-term events, and financial instruments for long-term mitigation planning.

In this context, the National Center of Monitoring and Alerts of Natural Disasters (CEMADEN) was established to consolidate the national monitoring and warning system for natural disasters. This initiative, in collaboration with various state-wide institutions, aims to implement, complement, and consolidate the network of meteorological, hydrological, and geotechnical instruments for monitoring and warning of extreme events and their effects (landslides, droughts, and floods). CEMADEN was created by Presidential Decree No. 7,513. It is a research unit (UP) linked to the Ministry of Science, Technology, Innovation, and Communication (MCTIC) and has a specialized technical-scientific structure.

Furthermore, according to IPCC/AR6, global warming of more than 1°C has triggered an increase in the frequency and magnitude of hydrological extremes, particularly droughts and floods, on a scale unprecedented in recent history, (Kreibich et al., 2022). Moreover, the impacts of climate on water resources and user sectors are more far-reaching and severe than expected, and future risks increase with every fraction of a degree of warming. At the same time, adaptation measures can strengthen resilience, but more resources are needed to scale up solutions. Therefore, the IPCC/AR6 warns greenhouse gas emissions would peak before or just before 2025 on a 1.5°C trajectory. Consequently, climate finance for both mitigation and adaptation will need to be significantly increased in this decade. Therefore, risk management can be guided by instruments such as early warning systems and financial insurance.

Early Warning Systems

An early warning system is a set of procedures and technologies designed to detect, monitor, and warn of potential hazards or threats in advance, so that people and organizations can take preventive action to mitigate their effects. These systems can range from weather alerts to warnings of natural disasters, conflicts, disease outbreaks, and other critical events. For water resources, some warnings related to weather alerts are important, such as the “TerraBrasilis”/INPE system (https://terrabrasilis.dpi.inpe.br/app/map/alerts), INPE/Portal (https://portal.inmet.gov.br/), CEMADEN’s warnings of floods, drought, and other extreme weather events (https://www.gov.br/cemaden/pt-br/). In Brazil, Law No. 12.608/2012 established the National Policy for Civil Protection and Defense (PNPDEC),and the National System for Civil Protection and Defense (SINPDEC) and the National Council for Civil Protection and Defense (CONPDEC). It also authorizes the creation of an information and monitoring system for disasters and amends other laws related to civil protection and urban planning.

Between 2011 and 2025, CEMADEN issued hydrological and geological warnings for more than 1,000 priority municipalities in Brazil (Figure 2).

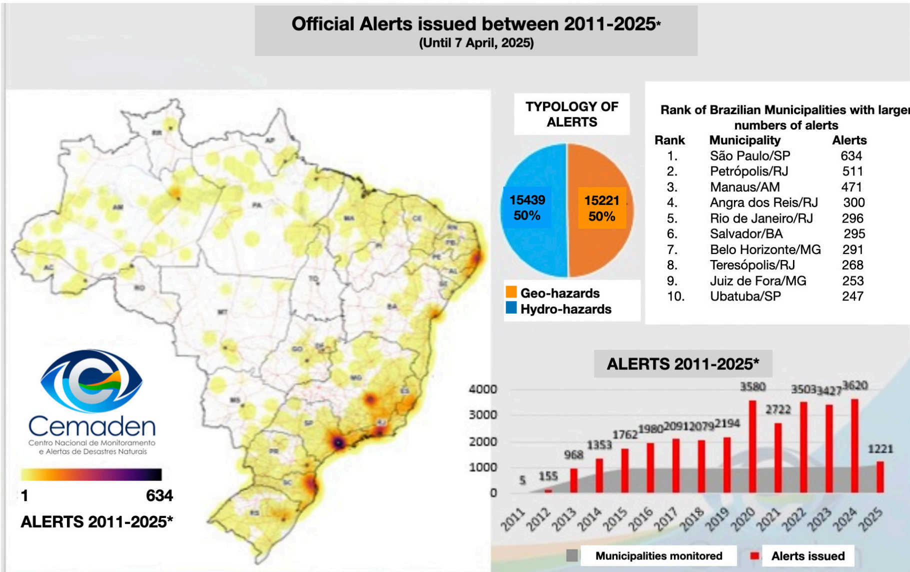


Figure 2: Map of total number of alerts issued in the Brazilian territory (left), with typologies of hydrometerologically-driven hazards, with "Geo" and "Hydro" related to the risks of landslides and floods, respectively. The inner table shows the Brazilian top-ranked municipalities with the largest number of official alerts. A timeline between 2011 and 2025(June) depicts the number of prioritized municipalities (grey-shadowed curve) and the number of alerts issued yearly (red columns,right, bottom part of the figure). Source: Courtesy of Dr. Marcelo Seluchi, General Coordinator of the CEMADEN/MCTI.

In 2024, 3,620 warnings were issued for 1,690 disasters, of which 68% were of hydrological origin and 32% of geological origin (landslides). According to CEMADEN, the dominance of hydrological events reflects the recurring impact of floods and downpours, especially in vulnerable urban areas. The warning is issued based on the potential impact of an intense event, while the actual impact depends on the conditions and vulnerability of the location. CEMADEN monitors 1,133 Brazilian municipalities, representing 20% of Brazilian cities and approximately 60% of the country's population.

Between 2014 and 2024, Brazilian research in conjunction with CEMADEN and INCT-Climate Change Phase 2 (http://inctmc2.cemaden.gov.br/), has advanced the development of models for forecasting and issuing hydrological warnings, especially for flooding in urban areas. To technically support the legal framework for civil protection (Federal Law 12.608/2012), these advances include machine learning and chaotic systems (Furquim et al., 2016), geographic information systems with citizen science (Horita et al., 2015; Fava et al., 2019), and the use of social media (Restrepo-Estrada et al., 2018). On the other hand, new sociohydrological models (Souza et al., 2021; Sarmiento-Buarque et al., 2021) warn that social memory and community perceptions of urban waters serve as long-term warning systems for the risks of future impacts of climate change scenarios. Souza and Silva (2025) provide an overview of trends, challenges, and methodological perspectives on flooding.

During the exceptional floods in Rio Grande do Sul, between April 28 and May 2, 2024, CEMADEN issued 53 hydrological warnings with “high” and/or “very high” risk. In 2024, the federal government launched the “Civil Protection Warning” initiative at the National Center for Risk and Disaster Management (CENAD). These warnings warn of impending natural or man-made disasters, as defined in the Brazilian Disaster Classification and Coding (Cobrade), and advise city residents on what they should do at that time. The state civil defense authorities are responsible for the content of these warnings.

Financial Insurance for Risk Mitigation

Environmental risk and its climate-related variables have always been a financial risk at its core, and are also highly relevant, for example, for risks related to climate phenomena such as droughts and heavy rainfall. From a climate risk perspective, it is worth highlighting an important movement stimulated in particular by the TCFD (Task Force on Climate-related Financial Disclosures), which recommends scenario studies and stress tests in relation to this risk and its potential impact on the results of companies in various sectors, including insurance. At a global level, insurers rallied around the PSI (Principles for Sustainable Insurance), of UNEP-FI, the United Nations Environment Program Finance Initiative, in 2020.

Water crises, in particular, have increased in recent decades. In Brazil, droughts and floods are responsible for more than 80% of natural disasters. According to the ANA (National Agency for Water and Agriculture), the direct economic losses between 1995 and 2014, totaled R$ 9 billion per year, and caused losses for families, industry and farmers. Globally, climate events between 1971 and 2012 caused losses of almost USD 287 billion, according to the World Meteorological Organization. The economic impact of the natural disasters caused by these climate changes is undeniable.

The last drought in the São Paulo metropolitan area, between 2013 and 2015, drove up water bills and led to rationing for at least 9 million people supplied by the Cantareira system. The drought, combined with persistent water demand, led to a supply deficit. It was the worst water and financial crisis in the history of the State Water Company of São Paulo (SABESP). The company's profits fell by 60% between 2014 and 2015. In terms of flooding, the floods in Rio Grande do Sul in May 2024 stand out. According to the National Association of Municipalities, this disaster caused damages of between R$12 billion and R$100 billion, with the insurance market paying out claims of around R$4 billion to R$7 billion for this period, according to sources based on preliminary data.

Although climate insurance remains a challenge for resilience in Brazil, there are technological advances in what is known as "indexed insurance"." In this type of insurance, the amounts paid out to families or businesses in the event of water shortages or environmental disasters, for example, can vary depending on the risk of a disaster occurring and its potential for damage. With the help of satellite images, precipitation data, and analyses of river courses and water flows, it is possible to map an area, simulate scenarios, estimate damage caused by climate events, and calculate fair prices and compensation amounts in the event of drought or flooding. In the period 2017-2025, progress was made in the development of water-indexed insurance with the support of INCT Climate Change Phase 2.

On the one hand, climate insurance between 2017 and 2020, still using CMIP5/IPCC/AR5 scenarios, was based on semi-conceptual and distributed hydrological models (Mohor & Mendiondo, 2017; Guzmán et al., 2020; Taffarello et al., 2020). Insurance models for water-using sectors are sensitive to the magnitude of hydrological extremes, the radiative forcing of future scenarios, and the evaluation criteria for water-producing environmental services. This is particularly important given the recent regulatory framework for wastewater management (Federal Law 14.014/2020) and payment for environmental services (Federal Law 14.119/2021).

In the period 2021 to 2025, with the new CMIP6/IPCC/AR6 scenarios, new insurance models in Brazil have incorporated an exploratory analysis of data patterns, and the combination of multiple climate threats, and have been linked to computable general equilibrium models (Silva et al., 2021; Benso et al., 2023; 2025; Gesualdo et al., 2024).

On the other hand, the National Confederation of General Insurance, Private Pension and Life Insurance, Supplementary Health, Insurance and Capitalization Companies unites the associations. Thus, CNSeg (2022), together with UNEP FI, has included indicators of climate change and the geographical exposure of Brazil to 11 physical climate risks, considering two climate scenarios (2°C and 4°C increase) and two-time horizons (2030 and 2050). Among these risks, four are related to water resources: 1) urban flooding, 2) river flooding, 3) water stress and 4) drought. The Brazilian legal framework, Law 15.040/2024, known as the "Insurance Legal Framework"," establishes private insurance standards and requires policyholders to declare their daily risks in a risk assessment questionnaire at the time of contracting. This mechanism makes risk identification more transparent and allows for appropriate pricing, tailored to each customer's profile. Circular SUSEP 666/22, which strengthens climate risk management, and Resolution CNSP 473/24, which establishes sustainability rules for the classification of insurance products, complete the regulatory framework for insurance.

Resilience and Adaptation to Droughts

This section discusses a range of management and adaptation measures to increase the resilience of communities to drought. The discussion here largely mirrors the one presented in Martins and Reis (2021), which was part of the Special Report on Droughts, organized by the United Nations Office for Disaster Risk Reduction (UNDRR, 2021).

Extensive investments in water infrastructure in Brazil during the period 1990-2010, especially in the Northeast of Brazil, created a false sense of security in terms of water safety. However, the recent multi-year drought (2012-2018) has shown that coping with droughts requires not only the improvement of infrastructure, but also the identification of vulnerabilities and the development of contingency plans for each sector and water management system, as well as the need for better coordinated management at both local and higher levels.

The prolonged drought of 2012–2018 has triggered discussions in Brazil on how to improve drought policies and management (Martins et al., 2016a). The need for more coordinated government action in response to droughts, involving all levels of government (federal, state, and municipal), in both short-term reactive and long-term proactive measures, led to the development of a more structured and proactive national drought policy that follows the disaster risk management cycle (Figure 3). This policy is based on a three-pillar framework (Figure 4), as described by Wilhite et al. (2005), and consists of the following analytical categories: (1) monitoring and early warning/forecasting, (2) vulnerability/resilience and impact assessment, and (3) mitigation and response planning (Gutierrez et al., 2014).

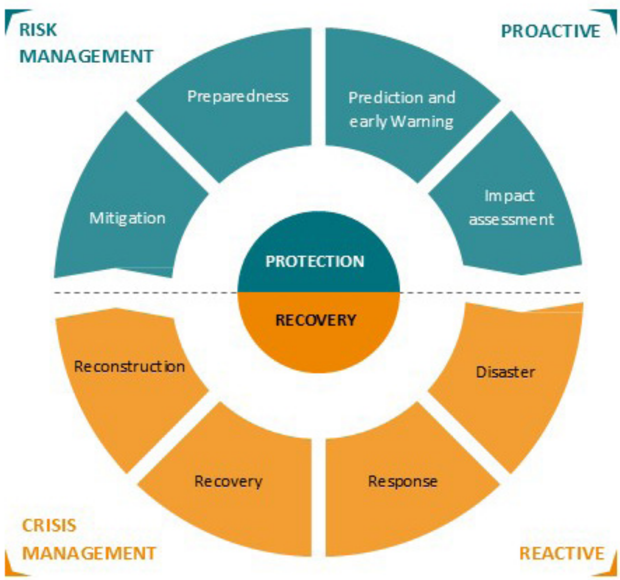


Figure 3: The cycle of disaster risk management. The typical reactive and crisis management emphasis of droughts is noted in red on the bottom half of the figure, whereas the paradigm shift needed toward more proactive risk management and drought preparedness is noted in the top half of the figure in blue. Source: Figure provided by Donald Wilhite, University of Nebraska, Lincoln.

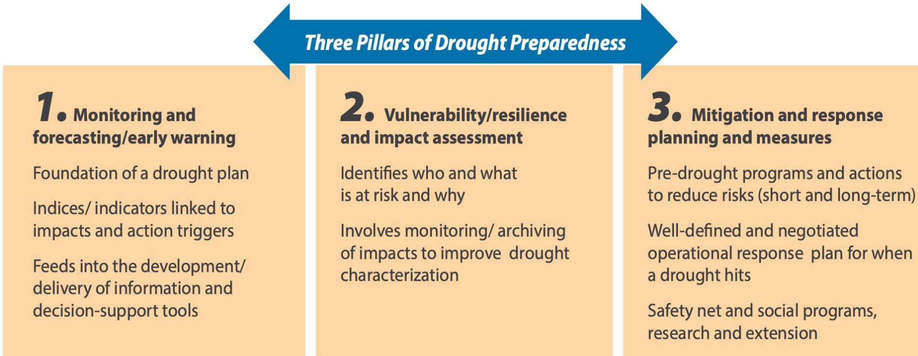


Figure 4: The three pillars of drought preparedness that support a paradigm shift away from reactive crisis management and toward more proactive approaches to drought events. Source: Gutiérrez et al., 2014.

Drought prediction for the Brazilian Northeast - The case of the state of Ceará and contributions to the consolidation of public policies

The development of reliable forecasting systems capable of predicting the future evolution of a prolonged drought or identifying the onset, severity, and spatial extent of a future drought in a normally stable region can be a crucial step in the development of a drought risk management plan. Many such initiatives have already been implemented worldwide, including in North America, Europe, Australia, and Northeast Brazil (Steinemann, 2006; Shafiee-Jood et al, 2012; Wood et al, 2015; Cancelliere et al, 2006; Lavaysse et al, 2015; Prudhomme et al, 2015; Werner et al, 2015; Souza Filho et al, 2003; Sun et al, 2005; Canamary et al, 2015; Pereira et al, 2015).

The advantages of these systems for drought risk management are obvious. They can provide valuable, albeit uncertain, information on various aspects of a drought, giving managers and decision-makers sufficient time to take the necessary actions to reduce the economic, social, and environmental impacts of droughts. In the late 1990s, meteorological institutions in Brazil, including CPTEC/INPE and FUNCEME, committed to developing a climate forecasting system for the region. This initiative inspired the development of a drought monitoring strategy that is being applied throughout Brazil.

By the late 1990s, the potential benefits of using climate precipitation forecasts for water resource management were widely recognized, and the state of Ceará invested in the development of numerical climate models by FUNCEME. In 2001, FUNCEME, the International Research Institute for Climate and Society (IRI) at Columbia College, and the IRI itself pioneered the operationalization of a system to regionalize forecasts from the IRI's global model ECHAM4.5. Over the years, several numerical and statistical climate prediction systems have been developed and presented in prediction forums, but they received little attention until they became the focus of the official Climate Forum in January 2012.

In January 2012, during discussions on the release of the consensus forecast for the February-to-May rainy season, Martins (2012) pointed out the need for immediate changes to the climate prediction system. Based on an analysis of the consensus forecasts for the rainy season between 2001 and 2012, published in January, he found that the consensus indicated the middle tertile ("around the mean") as the most likely category in 80% of cases, which was far from the categories actually observed.

To solve this problem, Martins (2012) proposed a new system based solely on numerical predictions from climate models and the past performance of these models. Arguments put forward included: the complexity of the problem, a lack of understanding of probability and statistics, the involvement of the forecasting team with the end user, the political agenda of the meeting leader, consensus forecasts limited to areas where the models have expertise, a conservative approach to reaching consensus in negotiations, and the incompatibility between the forecasting format and the decision-making process. It was also noted that these factors can occur in combination.

Personal political motivations often hinder the improvement of the system. To overcome this, FUNCEME introduced a model-based forecasting system in 2012 and has made continuous efforts to increase its accuracy and attract national stakeholders to participate.

CPTEC/INPE, INMET and FUNCEME recognized the need for change, and jointly developed a methodology that combines models from the three institutions to obtain objective probabilities by tertile. This system became operational in July 2012. Currently, FUNCEME's runs are part of the national multi-model ensemble initiative, which includes INMET's national statistical climate model, CPTEC/INPE's three global model runs, and FUNCEME's ECHAM 4.6 run.

The impact of this forecasting system on the prediction of droughts became clear in rainy years such as 2008 and 2009, providing important information for the operation of reservoirs in the region to ensure supply for several years. In 2009, the difficult decision was made to prioritize the use of climate and weather monitoring and forecasting systems over the flood control plan for the state's largest reservoir. This decision resulted in additional water storage and a guaranteed water supply for the Fortaleza metropolitan region during the multi-year drought of 2012-2018. Using climate forecasts for decision-making processes in the areas of water resources and agriculture is not straightforward. To maximize the value of these forecasts, it is important to create user-oriented products that provide sector-specific information at the right time.

For example, at the 2015 Climate Prediction Forum, evidence was presented that the drought that has persisted in the state since 2012 could continue into 2016, based on long-term sea surface temperature predictions. Despite the high degree of uncertainty in this type of prediction, government decision-makers took the potential impact of two consecutive years of drought very seriously and decided to act pre-emptively by launching a large-scale tender for well drilling, which ultimately helped to mitigate the impact of subsequent droughts. The construction of 6,000 wells would not have been possible without the government's use of available climate information. While this is a successful example of the use of climate information in decision making, it is reasonable to assume that effective communication between scientists and policy and decision makers would not have been possible if the impact of the drought had not already been apparent at the time of decision making.

Drought Monitoring

The context of the 2012-2018 period has stimulated a well-known dialog in the country on improving drought policy and management. The Ministry of National Integration recognized the need for a more comprehensive government response to drought that involves all administrative sectors — federal, state, and local — and takes a long-term perspective rather than a limited emergency response. This realization prompted the Ministry to formulate a more structured national drought policy (De Nys et al., 2016).

In the past, the debate on drought management waxed and waned depending on the drought cycle, resulting in limited progress towards proactive management. To address the complexity of the issue, the government initially focused its efforts on the most important aspect of drought preparedness — monitoring — and also produced three drought preparedness plans for manageable systems to demonstrate the viability of the concept (pilot projects for urban water supply, water resources and rainfed agriculture).

Following the example of Mexico and the United States, a monitoring model was chosen that combines information from federal and state institutions to produce a single monthly map of drought conditions in the region (Martins et al., 2016bc). This required close collaboration between state and federal institutions, which is why it was first implemented in the northeastern region, and now covers the whole country.

The process was a major challenge for a country unfamiliar with such coordinated initiatives. It involved the integration of all relevant state and regional databases, which enabled the calculation of various drought indicators and the integration of different sources of information, including remote sensing. The Drought Monitor was launched in July 2014 and was initially led by FUNCEME, focusing on the Northeast region, with the support of the region's network of climate and water institutions. In February 2017, a cooperation agreement was signed between the Federal College of Ceará (UFC), FUNCEME, and the management of ANA.

Figure 5 illustrates the different state actors involved in this process, as well as the changes in leadership that ensure the formal participation of federal institutions. A decade after this paradigm shift (since 2014), the country now has a robust drought monitor that initially covered only the northeastern region (9 states) but has grown over time to include all 27 states (the entire country), and involves more than 60 state and 5 federal institutions. This shows that drought preparedness has become a national concern. The goal of the monitor and the resulting map is to improve the understanding and definition of drought and increase the effectiveness of public policies to support the affected population.

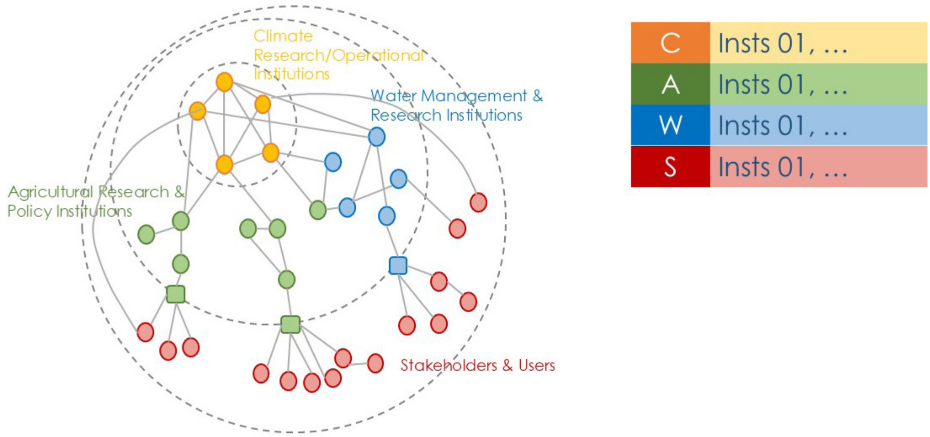


Figure 5: Drought Monitor process involving at state level institutions from (C)limate, (A)griculture and (W)ater sectors and (S)takeholders/Users (Civil Defense, Environment Agency and other stakeholders). The figure also shows the start and the current status of the Drought Monitor, first having FUNCEME as Central institution from July of 2014 to February/2017, when ANA assumed this role. Source: FUNCEME.

Planning

The Contingency Plan - The Drought Monitor primarily reflects physical or natural drought, while water scarcity, which is closely linked to farming systems, requires complementary information. To address this issue, a pilot program was conducted in the region to establish links between the Drought Monitor and the Drought Preparedness Plan, which focuses on controllable systems. The main objective of the program was to examine the relationships between physical drought (represented by the Monitor) and operational drought (indicated by the Preparedness Plan) in three sectors: urban supply, water resources, and rainfed agriculture. The Drought Monitor provides important information, but not enough to fully inform sectoral drought preparedness plans. The specific characteristics and scope of each sector play an important role in the development of these plans.

The drought preparedness plans aimed to demonstrate the practical application of proactive drought management through the use of specific tools and strategies. The correlation between the drought monitor and the preparedness plans varies, because it depends on how the physical drought, represented by the monitor relates to the operational drought represented in the preparedness plans. In the case of the Dryland Agriculture Preparedness Plan, the operational drought is strongly related to the drought shown by the monitor. However, for other plans, this relationship may not be as strong.

In the Northeast pilot, five preparedness plans were introduced as case studies in three sectors (De Nys et al., 2016, for specific details on each plan): Water Supply (Jucazinho system – state of Pernambuco; Greater Fortaleza – state of Ceará), River Basin Planning (Piranhas Açu Basin – states of Rio Grande do Norte and Paraíba), Multipurpose Water System (Jucazinho Reservoir – state of Pernambuco), and Smallholder Dry Agriculture (municipality of Piquet Carneiro – state of Ceará). The aim of these plans was to facilitate access to drought preparedness for decision-makers and to promote proactive drought management.

The plans were designed to link drought categorization with specific policy and management measures, following the three-pillar framework. However, the relationship between the Drought Monitor and the Preparedness Plan may vary by sector, as some sectors require adaptation of the monitoring system due to their scale and specific characteristics. Following the Drought Preparedness Plan pilots, additional case studies were initiated in the Northeast region, including on urban water supply and water systems, as well as rainfed agriculture by small-scale producers.

Following the pilot efforts, the National Water Agency, the UFC, and FUNCEME initiated additional case studies in the Northeast region, including urban supply and hydrosystems in Caicó and Sousa (Paraíba state) and Engenheiro Avidos-São Gonçalo and Curema-Mãe D'Agua hydrosystems. Ceará state, with FUNCEME's support, also implemented six plans for rain-fed smallholder agriculture in Quixeramobim, Campos Sales, Salitre, Sobral, Irauçuba, and Tauá.

In 2024, UFC established the Strategic Center of Excellence in Water and Drought Policies (CEPAS) to support its engagement with decision-makers in water and drought policies. The objectives of CEPAS include supporting decision-maker engagement, monitoring the Center's initiatives, recommending strategies and projects, and proposing financing mechanisms. This center formalizes the collaboration between the Department of Water Resources and Environmental Sanitation (DEHA/UFC) and the Ceará State Water Resources System, as well as with the World Bank, facilitating the exchange of experiences between Ceará and other countries.

Several states have allocated significant resources to promote the other two pillars, particularly for the development of drought contingency plans tailored to the different sectors. Lessons from the Brazilian experience are being shared and adapted with other countries, such as Eswatini and Jordan, as part of South-South exchanges. However, such initiatives take time, as they are sectoral and need to be tailored to the individual systems (e.g., water systems, cities, etc.) for which they are responsible. As adaptation primarily takes place at the local level, new initiatives have been implemented at the municipal level in a participatory manner. These initiatives take into account the innovative capacity of each municipality in terms of water management and ensure that they are actively involved in diagnosis, forward planning, and implementation.

In times of drought, maximizing water use is not limited to economic efficiency, but also includes the integration of public policies that promote the connection between water, food, energy and the environment. In the Brazilian semi-arid region, for example, drought management combines water harvesting and storage technologies (cisterns, underground dams) with sustainable agricultural practices, such as the cultivation of drought-resistant crops. These strategies are encouraged by market dynamics, such as rising prices for agricultural commodities in times of scarcity. However, they also require planning to avoid overuse of water resources, which can affect long-term resilience.

Resilience and adaptation to extreme precipitation events

The conceptual aspects related to adaptation issues in urban waters must ensure “sustainability and resilience – especially in the context of extreme events”,” in accordance with the Recife 2024 Charter, of the XV National Meeting on Urban Water (ENAU) and the V Symposium on Urban River Revitalization (SRRU), of the Brazilian Association of Water Resources (ABRHidro). To set the context, In addition to the countless material losses, there have been a large number of fatalities in recent years (more than 600 deaths due to rainfall, considering the cases of Petrópolis, the metropolitan region of Recife, São Sebastião, and cities in Rio Grande do Sul).

Such extreme events and their impacts illustrate the scale of the challenges and the urgency of discussing alternatives and technical, political, and financial means to implement them, while respecting the principles of sustainability and social inclusion. Based on a reflection on the events that have occurred and the climate challenges that lie ahead, measures such as these are therefore being taken:

- Recognizing that Brazilian cities are increasingly vulnerable to problems caused by heavy rainfall, so that city managers and society as a whole can address the problem in a comprehensive and multidisciplinary way.
- Promote city residents' understanding of the risks associated with settling on hillsides, riverbanks and streams, and how these risks may be exacerbated by climate change. This will allow city managers to develop water-environment education programs to raise awareness of the risk and adequately prepare for events.
- Ensure that infrastructure and operational facilities for urban stormwater drainage and management are designed and implemented using the best techniques and are subject to ongoing preventive and corrective maintenance, as well as the replacement and updating of warning systems and their components.
- Develop a culture of prevention to keep the memory alive and prevent forgetting, even if the time between extreme events is long. One effective measure could be to include a culture of disaster preparedness in the formal curriculum, at all levels.
- Promote advanced scientific knowledge, including computer modeling, remote sensing, the Internet of Things, and artificial intelligence, as tools to be used in defining programs and projects and, whenever possible, in considering climate change.
- Expand and modernize the urban area's qualitative and quantitative monitoring network to create a robust database, essential to support model calibration and validation, and decision-making for waterway revitalization and flood mitigation projects.
- Recognize that universities, among other teaching and research institutes, have the expertise to propose solutions tailored to the realities of the urban centers in which they operate and, should therefore, be taken into account by city governments when developing public policies integrated with urban micro and macro drainage projects.
- In public policies, prioritize socio-economically vulnerable populations that are more susceptible to hydrological risks, and use social technologies that contribute to risk reduction.

- Prioritize among public policies public policies that take into account the impacts of extreme events and climate change, using the most advanced and innovative knowledge, to achieve greater sustainability and resilience in the urban environment.

Groundwater resources

The changes in groundwater resources in Brazil due to climate change have potential consequences, depending on the region, mainly for human water supply, agriculture, and ecosystems, but also for industry and other user sectors. Integrated surface and groundwater management is essential to meet current and future challenges. This is , also underlined by recent research by Hirata et al. (2025), in addition to investments in hydrogeological monitoring (Uchôa et al., 2024), which is still very much in its infancy in the country and shows significant regional asymmetries. Supporting tools based on remote sensing also need to be further disseminated. In its latest report, “Water Resources Situation in Brazil”,” ANA (2024) emphasizes the need for studies to assess the interdependence between surface and groundwater flows and their importance for integrated management. The Conjuntura report emphasizes the importance of identifying the parts of the basins where rivers are most dependent on aquifers to maintain their water flows. These regions become a priority for the implementation of integrated river/groundwater aquifer management.

Artificial recharge of aquifers, also called RGA (Managed Aquifer Recharge), is an excellent adaptation strategy for groundwater. Although it is not yet regulated in Brazil, there are several studies that can guide the formulation of public policies in this regard. RGA can consider different water sources for this purpose, such as reused water from treated wastewater, rainwater harvesting in urban buildings, and others. Recently, OODARZI et al. (2024) conducted research to assess the potential of RGA in the state of São Paulo as a strategy to address the impacts of climate change on water resources.

As groundwater management in Brazil is the responsibility of the states, the need to strengthen state management authorities is further reinforced.

Water quality

Considering that water systems are prone to extreme events (droughts and floods) and the complexity of the hydrodynamic, morphodynamic, and biogeochemical processes that characterize these environments, the impacts of a variety of extreme events triggered by climate change (frequency and increased intensity) indeed indicate a potential risk of water quality degradation.

In this context, the importance of systematic monitoring of water quality parameters is emphasized as part of the qualitative and quantitative management process, but also allows the assessment of physical, chemical, and biological impacts in the context of integrated ecosystem dynamics. There is still much to learn about the impacts of climate change on water quality management. This requires the adoption of multi-risk approaches that integrate multiple stressors in the assessment of climate change impacts on water quality in environmental systems.

Innovative modeling and monitoring tools are crucial to capture the complex and dynamic interactions between climate change-induced stressors, ecosystem processes, water quality constituents, and site-specific morphological features (Kozak, 2021). Advances in long-term, high-resolution monitoring, together with the development of sophisticated process- and data-driven AI models, and hybrid strategies, should be a central focus of future research to close knowledge gaps, improve predictive capability and reduce uncertainties.

Furthermore, the consideration of human-influenced factors, such as land use and adaptation measures, is crucial to decipher the complex dynamics of the system under multiple stresses. Furthermore, future work could be improved by more accessible (low-cost and user-friendly) initiatives that involve citizens in sociohydrological contexts (Almeida, 2024) in data collection, e.g. by disseminating visual indicators of poor water quality to alert local authorities.

This integrated approach would promote more participatory, collaborative, and community-driven research, and improve scientific and societal understanding of the dynamics of complex systems exposed to multiple pressures.

PUBLIC POLICY ASPECTS AND INNOVATIONS IN THE ADAPTATION AND RESILIENCE AGENDA

Public water resources policies in Brazil face the challenge of responding to a scenario of worsening climate change, which increases the risks of water scarcity, flooding, and conflicts over water use. This section identifies ways to modernize the instruments of the National Water Resources Policy and examines socio-technical, regulatory, and institutional innovations that strengthen the country's resilience and adaptation. The aim is to demonstrate progress and propose strategies that align science, management, and society in developing a preventive, integrated, and future-oriented water agenda.

Water Resources Management Instruments – A broader perspective

Given the worsening effects of climate change on hydrological systems and the multiple uses of water, it is essential to re-evaluate and improve the instruments of the National Water Resources Plan (PNRH), established by Law No. 9,433/1997. Although these instruments have brought important advances in decentralized and participatory water management in Brazil, many of them still do not fully incorporate the climate adaptation dimension and do not provide adequate responses to the new risks associated with hydrological variability and uncertainty. Below, we present suggestions for improvement for each of the PNRH instruments, organized by theme, with a focus on promoting more adaptive, preventive, territorial and science-based management. These improvements aim to modernize the regulatory framework, integrate a climate lens into decision-making processes, and strengthen national water resilience in the face of 21st century pressures.

i. Water Resources Plan

- Systematically include climate scenarios and water vulnerability assessments as mandatory content in plans, covering both scarcity and flood risks.
- Use tools such as water trackers to assess the integration of adaptation measures into the plans and monitor the effectiveness of the proposed measures.

- Territorialize risk analysis, from the basin level to the municipal level to identify local responses to climate change.
- Certify and qualify the adaptation potential of existing measures in plans, based on robust technical criteria and scientific evidence.
- Create a label or classification system that indicates the degree to which each measure contributes to water adaptation, facilitating prioritization and resource allocation by managers.
- Encourage regular review of plans based on new climate scenarios, to promote a continuous cycle of updating and adaptive learning.

ii. Bulk Water Pricing

- Introduce dynamic pricing mechanisms, inspired by the electricity sector's tariff flag system, to better reflect water scarcity conditions.
- Link the bulk water prices to hydrological status in near real-time, through scarcity decrees and hydrometeorological monitoring.
- Use bulk water pricing as an economic signal to promote rational use of water in climate stress scenarios.

iii. Water Use Rights

- Develop an adaptive model, whose revisions depend on hydrological triggers.
- Integrate indicators for water availability and temporary restrictions during critical events.
- Use recent historical data to estimate water supply in line with the new climate regime.
- Explicitly consider uncertainties in water balance analyses, to strengthen risk management.

iv. National Water Resources Information System (SNIRH)

- Consolidate the SNIRH as a technical-scientific basis for adaptive management.
- Harmonize climate scenarios and support scientific production with high-quality hydrological data.
- Provide ongoing training and methods for risk and vulnerability assessment.

- Modernize the hydrometeorological network based on risk criteria and invest in data governance and institutional integration.

v. Water Body Planning for Classification

- Consider the impact of climate change on water availability, especially on dilution flows.
- Articulate water quality and quantity from a risk perspective, particularly to guide investments in sanitation and resilient infrastructure.
- Adapt the framework to the new climatic realities, especially in the most vulnerable regions.
- Promote the evaluation of plans to implement the framework.
- Set targets and measures using approaches based on citizen science strategies (Ramirez et al., 2023) and sociohydrology.
- Integrate an ecosystem approach into the framework processes.

Complementary strategies and Sociotechnical innovations

i. Nature-Based Solutions (NBS)

NBS have consolidated their position as an essential strategy for adapting the water resources sector to climate change. Rather than relying solely on large infrastructure projects, they promote the conservation of ecosystems, increase water infiltration into the soil, and contribute to the regulation of water flows. They not only strengthen resilience to climate variability, but also bring additional benefits for biodiversity, water quality, and the provision of ecosystem services.

Key measures include decentralized and small-scale solutions, such as mapping and strategic use of small reservoirs, which can ensure water availability during dry periods and reduce the impact of extreme events. Combined with forest restoration, wetland restoration and sustainable land use management, these initiatives demonstrate the potential of NBS to combine natural and gray infrastructure in more flexible and adaptive responses.

In this scenario, Payments for Environmental Services (PES) become increasingly important as an incentive mechanism for NBS. By rewarding farmers and communities for the conservation of strategic ecosystems, PES strengthens the protection of water services and broadens the scope of solutions. Integrating NBS and PES into public policy is therefore an opportunity to reconcile environmental and social benefits, strengthen governance, and ensure greater water security in the face of climate change.

ii. River Basin Revitalization

Although they are not yet widespread, various efforts have been made to revitalize watersheds, which can also be seen as a strategy for adaptive management and climate resilience. ANA's Water Producer Program was created to encourage rural producers to invest in measures that contribute to water conservation. The Water Producer Program is based on the PSA concept, and encourages rural producers to implement water conservation measures on their land, such as erosion control and proper vegetation management. In return, they receive technical and financial support in implementing these measures.

Since its inception, the program has proven effective in revitalizing watersheds and improving water quality and supply. ANA supports 76 projects throughout the country, covering the metropolitan areas of large cities such as Brasília, Campo Grande, Florianópolis, Goiânia, Palmas, Rio Branco, Rio de Janeiro, and São Paulo.

In addition to the ANA, other federal, state, and municipal institutions, as well as civil society organizations are also participating in the program. The initiative is part of the ANA's strategic planning and is in line with the National Plan for Water Resources, according to the ANA. The Water Producer Program will be completed in 2024 after 10 years and will have restored more than 47,000 hectares.

In 2022, the then Ministry of Regional Development (MDR) coordinated and commissioned the development of the National Watershed Revitalization Program, whose final document includes guidelines, objectives, management models, and institutional arrangements. The document highlights, , the recognition of the importance of NBS in the global water agenda as an important milestone in the reorientation of Brazil's watershed revitalization strategy. According to UNESCO (2018), the expansion of NBS, particularly in terms of improving water security, is fundamental to the implementation of the 2030 Agenda.

iii. Public Services for Urban Drainage and Stormwater Management

Urban drainage issues play an important role in adaptation strategies, especially with the aim of minimizing the impact of urbanization, reducing water pollution, promoting water security, and integrated stormwater management.

A recent contribution is the Reference Standard for Drainage and Management of Urban Stormwater (DMAPU) – NR No. 12/2025 – issued by the ANA. This standard establishes guidelines and criteria for the structuring, regulation, and provision of DMAPU services, to minimize the impact of urbanization on the water cycle and pollution of water bodies. It emphasizes the strategic need to integrate DMAPU systems into the territorial and socio-ecological scale of the river basin.

iv. Regulatory Frameworks, water allocation, and adaptive water management

An innovative and relevant experience in the management of shared river basins (with a dual water authority at federal and state level) are the so-called “Regulatory Frameworks”, which are formal agreements between the ANA (National Agency for Water Resources) and the relevant state agencies, with the participation of users. These instruments function as pacts that define responsibilities and common rules for managing water crises or settling existing disputes.

Once the regulatory framework is established, it serves as a reference for regulating water use, and guiding management decisions in the relevant basin or water system. In the context of increasing climate variability and climate change, it is important to create more flexible legal frameworks that provide for regular review of allocation and contractual reassessment clauses in the event of extreme events.

Another innovative initiative related to the integrated management of water resources in Brazil is the negotiated water allocation, developed in the state of Ceará and later extended to other regions of water stress in the country. In ANA’s current situation reports, negotiated water allocation is presented as a management tool that attempts to reconcile multiple uses in conflict situations, especially in catchment areas and water systems with limited availability. It is a participatory process that involves users, managing authorities and basin committees, and leads to agreements that set temporary rules for water use.

ANA emphasizes that this mechanism has proven to be effective in avoiding disputes and reducing economic and social impacts in times of scarcity, as it promotes dialog, transparency, and shared responsibility among the actors involved. In addition to the Ceará experience, national experiences, such as that of the São Marcos river basin are often highlighted as examples of institutional arrangements that ensure greater water security in critical situations. Given the intensification of drought events across the country, it is crucial to expand and strengthen negotiated and adaptive allocation instruments, based on climate risk.

Recently, the ANA has been testing two innovative tools in an experimental regulatory environment, namely Granting with Guarantee and Priority Management (OGP) and Granting with Shared Management (OGC). OGP consists of granting subsidies with a lower guarantee than the ANA normally accepts, without limiting them to a fixed reference rate. OGC, on the other hand, provides for the reallocation, or shared use of water volumes that are formally granted but not currently used.

Both initiatives aim to maximize water use and serve users who could not be allocated water under traditional approaches. Furthermore, these initiatives were built with user participation and decentralize decision-making on how water should be used on a daily basis. This represents an innovation from the perspective of decentralized, participatory, and socio-hydrological management in the context of adaptation.

v. Economic and financial instruments

Adapting the water resources sector to climate change requires strengthening economic and financial instruments that can reduce vulnerabilities and increase resilience. Climate and water insurance can provide protection to strategic sectors, such as agriculture and urban water supply, and mitigate losses in extreme events.

Another approach is to set the price of water based on risk and scarcity criteria, adapted to social and territorial conditions, in order to promote a more efficient and equitable use of water resources. This approach can promote sustainable practices while ensuring fair access for the most vulnerable populations.

In addition, the creation of resilience funds and payment mechanisms for hydrological services offers the opportunity to integrate different levels of government and local communities. These instruments help to finance adaptive solutions, support the conservation of strategic ecosystems, and consolidate water security in the face of climate variability and uncertainty.

Governance and resilience-building challenges

Water governance is a complex and multi-layered issue that requires the involvement of different stakeholders and coordination across levels and sectors to ensure the sustainable use of water resources. In the context of climate change, resilient water governance is crucial, especially in areas characterized by semi-arid conditions and high water variability.

Innovation and governance challenges

As Martins (2025) points out, innovation in water management is constrained by the complexity of governance at national, regional, and local levels. These constraints often hinder the development of community-specific modeling approaches tailored to local needs and contexts, especially in vibrant areas where viability and resilience must be balanced in highly variable contexts, such as semi-arid regions practicing coexistence with drought. This approach, based on the principle of subsidiarity, emphasizes local self-determination in a broader global context to ensure that solutions are context-specific.

Furthermore, the multiplicity of initiatives at different levels in water areas can lead to a deliberate “redundancy” of solutions. While this may be at odds with efficiency and performance —which are often associated with linear solutions — it is necessary to address the impacts of climate and land use variability and change on water systems.

The overreliance on infrastructure-based solutions (hard engineering) is also a problem. While these solutions are necessary, they can lead to vulnerabilities in the long term, especially if they are not adapted to climate change or the degradation of existing systems. This illustrates the difference between a management system that focuses only on technical performance (efficient water) and a system that emphasizes social and environmental adaptation (resilient water).

Fragmentation of policies in different sectors — such as agriculture, urban planning, and water management — leads to poorly coordinated resource allocation and compromises integrated strategies. Standardized financing models ignore territorial diversity, and limit the implementation of effective solutions in different urban and rural contexts.

Operational and Systemic Challenges

Traditional planning approaches are based on the assumption that climate and land use are stable, which no longer corresponds to reality. This outdated view impairs the effectiveness of long-term strategies, especially in regions with high climate variability. Although climate data are available, its use in public policy and decision-making is still limited (see Martins, 2025).

The lack of local strategies for dealing with extremely dry or rainy years leads to logistical failure, overconsumption of resources and increased community vulnerability. Public communication during climate crises — such as floods or droughts — is also inadequate, reducing the population's ability to respond.

Changes in leadership and poor resource management hinder the continuity of adaptation strategies and measures. This underlines the need for greater transparency, long-term planning, and the active involvement of multiple stakeholders — including governments.

Another critical aspect is the financing of resilience building. In addition to the difficulty of accessing funding in competition with other investment requirements at the level of individual administrative units, one of the main obstacles is the territorial imbalance of the financing instruments used to develop solutions adapted to the territorial level. These instruments, often characterized by a rigid structure of predefined investments, limit or hinder the participation of local actors at different levels, in the design, implementation, and operation of the solutions.

In the area of capacity building and communication, it is recommended to define effective strategies for education/training and communication on climate change and water in the context of adaptive management. These strategies include focusing on problems and solutions, linking global and local issues, incorporating hands-on activities and digital resources, understanding the concept of risk, and promoting a sense of environmental justice in the adaptive management process. Strategically, it is recommended to integrate education on climate change, water, and adaptation into curricula, to not only promote professional, technical, and scientific development, but also to make society “agents of change”.

1. In this sense, priorities include:
2. focusing on solutions and problems;
3. linking global issues to local realities;
4. Integrating climate change and water security into outreach projects;
5. Promoting hands-on activities and digital resources;
6. Stimulating reflection on environmental justice and social impact;
7. Promoting professional development and support in the context of citizen science;
8. Empowering students as agents of change;
9. Rethinking school infrastructure in light of new climate and environmental demands.

Monitoring and Information System Challenges

The prospect of developing adaptation strategies is based on an understanding of hydrological processes. Despite advances in the use of models not only as planning tools but also as knowledge of the physical nature of hydrological processes, hydrological science is only sustained by the relevance of monitoring and the foundation of information systems and their availability in open formats, such as the already established National Water Resources Information System (SNIRH).

In this context, more integrated and multidisciplinary information, based on future scenarios and uncertainty assessments, is needed for future planning to enable the following: (i) assessing the magnitude and nature of climate change and its impacts on river basins, taking into account downscaling and spatial and temporal dynamics aspects; (ii) identifying the capacity of ecosystems to adapt to climate change and hydrological dynamics naturally or through managed interventions; (iii) considering future population growth and economic activities, with their potential impacts on natural resources; (iv) enabling the establishment of water infrastructure sizing criteria; and (v) adapting human society through the logical responses of individuals, businesses, policy changes, and security, within the framework of citizen science and sociohydrology.

Adaptation to climate change must be dynamic, and institutional issues, biodiversity, and ecosystem services must be considered in integrated, development-oriented processes. However, ensuring effectiveness lies in the tacit recognition that maintaining hydrometeorological information systems and ensuring the effectiveness of planning and consistent implementation of resilient climate change adaptation measures.

Integrating actions

Policies and programs are often designed, implemented, and operated in isolation, without coordination or synergy, and without consideration of their mutual impacts. Modeling solutions based on the water-food-energy-environment nexus is essential for developing integrated approaches that combine sectoral data, promote collaboration between public policies and programs, and avoid wasted efforts. Promoting this integration requires:

- Coordination at multiple levels: Connect federal, state, local and river basin levels, with clearly defined roles and coherent decision-making and funding pathways.
- Combined portfolios: Integrate gray infrastructure with nature-based solutions, demand management, economic tools and adaptive governance.
- Smart redundancy and flexibility: Provide operational alternatives for shocks, including triggers that extend the response in years of drought or extreme flooding.
- Territorially aligned financing and regulation: Replace standardized models with context-adapted regulations that promote monitoring, transparency, and accountability.
- Capacity building and information dissemination: Transform climate data into effective decision-making, tools by strengthening technical advisory services and risk communication with managers and communities.

In short, the transition from “efficient” to “resilient” water requires reducing institutional fragmentation, planning for variability, and linking actions across the nexus. This focuses the chapter on water security as a public goal: safeguarding ecosystem functions, quality of life, and continuity of services, today and in the future.

CHALLENGES FOR WATER RESOURCES MANAGEMENT UNDER CLIMATE CHANGE – THE PERSPECTIVE FROM THE NATIONAL WATER AND SANITATION AGENCY (ANA)

The intensification of extreme weather events and the progressive changes in Brazil's hydrological system have put pressure on water resources management beyond its institutional, regulatory, and financial capacity. The climate crisis not only exacerbates existing hydrological risks, but also highlights the structural limits of the current model of water management, which is still strongly based on assumptions of predictability, stability, and sectoral allocation. In this context, there is an urgent need to understand the main challenges that hinder the adaptation of the water resources sector to the new conditions created by climate variability and change.

Below, we present some of the main obstacles that affect the effectiveness of water management in Brazil in a climate change scenario. These challenges, although different, are interrelated and require coordinated and systemic approaches. From the difficulty of using climate scenarios in a standardized and practical way, to the need to deal with profound uncertainties and still rigid legal frameworks, to the institutional, budgetary, and political weaknesses that threaten the sustainability of the SINGREH, each of these issues represents a critical aspect that must be addressed as a priority.

The challenges listed show that adapting the water sector to climate change requires more than isolated adjustments or individual measures. It requires a profound change in legal and planning instruments, the financing model, the integration of public policies, and the decision-making culture itself. Recognizing these weaknesses is the first step towards building structural solutions based on evidence, institutional flexibility, innovation, and climate justice.

i. Standardization and use of climate scenarios

- The lack of methodological standardization hinders the application of climate scenarios in water planning.
- A lack of regional projections and the absence of downscaling impair the local benefits of climate models.
- SNIRH represents a low-risk alternative for the integration of data and the dissemination of standardized methods.

ii. Management of Deep Uncertainties

- The unpredictability of the climate requires more robust and flexible approaches to decision-making.
- Adoption of decision-making methods under high uncertainty (such as robust decision making and decision scaling) that enable testing of strategies under multiple possible futures.
- Adaptive management, based on iterative planning and review cycles, requires regulatory frameworks that allow for dynamic adjustments.
- Risk studies are essential to support decision-making in uncertain contexts, and promote institutional resilience.

iii. Rigidity of legal and regulatory frameworks

- Law No. 9,433/1997 and its instruments were conceived under the assumption of stationarity, which limits their current application.
- The National Policy on Climate Change (PNMC) is not yet fully integrated into water resources policy, creating a regulatory vacuum.
- The PNRH instruments (river base plans, water rights, water body planning for classification) need to be improved to include climate adaptation criteria, adaptation clauses, and regular reviews.

iv. Institutional fragmentation and lack of coordination

- The lack of coordination among water managment, disaster risk, land use, and climate policies hinders a coordinated approach.
- The lack of integrated data platforms, common goals and formal cooperation channels reduces the effectiveness of public policy.

- Redesigning governance with a focus on cross-sectoral synergies is essential to promote integrated and preventive solutions.

v. Implementation of Nature-Based Solutions (NbS)

- The difficulty of quantifying the benefits of NBS using metrics recognized by traditional evaluation systems.
- The lack of legal frameworks, regulatory criteria, and specific financial incentives limits their inclusion in water planning.
- There is a need to develop hybrid approaches and standardized methods to assess the multiple benefits of NBS.

vi. Insufficient and discontinued funding

- The water resources sector remains underfunded, and heavily dependent on unstable public funding.
- Users and managers struggle to access climate finance due to the complexity of public notices and lack of technical training.
- Projects that do not incorporate climate risk limit access to national and international finance.
- Clear and accessible guidelines are needed to facilitate access to funding sources for water adaptation.

vii. Political fragility and risks to SINGREH

- Institutional instability, budget cuts, and staff changes weaken SINGREH.
- The lack of integration of water and climate policy prevents the consolidation of an adaptation agenda as public policy.
- Legislative reforms, budget protection, and evidence-based governance are essential to ensure the sustainability of public water policy in the context of the climate crisis.

A WAY FORWARD: SCIENCE–POLICY INTEGRATION FOR WATER SECURITY

To overcome the identified challenges, the introduction of integrated, data-driven water management models that link local, regional, and national strategies is essential. These models must be flexible, capable of accounting for climate and land use changes, and should promote cooperation between sectors to ensure policy coherence and resource efficiency.

The deliberate adoption of "redundant" solutions can be advantageous in this context, as it provides alternatives in the face of uncertainty. Increased use of climate information, through tools such as drought monitoring and forecasting in Brazil, is crucial to support public policy and improve risk management. Better communication, local stakeholder engagement, and institutional transparency are essential for crisis preparedness and response, ensuring that the technical and social aspects of water management are integrated.

Overcoming structural and operational barriers requires a new approach to water management that goes beyond traditional technical efficiency to focus on resilience, adaptability and inclusiveness. Data-driven models supported by broad societal participation are essential for building sustainable water systems that can cope with the uncertainties of a changing climate and meet hydrological and human needs.

Responding to the impacts of climate change on water resources requires more than generating new data or developing technologies: it requires ensuring that scientific knowledge is translated into concrete actions that guide policy and decision-making at the right time. This approach still faces barriers — differences in language, pace, and priorities — that reduce the potential for integrated and effective action.

While science provides sound diagnoses, forward-looking scenarios, and innovative solutions, management operates under immediate pressures, budgetary constraints, and political demands. To reduce this discrepancy, we need to invest in permanent channels of dialogue, consolidate trust among stakeholders, and recognize the structuring role of science in public policymaking.

Adaptive governance must go beyond institutional formalities and take on the role of a living articulation between different fields of knowledge and sectors, capable of dealing with risks and uncertainties. Bridging the gap between science and policy is not just a technical strategy, but a political and social commitment to water security and building a more resilient future.

Integrating scientific knowledge into the core of water decision-making expands responsiveness, improves the resilience of management systems, and sustainably protects a resource essential to life and development. The challenge — and also the opportunity — is to make this integration an ongoing practice, so that the best available science not only informs, but also drives concrete action on the front lines.

Technical and scientific associations have a strategic role to play in this process. In Brazil, the Brazilian Association of Water Resources (ABRHidro), the Brazilian Association of Sanitary and Environmental Engineering (ABES), the Brazilian Groundwater Association (ABAS), and the Brazilian Association of Irrigation and Drainage (ABID) have contributed to disseminating knowledge, training professionals, and fostering dialog between science, society, and public policy. Their work is crucial to strengthen governance, promote innovation, and broaden societal participation in adaptation and resilience agendas.

At the international level, initiatives such as the International Association of Hydrological Sciences (IAHS) and its current Scientific Decade, HELPING (Hydrology Engaging Local People IN one Global world, 2023-2032), emphasize the need to bridge science and practice, and develop solutions in partnership with local communities. Aligning national efforts with these global movements expands Brazil's ability to address the impacts of the climate crisis on water and achieve sustainable water security.

The conceptual relevance of issues related to mitigation and adaptation has assumed the dimension of a national planning strategy in science, technology and innovation. The Free Conference "Water Security and Society" (2024), jointly organized by INCT ONSEAdapta and ABRHIDRO, synthesized a relevant contribution focused on public policies, with the inclusion of this theme in the 5th National Conference on Science, Technology and Innovation (5th CNCTI - https://5cncti.org.br/), in 2024, which served as "an important space for dialogue between different actors in society to reflect on the role of ST&I in the country and its direction in the coming years".

REFERÊNCIAS

Almeida, C. Water quality management, Governance, and Socio-hydrology:strategies for an Urban Basin. Thesis. Federal University of Parana. 271p. 2024.

ANA - AGÊNCIA NACIONAL DE ÁGUAS (Brasil). Plano Nacional de Segurança Hídrica (PNSH). Brasília, 2019a. 112 p.

ANA - Agência Nacional de Águas e Saneamento Básico (Brasil). Conjuntura dos recursos hídricos no Brasil 2022 : informe anual / Agência Nacional de Águas e Saneamento Básico.- Brasília : ANA, 2022.

ANA - Agência Nacional de Águas e Saneamento Básico (Brasil). Conjuntura dos recursos hídricos no Brasil 2024 : informe anual / Agência Nacional de Águas e Saneamento Básico.- Brasília : ANA, 2024.

Arias, P.A., et al. (2021). Technical Summary. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33−144, doi:10.1017/9781009157896.002.

Benso, M. R., Gesualdo, G. C., Silva, R. F., Silva, G. J., Castillo Rápalo, L. M., Navarro, F. A. R., Marques, P. A. Marengo, J. A., Mendiondo, E M (2023), Review article: Design and evaluation of weather index insurance for multi-hazard resilience and food insecurity, *Nat. Hazards Earth Syst. Sci.*,

Benso, M. R., Silva, R. F., Chiquito Gesualdo, G., Saraiva, A. M., Delbem, A. C. B., Marques, P. A. A., Marengo, J. A., and Mendiondo, E. M.(2025) A data-driven framework for assessing climatic impact drivers in the context of food security, *Nat. Hazards Earth Syst. Sci.*, 25, 1387–1404, https://doi.org/10.5194/nhess-25-1387-2025.

Blöschl, G., Chaffe, P.L.B., Water scarcity is exacerbated in the south. Science382, 512-513 (2023). DOI:10.1126/science.adk8164.

Borges De Amorim, P.; Silva De Souza, K. I.; Chaffe, P. L. B. (2020) A web-based tool for synthesis assessments of the impacts of climate change on water resources. Environmental Modelling & Software, v. Online First, 2020. https://doi.org/10.1016/j.envsoft.2020.104848

Borges, PB, Chaffe, P.B. Towards a comprehensive characterization of evidence in synthesis assessments: the climate change impacts on the Brazilian water resources. Climatic Change 155, 37–57 (2019). https://bit.ly/429nust

Brasil. Agência Nacional de Águas e Saneamento Básico. Conjuntura dos recursos hídricos no Brasil 2024 : informe anual / Agência Nacional de Águas e Saneamento Básico.- Brasília : ANA, 2024. 154 p.

Brasil. Agência Nacional de Águas e Saneamento Básico. Conjuntura dos recursos hídricos no Brasil 2023 : informe anual / Agência Nacional de Águas e Saneamento Básico.- Brasília : ANA, 2023. 118 p.

Brasil. Agência Nacional de Águas e Saneamento Básico. Conjuntura dos recursos hídricos no Brasil 2021: relatório pleno / Agência Nacional de Águas e Saneamento Básico.-- Brasília : ANA, 2022. 132p.

Brêda, J. P. L. F.; Paiva, R.C.D. et al., (2020). Climate change impacts on South American water balance from a continental-scale hydrological model driven by CMIP5 projections. CLIMATIC CHANGE, v. 158, p. 1-20, 2020.

Brêda, J. P. L., de Paiva, R. C. D., Siqueira, V. A., & Collischonn, W. (2023). Assessing climate change impact on flood discharge in South America and the influence of its main drivers. Journal of Hydrology, 619, 129284.

Canamary, E. C.; Reis Junior, Dirceu Silveira; Martins, Eduardo Sávio P. R. Evaluation of ensemble SPI forecasts for Ceará, Northeastern Brazil. In: Drought: Research and Science-Policy Interfacing. Editors: Joaquin Andreu, Abel Solera, Javier Paredes-Arquiola, David Haro-Monteagudo, Henny van Lanen. CRC Press, DOI: 10.1201/b18077-42, 2015.

Cancelliere, A., Mauro, G. D., Bonaccorso, B., & Rossi, G. Drought forecasting using the Standardized Precipitation Index. Water Resources Management, 21(5), 801–819. http://doi.org/10.1007/s11269-006-9062-y, 2006.

CEMADEN (2024). Nota Técnica Nº 679/2024/SEI-CEMADEN: Análise das Secas no Brasil: Diagnóstico e Projeções Futuras. Brasília: CEMADEN

Chagas, V. B. P., Chaffe, P. L. B., Addor, N., Fan, F. M., Fleischmann, A. S., Paiva, R. C. D., and Siqueira, V. A.: CAMELS-BR: hydrometeorological time series and landscape attributes for 897 catchments in Brazil, Earth Syst. Sci. Data, 12, 2075–2096, https://doi.org/10.5194/essd-12-2075-2020, 2020.

Chagas, V.B.P., Chaffe, P.L.B. & Blöschl, G. Climate and land management accelerate the Brazilian water cycle. Nat Commun 13, 5136 (2022a). https://doi.org/10.1038/s41467-022-32580-x

Fava, M C, Abe, N, Restrepo-Estrada, C E, Kimura, B, Mendiondo, E M (2018) Flood Modelling Using Synthesized Citizen Science Urban Streamflow Observations, Journal of Flood Risk Management, https://doi.org/10.1111/jfr3.12498

Furquim, G., Pessin, G, Faisal, B, Ueyama, J., Mendiondo, E M (2016) Improving the accuracy of a flood forecasting model by means of machine learning and chaos theory, Neural Computing and Applications 27(5): 1129–1141, https://doi.org/10.1007/s00521-015-1930-z.

Gesualdo, G. C., M R. Benso, K Sass, E M Mendiondo (2024) Index-based insurance to mitigate current and future extreme events financial losses for water utilities, Int. J. Dis. Risk Reduction, https://doi.org/10.1016/j.ijdrr.2023.104218

Gutiérrez, A.P.A.; Engle, N.L.; de Nys, E.; Molejón, C.; Martins, E.S. Drought preparedness in Brazil. Weather Clim. Extrem., 3, 95–106, 2014.

Guzman, D A, Mohor, G S, Mendiondo, E M, (2020) Multi-Year Index-Based Insurance for Adapting Water Utility Companies to Hydrological Drought: Case Study of a Water Supply System of the Sao Paulo Metropolitan Region, Brazil, Water, https://www.mdpi.com/2073-4441/12/11/2954

Hirata, R. e Conicelli, B. P. . Groundwater resources in Brazil: a review of possible impacts caused by climate change. Anais da ABC, v. 84, n. 2, p. 297-312.

Hirata, R., Goodarzi, L., Rörig, F.S. *et al*. Climate change impacts on groundwater: a growing challenge for water resources sustainability in Brazil. *Robust decision making* 197, 784 (2025). https://doi.org/10.1007/s10661-025-14235-8.

Horita, F, Albuquerque, J P, Degrossi, L C, Mendiondo, E M, Ueyama, J, (2015) Spatial decision support system for flood risk management in Brazil with volunteered geographic information and wireless sensor networks, Computers & Geosciences 80: 84-94, https://doi.org/10.1016/j.cageo.2015.04.001

Horita, F, Albuquerque, J P, Marchezini, V, Mendiondo, E M (2017) Bridging the gap between decision-making & emerging big data sources: Application of model-based framework to disaster management in Brazil, Decision Support Systems, https://doi.org/10.1016/j.dss.2017.03.001

Instituto Brasileiro de Geografia e Estatística – IBGE. Dados populacionais e distribuição regional no Brasil. Rio de Janeiro, 2023.

Kozak, Caroline ; Leithold, Juliana ; do Prado, Luciane Lemos ; Knapik, Heloise Garcia ; de Rodrigues Azevedo, Júlio César ; Braga, Sérgio Michelotto ; Fernandes, Cristovão Vicente Scapulatempo . Adaptive monitoring approach to assess dissolved organic matter dynamics during rainfall events. ENVIRONMENTAL MONITORING AND ASSESSMENT, v. 193, p. 423, 2021.

Kreibich, H., Van Loon, A.F., Schröter, K. *et al*. The challenge of unprecedented floods and droughts in risk management. Nature 608, 80–86 (2022). https://doi.org/10.1038/s41586-022-04917-5

Lavaysse, C., Vogt, J., & Pappenberger, F. (2015). Early warning of drought in Europe using the monthly ensemble system from ECMWF. Hydrology and Earth System Sciences, 19(7), 3273–3286. http://doi.org/10.5194/hess-19-3273-2015

Martins, Eduardo S. P.R., Vulnerabilidades e desafios para a segurança hídrica (regiões e setores) e arranjos de governança, Em: Mudanças Climáticas: Adaptação, Resiliência e Controle de Riscos, PAINEL – 2º FÓRUM BRASIL DAS ÁGUAS, João Pessoa, 2025.

Martins, Eduardo Sávio P.R. An analysis of past seasonal forecasts for the Northeast Region: Why do we need to change our Climate Forecasting System? (*In*

Portuguese). In: XIV International Climate Assessment Workshop for the Northeast Region, Fortaleza, 2012.

Martins, Eduardo Sávio P.R.; Reis Junior, Dirceu Silveira. Drought impacts and policy responses in Brazil: The Case of the Northeast Region. In: GAR Special Report on Drought, 2021, ed.1. Geneva: United Nations Office for Disaster Risk Reduction, 2021.

Martins, Eduardo Sávio P.R.; Teixeira, Francisco José Coelho; Conejo, João Gilberto Lotufo; Machado, José; Moura, Antônio Divino. Crisis, Opportunity, and Leadership,. In Drought in Brazil: Proactive Management and Policy, CRC Press, 19-26, 2016a.

MCTIC. Ministério de Ciência, Tecnologia, Inovação e Comunicações. ENCTI 2016-2022. 2016.

Miranda, P. T., Petry, I., Alves, W. R. G., Fernandez, G. M. R., Paiva, R. C. D., Collischonn, W., Fagundes, H., Rossi, J. B., Kolling Neto, A., Abdalla Araujo, A., & Souza, S. (2024). SACCI-CMIP6: South American Climate Change Impacts on floods and droughts (1.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.15398093

Mohor, G. S., Mendiondo, E M (2017) Economic indicators of Hydrologic Drought Insurance Under Water Demand & Climate Change Scenarios in a Brazilian Context, Ecol. Economics, https://doi.org/10.1016/j.ecolecon.2017.04.014

OMM - Organização Meteorológica Mundial (2023) Early Warnings for All Initiative. Geneva: OMM, https://wmo.int/activities/early-warnings-all

Oodarzi, L. ; Hirata, R. ; Andrade, L. C. . Managed aquifer recharge in São Paulo state, Brazil: opportunities for facing global climate change issues. Environmental Earth Sciences, v. 83, p. 666, 2024.

Paiva RCD de, Chaffe PLB, Anache JAA, Fontes AS, Araujo LMN de, Araujo AN de, *et al*.. Advances and challenges in the water sciences in Brazil: a community synthesis of the XXIII Brazilian Water Resources Symposium. RBRH. 2020;25:e50. https://doi.org/10.1590/2318-0331.252020200136

Paiva, R. C. D., Collischonn, W., Miranda, P. T., Fagundes, H.O., W., Kolling, A., Castro, L., Rossi, J., Matte, G., Laipelt, L., Alves. W, Petry. I (2024). Cooperação em tecnologias para análises hidrológicas em escala nacional. CLIMA: Impactos de Mudanças Climáticas em Extremos de Vazão (Cheias e Estiagens) – Relatório Final. IPH-ANA-HGE-CLIMA-A3.

Pereira, José Marcelo Rodrigues; Vasconcelos Júnior, Francisco das Chagas; Martins, Eduardo Sávio P. R.; Reis Júnior, Dirceu Silveira; Noronha, Aurélio Wilson Tavares. Climate Seasonal Forecast and derived Indexes for droughts in Ceará, Brazil. In: Drought: Research and Science-Policy Interfacing. Editors: Joaquin Andreu, Abel Solera, Javier Paredes-Arquiola, David Haro-Monteagudo, Henny van Lanen. CRC Press, DOI: 10.1201/b18077-53, 2015.

Petry, I., Miranda, P. T., Paiva, R. C. D. D., Collischonn, W., Fan, F. M., Fagundes, H. D. O., ... & Souza, S. (2025). Changes in flood magnitude and frequency projected for vulnerable regions and major wetlands of south America. Geophysical Research Letters, 52(5), e2024GL112436. https://doi.org/10.1029/2024GL112436

Prudhomme, C., Shaffrey, L., Woolings, T., Jackson, C., Fowler, H, Anderson, B. (2015). IMPETUS: Improving Predictions of Drought for User Decision-Making. In: Andreu et al. (Eds.), Drought: Research and Science-Policy Interfacing. Taylor & Francis Group, London, p. 273-278.

Prudhomme, C., Shaffrey, L., Woolings, T., Jackson, C., Fowler, H, Anderson, B. (2015). IMPETUS: Improving Predictions of Drought for User Decision-Making. In: Andreu et al. (Eds.), Drought: Research and Science-Policy Interfacing. Taylor & Francis Group, London, p. 273-278.

Ramirez, S. B., Meerveld, I., Seibert, J. Citizen Science approaches for water quality measurements. Science of Total environment, 897, 2023.

Restrepo-Estrada, C. E., Andrade, S., de Albuquerque, J P, Mendiondo, E M (2018_ Geo-social media as a proxy for meteorological data for flood monitoring, Computer and Geosciences, https://doi.org/10.1016/j.cageo.2017.10.010

Ribeiro, N. B.; Formiga-Johnsson, R. M. Discussões sobre governança da água: tendências e caminhos comuns. Ambiente & Sociedade, v. 21, 2018.

6. OCEAN AND COASTAL ZONES

Segen Farid Estefen[21], Moacyr Cunha de Araujo Filho[22], Regina R Rodrigues[23], Leticia Cotrim da Cunha[23], Margareth S Copertino[24], Beatrice Padovani Ferreira[25], Flávia Lucena Frédou[26], Ronaldo Olivera Cavalli[24], Carlos Alberto Eiras Garcia[24], Carla de Freitas Campos[27], Alexander Turra[28], Jose Luiz Moutinho[29], Wim Degrave[30], Paulo Gadelha[30], Leandra Regina Gonçalves[30], Ronaldo Christofoletti[30], Wânia Duleba[28], Milena Maltese Zuffo[28], Andrei Polejack[21]

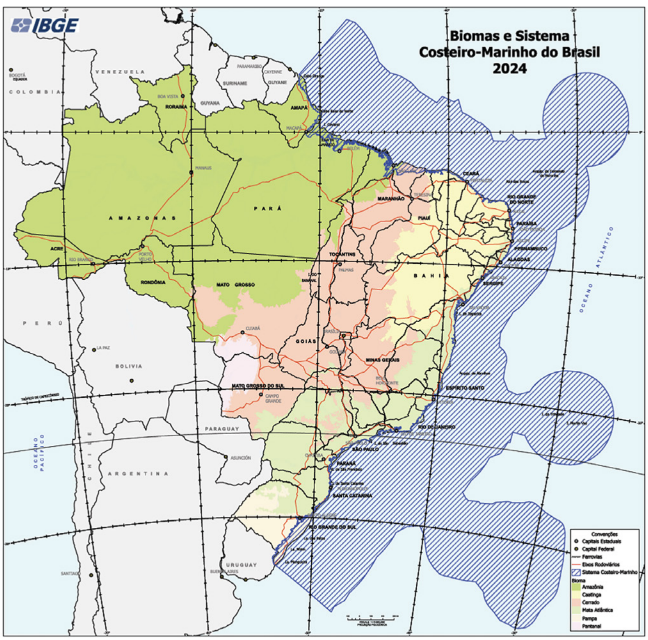
INTRODUCTION

The ocean has already absorbed 90% of the excess heat generated in the atmosphere by carbon dioxide (CO2), the main cause of the greenhouse effect, and has also absorbed 30% of the CO2 itself in its waters, as we will see in section 1 of this chapter. Nevertheless, its importance for climate regulation and, thus, for life on the planet, as well as its po-

21 Instituto Nacional de Pesquisas Oceânicas, INPO, Rio de Janeiro, RJ.
22 Universidade Federal de Pernanmbuco, UFPE, Recife, PE.
23 Universidade Federal de Santa Catarina, UFSC, Florianópolis, SC.
24 Universidade Federal do Rio Grandee, FURG, Rio Grande, RS.
25 Universidade Federal de Pernambuco, UFPE, Recife, PE.
26 Universidade Federal Rural de Pernambuco, UFRPE, Recife, PE.
27 Fundação Osvaldo Cruz, FIOCRUZ, Rio de Janeiro, RJ.
28 Universidade de São Paulo, USP, São Paulo, SP.
29 Ocean Quest Foundation, Thuwal, Arábia Saudita.
30 Universidade Federal de São Paulo, UNIFESP, Santos, SP.
corresponding authors: segen.estefen@inpo.org.br / moa.ufpe@gmail.com

tential contribution to climate change adaptation, has so far been little recognized by society in general and its political, economic, and social decision-makers.

With over 8,500 kilometers of coastline, Brazil has sovereignty over a total of 5.7 million square kilometers of ocean, which corresponds to more than half of the national territory. This is the so-called Blue Amazon, which includes the Exclusive Economic Zone (EEZ) of 4.5 million square kilometers.



The continental territory and the Blue Amazon (IBGE, 2024)

While this vastness offers the opportunity to exploit the sea's economic resources, it also means that the land is particularly vulnerable to the effects of rising sea temperatures, rising sea levels, water acidification, and lower oxygen concentrations. The Brazilian coastal and oceanic region is home to a diverse range of habitats, including lagoons, bays, inlets, river deltas, plains, mangroves, sandbanks, coral reefs, seagrass beds, and upwelling areas, to name a few. These ecosystems are vulnerable to climate change to varying degrees, as illustrated in Sections 2 and 3.

Brazilian science has already identified changes in the species richness and community structure of rocky coasts, beaches, bays, coastal lagoons, mangroves, macroalgae beds, and seagrass beds. Brazilian mangroves and coral reefs are particularly affected, as described in sections 3, 4, and 5. Although they occupy only 0.1% of the seabed, reefs harbor about 25% to 30% of all known marine species, including 65% of fish. Their biodiversity is comparable to that of tropical forests; they support human communities, provide food through fishing, support tourism, produce bioactive compounds with pharmaceutical potential, and protect coasts from wave erosion. Hence, the repeated scientific warnings of coral bleaching and coral mortality, which have intensified over the last two decades, affect more than 26 species. In addition to their role in marine biodiversity, coral reefs reduce wave energy, thereby protecting the coast from erosion and flooding.

At the boundary between land and sea, mangrove forests not only act as a physical barrier against erosion but also store up to three times more carbon in their soil than tropical terrestrial forests. In addition to the direct effects of global warming, they are also exposed to other stress factors, such as deforestation for urbanization.

While mangroves are losing ground due to deforestation and urbanization, they are also being reshaped by climate change, which is displacing other coastal areas.

The displacement of tropical species to extra-tropical regions in search of cooler waters is one of the most common consequences of rising sea temperatures. On the Brazilian coast, this species shifts from the warm waters of the northeast to the more temperate waters of the south, as observed in invertebrates, fish, macroalgae, and seagrasses. In addition to the gradual warming of the waters, marine heatwaves in the southwest Atlantic (between Cabo Frio and Argentina) have affected the availability of invertebrate larvae and reduced fish catches. The consequences of climate change for industrial and artisanal fisheries, as well as the aquaculture sector, are described in Section 6.

In Section 7, we observe that Brazilian science has a robust infrastructure for ocean and coastal monitoring and observation, as well as modeling tools for predicting trends. Additionally, it has an extensive network of national and global research collaborations that are essential for understanding climate and ocean change, protecting ecosystems, and informing public policy. However, there are still gaps in coverage and integration to account for the local specificities of the vast Blue Amazon.

The good news is that there are opportunities in coastal and marine waters themselves to address climate change through mitigation, adaptation, and even a combination of both. Section 4, for example, introduces so-called nature-based solutions (NBS), which, as the name suggests, use or are inspired by natural processes in ecosystems to solve environmental problems. Section 8 describes the multiple renewable energy sources available in the ocean — including wave and tidal action, thermal gradients, wind, and the potential to generate products such as green hydrogen and desalinated water — to enable a transition to renewable energy.

The final four sections address relatively new aspects of ocean science and climate change that go beyond the physical, biological, and technological aspects. They address the compelling need for change in the outlook, culture, and behavior of government institutions, the productive sector, and society in general. Section 9 emphasizes the significance of understanding the relationship between the sea and health, as the sea is both a source of physical and mental well-being and a vector for disease transmission. It must therefore be included in public health policy.

The development of climate justice, which addresses the inequalities in the impacts of climate change that most affect the economically and socially vulnerable populations, is the theme of Section 10. Section 11, in turn, describes efforts in an area where Brazil is a leader: the dissemination of a marine culture through education and communication initiatives, i.e., understanding how the ocean is present and affects our lives, even for those who live far from it, and how our actions affect it as well.

Finally, Section 12 demonstrates that the ideas, technologies, and actions proposed to address the impacts of the climate crisis on the ocean can only be implemented effectively if ocean and coastal governance establishes structural norms, institutions, policies, and practices for mitigation and adaptation. The intersection of ocean and climate regimes represents not only an urgent environmental imperative but also a strategic opportunity for Brazil to provide scientific and diplomatic leadership on the international stage.

6.1 Climate and Ocean

Regina R. Rodrigues

The ocean, which covers 70% of the Earth's surface, plays a crucial role in regulating our planet's climate and is essential to our response to global warming, caused by man-made greenhouse gases, and the resulting climate change. In its role as a climate regulator, the ocean has already absorbed 90% of the excess heat generated in the atmosphere (1) by carbon dioxide (CO_2) emissions, the main cause of the greenhouse effect, and has also absorbed 30% of the CO_2 itself in its waters.

Warming leads to rising sea levels due to the thermal expansion of ocean waters and the accelerated melting of the planet's ice sheets. Additionally, rising water temperatures also result in a decrease in the concentration of oxygen and nutrients in the ocean, which are crucial for sustaining marine life. This is exacerbated by the CO_2 absorbed by the water, which makes the water more acidic. The combination of ocean warming, oxygen depletion, and acidification is having a devastating impact on marine ecosystems, particularly in areas of high biological productivity and economic importance.

While the ocean helps reduce carbon concentrations in the atmosphere, thereby mitigating global warming, its warmer waters contribute to extreme weather events, such as droughts, excessive rainfall, and hurricanes, which have become more frequent and intense.

The heat content of seawater has risen steadily since measurements began in 1955, and set a new record in 2023, as shown in Figure 1. Most of the additional energy is stored in a shallow layer, ranging from 0 to 700 meters deep. Since at least the 19th century, when seawater temperatures began to be measured, the last decade has been the ocean's warmest. The record was set in 2024.

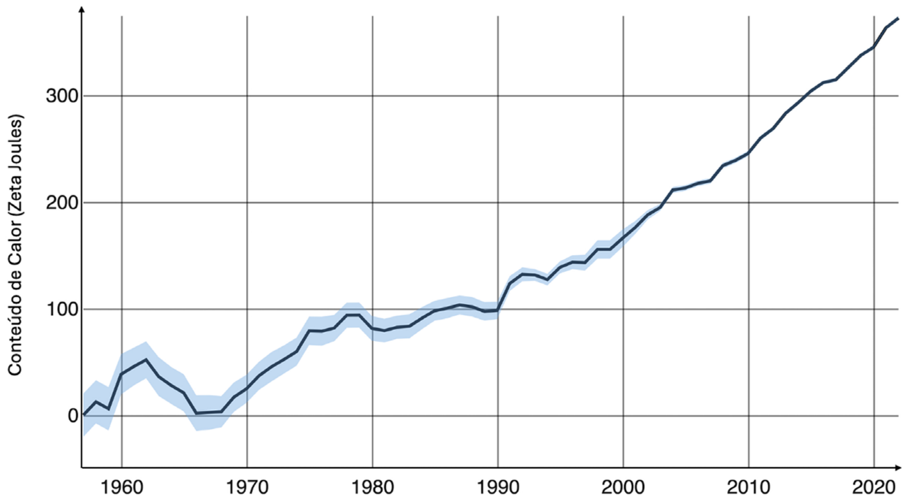


Figure 1: Annual estimates of heat content for the first 2,000 meters of ocean depth in zettajoules (10^{21} joules). Each point represents a five-year average. The blue shaded area indicates the margin of uncertainty within the 95% confidence interval. Source: NASA Climate.

All this extra heat leads to more extreme temperature events in the ocean, known as marine heatwaves. Recent global studies have shown that the frequency, duration, and intensity of marine heatwaves have increased significantly worldwide (2,3). Other studies focus on specific events in the North Pacific, North Atlantic, Western Australia, and the Mediterranean (4,5).

Marine heatwaves can be caused by atmospheric or oceanic processes, depending on the event and location (6). They have devastating effects on marine ecosystems (7). For example, the 2003 Mediterranean heatwave caused mass mortality of at least 25 species of rocky shore invertebrates (8). The 2012 heatwave in the Northwest Atlantic impacted commercially important fisheries (9). Heatwaves can even have a negative impact on birds and other marine animals (10). A global study examined the effects of marine heatwaves on human society. The ecological damage, which ranged from harmful algal blooms and mass die-offs to the transformation of entire ecosystems, resulted in economic costs of over US$800 million in direct losses and US$3.1 billion in indirect losses of ecosystem services over several years (11).

Sea levels have already risen by more than 101 millimeters since measurements began in 1992, leading to increased coastal flooding in some places. One-third to one-half of this rise is attributed to the expansion of water due to stored heat (12). But this is not the only reason. The extra heat in the air and ocean is also melting the Earth's ice sheets and glaciers, releasing freshwater into the ocean and further raising sea levels (13).

Sea ice is also melting, and although it has no direct influence on sea levels, it does have an impact on global temperatures. Sea ice is bright and reflects sunlight into space, whereas open water is darker and absorbs more sunlight. The warming of the ocean water melts the sea ice from below, while the warmer air supports the melting from above. As the ice sheet thins and shrinks, more ocean is exposed and less sunlight is reflected, leading to further warming of the water and air.

Ocean currents play a crucial role in transporting heat around the planet. When the ice sheets of Greenland and Antarctica melt, excess fresh water flowing into the ocean can disturb the balance of temperature and salinity that drives deep-sea currents. Circulation in the deep sea may slow down.

The warmer the ocean is, the more energy and moisture it releases into the atmosphere. For this reason, it can fuel extreme storms such as hurricanes, typhoons, and tropical and extratropical cyclones. These storms need warm water to form and intensify. Recent research indicates that rising ocean temperatures are a key factor in the rapid intensification of hurricanes (14). In addition, higher sea levels exacerbate the flooding caused by storm surges as they move along coastlines.

The ocean also acts like a sponge, absorbing carbon dioxide from the atmosphere. Increasing CO_2 emissions from human activities and their uptake by the ocean result in the acidification of the water. This process is happening faster today than at any time in the last 300 million years.

When the ocean becomes more acidic, corals and other marine organisms have difficulty forming their structures, and their growth rate slows. It is because coral skeletons are made of a type of calcium carbonate. When carbon dioxide from the atmosphere is added to water, chemical reactions occur that cause carbonate ions to bind with excess hydrogen ions rather than calcium ions, hindering the calcification of the skeletons of many marine animals. If the water becomes too acidic, it can even dissolve these structures. The heat waves in the sea complicate the situation, as the water is too warm for many corals to survive. According to current projections for greenhouse gas emissions, almost all reef corals will soon be threatened with extinction without human intervention. If urgent action is taken to reach pre-industrial emission levels, corals and other life forms can recover.

Marine and climate research in Brazil has made significant progress. Recent studies have noted the occurrence of ocean extremes in the South Atlantic, not only marine heat waves and their link to precipitation extremes over Brazil (15), but also acidification and low chlorophyll concentrations (16), with their effects on coral bleaching (17). Other studies have shown that marine heatwaves affect species along the Brazilian coast and may reduce the abundance of commercially important species (18).

As the challenges posed by the oceans to coastal areas increase, measures to mitigate (reducing greenhouse gas emissions to prevent climate change) and adapt to existing changes (increasing the resilience of ecosystems and coastal populations) should be among the most essential goals in coastal public policy planning and implementation. The ocean offers many opportunities for mitigation and adaptation.

Reducing greenhouse gas emissions is crucial to prevent further warming, acidification, and deoxygenation of the ocean's seawater. To achieve this, Brazil needs to transition to renewable energy. The ocean presents significant opportunities, including the utilization of offshore wind and tidal energy. Brazil needs to develop research to advance these areas of great potential. Additionally, marine and coastal environments possess a significant carbon sequestration capacity. Therefore, preserving and restoring these environments can help reduce emissions. These nature-based measures are also effective in protecting coastal areas from storms and storm surges, serving as adaptation measures.

Successful adaptation relies on a wide range of resources, from science-based models to the knowledge of local communities, and encompasses various types of measures, including engineered structures and so-called nature-based solutions. In particular, next-generation climate models will provide unprecedented detail on local climate impacts. These will help improve early warning systems and can be integrated into disaster preparedness and long-term adaptation strategies. Investments in in-situ observation platforms are necessary to enhance initial prediction conditions and provide the so-called «ground truth» for model predictions and projections. Solutions that adapt to climate change can bring a range of benefits, including progress towards achieving the UN Sustainable Development Goals (SDGs). Interdisciplinary research is crucial for identifying the co-benefits and trade-offs of adaptation strategies and for optimizing their planning and implementation.

REFERENCES

1. K. Von Schuckmann et al., Heat stored in the earth system: Where does the energy go? The GCOS earth heat inventory team. *Earth System Science Data Discussions*, 1-45 (2020).

2. E.C. Oliver et al., Longer and more frequent marine heatwaves over the past century. *Nature Communications* 9, 1-12 (2018).

3. J. Terhaar, F.A. Burger, L. Vogt, L., T.L. Frölicher, T.F. Stocker, Record sea surface temperature jump in 2023–2024 unlikely but not unexpected. *Nature* 639(8056), 942-946 (2025).

4. H.A. Scannell, A.J. Pershing, M.A. Alexander, A.C. Thomas, K.E. Mills, Frequency of marine heatwaves in the North Atlantic and North Pacific since 1950. *Geophysical Research Letters* 43, 2069–2076 (2016).

5. A.J. Hobday et al., A hierarchical approach to defining marine heatwaves. *Progress in Oceanography* 141, 227-238 (2016).

6. N.J. Holbrook et al., A global assessment of marine heatwaves and their drivers. *Nature Communications* 10, 2624 (2019).

7. D.A. Smale et al., Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change* 9, 306 (2019).

8. J. Garrabou et al., Mass mortality in Northwestern Mediterranean rocky benthic communities: effects of the 2003 heat wave. *Global Change Biology* 15, 1090-1103 (2009).

9. K.E. Mills et al., Fisheries management in a changing climate: lessons from the 2012 ocean heat wave in the Northwest Atlantic. *Oceanography* 26, 191-195 (2013).

10. L.M. Cavole et al., Biological impacts of the 2013–2015 warm-water anomaly in the Northeast Pacific: winners, losers, and the future. *Oceanography* 29, 273-285 (2016).

11. K.E. Smith et al., Socioeconomic impacts of marine heatwaves: Global issues and opportunities. *Science* 374(6566), eabj3593 (2021).

12. R.J. Nicholls et al., A global analysis of subsidence, relative sea-level change and coastal flood exposure. *Nature Climate Change* 11(4), 338-342 (2021).

13. E. Rignot, Observations of grounding zones are the missing key to understand ice melt in Antarctica. *Nature Climate Change* 13(10), 1010-1013 (2023).

14. K.T. Bhatia et al., Recent increases in tropical cyclone intensification rates. *Nature Communications* 10(1), 635 (2019).

15. R.R. Rodrigues, A.S. Taschetto, A.S. Gupta, G.R. Foltz, Common cause for severe droughts in South America and marine heatwaves in the South Atlantic. *Nature Geoscience* 12(8), 620-626 (2019).

16. R.R. Rodrigues et al., Extreme compound events in the equatorial and South Atlantic. *Nature Communications* 16(1), 3183 (2025a).

17. R.R. Rodrigues, A.H. Gonçalves Neto, E.A. Vieira, G.O. Longo, The severe 2020 coral bleaching event in the tropical Atlantic linked to marine heatwaves. *Communications Earth & Environment* 6(1), 208 (2025b).

18. J.A.A. Perez, R. Sant'Ana, Tropicalization of demersal megafauna in the western South Atlantic since 2013. *Communications Earth & Environment* 3(1), 227 (2022).

6.2 Coastal and Oceanic Vulnerability and Resilience

Moacyr Cunha de Araujo Filho

The ocean warms up more slowly than the atmosphere, but it also cools down more slowly. As the heat stored in seawater is retained longer than in the atmosphere, ocean warming is a permanent and almost irreversible process. As a result of the continuous rise in ocean temperatures, particularly over the last 100 years, the ocean's ability to absorb excess carbon dioxide (CO2) from the atmosphere is decreasing. We are gradually losing an essential ally in the fight to reduce atmospheric carbon.

In fact, science warns that the "health" of the ocean is worse than previously thought and that time is rapidly running out to protect marine ecosystems. Two consequences of excess carbon uptake by the ocean are acidification (increased acidity) and deoxygenation (reduced oxygen levels) of the waters, which negatively impact marine life.

Acidification, for example, referred to as the "evil twin" of the climate crisis, occurs when carbon dioxide is absorbed by seawater. Excessive CO2 absorption reduces the concentration of calcium carbonate in seawater, harming life in coral reefs and other marine habitats. In severe cases, it can even dissolve the shells of molluscs such as oysters and mussels, which depend on these calcareous structures to survive.

Until recently, it was assumed that acidification had not exceeded its "planetary boundary"; however, a new study has shown that this boundary was reached in 2020 and even exceeded in some regions (1). Planetary boundaries are natural limits for essential global systems, such as climate and biodiversity, and exceeding them can jeopardize the ability to maintain a healthy planet. In the case of ocean acidification, global average conditions in 2020 were found to be very close to the acceptable limit for reducing calcium carbonate concentrations in seawater, with no more than a 20% decrease compared to pre-industrial revolution levels. In some regions, this limit was exceeded, resulting in a significant decline in important habitats, including tropical and subtropical coral reefs.

Experts emphasize that the only way to combat acidification worldwide is to reduce CO2 emissions.

The situation in coastal areas is no less critical, as this is where most human activity takes place. This region has become an arena where the effects of climate change are visible almost daily. Heat waves, exacerbated by an excessively warm ocean, put a strain on our cities and the health of coastal populations. Extreme rainfall events lead to flooding and landslides, and, no less seriously, the ongoing rise in sea levels is increasingly eroding our coastline, with a variety of negative consequences.

All these processes have led deaths and irreversible losses and are mainly due to the high vulnerability of our coastal areas. Vulnerability is the combination of the atypical impact of natural forces and our ability to cope with these new forces.

Given the apparent tendency to warm the planet beyond the 1.5°C target set out in the Paris Agreement, atypical natural forces are expected to become more frequent and intense by the end of the century. The most important question, therefore, is how we can reduce vulnerability and increase the resilience of our coastal areas.

For example, the observed sea level rise may exacerbate coastal erosion, contribute to flooding, and increase the influx of saltwater into coastal estuaries and underground aquifers, thereby making coastal infrastructure more susceptible to damage from extreme weather events.

The truth is that sea levels are not only rising globally, but the rate at which they are rising is also increasing. This rise is primarily due to the interaction of two main processes: the thermal expansion of water as it warms, and the addition of freshwater to the ocean from the melting of land-based ice sheets and glaciers.

According to the Sixth Assessment Report of the IPCC (Intergovernmental Panel on Climate Change) (2), the average rate of sea level rise, which was 1.3 mm per year between 1901 and 1971, increased to 3.7 mm per year between 2006 and 2018. In other words, the average rate of sea level rise has almost tripled in the last 10 years, compared to the rate recorded over the entire last century. Furthermore, global sea are expected to rise even faster than antecipated before 2024, primarily due to the ocean's overheating, which is attributed mainly to the expansion of seawater. In recent years, approximately two-thirds of the sea level rise has been attributed to the melting of ice sheets and glaciers, while about one-third has been due to the thermal expansion of seawater. In 2024, however, these contributions were reversed, and two-thirds of the sea level rise will be due to thermal expansion. According to an analysis conducted by the US space agency NASA, the rate of mean sea level rise in 2024 was 5.9 mm per year, higher than the expected 4.3 mm per year.

Brazilian science has made significant contributions to understanding the vulnerability and resilience of marine and coastal regions to climate change. About 180 scientific articles, books, and book chapters, mainly in the last 15 years, have been written by research teams from national science and technology institutions, especially by researchers from public universities and the Oceans and Coastal Zones Subnetworks of the Brazilian Global Climate Change Research Network (Rede Clima) and the Center for Synthesis on Environmental and Climate Change (SIMACLIM).

The most important points relate to the expansion of knowledge about:

1. The variability of the El Niño Southern Oscillation in the South Pacific and its remote influence on rainfall patterns in Brazil, and the associated socio-economic consequences.
2. The marine biogeochemistry of the carbon and oxygen cycle, with emphasis on studies of CO2 fluxes in estuaries, shelf areas, and the ocean region, and the processes of acidification and reduction of dissolved oxygen concentrations due to warming seawater.
3. The variability of the Atlantic Meridional Overturning Circulation (AMOC), the most important climate-regulating ocean current. The focus of Brazilian research is on the ocean region bordering the western edge of the tropical and southern Atlantic.
4. The fluctuations observed in the Amazon River-Ocean Continuum (AROC), the region where the Amazon River joins the Atlantic Ocean. Brazilian studies are investigating the balance of water, salt, nutrients, and heat in the tropical Atlantic as a result of climate change.
5. The variability in the occurrence and intensity of oceanic heat waves and their consequences for Brazilian cities.
6. Changes in the variability of ocean-atmosphere heat exchange in the tropical and southern Atlantic, resulting from climate change.
7. The role of the tropical Atlantic, South Atlantic, and Antarctic Oceans in the increasing intensity and frequency of extreme weather events (excessive rainfall and droughts) in different regions of Brazil and South America.

8. The variability of sea level rise at the western edge of the Atlantic Ocean, focusing on the analysis of future climate scenarios and the high vulnerability of the Brazilian coastal region.
9. The loss of Brazilian marine biodiversity due to climate change and the associated socio-economic impacts and consequences for ecosystem services.
10. The use of nature-based solutions as an adaptation strategy in the Brazilian coastal region, focusing on the establishment of marine protected areas associated with coral reef systems and mangroves.
11. The role, importance, technological and economic feasibility of the use of renewable marine energy (coastal and offshore wind, thermal conversion, currents, waves, and tides) as part of the ongoing energy transition in Brazil.

Also noteworthy is the participation of Brazilian marine scientists in the ocean chapter of the IPCC Sixth Assessment Report (2021), and the preparation of Brazil's third and fourth communications to the United Nations Framework Convention on Climate Change (UNFCCC). These documents included the assessment of national greenhouse gas emission inventories, updated climate projection scenarios, and a reassessment of vulnerabilities and adaptation measures for the country.

In terms of public policy, Brazilian marine scientists have actively participated in the coordination of the work of Working Group 1 on the Scientific Basis of Climate Change of the PBMC (Brazilian Panel on Climate Change) (2016-2017), Rede Clima (Brazilian Research Network on Global Climate Change) (2014-2025), CONAPA (National Committee for Antarctic Research) (2023-2025) and, more recently, in the creation and implementation of INPO – National Institute for Oceanic Research (2023-2024).

At the international level, Brazil's contributions to the development of the Atlantic Ocean Observing System Blueprint (2018-2019), the Tropical Atlantic Observing System - TAOS Review (2018-2021), the Atlantic Ocean Observing System Blueprint (2018-2019) and the Life Science Group of the Scientific Committee on Antarctic Research (SCAR), as well as the coordination of the PIRATA project – Prediction and Research Moored Array in the Tropical Atlantic (2014-2022), - are worth mentioning.

Finally, it is worth mentioning some recent works that represent the current state of Brazilian marine and climate science. These productions help to identify areas where policies can have the most significant impact on promoting ocean sustainability, in line with relevant Millennium Development Goals (SDGs), such as SDG 14 - Life Below Water (3, 4, 5). There are also contributions to understanding the Blue Economy as a driver for Brazil's development (6, 7), identifying the impacts of climate change on the Brazilian marine environment, and an overview of the circulation, biogeochemistry, and CO2 fluxes between the ocean and the atmosphere in the tropical Atlantic (8). There is also an assessment of Brazil's marine coasts in terms of biodiversity and ecosystem services (9, 10, 11) and a summary of points relevant to Brazil from the IPCC's Sixth Assessment Report, which covers various aspects of the latest findings on the challenge posed by climate change to the country (6, 12).

REFERENCES

1. H.S. Findlay, R.A. Feely, L.Q. Jiang, G. Pelletier, N. Bednarsek, Ocean Acidification: Another Planetary Boundary Crossed. *Global Change Biology* (2025), doi 10.1111/gcb.70238.

2. IPCC, "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change", V. Masson-Delmotte et al., Eds. (Cambridge University Press, 2021), doi:10.1017/9781009157896.

3. L.C. Da Cunha, L.Q. Pinho, G.A.O Moser, C. Russi, "*Por Um Oceano Sustentável*" in Políticas Públicas e os ODS da Agenda 2030, A. C. Warpechowski, H.H.A.M. Godinho, S.N. Iocken, Eds. (Fórum, 2021).

4. C. Cunha, "Coastal Nutrient Supply and Global Ocean Biogeochemistry" in Life Below Water. *Encyclopedia of the UN Sustainable Development Goals,* W. Leal Filho, A.M. Azul, L. Brandli, A.L. Salvia, T. Wall, Eds. (Springer, Cham. 2022). Disponível em: https://doi.org/10.1007/978-3-319-98536-7_115 [Acessado em 25 de junho de 2025].

5. M. Araujo et al., "Circulation, Biogeochemical Cycles and CO_2 Flux Variability in the Tropical Atlantic Ocean" in *Tropical Marine Environments of Brazil: Spatio-Temporal Heterogeneities and Responses to Climate Changes*, J. M. L. Dominguez, R. K. P. Kikuchi, M. Araujo, R. Schwamborn, H. Vital, Orgs. (Springer Nature 2023), v. 1, pp. 231-264.

6. M. Araujo, L.C. Cunha, G.A. Hounsou-Gbo, R.R. Rodrigues, C.A. D. Lentini, "Oceano e Clima: Novos Desafios Advindos com as Mudanças Climáticas" in *Economia Azul: Vetor para o Desenvolvimento do Brasil*, T. Santos, A. P. Beirão, M. C. Araujo, A. B. Carvalho, Orgs. (Essential Idea Editora Ltda, 2022), v. 1, pp. 397-430.

7. T. Santos, A.P. Beirão, M.C. Araujo, A.B. Carvalho, *Economia Azul: Vetor para o desenvolvimento do Brasil* (Essential Idea Editora, 2022). Disponível em: https://www.marinha.mil.br/sites/all/modules/livro_economia_azul/arquivo.pdf [Acessado em 25 de junho de 2025].

8. J.M.L. Dominguez, R.K.P. Kikuchi, M. Araujo, R. Schwamborn, H. Vital, *Tropical Marine Environments of Brazil* (Springer, 2023), 266 p., doi 10.1007/978-3-031-21329-8.

9. M.S. Copertino et al., "Histórico de Mudança e o Estado Atual da Biodiversidade da Zona Marinha-Costeira" in *1º Diagnóstico Brasileiro Marinho-Costeiro sobre Biodiversidade e Serviços Ecossistêmicos*, C.S. Seixas, A. Turra, B.P. Ferreira, Eds. (Plataforma Brasileira de Biodiversidade e Serviços Ecossistêmicos (BPBES) e Cátedra Unesco para a Sustentabilidade do Oceano, 2023), pp. 62-127, doi:10.4322/978-65-01-27749-3.

10. W.C. de Sousa Júnior WC et al., "Cenários de Transformação da Zona Marinha-Costeira" in *1º Diagnóstico Brasileiro Marinho-Costeiro sobre Biodiversidade e Serviços Ecossistêmicos*, C.S. Seixas, A. Turra, B.P. Ferreira, Eds. (Plataforma Brasileira de Biodiversidade e Serviços Ecossistêmicos (BPBES) e Cátedra Unesco para a Sustentabilidade do Oceano, 2023), cap. 04, pp. 170-217, doi 10.4322/978-65-01-27749-3.

11. C.S. Seixas, A. Turra, B.P. Ferreira, *1º Diagnóstico Brasileiro Marinho-Costeiro sobre Biodiversidade e Serviços Ecossistêmicos* (Plataforma Brasileira de Biodiversidade e Serviços Ecossistêmicos e Cátedra Unesco para a Sustentabilidade do Oceano, 2023).

12. C.A.W. C. Coelho et al., *Mudança do Clima no Brasil: Síntese Atualizada e Perspectivas para Decisões Estratégicas* (Ministério da Ciência, Tecnologia e Inovação, 2024),106 p. Disponível em: https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/cgcl/arquivos/Relatorio_Mudanca_Clima_Brasil_v2025.pdf [Acessado em 25 de julho de 2025].

ACKNOWLEDGEMENTS

Special recognition to the scientists from the Brazilian Network of Research on Global Climate Change (Climate Network) and the Center of Synthesis on Environmental and Climate Change (SIMACLIM) for their dedication and public commitment.

6.3 Ocean acidification

Leticia Cotrim da Cunha

We already know that climate change is unequivocally due to man-made greenhouse gas emissions. In addition to the rise in the Earth's average surface temperature, climate change, and changes in the water cycle, the whole ocean is also affected (1).

Around 90% of the excess heat caused by the accumulation of greenhouse gases in the atmosphere has already been absorbed by the ocean, and around a quarter of anthropogenic CO_2 emissions are also absorbed annually. These effects are now measurable and are unfortunately, irreversible on the timescale of human life (2). It is important to remember that, while we have sedimentary records of climate change in the planet's past, there is nothing comparable to the human-induced changes of the last 150 years. Records from the geologic past (on time scales of more than ten thousand years) show that processes of change, including acidification, lasted several thousand years (3).

The uptake of excess atmospheric CO_2 by the ocean leads to a reaction with seawater, which in turn leads to the formation of carbonic acid (H_2CO_3). This acid is chemically dissociated, lowering the pH of the seawater and reducing the availability of carbonate ions (CO_3^{-2}). Carbonate ions are important for many organisms, from microscopic phytoplankton to reef-building organisms such as corals (4) and other marine animals, such as molluscs, which have structures made of calcium carbonate ($CaCO_{3,}$ Figure 1).

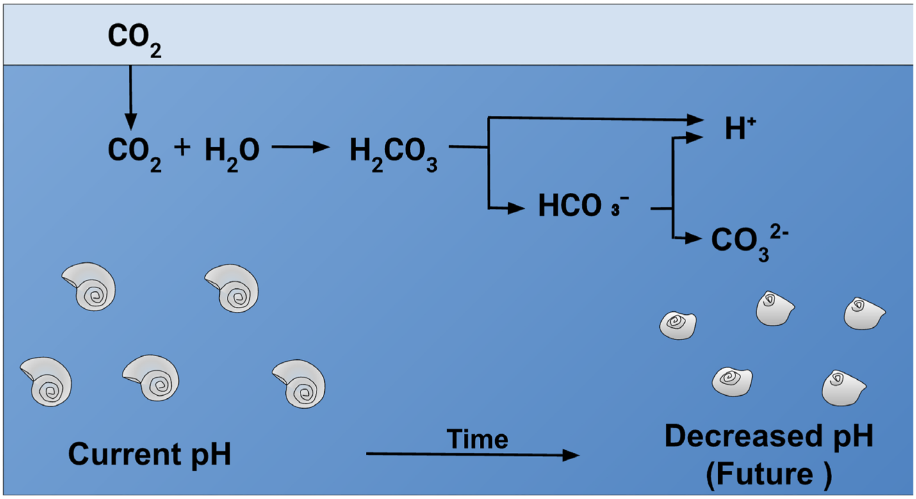


Figure 1: Chemical reaction between seawater and dissolved CO2: production of carbonic acid and its dissociation, leanding to acidification. Source: By Elizajans, Own work, CC BY-SA 4.0. Available at: https://commons.wikimedia.org/w/index.php?curid=79625305 [Last access 25th July, 2025].

In the Blue Amazon, we do not yet fully understand the effects of ocean acidification: This process requires continuous long-term observations, especially in coastal regions. However, we already know that the western equatorial part of the Atlantic shows a trend towards a decreasing pH of -0.001 pH units per year at the surface (5). This has been estimated from data collected by the buoy network PIRATA (Prediction and Moored Array in the Atlantic), a project that is being carried out for over 25 years in collaboration between Brazil, France, and the United States (6).

Further south in the Western Atlantic (7), a decrease in pH of about -0.17±0.07 (at depths influenced by the South Atlantic Central Water (ACAS), about 200 m) and -0.10±0.06 (at depths influenced by the Antarctic Intermediate Water (AIA), about 700 m) has been observed since the beginning of the industrial revolution.

From a global ocean perspective, the most recent analysis (8) of available data on ocean acidification shows that we have already crossed planetary boundaries that mark severe or even irreversible environmental changes within the time span of a human lifetime (9). About 40% of the ocean surface is already below the safe planetary boundary for carbonate ion availability (8) (see Figure 1), and about 60% of the subsurface layer of the ocean (up to 200 m depth) is already below this boundary compared to the pre-industrial state of the ocean. The most critical regions are the high latitudes, both in the south (the Southern Ocean, the strip of ocean surrounding the Antarctic continent) and in the north (the Arctic).

In Brazil, the topic of the “marine carbon cycle” and the associated aspects have been studied by various research groups for many years. Since 2012, however, the scientific community has organized itself around the topic of “ocean acidification,” and founded the BrOA Network – Brazilian Ocean Acidification Research Network, which is part of the global acidification research network, GOA-ON. The BrOA Network is active in various Brazilian marine ecosystems with researchers from more than 16 national research institutions, and in the Southern Ocean (10). In addition to the research itself, the BrOA network strives to ensure the excellence of its results by applying the best practices of the international scientific community in the analyzes required for acidification studies (11).

The BrOA network has identified coral reefs and carbonate platforms in the Blue Amazon— - i.e. those where calcium carbonate predominates in the bottom sediments — as areas that are sensitive to acidification. Examples include the rhodolith region, a type of macroalgae whose parts are composed of calcium carbonate, and the Royal Charlotte Bank, off the coast of Espírito Santo and southern Bahia. Other sensitive areas are estuaries and coastal ecosystems, that suffer from eutrophication. This exacerbates the effects of excess CO_2 in the water column, as microorganisms break down the organic matter contained in the sewage discharged into the sea, resulting in oxygen (O_2) depletion and increased CO_2 concentrations in the water (10).

The existence of long-term initiatives, such as the national program PELD (Long-Term Ecological Research) and the presence of coastal observatories and moored buoys (the SIMCosta system), is crucial for the diagnosis of acidification and the detection of trends (12). This type of initiative is also important for the detection and provision of data for the development of predictive models for isolated or combined heat waves and deoxygenation events, both at the coast (13) and in the oceanic regions of the South Atlantic (14).

To adapt to these events, the scientific community has long emphasized the importance of understanding the physical and chemical processes of acidification (among other issues related to climate change) and biodiversity, as well as using numerical modeling and early warning systems as adaptation strategies (15).

Reducing greenhouse gas emissions, even at the regional scale, should be pursued, as well as controlling pollution and eutrophication, processes that can exacerbate acidification (16). Studies are currently underway on measures to mitigate acidification that include the conservation of coastal ecosystems and so-called ‘mCDR’ (Marine Carbon Dioxide Removal) strategies, which involve the removal of carbon from the sea through the cultivation of macroalgae (17), the promotion of primary phytoplankton production in marine areas, as photosynthesis “captures” CO_2, converts it into biomass and exports it to the ocean interior (18), or the addition of alkalinity to the ocean (19, 20).

Any adaptation and/or mitigation measures will require national and regional public policies to combat climate change, including maritime spatial planning, as the Brazilian Blue Amazon is very heterogeneous and has regional specificities.

As explained earlier, ocean acidification is a serious problem with long-lasting consequences that extend beyond the human lifetime (21). In Brazil, the scientific community has highlighted the vulnerability of coastal ecosystems and is in the process of studying this problem (10-12). It has even identified acidification trends in water masses reaching the Brazilian continental margin (-0.10 to -0.17 pH units) (7), in the South Atlantic during events caused by marine heat waves (14), and in the equatorial ocean (-0.001 pH units per year) (5). And it shows ways to mitigate and adapt. In addition to the need for rapid and consistent reductions in carbon dioxide emissions, mitigation and adaptation measures are easier to implement, such as strategies to reduce eutrophication, conservation, the use of modeling in conjunction with long-term ecosystem monitoring and mCDR strategies: Growing macroalgal biomass, increasing phytoplankton production, or adding alkalinity to the ocean. However, it is also necessary to implement measures at different levels in government programs, including marine spatial planning, to consider the specificities and scale of the Blue Amazon.

REFERENCES

1. IPCC, “Summary for Policymakers” in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, V. Masson-Delmotte et al., Eds. (Cambridge University Press, 2021), pp. 3–32.

2. H.O. Pörtner et al., *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change* (2022), pp. 1–756. Disponível em: https://doi.org/10.1017/9781009157964 [Acessado em 25 de julho de 2025].

3. J.G. Canadell et al., “Global Carbon and Other Biogeochemical Cycles and Feedbacks” in *Climate Change 2021* – The Physical Science Basis, V. Masson-Delmotte et al., Eds. (Cambridge University Press, 2023), pp. 673–816.

4. S.C. Doney, V.J. Fabry, R.A. Feely, J.A. Kleypas, Ocean Acidification: The Other CO 2 Problem. Ann Rev Mar Sci 1, 169–192 (2009).

5. C.A.M. de Assis, L.Q. Pinho, A.M. Fernandes, M.Araujo, L.C.da Cunha, Reconstruction of the marine carbonate system at the Western Tropical Atlantic: trends and variabilities from 20 years of the PIRATA program. *Front Mar Sci* 11, 1286960 (2024).

6. B. Bourlès et al., PIRATA: A Sustained Observing System for Tropical Atlantic Climate Research and Forecasting. *Earth and Space Science* 6, 577–616 (2019).

6. M. de Carvalho-Borges, I.B.M. Orselli, M.L. de C. Ferreira, R. Kerr, Seawater acidification and anthropogenic carbon distribution on the continental shelf and slope of the western South Atlantic Ocean. *Journal of Marine Systems* 187, 62–81 (2018).

7. H.S. Findlay, R.A. Feely, L.Q. Jiang, G. Pelletier, N. Bednaršek, Ocean Acidification: Another Planetary Boundary Crossed. *Glob Chang Biol* 31, e70238 (2025).

8. J. Rockström et al., A safe operating space for humanity. Nature 461, 472–475 (2009).

9. R. Kerr et al., The Western South Atlantic Ocean in a High-CO_2 World: Current Measurement Capabilities and Perspectives. *Environ Manage* 57, 740–752 (2016).

10. A.R. Perretti, A.C.R. de Albergaria-Barbosa, R. Kerr, L.C. da Cunha, Ocean acidification studies and the uncertainties relevance on measurements of marine carbonate system properties. *Braz J Oceanogr* 66, 234–242 (2018).

11. G. Franz et al., Coastal Ocean Observing and Modeling Systems in Brazil: Initiatives and Future Perspectives. Front Mar Sci 8, 681619 (2021).

12. K.M. Brauko et al., Marine Heatwaves, Sewage and Eutrophication Combine to Trigger Deoxygenation and Biodiversity Loss: A SW Atlantic Case Study. *Front Mar Sci* 7 (2020).

13. R.R. Rodrigues et al., Extreme compound events in the equatorial and South Atlantic. *Nature Communications* 16, 1–15 (2025).

14. R.R. Rodrigues, A.H. Gonçalves Neto, E.A. Vieira, G.O. Longo, The severe 2020 coral bleaching event in the tropical Atlantic linked to marine heatwaves. *Commun Earth Environ* 6, 208 (2025).

15. E.A. Wolters et al., Shellfisheries' adaptation to ocean acidification in OR and CA: Linking strategies to strategic policy action. Mar Policy 171, 106484 (2025).

16. I. Eswar et al., Seaweed responses to ocean acidification: global impacts on growth, biochemical composition, and CO_2 mitigation potential. *Discover Oceans* 2, 19 (2025).

17. K.O. Buesseler et al., Next steps for assessing ocean iron fertilization for marine carbon dioxide removal. *Frontiers in Climate* 6, 1430957 (2024).

18. A.A. Anschütz et al., Direct effects of ocean alkalinity enhancement in the Baltic Sea–results from in-silico experiments. *Frontiers in Climate* 7, 1450468 (2025).

19. W. Yao et al., Exploring Site-Specific Carbon Dioxide Removal Options With Storage or Sequestration in the Marine Environment – The 10 Mt CO_2 yr−1 Removal Challenge for Germany. *Earths Future* 13, e2024EF004902 (2025).

20. N.L. Bindoff et al., "Changing Ocean, Marine Ecosystems, and Dependent Communities" in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, N.M.W.H.O. Pörtner et al., Eds. (2019).

6.4 Biodiversity

Margareth S. Copertino

Recent global warming is one of the greatest threats to marine life. Marine and coastal ecosystems are exposed to almost all the effects of climate change in the sea and on the coast. The increasingly warm, acidic, and low-oxygen ocean affects the metabolism, development, and interactions of marine organisms, and exposes them to environmental conditions that exceed their tolerance and acclimatization limits. The damage to biodiversity and ecological functions, in turn, has an impact on the goods and services that the ocean provides for society.

The Southwest Atlantic, the part of the ocean bordering Brazil, is one of the regions of the planet most affected by global warming (1). The intensification and southward shift of the Brazil Current (2), caused by the average increase in sea surface temperatures (3) and the warming of deep waters (4), is causing tropical species to move south in search of cooler waters and changing the routes of migratory animals. Recent temperature extremes and heat waves have increased coral bleaching and the incidence of opportunistic and harmful algal blooms. Water acidification, observed in coastal upwelling areas (Cabo Frio, RJ; Cabo de Santa Marta, SC) and along the northeast coast, threatens rhodolith beds and coral reefs (5,6). Along much of the Brazilian coast, sea level rise (between 1.8 and 4.2 mm per year since 1950, global average 4.7 mm between 2015 and 2024) (7, 8) is leading to an increase in wave energy and the frequency and intensity of extreme oceanographic events, exacerbating erosion and flooding.

The recent Marine-Coastal Assessment of the Brazilian Platform for Biodiversity and Ecosystem Services (DMC-PBBSE) has shown significant changes over the last 30 years, such as the loss of vegetated coastal habitats, the decline in the abundance of foundation species (which play a fundamental role in the formation of ecosystems), and changes in the structure of marine communities (9).

The effects of climate change in the Southwest Atlantic, combined with other anthropogenic factors, are altering the biodiversity of the Brazilian seashore from the emerged areas to the continental shelf (10, 11). Rocky coasts, sandy beaches, coastal bays and lagoons, mangroves, macroalgae beds, and seagrass beds have experienced changes in biodiversity and community structure. In addition to climate change, estuaries and large bays are experiencing rapid and intensive changes caused by numerous other influences such as habitat destruction, pollution, overfishing, tourism, and port development (12, 13).

The displacement of tropical species to extratropical regions is one of the most common consequences of rising temperatures. On the Brazilian coast, a southward expansion of the distribution limits of invertebrate species, fish, macroalgae, and seagrasses has been observed (11). In addition to the gradual warming of waters, marine heat waves in the southwest Atlantic (between Cabo Frio and Argentina) have affected the recruitment of invertebrate larvae and reduced fish catches (3, 13).

Coral bleaching has intensified in the last two decades, affecting more than 26 Brazilian coral species. In the 2019-2020 event, mortality in Abrolhos and Rocas Atoll reached 50% (14, 15), which is a warning about the future of these ecosystems.

At the boundary between land and sea, ecosystems are exposed to a variety of stressors, increasing their vulnerability to the effects of climate change. Between 2000 and 2020, Brazilian mangroves lost 2% of their forest cover (an average annual rate of -0.13%), and 12% of their apicuns (salt flats, sparsely or no-vegetated areas between mangroves and dry land) (16). These losses are primarily attributed to coastal erosion, extreme weather events, aquaculture, and salt extraction. In Pará State, rising sea level is causing mangroves to encroach on the mainland, particularly in the apicuns and wetlands (17). In the northeast, mangroves are encroaching into the estuaries due to reduced rainfall and salt intrusion (18), in addition to suffering from urbanization, shrimp farming, and resource exploitation (19, 20). In the southeast, the mangroves are squeezed between the ocean and the Serra do Mar mountain range and restricted by highways and urbanization, which will hinder their migration towards the continent. However, at the southern limit of its range (Laguna, SC), the mangrove is advancing across fields and marshes (grass-covered areas in estuaries), in response to global warming (21, 22).

Climate change is leading to altered less complex communities, colonized by opportunistic and exotic species, with invasive potential. The decline in stony coral and calcareous algal cover, followed by the increase in filamentous and foliaceous macroalgae, is a typical example of such changes in the tropical reefs of the Northeast, reducing the structural complexity of the system and opening space for colonization by invasive sun corals (*Tubastraea spp*.).

Aggregations of gelatinous animals, such as jellyfish, have increased worldwide and in Brazil, causing damage to fisheries and accidents to swimmers (23, 24). Large jellyfish alter the balance of food chains by consuming large amounts of zooplankton and fish (25).

The formation of a large *Sargassum* belt in the Central Atlantic, stretching from West Africa to the Caribbean and the Gulf of Mexico, is a typical example of this change, which has been considered the new normal since 2011 (26). The formation of this belt is linked to oceanographic changes and increased nutrient input from the Amazon basin and coastal upwelling in West Africa. Almost every year, large biomasses of algae build up and are transported to the coasts of the Americas, causing flooding and strandings of *Sargassum* seaweed on the beaches of the tropical Atlantic, including the north and northeast coasts of Brazil, with ecological, aesthetic, and tourism impacts (27).

The protection, conservation and restoration of coastal marine ecosystems increases resilience to climate change and contributes to adaptation and mitigation measures. Natural barriers formed by reefs, coastal dunes, mangroves, and marshes dissipate wave energy, and reduce the risk of erosion and flooding. The presence of reefs along the coast can mitigate the impact of increased waves by 46% in a one meter sea level rise scenario, while their absence would increase this risk to 76%. Mangroves can reduce vulnerability by 20%, while protecting the population at risk.

The conservation of carbon sinks and natural coastal barriers is an example of so-called nature-based solutions (NBS). The protection and restoration of mangroves removes excess carbon from the atmosphere and contributes to climate regulation. At the same time, it ensures the preservation of numerous ecosystem goods and services, that bring social and economic benefits. As coastal development and climate change intensify, the cost-benefit analysis of mitigation and adaptation measures is becoming increasingly urgent. In this respect, NBS are more economical and efficient, and fulfill multiple objectives: biodiversity and fisheries conservation, restoration of water quality, sequestration of greenhouse gases and reduction of the risk of flooding and coastal erosion. The implementation of a cost-effective combination of measures, combining NBS and technical solutions, can reduce the risk of losses by more than 50%.

The Brazilian coast has more than 2 million square kilometers of vegetated coastal ecosystems, such as mangroves, salt marshes, and seagrass beds (28). These ecosystems are important carbon sinks, referred to as "blue carbon" ecosystems. Those systems sequester atmospheric carbon dioxide (CO2) and store it as organic and inorganic carbon in their biomass, but most in the soils. If undisturbed, the buried carbon remains preserved in the aqueous soil for long periods of time. Brazilian mangroves store 8.4% of the Earth's total mangrove carbon (28, 29). Measurements of the net CO_2 flux at the interface between soil, vegetation and atmosphere showed the effectiveness of Brazilian mangroves and salt marshes in mitigating greenhouse gases (30, 31). The degradation and loss of these habitats not only reduces their ability to sequester carbon, but also causes greenhouse gas emissions (32, 33). The restoration and rehabilitation of mangroves therefore has the potential to generate additional carbon storage and/or avoid emissions, which can give great opportunity to Brazil in the international carbon market. However, regulatory frameworks between the public and private sectors still need to be established to attract investment in blue carbon and drive the restoration of Brazilian mangroves.

As we have seen, drastic and severe changes in Brazilian marine and coastal biodiversity have occurred in recent decades, driven by climate change, and exacerbated by other anthropogenic stressors. Understanding the different spatial responses, diversity, and heterogeneity of the Brazilian oceans remains a major challenge that needs to be addressed to prepare for future changes. Despite advances in research, there are numerous gaps that make impact assessment and attribution difficult. It is recommended to expand and strengthen continuous and integrated biodiversity monitoring programs, integration of climate and oceanographic data, predictive ecological modeling, ecosystem resilience assessment, and studies on the interactions between invasive species and native communities. Significant knowledge gaps at local and national levels require studies on how changes in biodiversity affect ecological functions, including the quantification of process flows and the assessment of ecosystem services provided by the sea.

REFERÊNCIAS

1. E. Popova *et al.*, From global to regional and back again: common climate stressors of marine ecosystems relevant for adaptation across five ocean warming hotspots. *Glob Change Biol* 22, 2038–2053 (2016).

2. H. Yang et al., Poleward shift of the major ocean gyres detected in a warming climate. *Geophys Res Lett* 47, e2019GL085868 (2020).

3. B.C. Franco *et al.,* Climate change impacts on the atmospheric circulation, ocean, and fisheries in the southwest South Atlantic Ocean: a review. Clim Change 162, 2359–2377 (2020).

4. C.S. Meinen, R.C. Perez, S. Dong, A.R. Piola, E. Campos. Observed ocean bottom temperature variability at four sites in the northwestern Argentine Basin: Evidence of decadal deep/abyssal warming amidst hourly to interannual variability during 2009–2019. *Geophys Res Lett* 47, e2020GL089093 (2020).

5. A. Piñango *et al.*, Ocean acidification and long-term changes in the carbonate system properties of the South Atlantic Ocean. *Glob Biogeochem Cycles* 36, e2021GB007196 (2022).

6. R.T. de Carvalho *et al.*, Global assessment of coralline algae mineralogy points to high vulnerability of Southwestern Atlantic reefs and rhodolith beds to ocean acidification. *Sci Rep* 12, 9589 (2022).

7. WMO, *World Meteorological Organization State of the Global Climate,* (2025). 55 p.

8. A. Bella-Manley, R.S. Nerem, B.D. Hamlington. Extrapolation of the satellite altimeter record to understand regional variations in future sea level change. *J Geophys Res Oceans* 130(5), e2024JC022094 (2025).

9. C.S. Seixas, A. Turra, B.P. Ferreira, Eds. *1º Diagnóstico Brasileiro Marinho-Costeiro sobre Biodiversidade e Serviços Ecossistêmicos* (Plataforma Brasileira de Biodiversidade e Serviços Ecossistêmicos (BPBES) e Cátedra Unesco para a Sustentabilidade do Oceano, 2024).

10. A. Turra, M.R. Denadai, Linking biodiversity and global environmental changes in Brazilian coastal habitats. *Braz J Oceanogr* 64, 3–4 (2016).

11. M.S. Copertino et al., “Histórico de mudança e o estado atual da biodiversidade da zona marinha-costeira” in *1º Diagnóstico Brasileiro Marinho-Costeiro sobre Biodiversidade e Serviços Ecossistêmicos*, C.S. Seixas, A. Turra, B.P. Ferreira, Eds. (Plataforma Brasileira de Biodiversidade e Serviços Ecossistêmicos – BPBES e Cátedra Unesco para a Sustentabilidade do Oceano, 2024), pp. 62–127, doi:10.4322/978-65-01-27749-3.cap02.

12. L. Travassos et al., “Vetores de mudança da biodiversidade e serviços ecossistêmicos da zona marinha-costeira” in *1º Diagnóstico Brasileiro Marinho-Costeiro sobre Biodiversidade e Serviços Ecossistêmicos*, C.S. Seixas, A. Turra, B.P. Ferreira, Eds. (Plataforma Brasileira de Biodiversidade e Serviços Ecossistêmicos – BPBES e Cátedra Unesco para a Sustentabilidade do Oceano, 2024), pp. 128–169, doi:10.4322/978-65-01-27749-3.cap03.

13. W.C. de Sousa Júnior et al., “Cenários de transformação da zona marinha-costeira” in *1º Diagnóstico Brasileiro Marinho-Costeiro sobre Biodiversidade e Serviços Ecossistêmicos*, C.S. Seixas, A. Turra, B.P. Ferreira, Eds. (Plataforma Brasileira de Biodiversidade e Serviços Ecossistêmicos – BPBES e Cátedra Unesco para a Sustentabilidade do Oceano, 2024), pp. 170–217, doi:10.4322/978-65-01-27749-3.cap04.

14. L.C.L. Ferreira et al., Different responses of massive and branching corals to a major heatwave at the largest and richest reef complex in South Atlantic. *Mar Biol* 168(54), (2021).

15. T.L. Gaspar et al., Severe coral bleaching of Siderastrea stellata at the only atoll in the South Atlantic driven by sequential marine heatwaves. *Biota Neotrop* 21(2), e20201131 (2021)

16. MapBiomas, *Projeto MapBiomas. Mapeamento anual de cobertura e uso da terra na zona costeira*, (Coleção 7, 2022). Disponível em: https://brasil.mapbiomas.org/2022/11/18/radiografia-da-costa-brasileira-nos-ultimos-37-anos-manguezais-estaveis-praias-e-dunas-em-retracao/ [Acessado em 11 de novembro de 2024].

17. M.C. Cohen, A.V. de Souza, D.F. Rossetti, L.C. Pessenda, M.C. França, Decadal-scale dynamics of an Amazonian mangrove caused by climate and sea level changes: Inferences from spatial–temporal analysis and digital elevation models. *Earth Surf Process Landf* 43(14), 2876–2888 (2018).

18. T.C. Jennerjahn *et al.*, “Mangrove ecosystems under climate change” in Mangrove Ecosystems: *A Global Biogeographic Perspective: Structure, Function, and Services*. Cham: (Springer, 2017), pp. 211–244.

19. L. Pelage, G. Domalain, A.S. Lira, P. Travassos, T. Frédou. Coastal land use in Northeast Brazil: mangrove coverage evolution over three decades. *Trop Conserv Sci* 12, 1940082918822411 (2019).

20. D.N. Bryan-Brown *et al.,* Global trends in mangrove forest fragmentation. *Sci Rep* 10, 7117 (2020).

21. A.E. Torres *et al.*, A 1500-year multi-proxy record of subtropical mangrove dynamics in relation to sea level and climate changes on Babitonga Bay, Southern Brazil. *Holocene* 34, 387–399 (2024).

22. M.C. França *et al.*, Late-Holocene subtropical mangrove dynamics in response to climate change during the last millennium. *Holocene* 29, 445–456 (2019).

23. C. Resgalla *et al.*, Outbreaks, coexistence, and life cycle of jellyfish species in relation to abiotic and biological factors along a South American coast. *Hydrobiologia* 839, 87–102 (2019), doi:10.1007/s10750-019-03998-0.

24. V. Haddad Junior, A.C. Morandini, L.E. Rodrigues. Jellyfish blooms causing mass envenomations in aquatic marathonists: report of cases in S and SE Brazil (SW Atlantic Ocean). *Wilderness Environ Med* 29, 142–145 (2018), doi:10.1016/j.wem.2017.09.012.

25. R.M. Nagata, A.C. Morandini. Diet, prey selection, and individual feeding rates of the jellyfish Lychnorhizalucerna (Scyphozoa, Rhizostomeae). *Mar Biol* 165, 1–17 (2018), doi:10.1007/s00227-018-3445-5.

26. N.F. Putman *et al.,* Systems to monitor and forecast pelagic Sargassum inundation of coastal areas across the North Atlantic: present tools and future needs. *Harmful Algae* 123, 102933 (2025).

27. M.N. Sissini *et al.*, The floating Sargassum (Phaeophyceae) of the South Atlantic Ocean – Likely scenarios. *Phycologia* 56, 321–328 (2017), doi:10.2216/16-92.1.

28. V. Hatje *et al.*, Vegetated coastal ecosystems in the Southwestern Atlantic Ocean are an unexploited opportunity for climate change mitigation. *Commun Earth Environ* 4, 160 (2023), doi:10.1038/s43247-023-00828-z.

29. A.S. Rovai, R.R. Twilley, T.A. Worthington, P. Riul. Brazilian mangroves: blue carbon hotspots of national and global relevance to natural climate solutions. *Front For Glob Change* 4, 787533 (2022), doi:10.3389/ffgc.2021.787533.

30. R.B. Souza et al., Salt marsh-atmosphere CO_2 exchanges in Patos Lagoon Estuary, southern Brazil. *Front Mar Sci* 9, 892857 (2022).

31. A.S.C. Freire, M.I. Vitorino, A.M.L. de Souza, M.F. Germano, Analysis of the energy balance and CO_2 flow under the influence of the seasonality of climatic elements in a mangrove ecosystem in Eastern Amazon. *Int J Biometeorol* 66, 647–659 (2022).

32. J.B. Kauffman et al., Shrimp ponds lead to massive loss of soil carbon and greenhouse gas emissions in northeastern Brazilian mangroves. *Ecol. Evol.* 8, 5530–5540 (2018).

33. L.D. Lacerda et al., 20-years cumulative impact from shrimp farming on mangroves of Northeast Brazil. *Front. For. Glob. Change* 4, 653096 (2021).

6.5 Coral Reefs

Beatrice Padovani Ferreira

Coral reefs are diverse and complex marine ecosystems, whose structure is mainly formed by the activity of corals and other benthic animals that produce calcareous skeletons. When these are secreted, they coalesce and accumulate, forming complex structures that are distributed throughout the tropical ocean. Although they occupy only 0.1 % of the ocean floor, reefs are estimated to harbor about 25 to 30 % of all known marine species (1). Their diversity is comparable to that of tropical forests, and their importance goes far beyond biodiversity: they sustain human communities, provide food through fishing, support tourism, produce bioactive compounds with pharmaceutical potential, and protect coasts from wave erosion. Estimates for Brazil show that coral reefs generate up to R$167 billion for Brazil in the form of conservation and tourism (2).

Despite their ecological and economic importance, the reefs are exposed to serious threats. These include the damage caused by human intervention that has been observed for decades, as well as the ever-increasing effects of climate change (3). Since the 1980s, rising sea surface temperatures due to global warming have caused unprecedented coral bleaching, threatening their survival and the goods and services they provide (4). Four global mass bleaching events have already been recorded, with two occurring within the last decade (5).

In addition, ocean acidification, caused by the increased uptake of atmospheric CO_2 by seawater, is affecting the calcification of coral skeletons and negatively impacting the growth and resilience of reef structures (6). Synergistic interactions among heat stress, acidification, eutrophication, overfishing, and pollution exacerbate the vulnerability of reefs and impede their recovery (7).

Brazil is home to the only shallow coral reefs in the South Atlantic (8). Shallow reef formations are found on oceanic islands and along the Brazilian coast, from Maranhão to southern Bahia (8, 9), and include recently described formations in Espírito Santo (10). The reefs along the

Brazilian coast have low diversity but a high degree of endemism — up to 50% — and unique forms that are already extinct in other parts of the world and are therefore considered “relicts” (9). Studies have shown that, in addition to corals, other anabolic organisms, such as calcareous algae (11) and bryozoans, small invertebrates that played a surprising role in the formation of the Abrolhos Bank, off the coast of Bahia, make an important contribution to the uniqueness of Brazilian reef formations (12).

In addition to the shallow reefs, which are the best explored and most accessible, mesophotic reefs occur at greater depths, generally between 30 and 150 meters. They are found on the middle and outer continental shelf from the north (13) to the northeast (14, 15), and east (9) coasts. These formations, which were created during the last ice age, did not accompany the rise in sea level at the end of the Pleistocene and are referred to as give-up reefs (8, 14). The so-called Amazonian reefs are examples of mesophotic reefs that are ecologically connected to other reef systems at the edge of the northeastern continental shelf (15) and form a deep corridor of biodiversity (16) that has formed and evolved in response to sea-level dynamics and specific oceanographic conditions.

Brazilian reefs have historically been affected by direct coral removal and increased sedimentation resulting from Atlantic Forest deforestation and agricultural activities, as well as unregulated fishing and tourism (8). In recent decades, despite efforts to protect the reefs, land-based pressures such as accelerated coastal development, increased sewage and pollutant inputs, and the invasion of exotic species have exacerbated the pressure on these habitats.

However, climate change poses the greatest threat. Persistent anomalous temperatures have increased in frequency and duration (17), with heatwaves occurring five times more frequently (18). This intensification has led to bleaching events causing high mortality rates in the most vulnerable coral species, including endemic and threatened species (19, 18).

Corals form a symbiotic relationship — a relationship that benefits both organisms involved with a particular type of dinoflagellate known as zooxanthellae, which live within their cells. Through photosynthesis, the zooxanthellae provide energy and receive carbon dioxide and nutrients from their host. It is estimated that this symbiotic relationship has existed for millions of years (20). Rising water temperatures cause corals to expel their zooxanthellae, which are responsible for their coloration and the main source of their energy, leading to bleaching and possible death.

Since 2023, the world has been experiencing the fourth and most severe mass bleaching of reefs ever recorded. According to the International Coral Reef Initiative (ICRI), 84% of global reefs were already affected in March 2025. According to the IPCC, between 70% and 90% of reefs could disappear if the average global temperature rises by 1.5°C. With a 2°C increase, the loss could reach 99% (21).

Brazilian science on coral reefs has its roots in pioneering studies conducted in the 1960s and 1970s (9). A key milestone was the 1997 Workshop on Brazilian Coral Reefs: Research, Integrated Management, and Conservation, which brought together experts from across the country and strengthened the link between science, public policy, and conservation (22). These efforts have also influenced environmental legislation. Since then, scientific and institutional mobilization has increased. New technologies have enabled advances in mapping shallow and deep regions (23, 24), discovering reef formations (25), detailing little-known and already threatened areas (26, 13), synthesizing knowledge on fisheries and restoration (27, 28), assessing recent warming scenarios and prospects for the tropical South Atlantic (29, 18), and studies on changes in symbiont composition (30, 31). In addition, ongoing monitoring initiatives have promoted Brazilian participation in the reports of the Global Coral Reef Monitoring Network (GCRMN) (32), which is linked to ICRI, and in which the Ministry of Environment plays the central role.

Heatwaves in the tropical Atlantic have increased in frequency, intensity, duration, and spatial extent (19), a prediction confirmed by the extreme event of 2024. This scenario is occurring at a time when the impact of activities carried out without due regard for the environment is intensifying. Given the global scenario, understanding these interactions is crucial for enhancing reef resilience and informing conservation and restoration efforts.

In this sense, many scientific advances have been driven by government programs, such as those of the ministries of Environment and Science, Technology, and Innovation, as well as the CNPq (National Council for Scientific and Technological Development). Notable programs include the long-term ecological program PELD/CNPq, which has several sites in coral reef areas, conducting long-term monitoring and research, and the National Institutes of Science and Technology (INCTs), with nationwide biodiversity coverage, such as the INCT Amb Trop and the Biodiversity of the Blue Amazon, as well as SinBiose. Strengthening these and other programs, as well as integrated and collaborative science, is essential to underpin conservation and adaptation measures in the current scenario.

The National Strategy for the Protection and Sustainable Use of Coral Reefs (ProCoral), adopted in 2025, aims to implement, guide, formulate, and coordinate an integrated public policy for the protection, sustainable use, and restoration of coral reefs. The creation and effective management of marine protected areas to protect vulnerable areas and promote the natural regeneration of ecosystems is just as important as promoting the engagement of coastal communities and valuing their knowledge and resilience. Environmental education and citizen science also play a fundamental role in long-term conservation.

The future of coral reefs depends on the actions we take now. There is an urgent need to reduce carbon emissions, tackle pollution, restore coastal ecosystems, and strengthen ocean governance. Protecting reefs means protecting marine biodiversity, the livelihoods of those who depend on the ocean's resources, and the planet's climate balance. It is still possible to prevent the collapse of these extraordinary ecosystems - provided that science, politics, and society act together.

REFERENCES

1. R. Fisher *et al.*, Species richness on coral reefs and the pursuit of convergent global estimates. *Current Biology* 25(4), 500-505 (2015).

2. Fundação Boticário, Oceano sem mistérios – Desvendando os recifes de corais, (Fundacao Grupo Boticario, 2024). Disponível em https://fundacaogrupoboticario.org.br/wp-content/uploads/2024/11/OsM_outubro-3_leve31-10-23.pdf [Acessado em 25 de julho de 2025].

3. T.P. Hughes *et al*., Global warming and recurrent mass bleaching of corals. *Nature* 543(7645), 373-377 (2017).

4. O. Hoegh-Guldberg, E.S. Poloczanska, W. Skirving, S. Dove, Coral reef ecosystems under climate change and ocean acidification. *Frontiers in marine science* 4, 252954 (2017).

5. J.D. Reimer *et al*., The fourth global coral bleaching event: where do we go from here? *Coral Reefs* 43(4), 1121-1125 (2024).

6. J.S. Kikstra *et al.*, The IPCC Sixth Assessment Report WGIII climate assessment of mitigation pathways: from emissions to global temperatures. *Geoscientific Model Development* 15(24), 9075-9109 (2022).

7. T.P. Hughes *et al.*, Global warming and recurrent mass bleaching of corals. *Nature* 543(7645), 373-377 (2017).

8. M. Maida, B. Ferreira, “Coral Reefs of Brazil: Overview and field guide” in Proc. *8th Int Coral Reef Sym.*, (1), 263-274 (1997).

9. Z.M. Leão *et al.*, Brazilian coral reefs in a period of global change: A synthesis. *Brazilian Journal of Oceanography* 64(spe2), 97-116 (2016).

10. E.F. Mazzei *et al.*, Newly discovered reefs in the southern Abrolhos Bank, Brazil: Anthropogenic impacts and urgent conservation needs. *Marine pollution bulletin* 114(1), 123-133 (2017).

11. M.A. Oliveira de Figueiredo, M. Abreu, P.A. Horta, A.G. Pedrini, J.M.C. Nunes, Benthic marine algae of the coral reefs of Brazil: a literature review. *Oecologia Brasiliensis* 2(12), 7-11 (2008).

12. L.V. Ramalho et al., Bryozoan framework composition in the oddly shaped reefs from Abrolhos Bank, Brazil, southwestern Atlantic: taxonomy and ecology. *Zootaxa* 4483(1), 155-186 (2018).

13. R.L. Moura *et al.*, An extensive reef system at the Amazon River mouth. *Science Advances* 2(4), e150125 (2016).

14. J.M.R. Camargo, T.C.M. Araújo, B.P. Ferreira, M. Maida, Topographic features related to recent sea level history in a sediment-starved tropical shelf: Linking the past, present and future. *Regional Studies in Marine Science* 2, 203-211 (2015).

15. M.O. Soares, T.C.L. Tavares, P.B.M. Carneiro, Mesophotic ecosystems: Distribution, impacts and conservation in the South Atlantic, *Diversity and Distributions* 25.2, 255-268 (2019).

16. G. Olavo, P.A. Costa, A.S. Martins, B.P. Ferreira, Shelf‐edge reefs as priority areas for conservation of reef fish diversity in the tropical Atlantic. *Aquatic conservation: marine and freshwater ecosystems* 21(2), 199-209 (2011).

17. G.L.X. da Silva, M. Kampel, T. Nakamura, Thirty years of coral bleaching in the Southwestern Atlantic Ocean: a historical assessment based on degree heating week indices. *Coral Reefs*, 1-15 (2025).

18. R.R. Rodrigues, A.H. Gonçalves Neto, E.A. Vieira, G.O. Longo, The severe 2020 coral bleaching event in the tropical Atlantic linked to marine heatwaves. *Communications Earth & Environment* 6(1), 208 (2025).

19. T.J. Vidal *et al.*, Mortality patterns and recovery challenges in Millepora alcicornis after mass bleaching event on Northeast Brazilian reefs. *Marine Environmental Research* 204, 106864 (2025).

20. T.C. LaJeunesse et al., Systematic revision of Symbiodiniaceae highlights the antiquity and diversity of coral endosymbionts. *Current Biology* 28(16), 2570-2580 (2018).

21. National Oceanic and Atmospheric Administration (NOAA), International Coral Reefs Initiative (ICRI), 2024. Disponível em: https://icriforum.org/news-4gbe/. [Acessado em 28 de julho de 2025].

22. B.P. Ferreira, M. Maida, Monitoramento dos Recifes de Coral do Brasil. Situação Atual e Perspectiva. *MMA* (1), 120 (2006).

23. A.P.L. Prates, *Atlas dos recifes de coral nas unidades de conservação brasileiras* (Ministério do Meio Ambiente/Secretaria de Biodiversidade e Florestas, 2003).

24. C.B.L. da Silveira, G. M. R. Strenzel, M. Maida, B.P. Ferreira, Pushing satellite imagery to new depths: Seascape feature mapping in a tropical shelf. Remote Sensing Applications: *Society and Environment* 19, 100345 (2020).

25. E.F. Mazzei *et al.*, Newly discovered reefs in the southern Abrolhos Bank, Brazil: Anthropogenic impacts and urgent conservation needs. *Marine Pollution Bulletin* 114(1), 123-133 (2017).

26. R.B. Francini-Filho *et al.,* Perspectives on the Great Amazon Reef: extension, biodiversity, and threats. *Frontiers in Marine Science* 5, 142 (2018).

27. L. Eggertsen *et al.*, Complexities of reef fisheries in Brazil: a retrospective and functional approach. *Reviews in Fish Biology and Fisheries* 34(1), 511-538 (2024).

28. M. Mies *et al.,* Challenges for coral restoration in Southwestern Atlantic reefs: guidelines for ethical and sustainable practices. *Biodiversity and Conservation*, 1-27 (2025).

29. G.L.X. da Silva, M. Kampel, T. Nakamura, Thirty years of coral bleaching in the Southwestern Atlantic Ocean: a historical assessment based on degree heating week índices. *Coral Reefs*, 1-15 (2025).

30. L.B. Villela *et al.*, Bacterial and Symbiodiniaceae communities' variation in corals with distinct traits and geographical distribution. *Scientific Reports* 14(1), 24319 (2024).

31. L.B. Villela, Y.R. Aiube, A.W. Silva-Lima, R.L. Moura, P.S. Salomon. Climate-driven introduction of an opportunistic symbiont in the most extensive reef system of the Southwestern Atlantic Ocean (2024).

32. B.P. Ferreira *et al.*, «Status and trends of coral reefs of the Brazil region» in D. Souter *et al.*, Eds. *Status of coral reefs of the world: 2020 Report* (International Coral Reef Initiative, 2021).

6.6 Fishery and Aquaculture

Flávia Lucena Frédou, Ronaldo Olivera Cavalli

Brazilian fish production is a strategic activity for socio-economic development, food security, and regional development. However, the impact of climate change poses growing challenges to the sector, such as the development of more efficient and sustainable technologies and management systems that contribute to climate change mitigation and adaptation.

Fisheries and aquaculture are important sources of food, employment, and income for hundreds of millions of people worldwide. Contrary to popular belief, the most produced, consumed, and traded animal protein in the world is not chicken, pork, or beef, but fish. In 2022, global fish production (fisheries and aquaculture combined) was estimated at 185.4 million tons (1). In recent years, global fish production has been evenly split between fisheries and aquaculture. However, given population growth and stagnating fishing volumes, it is expected that the supply of edible fish from aquaculture will need to increase further to meet future global demand.

In Brazil, the statistical situation is less clear, as there has been no official data since 2011, when the last bulletin from the Ministry of Fisheries and Aquaculture (MPA) was published. The uncertainty of the statistics mainly concerns fishing, with its different modalities (industrial fishing, artisanal fishing) and the many landing sites along the large Brazilian coast and the extensive network of rivers in the North region, the region with the largest continental fish production.

Fishing is a traditional activity in Brazil, with historical, cultural, economic, and nutritional importance. Although it represents only a small part of the national GDP, it is crucial for the food security of millions of Brazilians, especially in traditional communities. In 2018, Brazilian fish consumption was estimated at 9.75 kg/person/year.

Fishing is practiced in a variety of ecosystems — from the continental environment to the deep sea - and uses more than 70 methods, such as gillnets, lines, and traps, to catch fish, crustaceans (such as shrimps, crabs, lobsters, and crayfish), and molluscs (such as oysters, cockles, and mussels). The latest MPA report showed a total national production of 1,431,974.4 tons, with marine fisheries accounting for 553,670.0 tons (38.7% of the total catch), followed by inland aquaculture (544,490.0 tons; 38.0%), inland marine fisheries (249,600.2 tons; 17.4%), and marine aquaculture (84,214.3 tons; 5.9%). Artisanal fisheries dominated, producing more than half of the total national fish catch (2), with fishermen from the Northeast standing out, with 31.7% of the catch.

In aquaculture, the statistical landscape is more recent. Since 2013, the Brazilian Institute of Geography and Statistics (IBGE) has provided official statistics on the sector. Between 2013 and 2023, aquaculture production increased by 66.6% - from 488.6 thousand tons to 813.7 thousand tons (3). Aquaculture therefore represents one of the most promising opportunities, especially in Brazil, which has approximately 8,500 km of coastline with several estuaries and an Exclusive Economic Zone (EEZ), great biodiversity, a large consumer market and a solid scientific community that supports the sustainable use of marine ecosystems (4).

The figures seem to indicate that Brazil is following the global trend of fisheries production being surpassed by aquaculture. However, the lack of statistical data on fisheries calls for caution in this comparison. As we do not have up-to-date and reliable data on the quantities of fish caught in Brazil in recent years, it is difficult to estimate the proportional share of fisheries and aquaculture in the country.

In both cases, however, the effects of climate change have raised concerns about the stability and profitability of fisheries production. Rising water temperatures, changing precipitation patterns, ocean acidification, sea level rise and the occurrence of extreme events are threatening water quality, and the productivity and health of aquatic organisms (5).

Rising temperatures and changing precipitation patterns can reduce species growth and, thus productivity, both in aquaculture farms and in the wild. Being poikilothermic (their body temperature fluctuates with the environment), fish, crustaceans, and molluscs have an ideal temperature range for their development, feeding, metabolism, and reproduction. Therefore, higher temperatures can accelerate growth, but also negatively affect the immune system and increase susceptibility to diseases and parasites (6). Fluctuations in salinity due to flooding, water stress, or rising sea levels can lead to osmotic stress and also affect species performance.

Similarly, climate change can influence the dynamics of marine ecosystems. Rising temperatures favor harmful algal blooms and can lead to the accumulation of biotoxins in molluscs, which is increasingly leading to marketing bans in the country's main production areas (7). Warming also leads to lower concentrations of dissolved oxygen, which worsens conditions for species development. Water acidification, caused by the absorption of excess CO2 from the atmosphere, impairs essential physiological processes in fish, crustaceans, and molluscs, such as skeletal calcification and the formation of shells and valves.

In the case of aquaculture, it is already known that changes in rainfall patterns and surface runoff affect water quality for this activity. Periods of prolonged drought and flooding have a direct impact on the estuaries, where much of Brazil's shrimp and mangrove oysters are farmed. Cyclones and flooding caused by above-average rainfall can also affect fixed structures, such as shrimp farms, oyster tables, rafts, and longlines, causing significant losses to producers in different regions of the country, including structural losses, dead animals and supply chain impacts.

The effects of climate change can impact fish production, and affect millions of workers, especially the most vulnerable. Almost 2 million fishermen are registered in the fishing sector, with the states of Maranhão, Pará, Bahia, and Amazonas employing the most people in this activity (2). In terms of gender, women represent around 50% of the total, but dominate in the northeastern region. In terms of vessels, there are just over 28,000 registered (2), mostly small ones. It is estimated that the number of vessels in coastal/marine fisheries in Brazil is much higher. There is not even a fleet registration program for inland fishing. Therefore, the number of vessels in Brazil is unknown.

In 2023, there was a breakthrough in the availability of fisheries data, with the publication of studies by researchers who assessed stocks in 70 of Brazil's 135 marine fisheries (8). To overcome the lack of data, the researchers used a new family of models called "data-poor," that can model stocks in a way that requires little information. The studies showed that regions in the south and southeast concentrate the largest number of marine fisheries and those, are proportionally more regulated, compared to regions in the north and northeast. Although the assessed stocks represent only just over 50% of the total, this progress was seen as a leap forward in knowledge after a long period of scarcity, a veritable "blindness" in relation to marine resources. However, of the stocks assessed, more than 60% are in a critical situation of overfishing, meaning that the current biomass is less than the biomass required to maintain the stock at a sustainable levels.

The MPA announced measures to resume marine fisheries statistics in Brazil, including the historical reconstruction of landings data from 1950 to 2022, and the resumption of marine fisheries statistics in regions with critical temporal and spatial gaps. In addition, the MPA has been re-registering fishermen (both at sea and inland) since 2023 and has launched the National Program for the Regularization of Fishing Vessels (PROPESQ), which aims to regularize and update information on fishing vessels.

The gap in the country's fisheries data collection leads to a weakness in the management of Brazil's marine resources. Less than 10% of the assessed stocks have a management plan, and only slightly more than half have regulatory measures, such as quotas (limits), closed seasons for harvesting and size restrictions [8]. Furthermore, it should be noted that many of these regulations only apply to target species, i.e. those of direct interest to fisheries. There is a large amount of so-called "bycatch"," i.e. species that are caught incidentally — either because they are unwanted or have no commercial value. These include whales, dolphins, sharks, and other species that are not commercially traded. Only 12% of fisheries are required to take measures to reduce or mitigate bycatch (5).

The ability of the aquatic environment to respond to environmental changes, maintain ecosystem functions, and preserve the sustainability of the resources used by fisheries is limited. In addition to the threat of overfishing, this activity is threatened by various impacts such as pollution from pesticides, heavy metals, and plastics. The warming of the oceans and the resulting climate change exacerbate this scenario, and have a significant impact on fishing activities. In tropical regions, such as Brazil, catches could fall by up to 40 % by 2050 (9).

The decline in the availability of certain species may be a result of either overfishing or climate change. Or even a combination of both. This has already been proven for the shrimp fisheries in Brazil (10). In the Northeast, as droughts worsen, the amount of mud, that provides nutrients for shrimps, decreases. Models simulated an increase in fishing effort and an increase in drought to see the response of biomass and catch. This showed that the combined effect of the two factors was even worse than either one individually.

Fisheries resources can also be affected by the migration of species in search of optimal temperatures for their functioning, thus altering the potential of a given site (11). A well-known example: a small tuna, species traditionally fished in the northeast is expanding its range, and moving south in search of cooler waters. It will soon reach Uruguay and Argentina, which will require negotiations on joint management between the three countries.

There are also social impacts, as the environmental effects are not evenly distributed among the population, with the marginalized and historically invisible part being the most affected. In this case, these are small traditional communities, that practice artisanal fishing.

The conservation of fisheries resources depends on a structured project of fisheries statistics and the valuation of marine and continental resources, the latter being practically invisible in public policies. Existing measures are too weak to form the basis of a long-term project, as they are initiatives that are discontinued at the end of a funding cycle or a change of government. Institutional instability and gaps in fisheries statistics lead to poorly managed fisheries. The lack of adequate management creates risks. This also applies to other impacts, particularly those of climate change.

With the exception of a few specific studies, Brazilian science has been timidly dedicating itself to studying the impact of climate change on fisheries and aquaculture. Consequently, technical and scientific knowledge of Brazilian conditions is limited. This is also true for aquaculture, a newer activity that is inherently easier to manage and collect data to support research and action. While there are some studies on temperature and salinity tolerance, and adaptive management, maps of climate vulnerability by region and species are unknown. Local climate monitoring systems that are integrated into production do not exist. The lack of real-time data and predictive models limits the ability of aquaculture farmers to respond to sudden climate changes. Significant gaps in public policy remain, as although Brazil has a National Policy on Climate Change (PNMC) (12), aquaculture and fisheries are only included in adaptation strategies to a limited extent.

Addressing the challenges of climate change requires a variety of adaptation and mitigation measures, that need to be tailored to regional circumstances, as different threats require different adaptation options. In the case of aquaculture, improving management practices is the first step towards climate adaptation, in particular improving biosecurity, considering lower stocking densities, and ensuring appropriate siting of production areas. In this sense, implementing best management practices

(BMPs) in all aspects of aquaculture production will improve overall resilience. Susceptibility to diseases and parasites tends to increase with climate change, especially in stressed animals. Ensuring the health of fish and shrimp by implementing BMPs will reduce health risks.

In the field of aquaculture, the development of closed production systems with little or no water exchange, such as recirculating aquaculture systems (RAS) or biofloc systems (BFT), is also a promising strategy, as they are less dependent on external environmental resources, apart from energy requirements. Integrated multitrophic aquaculture (IMTA) creates a more efficient and environmentally friendly system by using species from different trophic levels (fish, shrimp, molluscs, algae and/or halophytes). In IMTA, the waste from one species is used by another, optimizing the use of resources and minimizing the amount of waste. In addition to a lower environmental impact, IMTA offers other advantages such as higher production efficiency and product diversification.

Other important strategies include species diversification, which can help mitigate the risk of losses, as some species may be more resilient to climate change than others, and genetic improvement of species with greater resistance to various environmental stressors. Both strategies can help to ensure production security and the sustainability of the aquaculture sector. By moving away from coastal waters and thus reducing pressure on coastal ecosystems, open sea (or offshore) aquaculture can be an option to reduce the impact of climate events in these regions, but its development in Brazil requires technological, logistical, and regulatory advances (13).

Another approach is the production of sustainable feed, mainly by reducing dependence on fishmeal and fish oil, through a switch to ingredients based on plants, insects, or microbial biomass. Dependence on commercial feed increases the vulnerability of the sector, as climate change affects the production of raw materials such as soybeans and corn. It is therefore recommended to prioritize aquaculture of species at the base of the food chain, that do not require feed. Mollusc farming and the cultivation of algae and halophytes should be prioritized, as they have a lower potential for environmental impact, lower technology and capital requirements, and, at the same time, significant potential for income and employment generation.

Technical training of aquaculture farmers in sustainable and adaptive practices, through extension programs focused on climate adaptation, is critical to promote the adoption of best practices and preventive management. The inclusion of aquaculture in adaptation plans, access to climate credit, special agricultural insurance, and technical assistance programs are essential to ensure the sustainability of the sector.

In the case of fisheries, the most urgent needs are very basic: the country needs sustainable fisheries statistics and a fisheries management program. It is important to ensure institutional stability and continuity of management and research activities, to anticipate and understand the potential impacts of environmental pressures, and to support managers in formulating plans and decisions.

Adaptation to climate change is closely linked to the ability to anticipate and understand these changes. Current research can predict the impacts and therefore help managers formulate plans and make decisions. Time is of the essence.

REFERENCES

1. FAO, *The state of world fisheries and aquaculture 2024*. Blue transformation in action (FAO, 2024).

2. BRASIL, Ministério da Pesca e Aquicultura, *Boletim Estatístico da Pesca e Aquicultura* – Ano 2011 (Ministério da Pesca e Aquicultura, 2011).

3. IBGE, *Pesquisa da Pecuária Municipal 2013*, *e 2023*. Disponível em: https://sidra.ibge.gov.br/tabela/3940 [Acessado em 02 de junho de 2025].

4. W.C. Valenti et al., Aquaculture in Brazil: past, present and future. *Aquaculture Reports* 19, 100611 (2021).

5. S.S. De Silva, D. Soto, "Climate change and aquaculture: potential impacts, adaptation and mitigation" in *Climate change implications for fisheries and aquaculture: overview of current scientific knowledge*, K. Cochrane, C. De Young, D. Soto, T. Bahri. Eds. (FAO, 2009), pp. 151-212.

6. S. Zeng et al., Warming-driven migration of enterotypes mediates host health and disease statuses in ectotherm Litopenaeus vannamei. *Communications Biology* 8, 126, 2025.

7. L.F.N. Vianna, R.V. de Souza, M.A. Schramm, T.P. Alves, Using climate reanalysis and remote sensing-derived data to create the basis for predicting the occurrence of algal blooms, harmful algal blooms and toxic events in Santa Catarina, Brazil. *Science of the Total Environment* 880, 163086 (2023).

8. Oceana Brasil. *Auditoria da Pesca Brasil* 2023 (Oceana Brasil, agosto 2024).

9. V.W.Y. Lam et al., Climate change, tropical fisheries and prospects for sustainable development. *Nature Reviews Earth & Environment* 1, 440–454 (2020).

10. A.S. Lira, F.L. Frédou, F. Le Loc´h, How the fishing effort control and environmental changes affect the sustainability of a tropical shrimp small scale fishery. *Fisheries Research* 235, (March 2023). Disponível em: https://doi.org/10.1016/j.fishres.2020.105824 [Acessado em 25 de julho de 2025].

11. L.G. Cardoso et al., Poleward catch displacement of blackfin tuna Thunnus atlanticus in the southwestern Atlantic Ocean: Possible effect of increasing water temperatures. *Fisheries Management and Ecology* 31(4), (2024).

12. Brasil, MMA, *Plano Nacional sobre Mudança do Clima* (MMA, 2008).

13. R.O. Cavalli, Ed. *Aquicultura do beijupirá (Rachycentron canadum)* no Brasil (Editora da FURG, 2021).

ACKNOWLEDGEMENTS

To journalists Dominique Ribeiro and Terezinha Costa, for their contribution as executive editor and text editor of this chapter.

6.7 Oceanic and Coastal Observation

Carlos Alberto Eiras Garcia

The ocean covers 70% of the Earth's surface, regulates the climate, absorbs around 90% of excess heat, and, according to the IPCC (Intergovernmental Panel on Climate Change) (1), captures 25% of the CO_2 emitted annually. It sustains ecosystems, regulates the water cycle, and provides food, energy, and livelihoods for billions of people. Marine and coastal monitoring is, therefore, an essential activity to protect ecosystems and provide information for those formulating and implementing public policies to mitigate and adapt to climate change.

More than 40% of the world's population lives in coastal areas, which are highly vulnerable to impacts such as sea level rise, storms, erosion, salinization of aquifers, changes in the hydrological system, acidification, marine heat waves, and biodiversity loss. In addition to these vulnerabilities, uncontrolled urbanization and the low adaptive capacity of many communities lead to habitat degradation and exacerbate social inequalities.

In recent decades, global ocean and coastal observation has evolved with the creation and strengthening of networks such as GOOS (Global Ocean Observing System, coordinated by UNESCO's Intergovernmental Oceanographic Commission) and GLOSS (Global Sea Level Observing System, which maintains globally distributed tide gages). These international networks also include Argo, a global program of autonomous buoys that monitor temperature and salinity in the first 2,000 meters of ocean depth, CMEMS (Copernicus Marine Environment Monitoring Service), a European marine environment monitoring service that provides ocean data and forecasts, and OceanSITES, an international network of fixed sites and deep-sea observations covering the entire ocean.

The devices used by these networks, systems, projects, and services include satellites, buoys, radars, and gliders (autonomous underwater vehicles), which collect important data for understanding climate and ecosystems and for formulating public policies. In addition, artificial intelligence and digital twin technology — a virtual replica that reproduces ocean conditions in detail and in real time — have expanded analysis and forecasting capabilities.

In Brazil, initiatives such as GOOS-Br, the national version of GOOS, and ReNOMO (National Ocean Observation and Monitoring Network) are expanding our observation capacity, and providing real-time data on variables that are important for coastal management and climate security.

GOOS-Br focuses on observing the southern and tropical Atlantic, and integrates various projects and services: PIRATA (Prediction and Research Moored Array in the Tropical Atlantic, a Brazilian–American-French collaborative project that maintains buoys in the tropical Atlantic); GLOSS-Br, the Brazilian section of GLOSS; MOVAR, which uses disposable thermographs to monitor heat transport in the surface layer of the ocean between Rio de Janeiro and Trindade Island; REMObs (Ocean Modeling and Observation Network), which monitors meteorological and oceanographic conditions in the marine region adjacent to the Brazilian territory; SiMCosta, the largest monitoring system on the Brazilian coast, consisting of buoys and meteorological and tidal stations for real-time monitoring; SAMOC/SAMBAR (South Atlantic Meridional Overturning Circulation/ South Atlantic MOC Basin-wide Array), which measures the meridional overturning circulation of the South Atlantic; Rede Dados; the coastal stations of INMET (National Meteorological Institute (MCTI) and the CHM (Hydrographic Center of the Navy); and iMePrO (Instrumentation and Best Practices in Oceanography), to standardize the collection and processing of observational data in Brazil.

ReNOMO was launched in 2022, through a public announcement by the MCTI (Ministry of Science, Technology, and Innovation) and CNPq (National Council for Scientific and Technological Development), to integrate the different networks, expand observational coverage, and qualify the data for applications such as climate prediction and maritime security. ReNOMO uses fixed (Figure 1), mobile, remote, and autonomous platforms and adopts international standards for the collection, processing, and distribution of data via a digital portal.

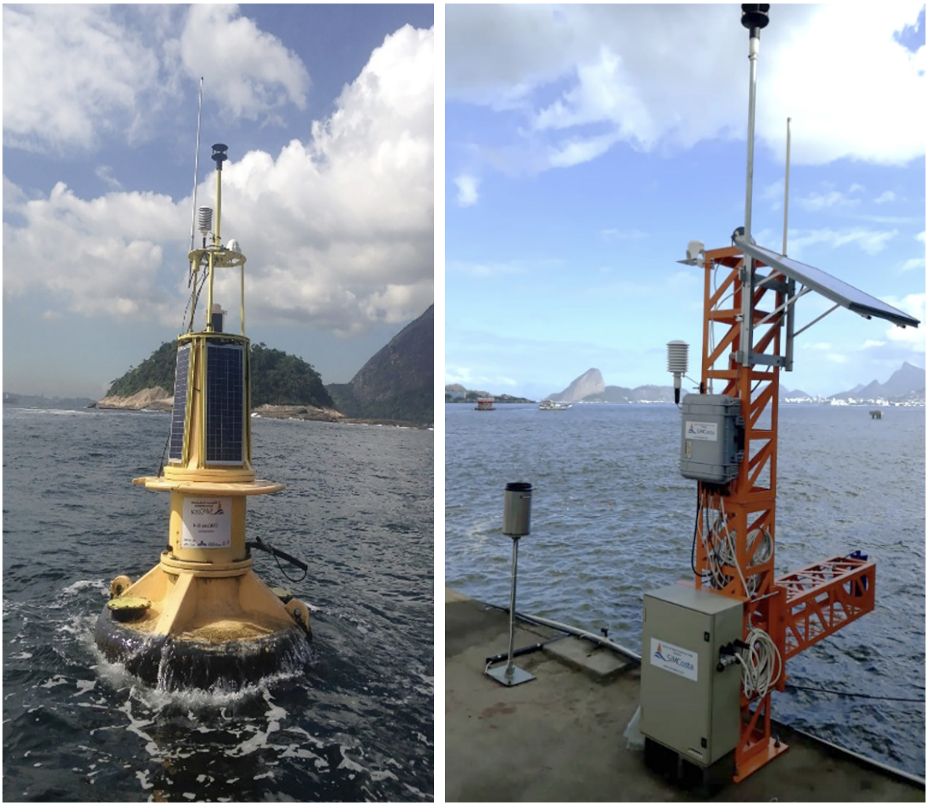


Figure 1: SiMCosta's fixed platforms. The instrumented buoy (left) and the meteo-tide gauge (right) are installed in the city of Rio de Janeiro.

ReNOMO has identified significant gaps in Brazil's coastal and ocean observation capabilities: lack of coverage in the north and northeast regions and in the so-called equatorial margin, the region of the continental shelf between Amapá and Rio Grande do Norte; lack of data on critical variables (sea level, marine heat waves, CO_2, oxygen, acidification); and weaknesses in equipment maintenance and calibration and data interoperability.

Recently, three important advances in ocean and coastal observations have been recorded in Brazil. In 2024, the National Multiuser Center (CNM) was created under a call for proposals from FINEP (the Brazilian Funding Agency for Studies and Projects), an initiative of SiMCosta and CEOCEAN (Center for Ocean and Climate Studies, of the Institute of Oceanography of the Federal College of Rio Grande do Norte). Its aim is to strengthen the sharing of infrastructures, technological innovation, scientific collaboration and the training of personnel. In 2025, ReNOMO entered a new phase with the creation of INCT-ReNOMO (National Institute of Science and Technology of ReNOMO). This is a national cooperative structure that focuses on technological development, monitoring, training, and the creation of applied products, with an emphasis on modeling and artificial intelligence. The new INCT is divided into four areas: Technology, Monitoring, Science/Education, and Products/Tools, which are expected to impact sectors such as fisheries, ports, energy, and climate change mitigation/adaptation.

Also in 2025, Petrobras announced an investment of R$100 million to expand the REMObs network, in collaboration with the Navy and universities. The aim is to increase offshore safety and provide real-time data on metoceanographic conditions on the continental shelf. Part of the data will be made available to the scientific community.

However, despite the progress, many observation gaps remain. There is also a need for transdisciplinary data integration. In this sense, governance and funding are priorities, as there is a significant gap between the resources needed and those received. Many structural measures are still pending, starting with geographic expansion to critical regions and standardization of protocols. Another need is to ensure data interoperability, i.e. our ability to integrate different observing systems to ensure that information is compatible and accessible in real or near real time, within the framework of the FAIR principles – a set of guidelines for the findability, accessibility, interoperability and reusability of scientific data.

More investment is also needed in autonomous sensors, radars, and national technologies. The integration of data into numerical models and the establishment of a national open data repository are essential. It is equally urgent to strengthen technical and academic training and establish regional centers. Finally, continuous funding must be ensured, combining public funding, private partnerships, and innovative mechanisms such as blue bonds – securities traded on the financial market to finance ocean protection and restoration projects. Strengthening marine and coastal observation is of strategic importance for combating climate change, protecting marine ecosystems, and formulating policy based on observational data.

The worsening environmental impacts in coastal and oceanic regions reinforce the urgent need to expand and consolidate observation systems in Brazil. Despite the progress made with networks such as GOOS-Br and ReNOMO, there are still significant gaps in geographic coverage, observed variables, and data integration. The establishment of INCT-ReNOMO is a strategic step forward. However, to address the challenges of climate change and ensure ocean sustainability, it is essential to ensure continued funding of ocean and coastal observation networks, standardization of data, and alignment with global initiatives.

REFERENCES

1. IPCC (Intergovernmental Panel on Climate Change), “Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the IPCC» (Cambridge University Press, 2021).

6.8 Energy Transition

Segen Farid Estefen

The switch to renewable energy, particularly from the sea, contributes to reducing greenhouse gas emissions and, consequently, combating climate change. Offshore wind energy has made significant progress over the last decade, thanks to technological innovation and investment. It offers greater energy efficiency due to the stronger and more constant winds at sea and also avoids disputes over coastal areas. The greater technological maturity compared to other ocean-based renewable energy sources suggests that the realization of large offshore wind farms will open up the possibility of utilizing their infrastructure for other renewable energy sources, leading to greater competitiveness for all. It is also worth noting the growing interest in offshore solar energy, particularly in the form of floating solar panels, which can cover large areas of the sea. Although they are still in the early stages of development, they demonstrate the potential to greatly serve coastal regions and the sustainable sectors of the marine economy, known as the blue economy.

Renewable energy from the sea can be divided into two groups. One includes renewable sources originating from saltwater, such as waves, currents, tides, and temperature and salinity gradients. The other group consists of sources that can be harnessed in the marine environment, such as offshore wind and floating solar energy. In addition to converting these sources into electricity, other products can also be obtained, such as desalinated water and a low-emission fuel, green hydrogen. This is obtained through the electrolysis of seawater, a process that uses electricity to separate hydrogen from oxygen. When the electricity is generated from renewable sources, the result is a fuel that, unlike fossil fuels, does not emit carbon dioxide into the atmosphere.

Local measurements and remote sensing are used to identify the most promising regions in terms of energy potential from renewable sources. Studies on the Brazilian Exclusive Economic Zone reveal the primary areas of interest for converting renewable energy sources (1).

Technologies suitable for the potential resources of the most promising regions are based on technical and economic feasibility studies to estimate the reliability of the conversion system and the cost of the energy and products generated.

Renewable energy sources require suitable structures for the installation of the conversion plants. Hydrodynamic and structural analyses are carried out to evaluate the proposed concepts. Depending on the region and the potential resources available, the effectiveness of the so-called Energy Hub — the combination of renewable energy sources to be converted, using a common infrastructure that includes an electrical transmission and storage system — must also be evaluated. Due to its higher level of technological maturity and economic competitiveness, offshore wind energy is currently proving to be the most suitable energy source to complement other sources, selected according to the available energy potential for wind generation.

Optimization based on advanced control systems and the use of artificial intelligence (AI) techniques have contributed to technological advances and increased the competitiveness of marine renewable energy sources. This could be a positive differentiator for the sustainable use of the sea, a feature of the blue economy, that balances environmental protection with economic and social development.

Offshore wind energy is consolidating itself as one of the most promising solutions for the global energy transition. The installation of wind turbines in the marine environment ensures greater efficiency in converting potential energy into electricity, as the winds are more intense and consistent, which favors the use of high-power turbines (2,3).

The infrastructure for implementing these farms requires the use of fixed wind turbines, utilizing piles or jackets for depths of up to 60 meters, and floating substructures for greater depths. Significant technological progress has been made, particularly with floating substructures (4,5). The use of this resource offers great potential for large-scale renewable power generation and the production of green hydrogen.

The impact on marine life, birds, and biodiversity, as well as on coastal communities during the construction and operational phases, requires regional monitoring to develop appropriate solutions (6). Another important issue is the improvement of wave, current, and wind forecasting, which will enable the optimization of generation systems and ensure greater operational safety.

In Brazil's exclusive economic zone, the offshore wind potential is approximately 5,833 GW (7), with the Northeast predominant in terms of wind potential and quality (speed and capacity factor), although there is also significant potential in the Southeast and South. The technical potential is substantially lower, considering the technological limitations and other uses of the marine space.

Another renewable source is wave action. By transmitting wind energy across the sea surface, wave motion can be converted into mechanical energy and electricity. With advances in engineering and materials, numerous technologies have been developed, resulting in hundreds of registered patents. Despite the technical challenges associated with designing efficient and economically competitive systems, wave energy conversion technologies represent promising alternatives in certain niche applications where this source has a reasonable wave height and frequency, as the energy potential is directly proportional to the square of the wave height and period. Given the relatively constant cyclical patterns, the availability of this resource can be predicted. The theoretical global wave energy potential is estimated at around 32,000 TWh/year (8).

As the majority of wave energy resources are located in deep and ultra-deep waters, these regions are crucial for the efficient utilization of wave energy. Weather conditions in nearshore environments tend to be more consistent, and waves exhibit greater regularity in terms of height and period, which is important for the continuous and predictable operation of wave energy converters.

The primary types of devices used for wave energy conversion are the Oscillating Water Column (OWC), the Oscillating Body (OB), and the Overtopping (OT) device. Registered patents are generally based on these concepts. In OWC, conversion is achieved by pneumatic compression in an air chamber that is in contact with the sea surface. As the air mass expelled from the chamber by varying wave heights drives a bidirectional turbine, the turbine continues to operate in the same direction as the air returns to the chamber. In the OB concept, the process typically involves a hydraulic or mechanical system that converts the relative motion of two bodies into a relative displacement, generating electrical or mechanical energy. In the OT concept, the water stored in a reservoir by the wave action drives a low-head hydraulic turbine located at the bottom of the reservoir, which converts potential energy into kinetic energy to generate electricity.

Research into marine renewable energy began in Brazil, specifically at COPPE/UFRJ in 2001, with a focus on wave and tidal sources. Fifteen years later, with the interest of other research groups, the National Institute of Science and Technology for Renewable Energy from the Sea and River (INEOF) was founded. Currently, the Ocean Renewable Energy Group (GERO) of the COPPE/UFRJ has two wave energy converter projects underway: the hyperbaric wave converter (9), a prototype of which was installed in the port of Pecém, in Ceará, from 2010 to 2014, and another, of the oscillating body type, which is in the laboratory testing phase.

Tidal power, also known as tidal energy, is a form of electricity generation that utilizes the cyclical fluctuations in sea level and water flow velocity resulting from the movement of the Earth relative to the moon and sun, and the interaction of their respective gravitational forces. Factors such as the Earth's axial tilt, its rotation, and the interaction between gravitational and rotational forces influence tidal dynamics, causing its conditions to change over time. These variations are more pronounced in coastal regions, especially in narrow channels, where the confinement of the water increases both flow and energy density available for conversion.

There are two main phenomena associated with the generation of tidal power: Tidal amplitude and tidal current. Amplitude refers to the difference in height between high and low tides. The greater this difference, the greater the available energy potential. Energy conversion refers to the process of converting potential energy into electrical energy. The tidal current, on the other hand, is generated by the flow of water during the tidal cycles. The resulting kinetic energy can be converted into electrical energy.

The La Rance power plant in France was the first large tidal power plant, with an installed capacity of 240 MW, which was commissioned in 1966. The Sihwa power plant in South Korea, with an installed capacity of 252 MW, was commissioned in 2012. Innovative concepts for underwater turbines have been tested and prototypes installed, particularly in the UK. Tidal energy exhibits a high level of predictability, enabling forecasts to be made for long-term electricity generation.

Global tidal energy resources are estimated to total 3 TW [8]. The importance of remote sensing, with the processing of satellite images to complement in-situ measurements, should be emphasized [10]. In Brazil, the most important resources are located in the Bay of São Marcos, in Maranhão, and on the Amazon coast in the northern region (11, 12).

Another renewable energy source present in seawater is the thermal gradient, i.e., the temperature difference between the sea surface and the depth. This difference can be converted into electricity using the Rankine cycle in a process called Ocean Thermal Energy Conversion (OTEC). The OTEC system has the highest theoretical potential among ocean saltwater sources, at approximately 44,000 TWh/year, and is primarily utilized in tropical regions (8). In these regions, temperatures at the sea surface can exceed 25°C, while at a depth of a thousand meters, they drop to values close to 5°C. Thermal gradients of 20°C or more are recommended for electricity generation. The primary advantage of OTEC is that it can serve as a baseload energy source, eliminating the fluctuations that characterize most renewable energy sources.

The technology is promising for countries in tropical regions, offering a sustainable and innovative alternative. The current challenge is the technological development that will enable a reduction in the cost of OTEC system components, thereby increasing competitiveness in terms of energy production costs. For floating systems operating at great depths, the additional technological challenge is the dimensioning of the cold water inlet pipes (13). The OTEC system can operate in open, closed, or hybrid circuits. The first is primarily used for seawater desalination, the second utilizes liquids with a lower evaporation rate, such as ammonia, for enhanced efficiency in power generation, and the third combines both processes to optimize the system.

There are two OTEC demonstration plants, one in Hawaii (USA) and the other in Okinawa (Japan), with an installed capacity of 100 kW each. Brazil has excellent conditions for OTEC plants in the northeast and north, where a temperature gradient of at least 20 degrees Celsius is maintained throughout the year. A site of scientific interest for the installation of a prototype is the island of Fernando de Noronha, which could benefit from OTEC for electricity generation and seawater desalination, as well as a laboratory for scientific research to optimize the technology for installation in other areas of the Exclusive Economic Zone.

From the above, it can be concluded that Brazil has immense potential for marine renewable energy resources, making the country an important player in the global energy transition. With an extensive coastline and favorable conditions for the exploitation of offshore wind, wave, tidal, and thermal gradient energy, the country can not only meet its domestic needs but also make a solid contribution to the international community.

The transfer of knowledge in resource assessment and conversion technologies will allow Brazil to share its experience and innovation, strengthen its relevance in the sector, and contribute to the promotion of global decarbonization and sustainability.

REFERENCES

1. M. Shadman et al., Ocean Renewable Energy Potential, Technology, and Deployments: A Case Study of Brazil. *Energies* 12, 3658-3695 (2019).

2. E.C. Nogueira, R.C. Morais, A.O. Pereira Junior, Offshore wind power potential in Brazil: Complementarity and synergies. *Energies* 16, 5912 (2023).

3. L.F. de Assis et al., Assessment of the offshore wind technical potential for the Brazilian Southeast and South regions. *Energy* 196, 117097 (2020).

4. A.A. Shittu et al., Reliability assessment of a hybrid floating wind turbine concept based on coupled aero-hydro-structural dynamics. *Journal of Ocean Engineering and Marine Energy* 15, 100 (2025).

5. M.M. Amiri, M. Shadman, S.F. Estefen, A review of physical and numerical modeling techniques for horizontal-axis wind turbine wakes. *Renewable & Sustainable Energy Reviews* 193, 114279 (2024).

6. O.M. Hernandez C. *et al*., Environmental impacts of offshore wind installation, operation and maintenance, and decommissioning activities: A case study of Brazil. *Renewable & Sustainable Energy Reviews* 144, 110994 (2021).

7. EPE, Roadmap Eólica Offshore Brasil, NT-EPE-PR-001/2020-r2 (2020).

8. A. Lewis, S.F. Estefen, Eds. "Ocean Energy" in *Special Report on Renewable Energy Sources and Climate Change Mitigation*, IPCC SRREN, Org. (Cambridge University Press, 2012), v. 01, pp. 497-534.

9. P.B. Garcia-Rosa et al., Wave-to-Wire Model and Energy Storage Analysis of an Ocean Wave Energy Hyperbaric Converter. *IEEE Journal of Oceanic Engineering* 39, 1-12 (2014).

10. R.M. Ferreira, S.F. Estefen, R.Romeiser, Under What Conditions SAR Along-Track Interferometry is Suitable for Assessment of Tidal Energy Resource. IEEE *Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 1, 1-12 (2016).

11. A. Aguiar, M. M. Almeida, M. Cirano, J. Pereira, L. Cotrim da Cunha, Numerical assessment of tidal potential energy in the Brazilian Equatorial Shelf. *Renewable Energy* 220, 119684 (2024).

12. R.W.Q. Farias, M. El-Robrini, O.R. Saavedra, Assessment of tidal current potential in the Amapa's inner continental shelf (Eastern Amazonia - Brazil). *Ocean Dynamics* 1, 1-15 (2024).

13. J. Tan *et al.*, Stability analysis on internal flow-induced cold-water pipe with non-uniform and variable cross-section for OTEC subject to multiple clump weights. *Ocean Engineering* 330, 121191 (2025).

6.9 Health and Ocean

Carla de Freitas Campos, Wim Degrave,
Alexander Turra, José Luiz Moutinho, Paulo Gadelha

Ocean warming and acidification, coastal erosion and extreme events are a reality. This ecological imbalance poses a significant risk to the health of humans, animals and ecosystems and carries the risk of emerging zoonoses and pandemics. Emerging or re-emerging pathogens and the occupation of new niches by insect vectors and reservoirs pose a direct threat to public health.

Climate change is currently one of the greatest global challenges facing humanity. Its effects are being felt in various natural and social systems, with oceans and coastal areas being particularly sensitive and vulnerable. It is important to remember that the health of humans, animals, ecosystems and the environment as a whole are interconnected and interdependent. This understanding, which has been consolidated in recent decades, underpins the "One Health" approach, which proposes integrated actions across different sectors, institutions and territories to address current health challenges. It is a strategy that articulates knowledge and practices in a transdisciplinary, multidisciplinary and collaborative manner, recognizing that sustainable and effective solutions depend on dialog between different fields of knowledge and collaboration between institutions and geographical regions (1).

The "One Health" approach takes the social and environmental determinants of health as a central axis and is based on the expanded concept of health – defined as the outcome of conditions in the areas of nutrition, housing, education, income, environment, work, transportation, employment, leisure, freedom, access to and ownership of land, and access to health services (2). In this context, the environment, including the Ocean, must have a strategic place in public health policy.

Brazil, with its more than 8,000 kilometers of coastline, several million people living in coastal regions, and its marine ecosystems with great biodiversity, occupies a strategic position in this panorama. It is also a country with an important scientific tradition in the environmental field, which has made an important contribution to understanding the impact of climate on marine and coastal systems.

Despite its vital importance, the ocean remains largely unrecognized as a health factor. It regulates the climate, stores carbon, modulates the water cycle and has an impact on food production, even in regions far offshore (3). Paradoxically, the health of the Ocean is little known and often neglected. Its contribution to human well-being and the preservation of life on Earth remains invisible in many decision-making processes and policies that should include them. On the other hand, several research initiatives in Brazil deserve special mention, such as the Brazilian Panel on Climate Change (PBMC), the Coastal Monitoring Project (MARE Project), and numerous studies by universities and research centers, such as the Oswaldo Cruz Foundation (Fiocruz), that focus on the relationship between health and the environment.

Aware of these gaps, Fiocruz and partner institutions launched a movement in 2023 to expand the recognition of the ocean in the field of health, giving rise to the "Blue One Health" proposal. The initiative aims to explicitly integrate ocean health into the "One Health" approach, taking into account the mutual impacts between marine systems and terrestrial life — human and non-human. In this sense, regional, national, and international networks and collaborations are crucial, aiming at cross-sectoral, multidisciplinary and transdisciplinary partnerships.

Brazil has taken a leading role in the "One Health" agenda, with the ongoing development of a national action plan. This plan should reflect the guidelines established by the High-Level Expert Panel on One Health (OHHLEP) (4). The inclusion of the ocean and inland waters in the plan represents a strategic opportunity to translate the accumulated scientific evidence into sound and transformative public policy and to emphasize the intrinsic relationship between ocean health and human health, by highlighting how protecting the oceans directly impacts our physical and mental well-being. The ocean not only provides food, oxygen, and regulates the climate, but also offers recreational opportunities and promotes mental health, - an opportunity that is still underestimated in our country.

On the other hand, the Ocean is also a vector for the transport of pathogens, viruses, bacteria, fungi and parasites in birds and marine animals, microalgae and their toxins, as well as organic and inorganic chemical contaminants from fertilizers, plastics, pesticides, hormones, pharmaceuticals, and drugs. However, there are promising opportunities for scientific studies to unlock the potential of marine organisms through bioprospecting, with the aim of discovering new biotechnological processes, drugs, molecules, and enzymes with industrial applications. However, marine biodiversity is under serious threat from illegal, unreported, and unregulated fishing and seawater acidification. Scientific research and biotechnological development can help combat the effects of climate change on the distribution of marine species and the availability of fishery resources.

In addition to promoting research, it is also crucial to raise awareness of the importance of ocean health, the need for sustainable practices to protect marine ecosystems, and the implementation of measures to reduce pollution, protect habitats, and use marine resources sustainably.

Adaptation and mitigation measures must take into account historical inequalities between populations and areas. Socially and environmentally vulnerable groups will be the most affected — and likely to be the first to suffer the most significant impacts of climate change (5). There is an urgent need to strengthen health systems (for humans and animals), expand environmental protection mechanisms, and ensure equitable access to decent living conditions. Effective responses also require the empowerment of communities and the adoption of an ecology of knowledge that includes the interaction between scientific knowledge and traditional and local knowledge, and values the experiences, practices, and perceptions of the populations that inhabit and care for these territories.

The main pillars of this integrated response include the study and restoration of coastal ecosystems, the formalization of large coastal and marine areas as environmental protection units, the prohibition of predatory fishing and trawling, with appropriate control, the reduction of greenhouse gas emissions, the conversion of energy supply to renewable sources, conscious consumption and the study and protection of biodiversity.

Among the international goals, the commitment to protect at least 30% of marine, terrestrial, and inland waters by 2030 stands out, as stated in the Kunming-Montreal Global Biodiversity Framework (6). To achieve this goal, countries, including Brazil, must strengthen governance systems and ensure investment in science, innovation, and resilient infrastructure. Measures such as the introduction of early warning systems, urban renewal and the regulation of the use of pollutants, such as pesticides and plastics, are also essential components. In terms of public policy in Brazil, the ecological-economic zoning of coastal areas is an important but underutilized tool. The integration of scientific data into climate adaptation plans at municipal and state level remains a challenge.

The coming years will be crucial for the consolidation of climate policy on Brazil's coasts. It is important to strengthen interdisciplinary and inter-institutional research networks, expand long-term funding for historical coastal data series, and invest in the training of marine science professionals.

But no change will be possible without a continuous process of education, communication, and social engagement. It is necessary to promote a cultural shift in the way we treat our planet, other living beings, and each other. When we explore, understand and care for the ocean, animals, and the environment, we are ultimately, caring for ourselves. Health must be understood as a universal right and duty of the state, based on its socio-ecological feature or characteristics and its interdependence with all forms of life. In this sense, the creation and implementation of national health plans — which explicitly include the ocean — are fundamental steps towards a more just, equitable and sustainable future.

REFERENCES

1. WHO Media Team, *Tripartite and UNEP support OHHLEP's definition of "One Health"*. Joint Tripartite (FAO, OIE, WHO) and UNEP Statement (2021). Disponível em: https://www.who.int/news/item/01-12-2021-tripartite-and-unep-support-ohhlep-s-definition-of-one-health [Acessado em 25 de junho de 2025].

2. Conferência Nacional de Saúde, 8, *Anais*... (Centro de Documentação do Ministério da Saúde, Brasília, 1987).

3. L.E. Fleming, B. Maycock, M.P. White, M.H. Depledge, Fostering human health through ocean sustainability in the 21st century. *People and Nature* 1, 276–283 (2019).

4. FAO, UNEP, WHO, WOAH, *One Health Joint Plan of Action* (2022–2026) (FAO, 2022).

5. K. Iskandar, A. Anas, S. Bahri, F. Mennec, T. Baharuddin, Social vulnerability and climate change: a bibliometric analysis. *Cogent Social Sciences* 10(1), (2024).

6. Convenção sobre Diversidade Biológica (CBD), *Marco Global de Biodiversidade de Kunming-Montreal*. COP-15, Montreal, Canadá (2022).

6.10 Climate Justice and Traditional Coastal Communities

Leandra Regina Gonçalves

Climate change has serious impacts on coastal areas, such as sea level rise, ocean acidification, and an increase in the frequency of extreme events, which threaten fragile ecosystems such as mangroves and coral reefs and affect the availability of natural resources that are essential for livelihoods (1). These regions are vital to coastal communities, especially traditional communities that are building their identity, way of life, and ancestral ties to the land (2).

Vulnerable coastal communities are disproportionately affected by the impacts of the climate crisis, despite historically bearing little responsibility for its occurrence. These environmental impacts are compounded by social and institutional inequalities, that create multiple vulnerabilities (3). Artisanal fisheries, for example, are highly sensitive to changes in oceanographic parameters, erosion, salinization, of aquifers and loss of biodiversity. All of this has a direct impact on food security and the economic stability of coastal communities (4).

In this context, climate justice becomes a fundamental field for the integration of ethical, social, and territorial dimensions in debates on adaptation and mitigation. Recognizing local knowledge, territorial rights, and the protagonism of affected populations is crucial for developing more equitable and effective responses (5). Expanding spaces for listening and co-construction and overcoming extractive practices of knowledge production are fundamental steps to promote inequity-aware climate and ocean governance (6). This means avoiding practices such as extracting information, knowledge, or data from local or traditional communities without direct reciprocation, recognition, or benefit to these populations. An example is the practice of researchers visiting coastal communities to collect data on artisanal fisheries but not sharing the results or involving the fishers in the interpretation and use of the information collected.

The literature on climate justice has expanded considerably in recent decades, with an increasing focus on intersectional approaches that recognize the differential vulnerability of historically marginalized groups, such as indigenous peoples, quilombola communities, and riverine and coastal dwellers (7,2). In the context of coastal and marine areas, studies show that the impacts of climate change — such as sea level rise, extreme weather events, and ocean acidification — exacerbate existing social inequalities and threaten sustainable livelihoods that are closely tied to the land (4, 8).

Recent studies have shown that coastal communities, which are highly dependent on natural resources, are at the frontline of climate change (8, 10). Fishing and agricultural productivity has declined, and critical infrastructure is increasingly at risk from rising sea levels and the intensification of events such as coral bleaching, - phenomena that seriously affect populations that rely on reefs for food, income, and coastal protection. The intensity of the impact varies for each region and community, depending on exposure to risk, the degree of dependence on the affected ecosystems, and the adaptive capacity of the groups.

Despite the increasing recognition of the need to strengthen adaptive capacity, there is little practical guidance on how to develop it effectively (2,3). Recent studies suggest that adaptation depends not only on the availability of financial, human, or social resources, but also on the willingness and ability to translate these resources into effective action (3). Furthermore, the lack of disaggregated data— - i.e. data disaggregated by categories such as gender, age, income, place of residence or ethnicity — hides structural inequalities, hinders the targeting of effective interventions and prevents the most vulnerable groups from being prioritized in adaptation plans. This favors the exclusion of vulnerable groups from decision-making processes and limits the development of fair and sustainable solutions (5).

Brazilian science has played an important role in analyzing socio-environmental vulnerabilities related to climate change, but coastal and marine areas require even more attention. Initiatives such as the Brazilian Panel on Climate Change (PBMC) and the Climate Network have fostered a link between science, public policy, and environmental justice — a crucial step towards integrating academic and traditional knowledge in formulating more equitable and effective responses to the climate crisis.

Projects such as Maretórios Amazônicos (FAPESP, FAPESPA, Fundação Araucária, and CNPq) and Vozes do Mar (British Council) are examples of participatory and transdisciplinary methodological approaches that aim to link scientific knowledge with the perceptions, experiences, and practices of coastal communities. These initiatives not only help to generate contextualized data, but also to strengthen community leadership in environmental governance (2).

Figure 1: Artisanal fishing community in Jubim (Marajó Island – PA) and its traditional practices. Photo: Lara Sartorio/Projeto Maretórios.

It is equally important to recognize the active role that traditional communities play in developing responses to the impacts, of climate change through their participation in management boards, public hearings, action research networks, and territorial consultation spaces. These processes underscore the central importance of knowledge dialogs in the formulation of public policies that respect the territorial and cultural rights of these communities.

The Brazilian experience shows that effective adaptation measures must be based on territorially and culturally sensitive solutions (10) (Figure 2). This means that solutions must be proposed that take into account the specificities of each territory (such as climate, geography, and local way of life) and the cultural values of the affected population. For example, an adaptation strategy that promotes the cultivation of native species in the caiçara mangroves, while respecting both traditional knowledge and the ecosystem, is more effective and socially legitimate than a standardized external intervention.

Strengthening food sovereignty, community-based natural resource management and the protection of strategic ecosystems, such as mangroves, reefs, and sandbanks, are fundamental measures to promote socio-ecological resilience in the face of climate change. In the area of climate change mitigation, it is important to recognize and support traditional sustainable use practices, that contribute to both biodiversity conservation and blue carbon sequestration.

Figure 2: Co-construction workshop in the community of Jubim, Marajó Island (PA). Photo: Projeto Maretórios.

However, for these strategies to gain scale and effectiveness, active listening mechanisms need to be expanded and citizen science promoted, with communities actively engaged in all phases of scientific research: Data collection, analysis, monitoring, and dissemination of results. Examples include projects where communities, use simple apps or protocols, to help feed databases with information on tidal fluctuations or marine species.

For such strategies and measures to be implemented, public funding must be secured for research that promotes environmental justice and, thus also climate justice. This also means strengthening inclusive and collaborative institutional arrangements that are able to articulate different scales and forms of knowledge. Building climate justice in coastal areas therefore involves valuing local experiences, promoting adaptive capacity, and reorienting scientific and policy agendas towards social and environmental justice.

Promoting climate justice in coastal areas requires recognizing the territorial, social, and cultural specificities of the traditional communities that live there. Not only do these groups face the disproportionate impacts of climate change, but they also have knowledge, practices, and strategies that can significantly contribute to sustainable and equitable solutions. Brazilian literature and experience show important advances in this area, with initiatives that combine local and academic knowledge, promote participatory management, and demand the recognition of territorial rights. Two examples: In the Canavieiras Nature Reserve, on the southern coast of Bahia, fishermen and shellfish collectors use traditional practices to manage Uçá crabs, which include voluntary closed seasons (interruption of fishing) based on observations of the species' reproductive cycle. These practices have helped to maintain healthy crab populations and have been incorporated into the reserve's rules. In the municipality of Jureia, on the south coast of São Paulo, the caiçaras combine traditional systems of slash-and-burn and artisanal fishing with knowledge of the cycles of tides, rainfall, and species reproduction. This knowledge has been integrated into co-management initiatives and coastal protection plans in this region.

Nevertheless, challenges remain. There is an urgent need to strengthen local adaptive capacities, expand the representation of these groups in decision-making processes, and ensure the continuity of policies and funding that support transdisciplinary approaches based on environmental and social justice. The response to the climate crisis cannot be independent of actively listening to and engaging traditional coastal communities. Investing in their resilience is both an ethical imperative and an effective strategy for building a more just and sustainable future.

REFERENCES

1. IPCC, “IPCC Special Report on the Ocean and Cryosphere in a Changing Climate” in H.O. Pörtner et al., Eds. (Cambridge University Press, 2019), doi:10.1017/9781009157964.

2. L.R. Gonçalves, M.T. Arruda Filho, P.H.C. Torres, *Justiça Climática em Regiões Costeiras no Brasil* (Paco Editorial, 2022), ISBN: 9788546227846.

3. P.H.C. Torres, G.P. de Araújo, I.C. Cavaco, M.T. Arruda Filho, L.R. Gonçalves, Políticas de Estado e Políticas de Governo: A Justiça Climática e as Estratégias de Resposta para a Zona Costeira Brasileira em Face à Emergência Climática. *Redes* 29, (2024).

4. I.M. Martins, M.A. Gasalla, Adaptive Capacity Level Shapes Social Vulnerability to Climate Change of Fishing Communities in the South Brazil Bight. *Front Mar Sci*. 7, 481 (2020), doi:10.3389/fmars.2020.00481.

5. J. Claudet, J. Blythe, D. Gill, N. Bennett, G. Gurney, Advancing Ocean Equity at the Nexus of Development, Climate and Conservation Policy. *Nat Ecol Evol*. (2024), doi:10.1038/s41559-024-02417-5.

6. 6.N.M. Dawson et al., The Role of Indigenous Peoples and Local Communities in Effective and Equitable Conservation. *Ecol Soc.* 26(3), 19 (2024), doi:10.5751/ES-12625-260319.

7. K.F. Strange, M. Satorras, H. March, Intersectional Climate Action: The Role of Community-Based Organisations in Urban Climate Justice. *Local Environ*. 29(7), 865–885 (2024), doi:10.1080/13549839.2024.2345678.

8. R.D. Pereira *et al.*, Traditional and Local Communities as Key Actors to Identify Climate-Related Disaster Impacts: A Citizen Science Approach in Southeast Brazilian Coastal Areas. *Front Clim* 5, 124300 (2023), doi:10.3389/fclim.2023.1243008.

9. IPCC, *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2022).

10. C.S. Seixas, A. Turra, B.P. Ferreira, Eds. *1º Diagnóstico Brasileiro Marinho-Costeiro sobre Biodiversidade e Serviços Ecossistêmicos* (Plataforma Brasileira de Biodiversidade e Serviços Ecossistêmicos e Cátedra Unesco para a Sustentabilidade do Oceano, 2024).

6.11 Ocean Literacy

Ronaldo Christofoletti

In a world characterized by rapid climate change, understanding the ocean and our relationship with it has become essential. Covering more than 70% of the Earth's surface, the ocean regulates the climate and sustains life. It therefore plays a central role in mitigating the effects of climate change. In Brazil, this connection is particularly important, as more than half of the population lives within 150 km of the coast, making the connection to the ocean an everyday reality.

Even those who live far from the sea are directly affected by it. By regulating temperature and rainfall cycles, the ocean affects human well-being, agricultural production, and water resources, even in regions such as the Brazilian Midwest. Therefore, developing ocean literacy — understanding how the ocean affects our lives and how our actions impact it — is essential. This awareness empowers individual and collective decision-making, promotes behavior change, and supports effective public policies aimed at mitigating and adapting to the climate crisis.

Ocean literacy has evolved from a focus limited to formal education to a collective and multidimensional social construct. It has been summarized in four interdependent dimensions: Education, Communication, Cultural Connections, and Knowledge Systems (1). This approach enables us to consider how various sectors of society interact with the ocean and mobilize change towards sustainability.

In education, there is global progress, such as UNESCO's call for a blue curriculum (2) — the inclusion of ocean literacy in curricula worldwide — and initiatives that promote participatory and territorially connected learning, such as the Blue School Program, which promotes interdisciplinary and inclusive projects to empower youth and connect the ocean to climate and environmental justice.

In the area of communication, research shows that while access to scientific information is necessary, it is not sufficient to generate public engagement. The integration of ocean knowledge and strategic communication is crucial for promoting behavioral change. Global initiatives such as the "The Ocean is Us" campaign (3) and the "EUceano" platform (4) exemplify how visual and emotional narratives increase social mobilization.

In terms of cultural connections, the centrality of the ocean to diverse and rich cultural expressions, spiritual practices, traditional rituals, and ancestral knowledge is increasingly recognized. Ocean culture needs to engage with this diversity by recognizing the different ways of knowing and experiencing the ocean and valuing the diversity of territories and experiences (1, 5).

In knowledge systems, transdisciplinarity and co-production have emerged as effective ways to address complex socio-ecological challenges. Various projects around the world demonstrate how partnerships between science, communities, and public administration can yield contextualized and sustainable solutions (5).

Another important advance is the acquisition of knowledge about public perception. Surveys such as the Brazilian study "Ocean without Mysteries" (7) and the international Ocean & Society Survey (8) reveal gaps in knowledge and point to ways of taking more effective action. There is also a growing understanding of ocean literacy as a support for marine conservation. Studies show that protected areas are more likely to be successful when coastal populations understand the importance of marine ecosystems (9).

These elements highlight that marine literacy is an emerging and strategic field with the potential to support structural change in the face of climate change. To achieve this, its dimensions need to be integrated into public policy, with approaches based on evidence, social justice, and the inclusion of diverse voices.

Brazil has pioneered ocean literacy, led by academics, civil society organizations, and schools. It is a leader among countries in the Global South in terms of scientific production related to ocean literacy (10) and a world leader in ocean literacy projects (11). These cross-sectoral initiatives, reflecting Brazil's diverse realities, have made Brazil a world leader in marine literacy, particularly the cross-sectoral and inter-institutional efforts coordinated by the Ministry of Science, Technology, and Innovation (MCTI), in collaboration with UNESCO and the Federal College of the State of São Paulo (UNIFESP), and involving various national action platforms. This mobilization has structured policies and strategies focused on climate resilience, food security, a sustainable blue economy, biodiversity protection, and the integration of scientific and traditional knowledge.

In education, through a partnership between the Ministry of Science, Technology, and Innovation (MCTI) and the Ministry of Education (MEC), the country was the first to respond to UNESCO's call and commit to the Blue Curriculum. Implementation is taking place on four fronts: multi-level public policy (24 municipalities and four states have already enacted specific legislation), teacher training (with the support of CAPES, the Coordination for the Improvement of Higher Education Staff), production of teaching materials, and community engagement. The Blue School Program is present in all regions of the country and promotes school projects related to global challenges (12). The Ocean Olympics, with national and international reach, reaches millions of people with integrated activities in the fields of science, art, culture, and integration (13).

In the field of communication, various research projects funded by the MCTI and civil society organizations have improved access to quality information. For example, since COP-28, the Brazilian Alliance for Ocean Culture has published technical reports that systematize the findings on the relationship between the ocean and climate. These reports have received wide media coverage, with thousands of supplements in national, regional, and local media covering topics such as coastal city management (14), nature-based solutions (15), extreme temperature events (16), and record sea ice melt (17).

The national public perception survey (7) found that 89% of Brazilians support the inclusion of marine culture in schools. The 2025 edition highlights a growing recognition of the ocean as a key component of the climate solution. This survey informs communication strategies and public policy formulation and is integrated into the international Ocean & Society Survey network (8).

In the area of knowledge systems, Brazil has consolidated co-production practices. The participatory development of the National Ocean Decade Plan (18) exemplifies coordination among science, civil society, indigenous peoples, and traditional communities. Projects funded by the CNPq and universities reinforce this approach by using diverse knowledge as a basis for climate change adaptation measures in coastal areas.

The cultural dimension has been explored through various forms, including festivals, artistic productions, exhibitions, educational materials, and community projects. Such actions recognize the ocean as part of the imagination, spirituality, and collective identity of many peoples and are essential for long-term social engagement.

Ocean literacy is one of the pillars of addressing the climate crisis in a fair, integrated, and transformative way. It goes beyond knowledge production, as it promotes the use of knowledge for the necessary changes in climate adaptation. Promoting understanding of our interdependence with the ocean strengthens individual and collective action for sustainability. Brazil is playing a global leadership role, with its initiatives recognized by the UN and UNESCO. It is now time to consolidate this leadership and inspire public policies that connect the ocean, climate, and society towards a more resilient and inclusive future. To achieve this, it is necessary:

- Expand public and private funding that focuses on ocean literacy, social justice, and territorial equity, from production to knowledge utilization.
- Integrate ocean literacy into climate adaptation plans and national education policies.
- Strengthen networks for educator training and the creation of contextualized educational resources.
- Promote data-driven communication campaigns and socially relevant narratives on the impacts of climate change. - Stimulate collaborative networks between countries of the Global South.
- Value the role of young people, artists, indigenous peoples, and local communities in developing solutions.

REFERENCES

1. UNESCO-IOC, Ocean Decade Vision 2030 – A Theory of Change for the Ocean Decade Challenge 10 (2025-2030). *The Ocean Decade Series*, 51, 11 (2025).

2. UNESCO-IOC, Um Novo Currículo Azul – Um Guia Prático para Formuladores de Políticas. *Manuais e Guias da COI* 90, (2022). Disponível em: https://unesdoc.unesco.org/ark:/48223/pf0000380544_por [Acessado em 30 de junho de 2025].

3. The Ocean is Us campaign. *How On Earth Radio* (2024). Disponível em: https://howonearthradio.org/archives/category/episodes/the-ocean-is-us [Acessado em 30 de junho de 2025].

4. Home. *EUceano*. Disponível em: https://www-euceano-org.rds.land/euceano [Acessado em 30 de junho de 2025].

5. UNESCO-IOC, Cultura Oceânica para todos: Kit Pedagógico. *Manuais e Guias da COI* 90 (2017). Disponível em: https://unesdoc.unesco.org/ark:/48223/pf0000373449 [Acessado em 30 de junho de 2025].

6. N.G.R. Mello et al., PWays forward in transdisciplinary research: insights from case studies on marine and coastal conflict transformations, *Sustainable Futures* 9, 100768 (2025).

7. Fundação Grupo Boticário, UNIFESP/Maré de Ciência e UNESCO, *Oceano sem Mistérios - A Relação dos Brasileiros com o Mar: Evolução de Cenários* (2022-2025). Fundação Grupo Boticário (2025). Disponível em: https://fundacaogrupoboticario.org.br/wp-content/uploads/2025/06/Oceano-sem-Misterios-A-Relacao-dos-Brasileiros-com-o-Mar-Evolucao-de-Cenarios-2022-2025.pdf [Acessado em 30 de junho de 2025].

8. J. McRuer *et al.*, Co-designing the Ocean & Society Survey – a global tool for understanding people-ocean connections and mobilizing ocean action. *Ocean & Society* (in press).

9. J. McRuer, E. McKinley, D. Glithero, R. Christofoletti, D. Payne, Human-ocean relationships: exploring alignment and collaboration between ocean literacy research and marine conservation. *Marine Policy* 171, 106418 (2025).

10. UNESCO-IOC, "State of the Ocean Report", pilot edition. *IOC Technical Series* 173, (2022). Disponível em: https://unesdoc.unesco.org/ark:/48223/pf0000381921.locale=en [Acessado em 30 de junho de 2025].

11. UNESCO-IOC, "State of the Ocean Report". *IOC Technical Series* 190 (2024). Disponível em: https://doi.org/10.25607/4wbg-d349. [Acessado em 30 de junho de 2025].

12. Home, *Programa Escola Azul Brasil*. Disponível em: https://escolaazul.maredeciencia.eco.br/ [Acessado em 30 de junho de 2025].

13. Home, *Olimpíada do Oceano*. Disponível em: https://olimpiada.maredeciencia.eco.br/ [Acessado em 30 de junho de 2025].

14. Fundação Grupo Boticário e Aliança Brasileira pela Cultura Oceânica, *Oceano sem mistérios. Construindo Cidades Azuis*. Fundação Grupo Boticário (2023). Disponível em: https://fundacaogrupoboticario.org.br/wp-content/uploads/2024/11/Oceano-sem-Misterios_-Construindo-Cidades-Azuis.pdf [Acessado em 30 de junho de 2025].

15. A.S. Martinez, *Cidades Azuis: soluções baseadas na natureza para a resiliência climática costeira* (Aliança Brasileira pela Cultura Oceânica UNIFESP-UNESCO-MCTI/FGB, 2024). Disponível em: https://maredeciencia.eco.br/wp-content/

uploads/2024/11/Ebook-Cidades-Azuis-Solucoes-Baseadas-na-Natureza-para-a-Resiliencia-Climatica-Costeira.pdf [Acessado em 30 de junho de 2025].

16. A.S. Martinez, R.A. Christofoletti, Brasil em transformação: o impacto da crise climática - 2024: o ano mais quente da história (Aliança Brasileira pela Cultura Oceânica (UNIFESP-UNESCO-MCTI)/FGB, 2024). Disponível em: https://maredeciencia.eco.br/wp-content/uploads/2024/12/Brasil-em-transformacao-1-2024-o-ano-mais-quente-da-historia.pdf [Acessado em 30 de junho de 2025].

17. R.A. Christofoletti, A. Pardal, "O declínio recorde do gelo marinho em 2023-2024: um alerta para o planeta" (Relatório Técnico do projeto Com-ANTAR do Programa Antártico Brasileiro, 2025). Disponível em: https://maredeciencia.eco.br/wp-content/uploads/2025/01/O-declinio-recorde-do-gelo-marinho-em-2023-2024-um-alerta-para-o-planeta.pdf [Acessado em 30 de junho de 2025].

18. Ministério da Ciência, Tecnologia e Inovação, *Plano Nacional de Implementação da Década da Ciência Oceânica para o Desenvolvimento Sustentável*. Brasil. Ministério da Ciência, Tecnologia e Inovação (2021). Disponível em: https://decada.ciencianomar.mctic.gov.br/wp-content/uploads/2022/01/Plano-Nacional-de-Implementac%CC%A7a%CC%83o-da-De%CC%81cada-da-Cie%CC%82ncia-Ocea%CC%82nica-links.pdf [Acessado em 30 de junho de 2025].

6.12 Ocean Governance

Wânia Duleba, Milena Maltese Zuffo, Andrei Polejack

Climate risks affect important sectors of the economy — such as fisheries, tourism, and urban infrastructure — and exacerbate social inequalities, especially countries of the Global South (1,2). Governance issues are of strategic importance as they structure norms, institutions, policies, and practices aimed at mitigating impacts and adapting to these risks. The intersection of ocean and climate governance represents not only an urgent environmental need, but also a strategic opportunity for Brazil's scientific and diplomatic leadership on the international stage.

Ocean governance encompasses the normative, political, and technical systems that regulate the rights and obligations related to the use and protection of the oceans (3). The international legal framework is the United Nations Convention on the Law of the Sea (UNCLOS), which divides the ocean space into zones and sets out the principles of sovereignty, environmental protection, and cooperation between states. The situation is similar with climate regulation, whose guiding instrument is the United Nations Framework Convention on Climate Change (UNFCCC). Although UNCLOS does not directly mention climate change, both regimes have been applied in the legal interpretation of the impact of the ocean-climate relationship.

In Brazil, a central element of the ocean regime is the Interministerial Commission for Marine Resources (CIRM), which was founded in 1974 and is responsible for the sectoral plan for marine resources and the survey of the Brazilian continental shelf, among other responsibilities. The climate regime, on the other hand, has the Interministerial Committee for Climate Change (CIM), which is responsible for the Climate Plan and the Nationally Determined Contributions (NDCs).

Both systems rely on national scientific evidence to support proposals for action. However, despite their similar objectives, there are no integration processes between them, which hinders the coordination of public policies and the improvement of knowledge-based decision-making processes (4). Brazil has advanced capacities in marine and climate research, and relies on a broad network of universities, research centers, and public and private laboratories. These institutions study ocean processes and climate impacts on marine ecosystems, and develop and evaluate strategies for coastal adaptation to climate change.

The Ministry of Science, Technology, and Innovation coordinates strategic science policies for both systems, such as the Climate Network and the National Institute of Ocean Research (INPO), which is the Ministry's newest social organization. Both the Climate Network and the INPO have advanced knowledge networks at the service of society, involving researchers from all over Brazil (Figure 1).

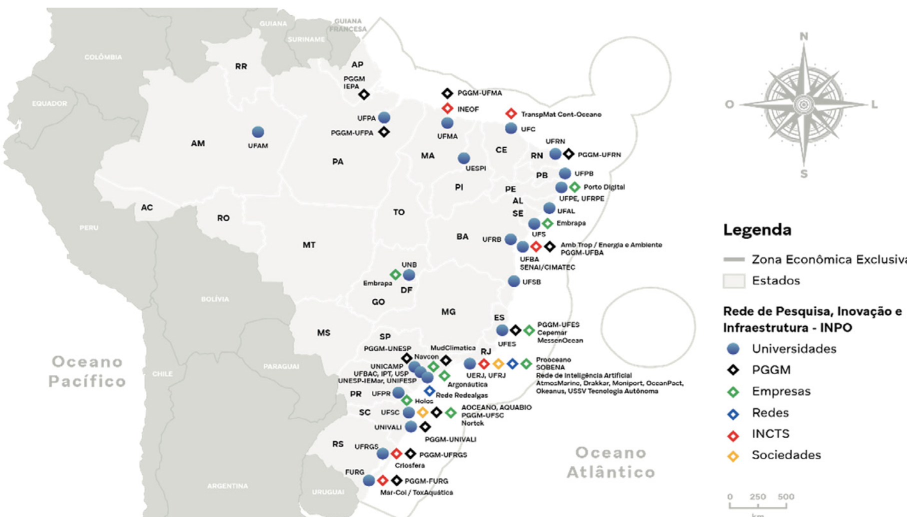


Figure 1: Research, Innovation and Infrastructure Network Map of the National Institute of Ocean Research – INPO.

Brazilian science has not only produced scientific knowledge about the ocean and climate, but has also contributed to the exploration of governance models and the link between science and traditional knowledge (5,6,7), which are applied in public policy instruments such as the National Coastal Management Plan (PNGC).

Due to the robustness of Brazilian science, the participation of Brazilian researchers in international forums has expanded, especially in international networks such as the All-Atlantic Alliance (8), which has enabled the implementation of new policy spaces such as ZOPACAS (Zone of Peace and Cooperation in the South Atlantic) and strengthened the country's role in science diplomacy (9).

Ocean governance is fundamental to tackling climate challenges in marine and coastal areas. The Brazilian experience shows that it is possible to integrate science, policy, and society into effective and scalable solutions. Strengthening institutional mechanisms, broadening the scientific base, and incorporating participatory approaches are important steps to increase coastal resilience and promote environmental justice. The success of this initiative will depend on our ability to translate national scientific advances into integrated public policy and continued investment in excellent marine research.

REFERENCES

1. P. Mazzega, D. M. Rugmini, A. F. Barros-Platiau, Where is the "Global South" located in scientific research? *Earth System Governance* 25, 100269 (2025) Disponível em: https://doi.org/10.1016/j.esg.2025.100269 [Acessado em 25 de julho de 2025].

2. M.M.C. Muelbert *et al.,* The Ocean and Cryosphere in a Changing Climate in Latin America: Knowledge Gaps and the Urgency to Translate Science Into Action. *Frontiers in Climate 3*, (November, 2021). Disponível em: https://doi.org/10.3389/fclim.2021.748344 [Acessado em 25 de julho de 2025].

3. A.F. Barros-Platiau *et al.,* "Ocean Governance in the Anthropocene: A New Approach in the Era of Climate Emergency" in *Eco-Politics and Global Climate Change. Environment & Policy*, S. Tripathi, R. Bhadouria, R. Singh, P. Srivastava, R.S. Devi, Eds. (Springer, 2023), v. 65, pp. 59–72. Disponível em: https://doi.org/10.1007/978-3-031-48098-0_4 [Acessado em 25 de julho de 2025].

4. L.R. Gonçalves *et al.*, "Oportunidades e opções de governança para conservar e restaurar a biodiversidade e os serviços ecossistêmicos da zona marinha-costeira" in *1º Diagnóstico Brasileiro Marinho-Costeiro sobre Biodiversidade e Serviços Ecossistêmicos*, C.S. Seixas, A. Turra, B.P. Ferreira, Org. (Editora Cubo, 2024).

5. M. Caldeira, A.T. Sekinairai, M. Vierros, Weaving science and traditional knowledge: Toward sustainable solutions for ocean management. *Marine Policy* 174, (2025). Disponível em: https://doi.org/10.1016/j.marpol.2025.106591 [Acessado em 25 de julho de 2025].

6. V. Renck *et al.,* Taking fishers' knowledge and it's implications to fisheries policy seriously. *Ecology and Society* 28(2), (2023). Disponível em: https://doi.org/10.5751/ES-14104-280207 [Acessado em 25 de julho de 2025].

7. C.N. El-Hani, L. Poliseli, D. Ludwig, D. Beyond the divide between indigenous and academic knowledge: Causal and mechanistic explanations in a Brazilian fishing community. *Studies in History and Philosophy of Science* 91, 296–306 (2022). Disponível em: https://doi.org/10.1016/j.shpsa.2021.11.001 [Acessado em 25 de julho de 2025].

8. A. Polejack, S. Gruber, M.S. Wisz, Atlantic Ocean science diplomacy in action: the pole-to-pole All Atlantic Ocean Research Alliance. *Humanities and Social Sciences Communications* 8(1), 52 (2021). Disponível em: https://doi.org/10.1057/s41599-021-00729-6 [Acessado em 25 de julho de 2025].

9. A. Polejack, A.F. Barros-Platiau, A Ciência Oceânica como ferramenta de Cooperação e Diplomacia no Atlântico, in *Conservation of living resources in areas beyond national jurisdiction*: BBNJ and Antarctica, A.F. Barros-Platiau, C.C. de Oliveira, Eds. (Lumen Juris, 2020), pp. 45–65.

6.13 Conclusions

A significant proportion of human activity, including the economic sector, depends on coastal and marine areas. They account for 80% of the world's traded goods and are a significant source of food production, potentially making an important contribution to the clean, renewable energy needed for the energy transition. They also sequester excess carbon released into the atmosphere in their seabed and mangroves. When preserved or restored, coastal zones also serve as a physical barrier against erosion and flooding exacerbated by extreme weather events such as storms and hurricanes.

Science offers knowledge and solutions. Brazilian science has demonstrated the impact of climate change and its exacerbation of the vulnerability of Brazil's coastal and marine areas; it has also highlighted ways in which Brazil can overcome these challenges. However, any action to adapt and/or mitigate climate change requires the formulation of public policies at the national and regional levels. Above all, it is essential to incorporate the climate problem and its ocean/coastal impacts into national priorities, ensuring continuous investment and effort in both scientific research and policy implementation. In addressing this challenge, local and traditional ecological knowledge must also be considered, and the representation of these groups in decision-making processes must be strengthened to facilitate transdisciplinary approaches that prioritize environmental and social justice.

As the ocean is local, national, regional, and global, an integrated approach encompassing all these levels needs to be developed. Due to the extent of its ocean and coastal territory, its position in global geopolitics, and its solid scientific base, Brazil has a strategic opportunity for scientific and diplomatic leadership on the international stage.

ACKNOWLEDGEMENT

Special thanks to the scientists from the National Institute for Ocean Reseah (INPO) Network who contributed to the chapter Ocean and Coastal Zones sharing their knowledge with the society.

To the journalists Dominique Ribeiro and Terezinha Costa for their contribution in editing the texts and in the executive version of this chapter.

7. THE CONTRIBUTION OF BRAZILIAN AGRICULTURAL SCIENCE TO THE CHALLENGES OF CLIMATE CHANGE

Eduardo Delgado Assad[31], StoécioMaia[32], Jurandir Zullo Jr[33], Vanessa Pugliero[34], Eduardo Pavão[34], João Paulo Silva[34]

INTRODUCTION

The agricultural sector is particularly sensitive to climate fluctuations and changes, and agriculture is one of the pillars of the Brazilian economy. Accounting for approximately 25% of GDP, it provides livelihoods and food security for 70-80% of the population, especially in rural areas.

Given the potential vulnerability to climate variability, especially in regions with lower yields that have a strong impact on food security, a more comprehensive approach to climate change and its impact on agriculture is therefore urgently needed. Taking a broader look at the impact of climate change on food security, this chapter assesses the issues around the relationship between climate, agriculture, livestock, and the economy and its impact on Brazil, as illustrated in the flowchart below (Figure 1). This flowchart refers to studies conducted under the Food Security sub-com-

31 Fundação Getúlio Vargas, FGV, São Paulo, SP.

32 Instituto Federal de Alagoas, ITAL, Maceió, AL.

33 Universidade de Campinas, UNICAMP, Campinas, SP.

34 Rede Brasileira de Pesquisas em Mudanças Climáticas, Rede Clima, Campinas, SP.

corresponding author: eduardo.assad@faunaprojetos.com.br

ponent of the INCT Phase 2 project, funded by FAPESP and CNPq. This assessment is part of a major effort undertaken by the MCTI climate network since 2009. During this time, several contributions have been made to better understand the impacts of climate change on agriculture, e.g. proposals for mitigation and adaptation measures and finally the attempt to quantify the emission and removal factors of agriculture in recent years.

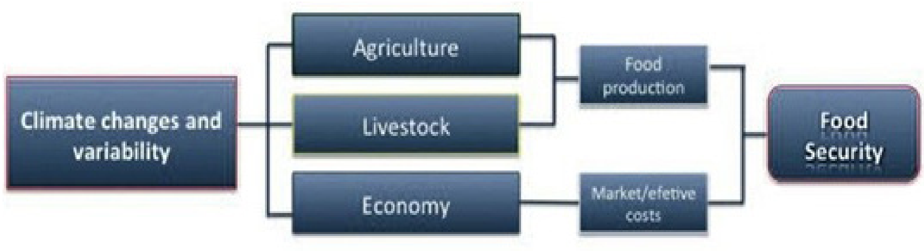


Figure 1: Flowchart of the food security subcomponente

The effects of climate change and its variability, with consequences for agriculture, livestock, and the economy, are closely linked to food production and the markets that regulate it. Food security is at the heart of this process.

Issues related to food security and climate change are increasingly being discussed and analyzed by researchers from different fields. These two issues pose significant challenges to the world's population and directly affect the agricultural sector and its relationship with other sectors of the economy. As the demand for agricultural products will increase in the coming decades in line with population and income growth, sectoral measures can make a significant contribution to achieving the international targets for reducing and stabilizing greenhouse gas concentrations in the atmosphere. In particular, there is a consensus that, , alternative practices in agriculture, forestry, and other land use (AFOLU) can contribute significantly to reducing greenhouse gas emissions through appropriate management and regional agriculture.

Production systems based on sustainable intensification of agricultural production inevitably require an integrated approach to climate change, adaptation measures and mitigation of greenhouse gas emissions. Identifying synergies between mitigation and adaptation in the AFOLU sector is essential, as food security and the impact of climate change on the agricultural sector require integrated action. The combined impact of mitigation and adaptation strategies is greater than if these measures are applied individually. Moreover, most of the mitigation techniques currently applied in agriculture were originally designed as “optimal management strategies,” to improve the long-term stability and resilience of agricultural systems, and create “win-win” scenarios. For example, the ABC Plan (2020) provides for an expansion of four million hectares of integrated crop, livestockand forestry (iLPF) systems. The government has launched the “National Program for the Restoration of Degraded Pastureland” (MAPA) (2024) with the aim of restoring 40 million hectares of pastureland and converting it into productive systems. These measures are expected to minimize the impact on food supply.

These systems enable, among other things, the sequestration of carbon and the reduction of nitrous oxide emissions, and thus greenhouse gas emissions. Similarly, the adaptation strategy aims to increase the productivity and resilience of agricultural systems, and make producers less vulnerable to climate change. In addition to improving the technical aspects and, in particular, the application of technologies to increase food productivity, it is necessary to stimulate reflection on the contribution of family farming to ensuring food security at a global level and to examine the challenges to food security in Brazil. To this end, it is necessary to ensure that this issue is placed on the political agenda of family farming in Brazil (CONTAG 2024) by analyzing the results of policies and programs aimed at bringing producers and consumers closer together. In addition, studying the conflicts between family farming and market price fluctuations can help to reduce farmers’ vulnerability.

Despite the large number of climate projections provided by global and regional climate models, there are still considerable uncertainties in climate projections for several regions of South America, and Brazil in particular. Some areas could become wetter, others drier, but the boundary between the two is not yet clearly defined. In many parts of Brazil, this could lead to water scarcity as precipitation decreases and/or evapotranspiration, increases. This would result in an estimated reduction in per capita water availability, which could lead to a significant increase in food insecurity due to the impact on food production and prices. Current projections indicate a possible reduction in food supply and, consequently, an increase in prices for agricultural products. According to Borges et al. (2025) https://portalibre.fgv.br/node/11106, food is becoming increasingly expensive, and the poorest population suffers the most from this trend, which also affects access to healthier, less processed food. There is more than one cause for rising food prices. However, several recent publications and studies point to the growing role of climate change. A June 2025 report from the OECD (Organization for Economic Co-operation and Development) found that, , severe or extreme droughts have affected 25-30% of the Earth's surface since 2015. This is double the approximately 15% observed in previous decades and almost triple the 10% observed at the beginning of the last century. The same report highlighted that Brazil, a leading net exporter of food, has suffered the most from droughts in the last two decades, both in terms of frequency and intensity.

This is clearly reflected in the aggregate productivity figures for Brazilian agriculture. According to the USDA, it only grew by 0.4 % per year between 2015 and 2022, after increasing by an impressive 3.0 % per year between 1995 and 2014. This slowdown in economic productivity growth (which, takes into account the economic costs of inputs as well as the development of yields per hectare) can also be observed in other major food exporters, such as the United States and Argentina. Studies by IPAM, Silva et al. (2023) show that rising temperatures and droughts in the Brazilian Cerrado are reducing the productivity of soybeans. The scientists calculated that every time the temperature in the Cerrado increased by 1°C above the historical average (1980 to 2018), soybean productivity decreased by 6%. It is important to remember that temperature increases due to heatwaves amount to much more than one degree. Therefore, climate change can have a strong impact on soybean production, as it has already done in southern Brazil (Assad & Assad, 2024). According to Buainain (2025), the impact on soybeans also extends to food security, an aspect that is often overlooked by its critics. As soybeans provide a plant protein with high nutrient density and are an important raw material for the production of meat, milk, and eggs, they make an important contribution to the food supply both domestically and internationally. In a world that is trying to secure affordable food for a growing population, Brazilian soybeans play a strategic role — directly and indirectly — in the fight against hunger and malnutrition. The recurring criticism that soy production jeopardizes food security ignores this important contribution, and also ignores the fact that the majority of food insecurity in Brazil is due to inequalities in access to income, not food shortages.

CURRENT AND PROJECTED SCENARIOS OF CLIMATOLOGICAL VARIABLES IN BRAZIL BETWEEN 1986 AND 2050

According to the OECD 2025 report, , Trends, Impacts and Adaptation Policies for a Drier World, climate change has increased the area affected by drought and worsened the impact on communities and economies. In addition to greater rainfall variability, rising temperatures are accelerating evaporation, reducing soil moisture, and increasing pressure on dwindling freshwater resources. It is estimated that the economic impact of an average drought today could be up to six times greater than in 2000, and costs are expected to increase by at least 35% by 2035. Figure 2 below shows the change in the average number of drought events (a) and (c) and their intensity (b) and (d) in the period 2000–2020 compared to 1950–2000, according to the same OECD report (2025).

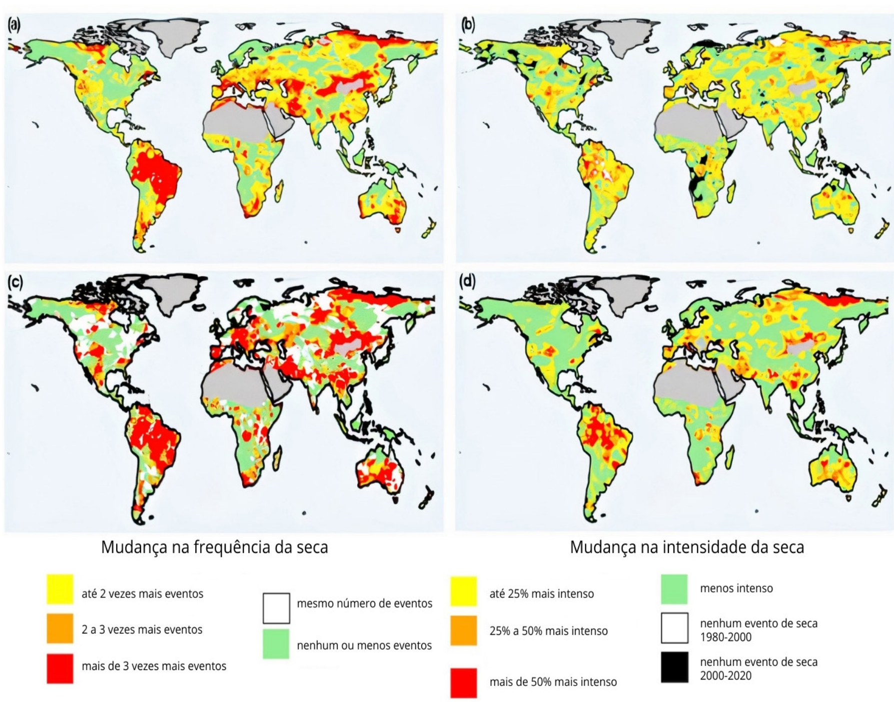


Figure 2: Change in the average number of drought events (a) and (c) and their intensity (b) and (d) in the period 2000 to 2020 compared to 1950–2000. Source: OECD 2025

From these maps we can see that Brazil is becoming drier and drier, with a high intensity of drought. To zoom in on this analysis and identify the fluctuations in the number of dry days in Brazil, a recent report from the Central Bank (https://www.bcb.gov.br/noticiablogbc/32/noticia), based on INPE data, shows a significant increase in the number of dry days, as shown in Figure 3 below.

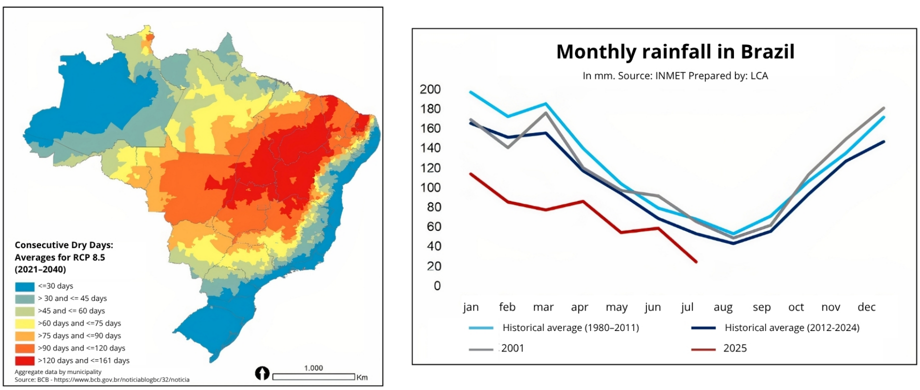


Figure 3: Consecutive dry days in the period 2021-2040, and rainfall distribution profile in Brazil with emphasis on 2025. Central Bank of Brazil - https://www.bcb.gov.br/noticiablogbc/32/noticia and LCA (IBRE FGV).

An analysis of Figure 3 shows that drought is increasing in Brazil and that rainfall in the country has also decreased recently. These events will have a direct impact on the increased climate risk for crops in the coming years.

On the other hand, when analyzing the impact of human activity on climate change, agriculture is cited as one of the main causes of tropical deforestation, which contributes to an increase in greenhouse gas emissions, as reported by Manzatto (2020).

The sector's emissions, which account for about 31% of total national emissions, come from the production process, methane emissions from livestock, the release of carbon through land management practices, and other factors. 4. National Inventory 2020, Brazil (2020). While these negative externalities caused by agriculture can weaken the sector's image, they also represent an excellent opportunity to reduce emissions or even replenish carbon stocks released in recent decades. Therefore, the impact of global warming in Brazil is increasingly measured using metrics that balance emissions and removals. Since the first greenhouse gas inventory in the 1990s, the climate network has played a key role in determining greenhouse gas emissions in agriculture. In the last inventory published in 2020, the Climate Network played a key role in determining emissions and removals of greenhouse gasses from livestock, land use, emissions from rice, nitrogen fertilizer and agricultural waste management.

SPATIOTEMPORAL ANALYSIS OF CLIMATE VARIABLES

A spatio-temporal analysis was carried out at the beginning of the establishment of INCT 2-Climate Change. The climatological data were collected, organized, and standardized for the entire Brazilian territory. The variables considered for the period from January 1, 1980, to December 31, 2015, were the reference evapotranspiration (ETo in mm), precipitation (mm), minimum temperature (°C), maximum temperature (°C), solar radiation (kWh/day/m^2), relative humidity (%), and wind speed (m/s), using the Daily gridded meteorological variables in Brazil (1980–2013) database (XAVIER et al., 2022). This climate data grid was estimated from the data of ground-based meteorological stations in Brazil operated by the Brazilian federal agencies (INMET and ANA) and the Ministry of Water and Electricity of the State of São Paulo, comprising a total of 3,625 precipitation stations and 735 meteorological control stations. Climatological information such as future precipitation (mm), minimum temperature (°C), and maximum temperature (°C) is obtained from the HADGEM2-ES model from 1970 to 2100 and then recalculated for the CIMP6 HadGem3 model. As mentioned above, tropical agriculture depends on rainfall; therefore, climate change has a strong impact on production systems. Climate models predict a significant increase in soil water deficit in the coming decades (Figure 4), while rainfall variability is already impacting smallholder and micro-peasant agriculture.

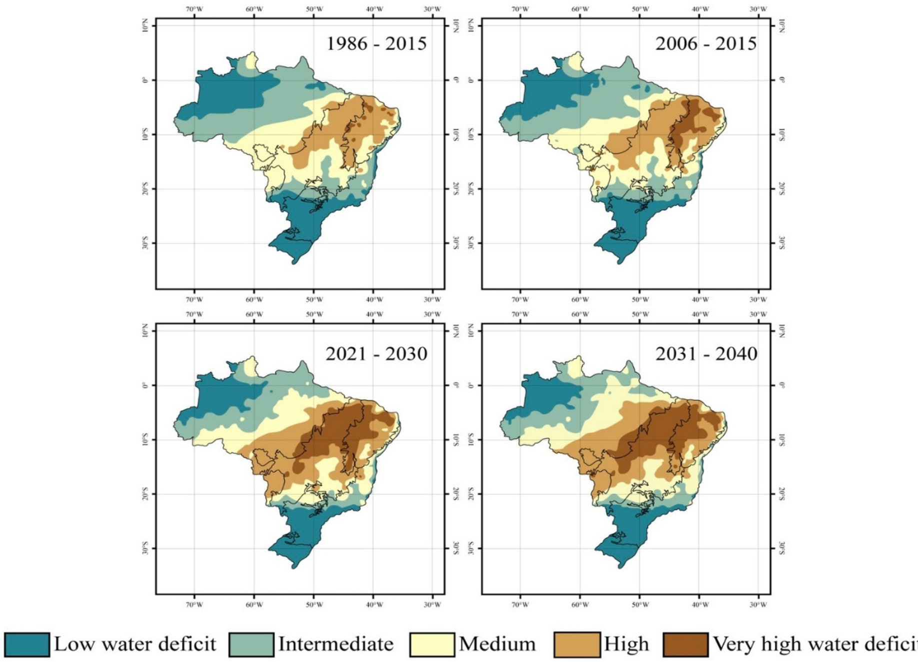


Figure 4: Projection of increased soil water deficit in the coming decades by climate models. Source: INCT Climate Change Phase 2 Ref: FAPESP 2014/50848-9 CNPq 465501/2014-1

The chronic drought that began in 2012 reduced agricultural productivity growth from 4.2% (1994–2011) to 1.5% (2012–2021) and caused a loss of 0.8 percentage points of annual GDP https://blogdoibre.fgv.br/posts/estiagem-de-2012-21-produtividade-agropecuaria-e-transbordamentos-na-economia In the Amazon, changing rainfall patterns and environmental degradation threaten the cultivation of soybeans and maize, which rely on the forest to ensure the onset of rain and adequate temperatures (Leite-Filho et al., 2024). Second crop yields could decline by up to 17% by 2050 (Pires et al., 2016; Abrahão & Costa, 2018), and annual losses could amount to up to USD 1 billion, with forest loss of up to 56% under weak governance scenarios (Leite-Filho et al., 2021). In the Cerrado, strong declines in cereal productivity are expected under the medium (RCP4.5) and high (RCP8.5) emission scenarios by the end of the 21st century (Camilo et al., 2018).

Models suggest that agricultural production, especially soy and maize, could gradually shift from Matopiba to the subtropical regions of the Cerrado and the Atlantic Forest (Zilli et al., 2020). However, this shift could reach limits, as some climate scenarios also predict significant losses in agricultural suitability in southern Brazil (65.7 % by 2049), with a particular impact on maize production as a second crop. In the southeastern Amazon region, agricultural suitability could also decline by up to 84.9 %, and an expansion of cultivated areas would not be sufficient to compensate for this decline in productivity, for example in sugar cane (Tanure et al., 2020). As a result of reduced productivity and job creation related to climate change, a cumulative decline in GDP in the legal Amazon region of 1.18 is projected by 2049 (Tanure et al., 2020).

A 65.7 % reduction in the area suitable for soybean cultivation could also occur in southern Brazil, with the main cultivation areas shifting to the southeastern part of the Amazon, region and the suitable area expected to decrease by 84.9 by 2050, primarily affecting maize production as a second crop. On the other hand, the effects of rising temperatures could benefit sugarcane productivity, particularly in southern Brazil, where the projected warming tends to reduce the frequency of frosts (Assad et al., 2013, Assad et al. 2016). Social and environmental disasters caused agricultural losses estimated at R$ 15.6 billion in 2024, representing 48.6 % of total losses, with droughts and dry spells and rainfall accounting for 51 % and 48.7 % of the causes respectively (CNM, 2024). In Rio Grande do Sul alone, , direct and irrecoverable losses in maize and soybean crops reached 21% and 16%, respectively in March 2020, corresponding to a total loss of R$ 4.8 billion (MAPA, 2022). Plunging winter temperatures also have an impact on Brazilian agriculture. Agricultural efficiency fell by 6.2 % and 10 % between 2005 and 2006, with total losses of 13.2 % due to cold and 30.5 % due to drought (Pereda & Alves, 2018). Climate change also favors the occurrence of pests and diseases in crops as the temperature and humidity in the air and soil increase (Assad & Assad, 2024).

EFFECTS ON FAMILY FARMS

Family farms in Brazil account for 77% of rural farms and occupy 23% of the total area (80.9 million hectares). Of this, 48% of the land was used for pasture, 31% was , forests, or agroforestry systems, and 15.5% was used for arable farming. These farms accounted for 23% of the value of agricultural production (IBGE, 2017). In the semi-arid region, which is home to 38% of the country's family farms (Melo and Voltolini, 2019), climate change and desertification are expected to greatly reduce productivity, especially in the caatinga, which has already been modified on 63% of the land, affecting food security, and exacerbating poverty, and conflict (Lindoso et al., 2014; Niemeyer & Vale, 2022). Increasing aridification threatens livelihoods, water, and energy security in the region, and causes migration and inequality (Milhorance et al., 2020; Costa et al., 2024). For key crops such as beans, maize and rice, the drought reduced expectations for agricultural production in 2024 by up to 68 % (CEMADEN, 2024b). The drought of 2024 affected the Cantareira system and the dams in the Amazon, region and jeopardized family farms. Family farmers in the Pampa region are already aware of the effects of climate change, and report irregular seasons, late frosts, weather extremes, pests, and soil degradation as the biggest risks (Liter & Bursztyn, 2015).

Given the large number of existing global climate models and the observed divergence between them, it is essential to apply a method for evaluating model behavior to identify those that adequately represent the region of interest. The development of the HadGEM2 model resulted in an Earth system model that is a useful scientific tool for predicting future climate and understanding climate dynamics within the Earth system (Collins et al., 2011). This model was created taking into account the dynamics of the terrestrial and oceanic carbon cycle, atmospheric chemistry, aerosols, chemical radiation, and chemical hydrology, as described by Martin (2011).

The model integration according to Protocol 5 (Coupled Model Intercomparison Project Phase 5, or CMIP5) suggests that it also adequately reflects current conditions (Collins et al., 2011).

Using the 14 climate projection models listed in CMIP5 for the entire geographic coverage of Brazil, in the RCP4.5 and RCP8.5 scenarios, Marcos Junior et al. (2018) produced projections for temperature, precipitation, and evapotranspiration for the 21st century. The regions most affected by the increase in average annual temperature are the North and the Central West. However, these variables are expected to increase throughout Brazil. The same behavior is expected for evapotranspiration, reflecting the increased future demand for water for irrigation. Precipitation is projected to decrease in the North and Northeast regions over the course of the century, while , most models indicate an increase in annual averages for the other regions.

The main results of the agriculture sub-component of INCT Phase 2 in 2019 were the finalization of spatial data on land use and the simulation of the water balance for the whole of Brazil, on a regular 25-km grid, for the years 1986-2005, 2005-2015, 2020-2030, 2030-2040, and 2040-2050, using the HADGEM2-ES model. Later in the project, the latest model, HadGEM3-GC31-MM, was used to assess the impact on productivity.

The climatological water balance (CWB) is the usual method for monitoring the amount of water stored in the soil throughout the seasons, which vary according to water loss and recharge. The CWB counts the amount of water flowing into and out of a region over a 30-year period, also known as climatological normal values, and the successful application of the tool depends on local variables (DANTAS et al., 2007).

The water demand in future scenarios can be predicted by the projected water balance. This means that the methodology is applied to a given baseline condition and the results are then compared with a range of future climate data (GONDIM, 2011; PONPANG-NGA, 2016).

The water balance was estimated according to the diagram shown in Figure 5.

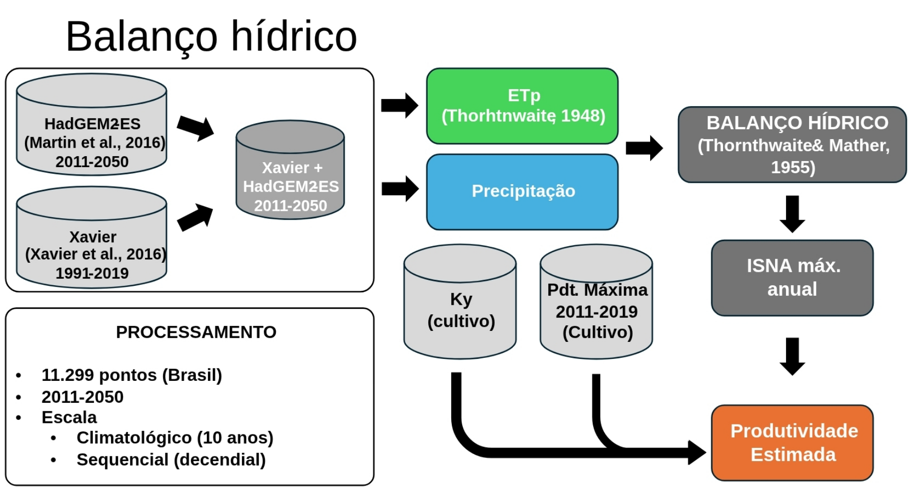


Figure 5: Water balance simulation scheme for estimating meteorological variables and subsequently used in estimating productivity.

The results of the water balance were used to create maps, of the water deficit (Figure 4) and temperature maps, (Figure 6), which show which areas will be most affected by rising temperatures and lower precipitation.

The sequence of steps to develop the methodology for climate projections is subject to numerous uncertainties that are incorporated into the mathematical modeling process. However, despite these limitations, this is the method that has been used to quantify the impact of anthropogenic influences on the climate system, with the aim of proposing mitigation and adaptation strategies for new scenarios (TORRES, 2014).

In order to predict the impact of climate change on agriculture, the climate projections developed through mathematical modeling steps also take into account radiation factors, the so-called RCPs, which consist of time series of atmospheric concentrations of greenhouse gasses and aerosols. The RCPs were selected to cover a range of realistic future scenarios, from optimistic scenarios, in which human-induced radiative forcing is reduced (RCP 2.6), to pessimistic scenarios (RCP 8.5). There are also intermediate scenarios, such as RCP 4.5 (LIDDICOAT et al. 2013).

In general, 85% of crop productivity depends directly on the degree of soil water deficiency.

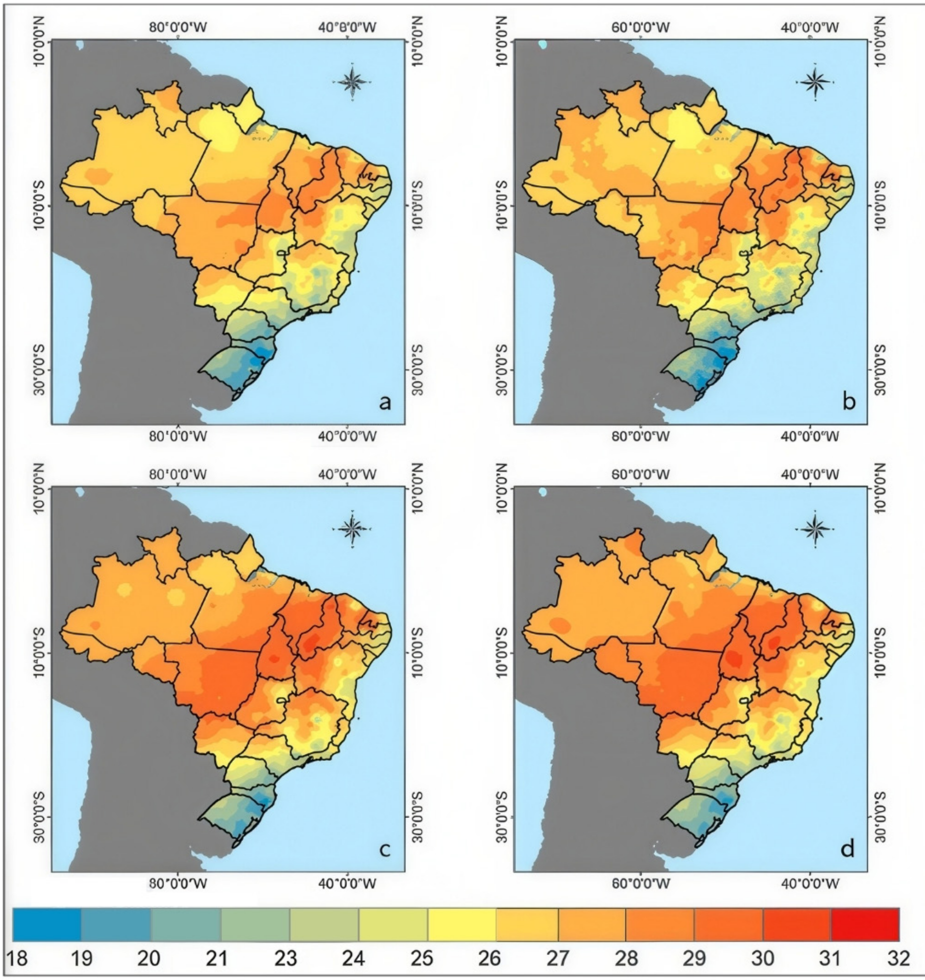


Figure 6: Temperature maps obtained from data from the HADGEM2 and Daily gridded meteorological variables in Brazil models for the periods 1986-2015, 2006-2015, 2021-2030 and 2030-2040.

The climatic average evapotranspiration in Brazil varies from 801 mm to 2,287 mm, with the maximum of the total ETP being 2,465 mm, 2,901 mm and 2,877 mm for the historical series 2006-2015, 2021-2030 and 2031-2040, respectively. While the minimum for 2006-2015 is 749 mm and remains at an average index of 826 mm for 2021-2030 and 2031-2040 for the entire area (Figure 7).

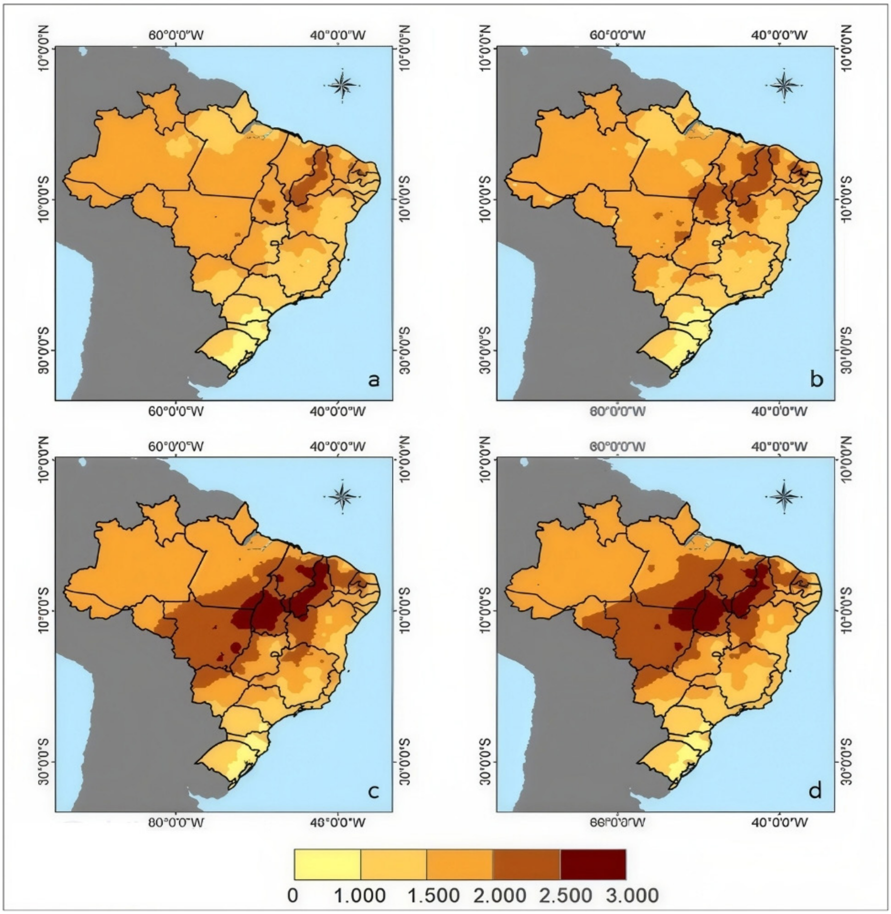


Figure 7: Total evapotranspiration (a) 1986 - 2016; (b) 2006-2015; (c) 2021-2030; (d) 2031-2040.

The use of meteorological data series in comparison to the climatological normal value enables a direct comparison between the conditions of the base period ("today") and the future scenarios. Therefore, using one of the IPCC future scenarios, such as the one presented in the HadGEM2-ES model, with the RCP8.5 forcing, the following effects are observed: increased temperature, increased potential evapotranspiration, decreased water surplus, and increased water deficit. This trend allows the proposal of a territorial organization model, together with alternative solutions, to solve or minimize the scenarios generated by the climate emergency.

CLIMATE CHANGE AND IMPACTS ON GRAIN PRODUCTION

Given the assessment of parameters that are strongly influenced by climate change, it is important to assess the evolution of food supply, in relation to agricultural production, for some components of the staple food basket, such as rice, beans, wheat, and cassava, which have a significant impact on food security.

Given the importance of the Brazilian agricultural sector, the planning of its activities and public policy proposals must be designed to maintain sustainable models for the coming decades. Brazilian soil and climate conditions vary throughout its range. Therefore, it is important to understand these variations and model them over time and space in order to assess the areas that can achieve higher or lower productivity, and their risk, especially in relation to climate factors. This knowledge is important for both public and private entities, as the negative impacts of climate change can affect the development of society in economic, social, and environmental terms. On the other hand, well-structured strategies offer the opportunity to choose better management for higher risk areas and improve investment allocation for lower risk, areas.

The simulation of climate variability with agrometeorological models must be well dimensioned in time and space to improve decision making. For example, water balance models can be applied nationwide to characterize the amount of water available for agricultural use. This practice is widely used in the assessment of climate risks for agriculture.

Since 1996, Brazil has adopted a public policy known as Agricultural Climate Risk Zoning (Zarc), with strong support from the MCTI climate network. This policy dictates to all 5,568 Brazilian municipalities what, when , and where crops with a 20% risk can be grown. In other words, Those who follow these guidelines generally have an 80% chance of a successful harvest. This system uses 30 years of daily rainfall and temperature data, which is updated over time. One strategy for deriving climate change is to include the previous year's data each year and eliminate the data from the first year of the simulation. In this way, the climate changes taking place can be taken into account. An urgent discussion is: should the 30-year series be retained or should this series be shortened to 10 years, in view of the speed of climate change?

The data used as input for the model (Zarc), used to estimate productivity losses, were extracted from two different meteorological models:

one focused on past meteorological modeling (Xavier et al., 2022) and the other aimed at modeling future trends in climate factors, mainly temperature and precipitation. Water gains due to precipitation and losses due to evapotranspiration are considered, taking into account the temporal variance in sequential and decadal intervals. In addition, three scenarios for the root system are considered: shallow (75 mm), medium (100 mm), and deepest (125 mm) water depth. Due to the large volume of data, all processing steps were performed using a framework that automates the calculation of the water balance for all more than 11,000 virtual meteorological stations in the model (Xavier et al., 2022). The resulting products were exported as results for a single season, for each value of available water capacity (representing the depth of the root system) and for each decade, as well as for the entire model. Data from the corrected CIMIP6 model were used to estimate future productivity losses. This makes it possible to check the impact on productivity in the coming years (2020 to 2050) using the Zarc methodological framework.

Despite considerable scientific progress in the use of satellite imagery to estimate crop area, there is still no accurate method to assess productivity losses. Therefore, the following crop parameters are used:

- Length of the vegetation cycle, divided into phenological phases, by identifying critical periods (stages), such as the early phase, plant development, mid-season, and late season;
- Kc (crop coefficient), as a method for determining the plant's water requirements;
- Depth of the root system, particularly important for estimating the available water capacity (AWC).

The data collection and analysis process for the productivity estimate is shown in Figure 8.

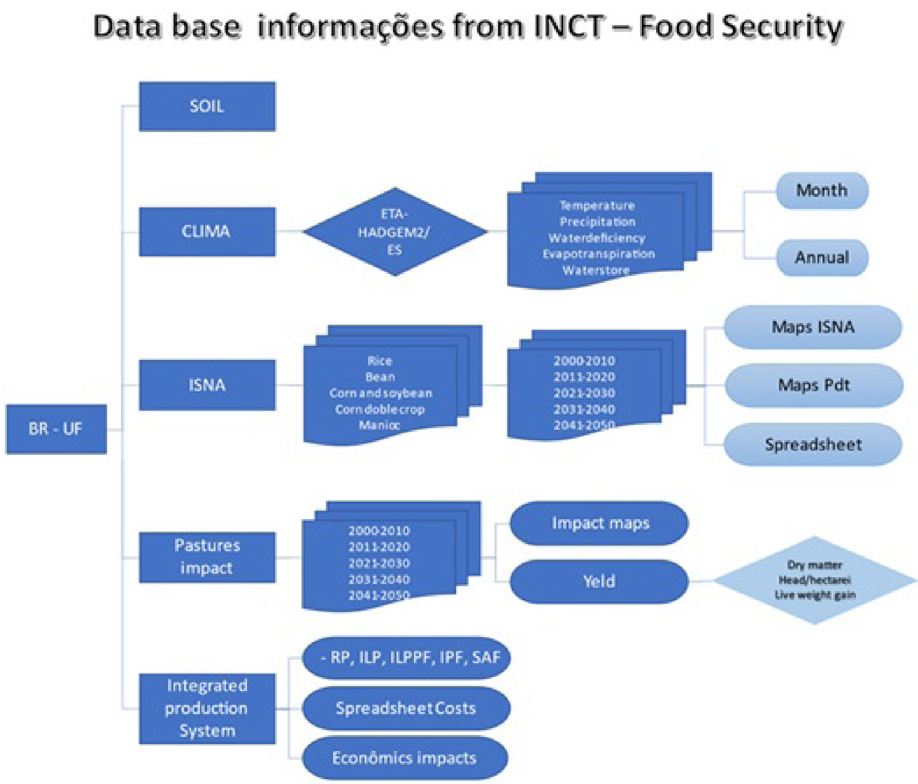


Figure 8: Scheme adopted to estimate crop productivity up to 2050.

This method was first used in Assad and Pinto (2008), using the IPCC Precis model to assess agricultural losses. Loss assessments were carried out up to the year 2070. In 2007, the model indicated that grain losses in the Southern region could amount to R$7 billion in 2020. In this case, there was an error in the absolute value. According to CONAB, in its report "Brazil 2021, a story of crop losses in Brazil"," the projected amount of losses in Brazil was 36.7 million tons. In the weekly quotation for March 2020 (March 21-25, 2020), the price paid to producers, the monetary value of the losses was equivalent to R$ 84.8 billion for each product, according to Brasil 2021, taking into account the corresponding shares of the losses.

The scenarios used to value the losses were adjusted based on the IPCC's new climate models. Assad et al. (2016), based on a report by the Intergovernmental Panel on Climate Change (IPCC) and using simulations of the latest climate change scenario models, projected by 2100, the impact on the main Brazilian crops grown in family agriculture, such as corn, second crop corn, beans, and rice. They also predicted how vulnerable these crops will be if temperatures continue to rise at current rates (0.3°C) per decade. At the same time, an attempt was made to characterize the extreme events that have been occurring with increasing frequency in recent years. For the coming years, projections were made for the frequency of daily temperatures above 34°C for the entire country, affecting all farmers. This was done for extreme rainfall, i.e. estimating the frequency of intense rainfall across the country, which has direct consequences for soil erosion, fertilizer losses, and soil disturbance, in addition to loss of crop productivity. All simulations were based on models from the latest IPCC AR5 report, with the extreme scenarios RCP 4.5 and RCP 8.5. The results of this 2016 simulation confirmed the trend of significant losses in agriculture, which, according to Conab, was 15% of crop losses.

In the INCT-2021 report, the , evaluation of the results with the HadGEM3-GC31-MM model shows more pessimistic results with regard to the food security component than those of the CIMIP5 HADgem2-ES model. The yield losses were greater than those achieved with the previous model.

Table 1 shows the results obtained with the CIMP6 HadGEM3-GC31-MM model and the respective loss trends in agriculture until 2050. For soybeans in the Cerrados, the estimated productivity loss over this period is 26%.

Tabel 1: Results obtained with the HadGEM3-GC31-MM model from CIMP6 and the respective trends in agricultural losses until the year 2050. Fonte: Relatório INCT-Fase2 2022. Assad & Assad (2024)

MODELO: HADGEM3 - GC - CMIP 6 - RCP 8.5

Produtividade (kg/ha)

Bioma	Cultura	2011/ 2020	2021/ 2030	Diferença	Diferença (%)	2031/ 2040	Diferença	Diferença (%)	2041/ 2050	Diferença	Diferença (%)
Amazônia	Soja	3.078	2.456	623	20	2.504	574	19	2.562	516	17
	Milho	2.543	2.795	252	10	3.597	1.054	41	2.867	324	13
	Arroz	1.917	1.907	10	1	1.825	92	5	1.766	151	8
	Feijão	678	679	2	0	672	6	1	660	18	3
Cerrado	Soja	3.244	2.399	845	26	2.277	967	30	2.486	758	23
	Milho	4.331	4.879	548	13	6.964	2.633	61	5.227	896	21
	Arroz	2.105	1.867	238	11	2.083	21	1	1.897	207	10
	Feijão	1.179	1.077	103	9	1.210	30	3	1.166	14	1
Floresta Atlântica	Soja	3.349	3.524	175	5	3.523	174	5	3.702	353	11
	Milho	4.818	5.329	510	11	6.176	1.358	28	5.608	790	16
	Arroz	3.542	3.433	109	3	3.708	166	5	3.513	29	1
	Feijão	1.171	1.112	58	5	1.193	22	2	1.178	7	1
Pampa	Soja	2.458	2.845	87	16	2.819	361	15	2.998	540	22
	Milho	3.812	3.756	56	1	3.314	498	13	3.936	124	3
	Arroz	7.337	7.337	-	-	7.337	-	-	7.337	-	-
	Feijão	1.030	1.030	-	-	1.030	-	-	1.030	-	-
Caatinga	Soja	-	-	-	-	-	-	-	-	-	-
	Milho	660	722	62	9	925	265	40	716	56	8
	Arroz	1.604	1.819	215	13	1.879	75	17	1.899	295	18
	Feijão	321	344	23	7	374	53	16	374	53	16

According to the results of the agrometeorological models using the CIMIP6 data, presented in Table 1, the impact on productivity is negative in all cases, indicating a possible reduction in food supply if current production practices are maintained. However, with the adoption of agricultural practices from the ABC, ABC+, and regenerative agriculture programs, and the intensification of production, productivity has increased, especially for soybeans and corn. Figure 9 shows soybean losses in the state of Rio Grande do Sul between 2010 and 2022.

Using mathematical models calibrated for the conditions of the Cerrado, Macena et al. (2024) were able to simulate nitrous oxide (N2O) emissions under different farming systems for a 50-year period. The authors found that, these emissions will increase with increasing temperatures over time, while biomass production and grain yield will decrease. These results, based on GHG emissions, clearly show that there will be losses in grain production in Brazil.

The study by Assad et al. (2019b) shows the areas with the greatest risk of losses. The red area in Figure 10 shows the extent of the problem, with a significant rise in temperature jeopardizing agricultural production in Brazil in the coming years.

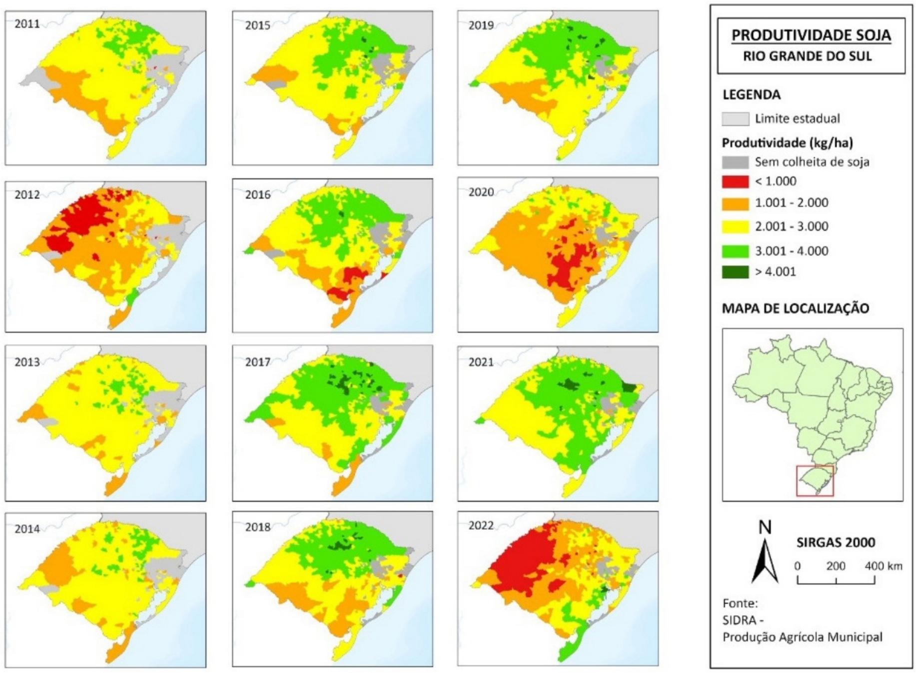


Figure 9: Spatial variation in productivity losses in Rio Grande do Sul, from 2010 to 2022. Source: Assad & Assad (2024)

Finally, Figure 10 shows in red the areas where high temperatures and severe heatwaves can occur, which can affect agricultural production.

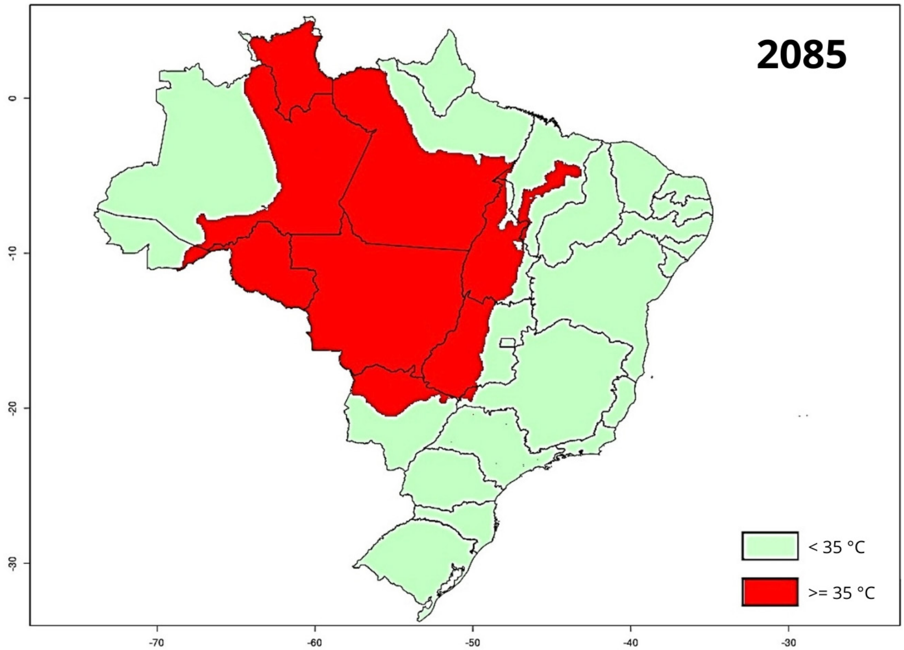


Figure 10: Map of Brazil showing the temperature cutoff above 35°C for the year 2085. The region in red is at high risk for agricultural production. Source: Assad et al. (2019b).

If we analyze the entire period and all crops, we can see a decrease in acreage, especially in rice, beans, and cassava, and a small increase in maize. This means that these areas will gradually be replaced by commodities such as soybeans and corn, which will certainly have an impact on food supply. Figure 11 illustrates the projected acreage for different crops in Brazil in 2050.

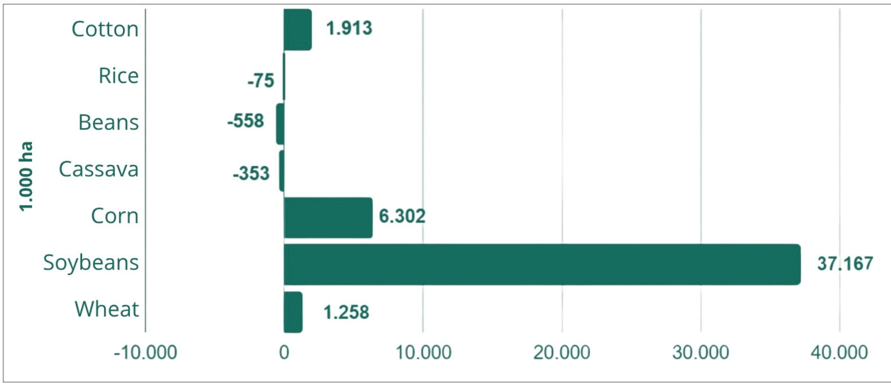


Figure 11: Variation in the planted area for various crops in Brazil between 2021 and 2050. Bean, rice, and cassava crops show a decrease in the planted area, while soybean and corn show an increase in the planted area.

Production and area forecasts for the main crops show that the area under cultivation in Brazil is expected to exceed 100 million hectares by 2050, compared to the current 78.2 million hectares. This expansion is focused on soybeans, corn (second crop), and sugar cane. Part of the increase in corn and cotton production is expected to take place on soybean acreage. Some crops, such as rice, beans, and cassava, are expected to lose area. Of course, some of the expansion of soybean, corn, and sugarcane acreage will likely take place in new areas, replacing other crops. This expansion may also take place in degraded pasture areas. However, it is crucial to accelerate the conversion, of , low or very low productivity pastures to cropland or integrated production systems, as these are under-managed.

By 2050, an increase in arable land of around 45.6 million hectares is required. This expansion means an increase of 37 million hectares in the current soybean cultivation area and around 6 million hectares in the current maize cultivation area. To reduce the pressure to expand acreage in Brazil, it is necessary to spread techniques and technologies that increase soil productivity without the need for new land. The expansion of high-quality no-till systems in combination with integrated production systems, can raise grain productivity to a new level. In addition, rapid advances in research, innovation, and technology for new crop varieties should increase the use of biological nitrogen fixation in legumes (beans) and grasses, contributing to the productivity of maize, rice, and pastures.

Rising temperatures and reduced rainfall, can affect food production. Over the past five years, climate change has severely affected soybean and maize production, reducing harvests by more than 25 million tons.

A necessary summary of these scenarios for cereal production shows that agriculture in Brazil and around the world, especially family farming, faces many problems, particularly those related to poverty and its effects. The current social vulnerability of these populations is likely to be exacerbated by the effects of climate change. The main problems, we have identified include:

1. 95% of losses in the Brazilian agricultural sector are due to floods or droughts (Assad et al., 2008). It is predicted that such extreme events will occur more frequently;
2. Looking at the relative magnitude of precipitation variability on three time scales — interannual, decadal, and long-term (100 years), - "the proportion of total variability explained by short-term variability is three times as large as the long-term trend (climate change) and twice as large as the decadal variability" (Baethgen, 2010);
3. future trend indicates a decrease in precipitation over time for the northern and north-eastern regions.
4. The main losses in the rural environment projected by recent studies point to the loss of arable land as the main factor;
5. The semi-arid regions of the Northeast will become drier, while the eastern part of the Brazilian Amazon will become a savannah-like biotope;
6. For agriculture, the drought could have a negative impact on food security, a factor that worries family farmers. One example that reflects this concern is the projection that cassava could disappear from the semi-arid regions of the northeast. Maize production in the Agreste region in the northeast is also expected to be severely affected.
7. Some seed crops adapted to the tropical climate could migrate to southern Brazil or to higher altitude regions to compensate for the rise in temperature (Assad et al., 2008). This migration can lead to

competition between areas, and to the migration of labor from rural areas to more favorable regions;

8. Other factors that are expected to occur as part of the stress on agricultural systems are a reduction in water flow and irrigation potential, increased incidence of pests and diseases, changes in biomes and a decline in animal and plant biodiversity.

PASTURES AND LIVESTOCK EMISSIONS

According to MAPA (2024), the National Program for the Conversion of Degraded Pastures into Sustainable Agricultural and Forestry Production Systems (PNCPD), established by Decree No. 11,815 of December 2023, underpins Brazil's commitment to the Sustainable Development Goals and the Paris Agreement by promoting policies and actions to reduce greenhouse gas emissions and adapt to climate change. This program arises in a context where the conservation and sustainable use of natural resources are linked to the promotion of food and nutrition security, and the country's economic development.

In terms of cattle breeding, the country had a population of 234.3 million animals in 2022 (IBGE, 2022), producing 8 million tons of beef (IBGE, 2024). Of this, 2.9 million tons were exported, representing 22.9% of global exports (FAO, 2023). To maintain this production, Brazilian livestock farming requires 179 million hectares of pasture land (LAPIG, 2022). However, more than 60% of these pastures are in low or medium condition (degraded or in the process of degradation), resulting in low productivity and high greenhouse gas emissions. Converting these degraded areas into sustainable production systems is crucial for preserving biomes, reducing emissions, and increasing agricultural productivity.

Another consideration is that, based on scientific advances in soybean and corn cropping systems, it can be pointed out that increasing the production of these crops should be done by converting degraded pastures. This strategy allows for the introduction of integrated production systems, where two crops can be grown on the same area, increasing meat productivity while reducing greenhouse gas emissions.

The Cerrado biome is a good example of the possible introduction of integrated systems. At the beginning of the colonization of the Brazilian Cerrado, with the introduction of soybean cultivation, crops were long-cycle with a productivity of about 1.7 tons per hectare (Arantes and Souza, 1993). Currently, the average productivity in the Cerrado has increased from 2.9 t.ha-1 to 3.26 t.ha-1 (PAM 2022). These official results indicate an average productivity increase of over 170%, or over 4% per year. However, these gains are declining and currently stand at 1.2%. Growing a single crop per year, including preparation, fertilization, planting, and harvesting, means that 42% of agricultural use time is spent on cultivation. After harvesting, the soil is exposed, and the remaining 58% of the utilization time is impacted by greenhouse gas emissions, erosion, low water infiltration, etc. This was the premise of previous studies— - deforestation to produce more, with high greenhouse gas emissions. By adopting soil management practices based on integrated systems, the soil stays covered longer, preventing soil loss and increasing water quantity and infiltration capacity. The combination of soybeans and maize enables an average national productivity of about seven tons of grain per hectare, with growth rates of over 3 to 4% per year. Therefore, deforestation for production alone is not a sustainable practice.

The above example can be illustrated by Figure 12, which shows how management works in areas with degraded pastures. In the case of Mato Grosso, the average productivity in integrated systems can reach 9.5 tons of grain/ha, with an average degradation of 1.3 t C/ha/year.

Figure 12: Evolution from single production systems to integrated systems. Source: Vilela, 2019. CBAGRO

Figure 13 shows the cycle of carbon emissions and removals following deforestation and pasture restoration over the years.

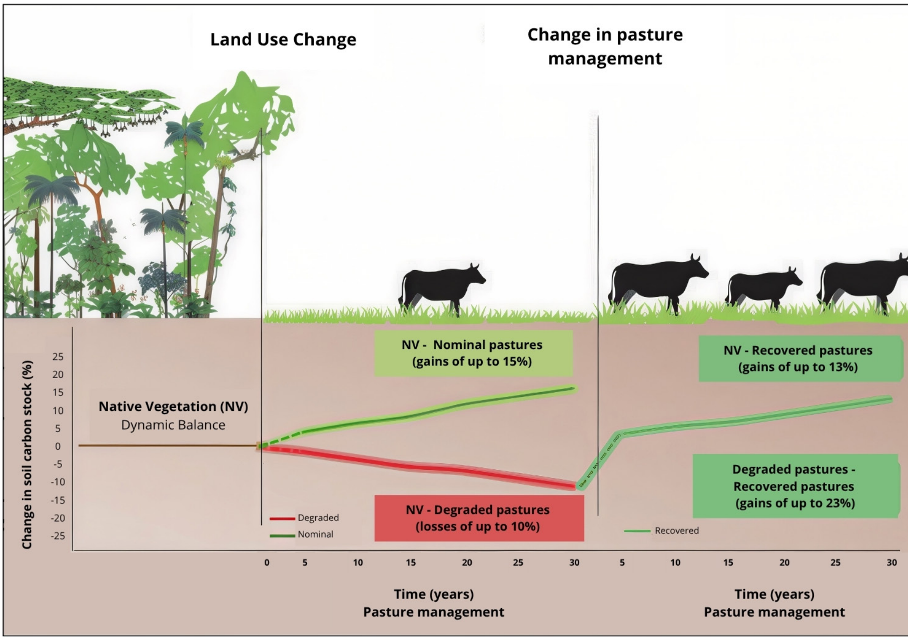


Figure 13: Cycle of emissions and removals after deforestation and with the adoption of recovered pasture management. Illustration by Bruna E. Schiebelbein. Source: Ruiz et al. 2023

It is observed that the , nominal loss of soil carbon over the years is estimated at 10%, with a potential gain of up to 23% in restoring degraded pastures. By introducing crops, such as soybeans and corn, the gain would be more carbon in the soil and higher productivity. This hypothesis, adopted from the ABC/MAPA plan, foresees a doubling of production without the need for deforestation.

The cycle of soybeans and corn does not sequester carbon, but the introduction of pasture into the system over the years, results in a significant increase in soil organic matter and, consequently, organic carbon, as shown in Figure 14.

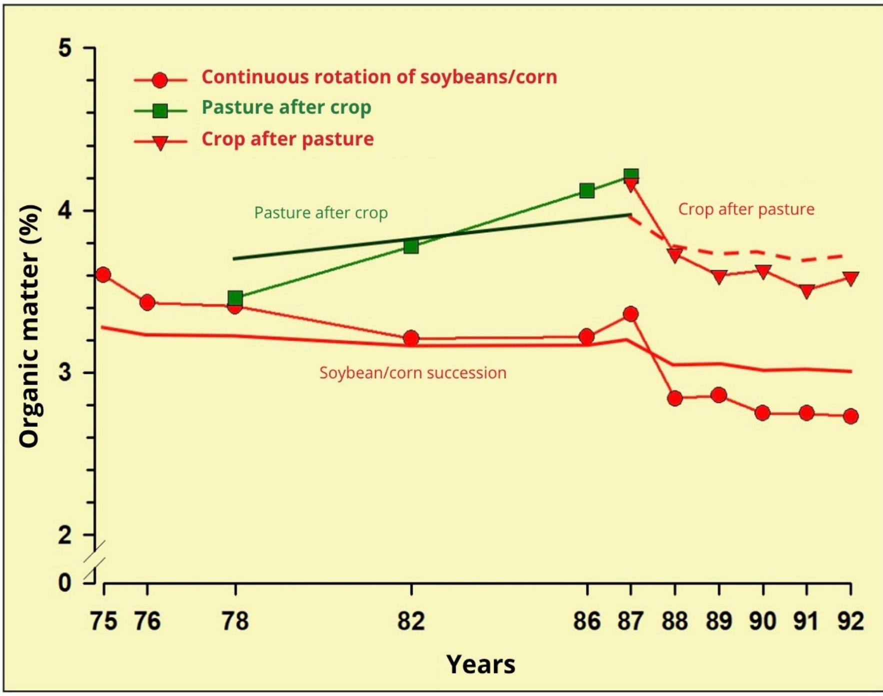


Figure 14: Variation in soil organic matter content in continuous rotation systems of soybean and corn, pasture after cropping and cropping after pasture. Source: Sousa et al. (1997).

With the enlargement of the root system of Brachiaria willows, a significant increase in soil organic matter and consequently an increase in organic carbon is observed. The benefits include increased water infiltration, reduced soil erosion, and increased tolerance to intense dry periods.

In the studies developed in phase two of the INCT climate change program, we sought to identify the location of these degraded pastures. Using the Embrapa method (2018) to prioritize degraded pastures that could be converted into productive systems, this potential was mapped and quantified.

In this case, 2,390 municipalities with degraded rangelands were identified, covering a total of 94 million hectares of degraded or moderately degraded land. Of these, 22.5 million hectares, spread across 432 municipalities, are considered priority areas for restoration at three levels: Communities with up to 30,000 hectares of degraded rangeland, up to 45,000 hectares, and up to 60,000 hectares. According to the prioritization criteria, this would be the final amount that could be converted to the Integrated Plant-Livestock-Forestry (ILPF) system. Figure 18 shows the municipalities that should be prioritized and their geographical distribution.

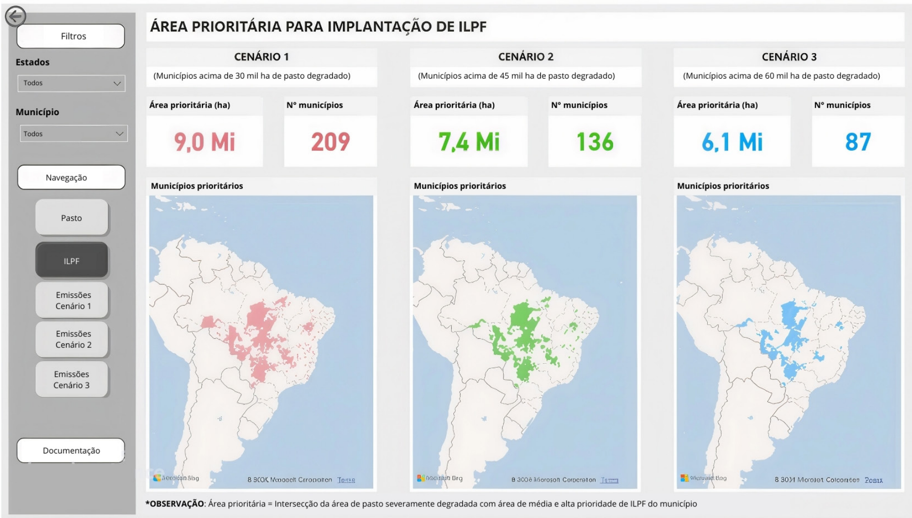


Figure 15: Municipalities identified as most suitable for implementing ILPF in degraded pastures.

This corresponds to a reduction of 11.5 million tons of CO2 equivalent through livestock farming, not including transport.

OFFICIAL ACTIONS OF THE BRAZILIAN GOVERNMENT

A closer analysis of the current situation of Brazilian farmers and ranchers shows that:

- The vast majority of farmers are conservative.
- They still have difficulties understanding the process of global warming.
- About 40% have not yet understood the causes of the climate emergency.
- There is a rapid shift towards regenerative agricultural practices.

- It is still observed that some farmers are practicing deforestation and slash-and-burn agriculture to grow crops.
- Technological advancement has enabled farmers to make significant progress in understanding climate change.
- A significant proportion of farmers, especially in the Central-West region, are guided by the advice of deniers who have a strong influence in the sector.

To circumvent and minimize this situation, the government has implemented several action plans with funds for the harvest plan, which would essentially be as follows:

- ABC Plan
- ABC+ Plan
- National Fertilizer Plan
- Harvest Plan
- Food Acquisition Program
- Degraded Pasture Recovery Program
- Forest + Program
- Control and prevention of deforestation and forest fires
- Biodiversity - Fauna and Flora

With these plans already funded in the crop plan, a significant window of opportunity is opening for the Brazilian agriculture and livestock sectors to reduce the impact of climate change and increase production. These opportunities include:

- Brazil can double its agricultural production without cutting down forests;
- With integrated systems, Brazil can offer products with a low or very low carbon footprint, and thus satisfy the demand of foreign markets;
- In a short time, the country can become the largest carbon sink on the planet, without burning or deforestation;
- With the right practices, a 30% reduction in methane emissions from livestock farming is possible;
- Brazil can meet the world's food needs with a further 40% increase in agricultural production.

FINAL CONSIDERATIONS

The food security sub-component of INCT-PHASE 2 dealt with agriculture and food supply from several perspectives.

First, the climate vulnerability of Brazilian agriculture was assessed, taking into account water stress, temperature, and evapotranspiration. The vulnerability assessment showed that, , agricultural production will be affected in all areas if no measures are taken to adapt to climate change by 2050. A significant increase in water stress was observed, shifting from the northeast to the central-western region. The consequences of increased water stress, combined with the increase in temperature and evapotranspiration, would have a strong impact on maize production (second harvest) and reduce the productivity of soybeans. In the south, this region would be less vulnerable to a possible increase in annual rainfall, for pulp production, as there is little or no water stress there and the production of perennial crops could be consolidated. Based on the studies conducted by the INCT and the Climate Network on the main staple crops, it was found that the areas under rice, beans, and cassava, in particular will decrease and maize cultivation will increase slightly. This means that these areas will gradually be replaced by commodities such as soybeans and maize, which will certainly have an impact on the food supply. Productivity increases were observed in rice production, while productivity in beans did not change, a reasonable increase in wheat production, mainly due to the expansion of irrigated wheat cultivation in the Central-West region, and a decrease in cassava production, indicating a reduction in the supply of this product, especially for the low-income population.

In terms of commodities, soybeans, maize and other staple foods were analyzed. Contrary to what was observed in the statistical analyzes of the MAPA data, when applying agrometeorological models fed with data from the IPCC CIMP6 climate models, there are no productivity gains for any crop in any biome. In order of intensity of productivity loss, the Amazon region will be the most affected, followed by the Cerrado, the Caatinga, and finally the Pampa and the Atlantic Forest. The prerequisite for this is that no adaptation measures are considered for the production systems in these biomes.

However, the introduction of integrated production systems, can reverse the situation and improve food supply. When analyzing the situation of degraded pastures, that can be converted into integrated production areas, 2,390 municipalities with degraded pastures were identified, covering a total of 94 million hectares of degraded or moderately degraded land. Of these, 22.5 million hectares, spread across 432 municipalities, are considered a priority for restoration at three levels: i) municipalities with up to 30,000 hectares of degraded pasture, ii) municipalities with up to 45,000 hectares and iii) municipalities with up to 60,000 hectares. According to the prioritization criteria, this would be the final amount that could be converted to the ILPF system. This could bring 202 million tons of grain (through the integration of agriculture, livestock and forestry) into agricultural production and an estimated 10 million head of cattle with a slaughter weight of 7 arrobas. This means that, given the extremely precarious situation of agriculture, and, therefore food production, measures to adapt production systems to more balanced models represent a significant opportunity for Brazil to maintain a high level of food supply, considering raw materials and staple foods. Therefore, it is crucial that the Brazilian agribusiness adopts practices that promote the quality and quantity of food supply, while maintaining connectivity to external markets. The main challenges in reducing the impact of climate change are: Ending deforestation, eliminating fires, reducing the use of fossil fuels, shifting the agricultural production model to more balanced models, increasing the adoption of integrated agricultural production systems such as ILP, ILPF, SAF, and restoring a huge area of degraded pastures.

REFERENCES

Abrahão, G. M., & Costa, M. H. (2018). Evolution of rain and photoperiod limitations on the soybean growing season in Brazil: The rise (and possible fall) of double-cropping systems. *Agricultural and Forest Meteorology*, 256–257, 32–45. https://doi.org/10.1016/j.agrformet.2018.02.031

Arantes, N. E.; Souza, P. I. de M. de. Cultura da soja nos cerrados. Piracicaba: Potafos, 1993. 535p. *Simposio sobre a cultura da soja nos Cerrados, Uberaba*, 1992.

Assad, E. D. (2021). Sistemas agrícolas adaptados às mudanças climáticas. *Ciência e Cultura*, 73(1), 35–40. https://doi.org/10.21800/2317-66602021000100007

Assad, E. D. *et al.* (2016) Impactos e vulnerabilidades da agricultura brasileira as mudanças climáticas . Modelagem climática e vulnerabilidades setoriais à mudança clima no Brasil, v.4, p.127-88.

Assad, E. D., & Assad, M. L. R. C. L. (2024). Mudanças do clima e agropecuária: impactos, mitigação e adaptação. Desafios e oportunidades. *Estudos Avancados*, 38(112), 271–292. https://doi.org/10.1590/S0103-4014.202438112.015

Assad, E. D., Marin, F. R., Evangelista, B. A., & Cunha, G. R. (2016). Agricultura. In PBMC (Ed.), *Impactos, vulnerabilidades e adaptação às mudanças climáticas* (Vol. 2, p. 339–375). Brasília: Ministério da Ciência, Tecnologia e Inovação.

Assad, E. D., Pinto, H. S., Zullo Junior, J., & Evangelista, B. A. (2013). Impacto das mudanças climáticas nos riscos de produção agrícola no Brasil. In M. A. Nobre (Ed.), *Mudanças climáticas e agricultura no Brasil*. Embrapa.

Assad, E. D.; Pinto, H. S. (2008). Aquecimento Global e a Nova Geografia da produção Agrícola no Brasil. Brasília: *Embaixada Britânica*, v.1. 82p.

Assad, E.D.; Lopes-Assad, M.L. (2024) Mudanças do clima e agropecuária: impactos, mitigação e adaptação. Desafios e oportunidades. *USP Estudos avançados* 38 (112), 2024

Baethgen, W. Climate Risk Management for Adaptation to Climate Variability and Change. CROP SCIENCE, VOL. 50, MARCH–APRIL 2010

Borges *et al* (2025) Perspectivas 2025. https://portalibre.fgv.br/node/11106

Brasil (2020). Ministério da Ciência, Tecnologia e Inovação. Secretaria de Políticas e Programas de Pesquisa e Desenvolvimento. Coordenação-Geral de Mudanças Globais de Clima. Quarta Comunicação Nacional do Brasil à Convenção-Quadro das Nações Unidas sobre Mudança do Clima. Brasília: Ministério da Ciência, Tecnologia e Inovação, 531 p.

Brasil. 2021 Ministério da Agricultura, Pecuária e Abastecimento.Histórico de perdas na agricultura brasileira : 2000-2021 / Secretaria de Política Agrícola . – Brasília : MAPA/AECS, 2022. ISBN: 978-85-7991-185-9

Buinain, A.M. 2025. Soja no Brasil: controvérsias em debate. https://jornal.unicamp.br/artigo/2025/07/30/soja-no-brasil-controversias-em-debate/ 3 p.

Camilo, J. A., de Lelis Teixeira de Andrade, C., Amaral, T. A., Tigges, C. H. P., de Melo, M. L. A., Chan, C. S., & Garcia y Garcia, A. (2018). Impact of climate change on maize grown in the Brazilian cerrado. *ASABE 2018 Annual International Meeting*. https://doi.org/10.13031/AIM.201800967

CEMADEN. (2024c). Cemaden registra recorde de alertas e mais de 1,6 mil ocorrências de desastre no Brasil em 2024. https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/cgcl/noticias/cemaden-registra-recorde-de-alertas-e-mais-de-1-6-mil-ocorrencias-de-desastre-no-brasil-em-2024
Acesso em: 20 de junho de 2025.

Collins, W. J.; Bellouin, N.; Doutriaux-Boucher, M.; Gedney, N.; Halloran, P.; Hinton, T.; Hughes, J.; Jones, C. D.; Joshi, M.; Liddicoat, S.; Martin, G.; O'connor, F.; Rae, J.; Senior, C.; Sitch, S.; Totterdell, I. Wiltshire, A.; Woodward, S. (2011). Development and evaluation of an Earth-System model – HadGEM2, Geosci. Model Dev., 4, 1051–1075, https://doi.org/10.5194/gmd-4-1051-2011.

Confederação Nacional de Municípios (CNM). (2024). Panorama dos desastres no Brasil: 2013 a 2023 (Estudo Técnico nº 202405). https://cnm.org.br/storage/biblioteca/2024/Estudos_tecnicos/202405_ET_Panorama_Desastres_Brasil_2013_a_2023.pdf
Acesso em: 20 de junho de 2025.

Contag, Observatório do Clima. (2025). Agricultura familiar e os sistemas alimentar remoção de carbono e transição justa São José dos Pinhais, PR. Seven Editora. 50p DOI: 10.56238/livrosindi202507-001

Costa, F. R. C., Marengo, J. A., Albernaz, A. L. M., Cunha, A. P., Cuvi, N., Espinoza, J.-C., Ferreira, J., Jimenez-Muñoz, J. C., Páez, M. B., Carramaschi de Algão Querido, L., & Schöngart, J. (2024a). *Policy Brief: Droughts in the Amazon*. https://doi.org/10.55161/LVYB6857

Dantas, A.A.A.; Carvalho, L.G.; Ferreira, E. Classificação e tendências em Lavras, MG. (2007). *Ciência e Agrotecnologia, Lavras*, v.31, n.6, p.1862-1866. http://dx.doi.org/10.1590/S1413- 70542007000600039.

FAO. 2023. Food Outlook – Biannual report on global food markets. Food Outlook, November 2023. Rome. https://doi.org/10.4060/cc8589en

Gondim, R. S.; Fuck Júnior, S. C. de F.; Evangelista, S. R. M.; Castro, M. A. H. de; Teixeira, A. dos S. (2011). Impacto das mudanças climáticas na evapotranspiração em nível de Bacia Hidrográfica utilizando um Sistema de Informações Geográficas.

IBGE Instituto Brasileiro de Geografia E Estatística I PAM Produção Agrícola Municipal (2022). Série histórica. Acessado em 10 de junho de 2024. Disponível em: ipeadata.gov.br.

Leite-Filho, A. T., Soares-Filho, B. S., & Oliveira, U. de. (2024). Climate risks to soy-maize double-cropping due to Amazon deforestation. *International Journal of Climatology*. https://doi.org/10.1002/JOC.8381

Leite-Filho, A. T., Soares-Filho, B. S., Davis, J. L., Abrahão, G. M., & Börner, J. (2021). Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. *Nature Communications* 2021 12:1, 12(1), 1–7. https://doi.org/10.1038/s41467-021-22840-7

Liddicoat, S.; Jones, C.; Robertson, E. 2013 CO2 Emissions Determined by HadGEM2-ES to be Compatible with the Representative Concentration Pathway Scenarios and Their Extensions. *Journal of Climate*, 26(13), 4381–4397. https://doi.org/10.1175/JCLI-D-12-00569.1

Lindoso, D.P., Dalboni Rocha, J., Debortoli, N., Ibiapina Parente, I., Eiró, F., Bursztyn, M., Rodrigues-Filho, S., Hutton, C., Boulanger, J.-P., Lindoso, D. P., Rocha,

J. D., Debortoli, N., Bursztyn, M., Rodrigues-Filho, S., & Parente, I. I. (2014). Integrated assessment of smallholder farming's vulnerability to drought in the Brazilian Semi-arid: a case study in Ceará. *Climatic Change,* 127, 93–105. https://doi.org/10.1007/s10584-014-1116-1

Litre, G., & Bursztyn, M. (2015). Climatic and socio-economic risks perceptions and adaptation strategies among livestock family farmers in the pampa biome. *Ambiente & Sociedade*, 18(3), 55–80. https://doi.org/10.1590/1809-4422ASOC668V1832015

Manzatto, C.V. 2020.Mitigação das emissões de gases de efeitos estufa pela adoção das tecnologias do Plano ABC: estimativas parciais / Celso Vainer Manzatto ... [*et al*.]. –Jaguariúna: Embrapa Meio Ambiente, 2020. PDF (35p.) – (Documentos / Embrapa Meio Ambiente, 1516-4691 ; 122).

Macena *et al*. Effects of agricultural management and of climate change on N2O emissions in an area of the Brazilian Cerrado: Measurements and simulations using the STICS soil-crop model. *Agriculture, Ecosystems & Environment*, v. 363, 108842. https://www.sciencedirect.com/science/article/abs/pii/S0167880923005017?via%3Dihub

Marcos Junior et al. (2018). Classificação Climática de Thornthwaite para o Brasil com Base em Cenários de Mudanças Climáticas do IPCC-AR5 Rev. bras. meteorol. 33 (4) • Oct-Dec 2018 • https://doi.org/10.1590/0102-7786334007

Martin, G.M.; Bellouin, N.; Collins, W.J.; Culverwell, I.D.; Halloran, P.R.; Hardiman, S.C.; Hinton, T.J.; Jones, C.d.; Mcdonald, R.E.; Mclaren, A.J.; O'connor, F.M.; Roberts, M.J.; Rodriguez, J.M.; Woodward, S.; Best, M.J.; Brooks, M.E.; Brown, A.R.; Butchart, N.; Dearden, C.; Derbyshire, S.H.; Dharssi, I.; Doutriaux-Boucher, M.; Edwards, J.M.; Falloon, P.D.; Gedney, N.; Gray, L.J.; Hewitt, H.T.; Hobson, M.; Huddleston, M.R.; Hughes, J.; Ineson, S.; Ingram, W.J.; James, P.M.; Johns, T.C.; Johnson, C.E.; Jones, A.; Jones, C.P.; Joshi, M.M.; Keen, A.B.; Liddicoat, S.; Lock, A.P.; Maidens, A.V.; Manners, J.C.; Milton, S.F.; Rae, J.G.L.; Ridley, J.K.; Sellar, A.; Senior, C.A.; Totterdell, I.J.; Verhoef, A.; Vidale, P.L.; Wiltshire, A. (2011) The HadGEM2 family of met office unified model climate configurations. Geosci Model Dev 4(3):723–757. doi: 10.5194/gmd-4-723-2011, 2011

Milhorance, C., Sabourin, E., le Coq, J. F., & Mendes, P. (2020). Unpacking the policy mix of adaptation to climate change in Brazil's semiarid region: enabling instruments and coordination mechanisms. *Climate Policy*, 20(5), 593–608. https://doi.org/10.1080/14693062.2020.1753640

Ministério da Agricultura Pecuária e Abastecimento (2024). Conversão de pastagens degradadas em sistemas de produção agropecuários e florestas sustentáveis. Plano de priorização de áreas e estimativa de investimentos. GPP (Grupo de Políticas Públicas - Esalq/USP) Deflo/SDI/Mapa (Departamento de Reflorestamento e Recuperação de Áreas Degradadas Secretaria de Inovação, Desenvolvimento Sustentável, Irrigação e Cooperativismo do Ministério da Agricultura e Pecuária). Brasília, 294 P.

Niemeyer, J., & Vale, M. M. (2022). Obstacles and opportunities for implementing a policy-mix for ecosystem-based adaptation to climate change in Brazil's Caatinga. *Land Use Policy*, 122, 106385. https://doi.org/10.1016/J.LANDUSEPOL.2022.106385

Niemeyer, J., & Vale, M. M. (2022). Obstacles and opportunities for implementing a policy-mix for ecosystem-based adaptation to climate change in Brazil's Caatinga. *Land Use Policy,* 122, 106369. https://doi.org/10.1016/j.landusepol.2022.106385

OCDE (2025), Perspectivas globais da seca: tendências, impactos e políticas para se adaptar a um mundo mais seco, Publicação da OCDE, Paris, https://doi.org/10.1787/d492583a-en .

Pereda, P., & Alves, D. (2018). Climate and weather impacts on agriculture: the case of Brazil. *Economia Aplicada*, 22(3), 5–26. https://doi.org/10.11606/1980-5330/EA119584

Pires, M. O. (2020). 'Cerrado', old and new agricultural frontiers. Brazilian Political Science Review, 14(3), e0004. https://doi.org/10.1590/1981-3821202000030006

Ponpang-Nga, P.; Techamahasaranont, J. Effects of climate and land use changes on water balance in upstream in the Chao Phraya River Basin, Thailand. Agric. Nat. Resour. 2016, 50, 310–320.

Ruiz, Francisco *et al*. Constructing soils for climate-smart mining. *Communications Earth & Environment*, v. 4, p. 1-6, 2023. Disponível em: https://doi.org/10.1038/s43247-023-00862-x. Acesso em: 26 maio 2024.

Silva, D. S., Arima, E. Y., dos Reis, T. N. P., & Rattis, L. (2023). Temperature effect on Brazilian soybean yields, and farmers' responses. *International Journal of Agricultural Sustainability*, 21(1). https://doi.org/10.1080/14735903.2023.2173370

Sousa, D. M. G. de; Vilela, L.; Rein, T. A.; Lobato, E. Eficiência da adubaçãofosfatada em dois sistemas de cultivo em um latossolo de Cerrado. In: Congresso-Brasileiro de ciência do solo, 26., 1997, Rio de Janeiro. Informação, globalização, uso do solo Rio de Janeiro: SBCS, 1997.

Tanure, T. M. do P., Miyajima, D. N., Magalhães, A. S., Domingues, E. P., & Carvalho, T. S. (2020a). The Impacts of Climate Change on Agricultural Production, Land Use and Economy of the Legal Amazon Region Between 2030 and 2049. *EconomiA*, 21(1), 73–90. https://doi.org/10.1016/J.ECON.2020.04.001

Tanure, T. M. do P., Miyajima, D. N., Magalhães, A. S., Domingues, E. P., & Carvalho, T. S. (2020b). The Impacts of Climate Change on Agricultural Production, Land Use and Economy of the Legal Amazon Region Between 2030 and 2049. *EconomiA*, 21(1), 73–90. https://doi.org/10.1016/J.ECON.2020.04.001

Torres, Roger Rodrigue. Análise de incertezas em projeções de mudanças climáticas na América do Sul. 2014. 271f. Tese (Doutorado em Meteorologia) – INPE, São José dos Campos, 2014.

Vilela, L. 2019. XXI CBAGRO, Congresso Brasileiro de Agrometeorologia.MCTI-2020- Quarto Inventário Nacional de Emissões e remoções antrópicas de Gases de efeito estufa.

Xavier, A. C. *et al*. New improved Brazilian daily weather gridded data (1961–2020). *International Journal of Climatology,* v.42, n.16, p.8390-404, 2022. https://doi.org/10.1002/joc.7731 2022.

Zilli, M., Scarabello, M., Soterroni, A. C., Valin, H., Mosnier, A., Leclère, D., Havlík, P., Kraxner, F., Lopes, M. A., & Ramos, F. M. (2020). The impact of climate change on Brazil's agriculture. *Science of The Total Environment*, 740, 139384. https://doi.org/10.1016/J.SCITOTENV.2020.139384

8. CLIMATE CHANGE AND HEALTH

Celia R. S. Garcia[35], Bruno Caramelli[35], Mariana Verasi[35], Marie-Anne Van Sluysi[35], Paulo Saldivai[35], Evangelina Araujoi[35], Mariana Farrel Côrtesi[35], Nazareno Scaccia[36], Thaís Guimarãesi[35], Silvia Figueiredo Costai[35], Maria Cassa Mendes-Correai[35], Ester Cerdeira Sabino[37], Giselle Maria Rachid Viana[38], Carolina Aguiar[39], Nathália Nogueira Chamma Siqueirai[35], Izis Monica Carvalho Sucupira[38]

INTRODUCTION

The interactions between climate change and public health have been intensifying at an alarming rate, requiring integrated and multidisciplinary approaches to mitigate their growing effects. This chapter is divided into five parts. In the first part, by Bruno Caramelli, it is discussed that the impacts on cardiovascular health are exacerbated by extreme events such as heat and cold waves, which induce dehydration, hypercoagulability, and cardiovascular problems, especially among vulnerable populations. These risks are exacerbated by social inequalities, air pollution, and inadequate urban infrastructure. The need for adaptive public policies and training in global health is therefore becoming urgent. Next, the text by Mariana Veras, Marie-Anne Van Sluys and Paulo Saldiva contributes by showing

---

35 Universidade de São Paulo, USP, São Paulo, SP.
36 Centro Universitário do ABC, FMABC, Santo André, SP
37 Universidade Municipal de São Caetano do Sul, USCS, São Caetano do Sul, SP.
38 Instituto Evandro Chagas, IEC, Belém, PA.
39 Universidade Federal de São Paulo, UNIFESP, São Paulo, SP.
corresponding author: cgarcia@usp.br

how unplanned urbanization has transformed the urban environment into an aggravating factor in the climate and health crisis. Soil sealing, the loss of green areas, and the concentration of activities in central regions create heat islands, alter rainfall patterns, and favor the increase in respiratory and cardiovascular diseases. Cities become territories of risk, requiring policies that integrate ethics, sustainability, and public health in urban planning. In the field of infectious diseases, the effects of the climate are equally devastating. The text by Evangelina Araújo, Marina Côrtes, Nazareno Scaccia, Thaís Guimarães, and Silvia Costa analyzes the impact of climate change on bacterial waterborne diseases, highlighting the need for coordinated action across sectors. The lack of adequate sanitation, increased flooding, and the proliferation of rodents pose a significant risk to entire communities. The implementation of warning systems, investments in infrastructure, and the use of climate modeling to anticipate outbreaks are key to protecting the population in extreme event scenarios

Next, Maria C. M. Correa and Ester C. Sabino expand this discussion by addressing arboviruses, such as dengue, whose expansion is directly linked to rising global temperatures, urbanization, and poverty. The proliferation of Aedes aegypti, favored by degraded climatic and environmental conditions, poses significant challenges to public health. Amazon once again emerges as an epicenter of vulnerabilities due to deforestation, migratory flows, and fragile health systems

Finally, Giselle. Viana, Carolina Aguiar, Nathália Siqueira, Izis Sucupira and Celia Garcia show that malaria, although with reduced mortality, is increasing in incidence, particularly in the Brazilian Amazon. Transmission is profoundly influenced by factors such as deforestation, climate variability, and human mobility. Resistance to antimalarials and limitations in the diagnosis of *P. vivax* reinforce the importance of investing in new therapeutic tools and vaccines aimed at protecting vulnerable groups.

Together, the texts highlight the necessity for a new preventive strategy in public health, one that considers the interdependence between climate, territory, infrastructure, science, and social justice. Addressing climate challenges requires both global and local responses, grounded in evidence, innovation, and cooperation among sectors and knowledge domains.

8.1 Climate emergencies, pollution and cardiovascular diseases: the (not so) invisible crisis of the 21st Century

Bruno Caramelli

INTRODUCTION

The second episode of the television series Extrapolations (Apple TV+, 2023), is set in 2046, a dystopian future marked by extreme climate change (1). The episode shows a very difficult period for humanity, with thaw, extreme heat, disappearance of coastal cities and extinction of species. Right at the beginning, the character is a ten-year-old boy in love with a whale, the last living representative of this species. The boy has physical limitations related to great fatigue and shortness of breath on exertion. The disease, easily identified by cardiologists as heart failure, was called by doctors at that time the "summer heart". The boy's heart problem is described as a condition resulting from global warming, a dramatic but scientifically provocative symbol of the physiological effects of the climate crisis on the human body (Figure 1).

Figure 1: TV series EXTRAPOLATIONS, Apple TV+, 2023.

I have developed a plausible pathophysiological hypothesis to explain the illness that affects the boy. With the extreme increase in temperature, the human body needs to intensify the heat dissipation mechanisms, reducing peripheral resistance through vasodilation. Circulating more through the skin, the blood loses heat and cools the body. The heart, in turn, needs to increase the frequency of contractions to pump blood to the enlarged vascular bed. To complicate the situation, dehydration resulting from excessive heat reduces the body's blood volume, making it difficult to increase cardiac output and overloading, in a sustained way, the work of the heart to maintain the perfusion of the organs. In predisposed or vulnerable individuals — such as children and the elderly — this overload can evolve into a phenomenon known as incessant tachycardia, a condition recognized as being one of the causes of tachycardial cardiomyopathy and heart failure. The "summer heart", therefore, ceases to be just a dramatic fiction and becomes a realistic metaphor for the invisible and underestimated impacts of the climate on the cardiovascular system.

Historical and Evolutionary Context

The characteristics of the environment, especially the climate, have always influenced the health of living beings. The analysis of the isotope curve of oxygen (δ18O) evaporated from the ocean and sequestered in glacial ice allows the study of natural climate variability over very long periods, such as millions of years. In the last 10 million years, profound changes in the planet's climate have been identified, but no previous phase compares to the current one in terms of global warming (2) (Figure 2).

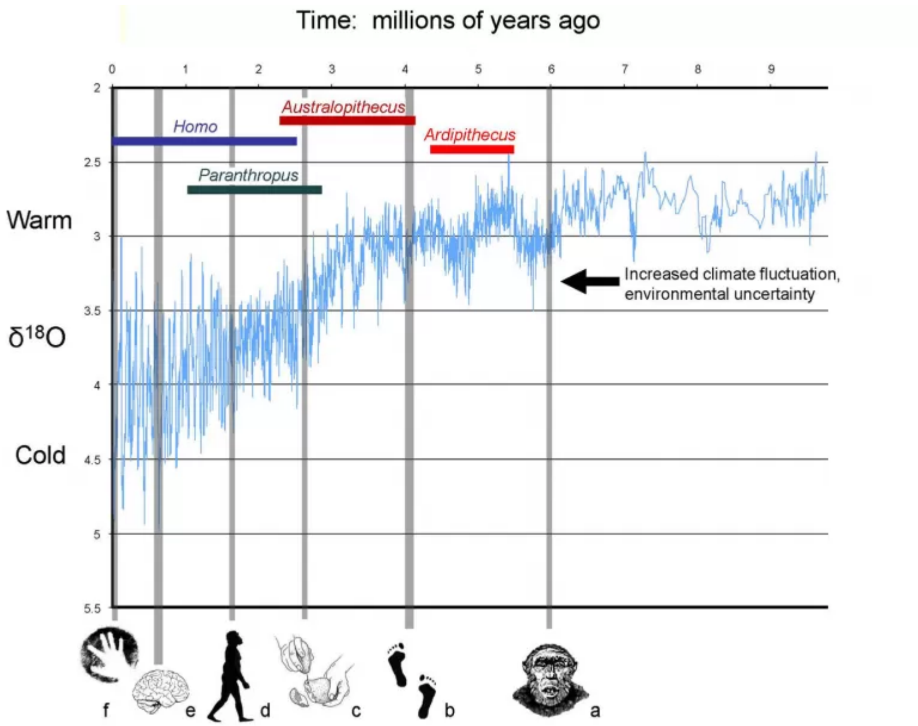


Figure 2: Climate variations over the last 10 million years, based on oxygen isotope curve (δ18O).

As can be seen in Figure 2, temperature variations have occurred previously on Earth. On the other hand, the study of the evolution and natural selection of living beings suggests that there are two important characteristics to determine the survival of species in the face of the challenges imposed by the environment: the ability to adapt and the speed with which environmental changes occur. The speed of current changes, driven by industrialization, deforestation, and the burning of fossil fuels, may have exceeded the adaptive capacity of the species (2) (Figure 3).

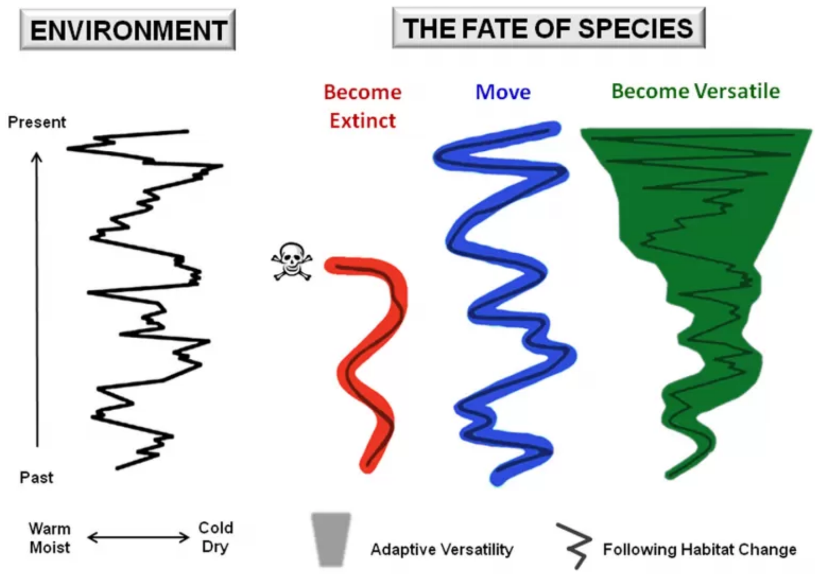


Figure 3: The environment, the capacity for adaptation and the fate of species.

Epidemiological Evidence

In 2024, Kazi and colleagues published a systematic review on the relationship between climate change and cardiovascular health. The research listed 11 Brazilian publications among the 492 observational studies that met the inclusion criteria for publications, 182 of which examined extreme temperatures, 210 ground-level ozone, 45 smoke from fires, and 63 extreme weather events, such as hurricanes, dust storms, and droughts. Ground-level ozone, also known as tropospheric ozone, is an air pollutant generated by chemical reactions between nitrogen oxides and volatile organic compounds. Tropospheric ozone increases when pollutants emitted by cars, power plants, industrial boilers, refineries, chemical industries, and other sources react chemically in the presence of sunlight. Higher temperatures accelerate the production of tropospheric ozone (3).

The studies analyzed in the systematic review presented results from 30 high-income, 17 middle-income and 1 low-income countries. The strength of the evidence was classified as sufficient to indicate an association between cardiovascular diseases and environmental conditions such as extreme temperature, tropospheric ozone elevation, tropical storms, hurricanes, cyclones, and dust storms. The evidence was found to be limited, however, for smoke from fires and unsuitable for droughts and landslides. Exposure to extreme temperatures was associated with increased cardiovascular mortality and morbidity, but the magnitude varied with temperature and duration of exposure. Tropospheric ozone, in turn, amplified the risk associated with elevated temperatures, and vice versa. Extreme weather events, such as hurricanes, were associated with an increased cardiovascular risk that persisted for many months after the initial event (3).

Some studies have observed a small increase in cardiovascular mortality, out-of-hospital cardiac arrests, and hospitalizations for ischemic heart disease after exposure to smoke from fires, another condition related to climate change, while others have not confirmed the association. Older people, radicalized populations, and ethnic minorities and low-income communities, however, were disproportionately affected, reinforcing the importance of targeted identification and prevention for vulnerable populations (3).

In Brazil, in 2019, Paula Santos and colleagues observed that exposure to small particles, mainly from vehicle traffic, is associated with increased blood pressure in hypertensive and/or diabetic workers. In a previous observational study, in 2008, the same authors had already found an association between air pollution and an increase in emergency room visits, and that individuals with diabetes are especially susceptible to the adverse effects of air pollution on their health conditions (4,5). In this way, it became evident once again that the main victims of climate change, with regard to health, are the most fragile people, those already with chronic diseases, the elderly, children and people with unfavorable economic conditions.

Figure 4 is represented in the Pocket Guide on Climate Change, published in 2024 by the Brazilian Ministry of Health, and summarizes the available evidence on the health consequences of climate change (6).

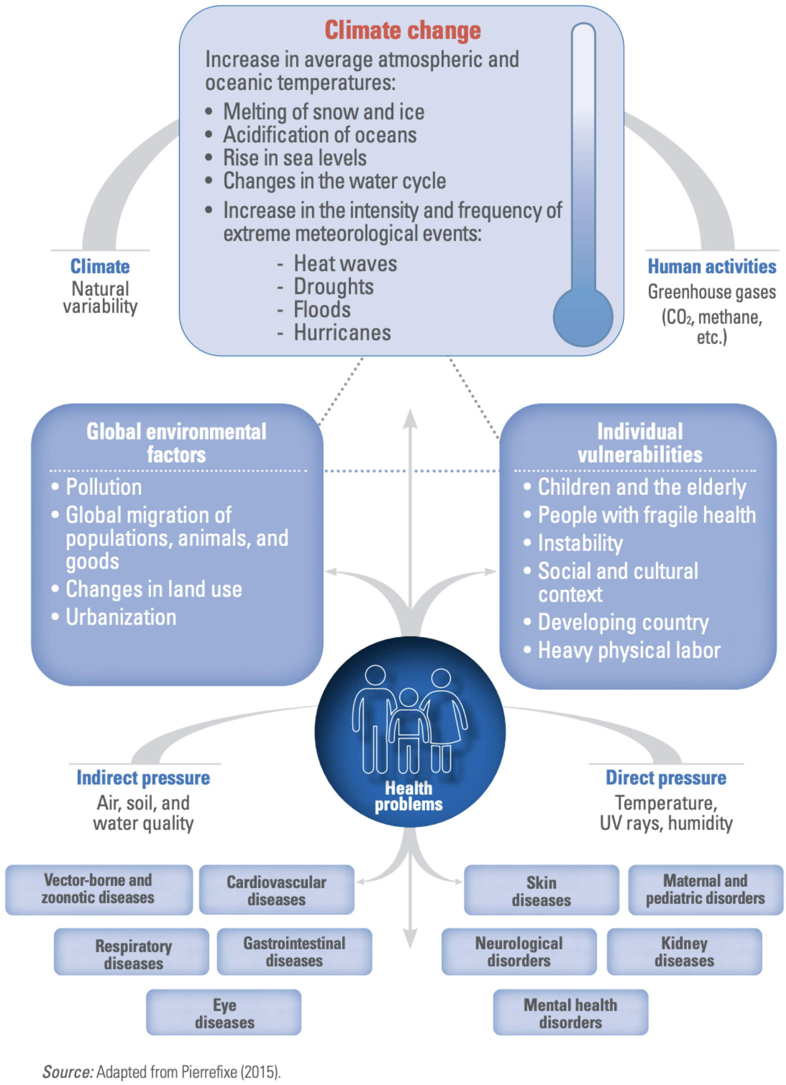


Figure 4: Climate change and its impacts on health (https://www.gov.br/saude/pt-br/centrais-de-conteudo/publicacoes/guias-e-manuais/2024/guia-mudancas-climaticas-para-profissionais-da-saude.pdf)

Pathophysiological Mechanisms

Several mechanisms can explain the harmful effects of climate change on cardiovascular health. Intense hot flashes can cause dehydration and acute cardiovascular events, while cold flashes increase the risk of myocardial ischemia by vasoconstriction and increased peripheral resistance, overloading the heart (7). Studies on physiological functions of the arterial vascular system have demonstrated the presence of endothelial dysfunction, autonomic imbalance and hypercoagulability in association with heat stress. In addition, dehydration associated with the increase in temperature increases hematocrit, making the blood more viscous and increasing hypercoagulability and the chance of thrombotic phenomena. On the other hand, air pollution, especially fine particulate matter, induces and perpetuates systemic inflammation, one of the risk factors for coronary atherosclerosis (3,7). In turn, chronic vasodilation, common in hot environments, leads to a sustained increase in cardiac output. In extreme conditions, this can precipitate heart failure, as illustrated by the "summer heart" hypothesis.

Smoke from fires and the increase in tropospheric ozone, related to the increase in temperature and dryness of the air, also contribute to cardiovascular risk (3). Elevated tropospheric ozone can lead to platelet activation, increased blood pressure, systemic inflammation, mechanisms that have not yet been fully elucidated, which may include oxidative stress, metabolic and coagulation changes, and autonomic dysfunction (8).

In September 2024, in the European Heart Journal, Eugene Braunwald, perhaps the most important cardiologist working in the world, published an article that identified the mechanisms involved in the genesis of cardiovascular complications associated with climate change (9) (Figure 5).

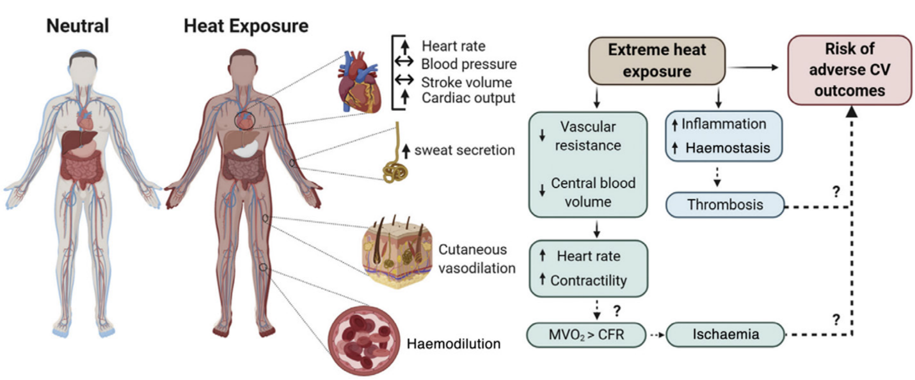


Figure 5: Pathophysiological mechanisms related to the cardiovascular effects of climate change.

Effects of Extreme Weather Events

Extreme weather events (hot flashes or intense cold) significantly increase the risk of cardiovascular death, especially among the elderly, hypertensive and patients with heart failure. High temperatures alter the hemodynamic balance more acutely and intensely, increasing the heart rate, the risk of arrhythmias and cardiac decompensation. In 2021, Turba Costa and collaborators described the relationship between extreme weather situations and hospitalizations for cardiovascular diseases. On days with temperature extremes, the authors observed higher hospitalization rates, both for hot and cold waves. In addition, there was a particularly high risk of hospitalization for up to seven days after the cold snap ended. Further analysis showed that hospitalizations for cardiovascular problems were higher in the winter than in the summer, suggesting that cold snaps have a greater impact on cardiovascular disease (10).

Robine and colleagues analyzed mortality data during the summer of 2003. In August of that year, due to the extreme heat wave, there were approximately 70,000 additional deaths (excess deaths) (11) (Figure 6).

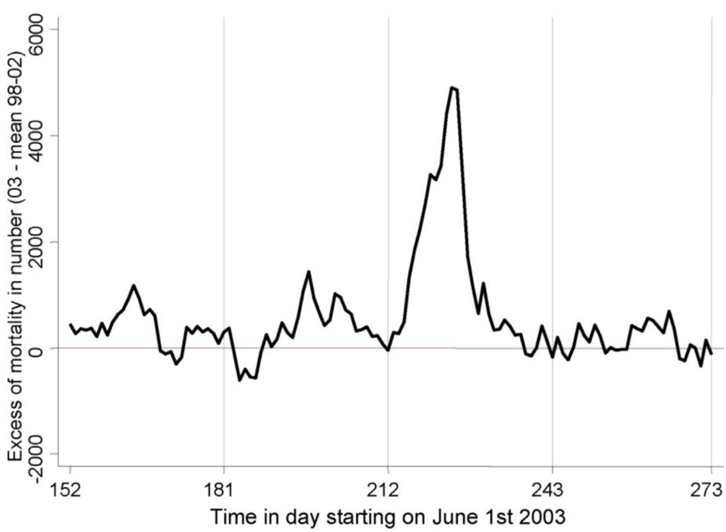


Figure 6: Variation between the number of daily deaths recorded in the summer of 2003 and the average number of deaths recorded on the same day during the reference period 1998-2002 for the 16 European countries studied. On the 152nd, the 152nd day of the year corresponds to June 1st, the 181st to the 30th of June, the 212th to the 31st of July, the 243rd to the 31st of August and the 273rd to the 30th of September.

In Brazil, recent extreme events, such as the floods in Rio Grande do Sul in 2024, have raised concerns from health authorities, since in these situations there is an increase in the incidence of respiratory and viral infections, which further contribute to the increase in morbidity and mortality from cardiovascular diseases (12).

VULNERABILITY AND INEQUITIES

Climate change and air pollution do not affect everyone equally. Individuals with lower incomes, living in peripheral regions and close to high-traffic roads, face greater exposure to pollutants and have less access to health care. Brazil has marked structural inequalities, which amplify the environmental effects on health. In 2020, Xu and colleagues described daily hospitalization and climate data in the 4 hottest months in the 2000-2015 period in 1,814 cities, covering 78.4% of the Brazilian population. The authors concluded that less developed cities had stronger associations between heat exposure and hospitalizations for all causes and certain types of hospitalizations for specific causes (13). These findings highlight that socioeconomic inequalities have important consequences in relation to the health of the populations involved and demand the need to prioritize more urgent public policies in more vulnerable places (13).

Mitigation Strategies

To mitigate the cardiovascular impacts of climate change, the effort must be concentrated in three areas of action: public policies, infrastructure adaptation, education & research. First, it is necessary to adopt public policies that reduce the emission of pollutants and adapt cities. Among the strategies are the promotion of sustainable transport, the increase of urban afforestation, the creation of low-emission zones, and environmental enforcement. The health sector needs to adapt to the new epidemiological scenario. Hospitals and health facilities must be prepared for seasonal outbreaks of illness exacerbated by heat or pollution. Environmental surveillance integrated with public health can anticipate outbreaks and direct resources. With respect to the necessary adaptation for health infrastructure, the priorities should be:

- Retrofitting hospitals and outpatient clinics by investing in renewable energy through local and outdoor solar and wind installations;
- Stimulate and implement the interdisciplinary interface between health professionals, architects and engineers seeking infrastructure alternatives with better environmental comfort and less dependence on air conditioning;
- Gradually eliminate the use of natural gas for heating and cooling, replacing it with renewable energy (geothermal and hydrogen);
- Incorporate environmental risk into routine cardiovascular assessment, such as risk estimation for surgical interventions and examinations.
- Achieve zero emissions by replacing fossil fuel-powered vehicles (ambulances and other vehicles);
- Replace anesthetic gases with alternatives with lower emissions (eliminate the use of desflurane);
- Reduce business travel through increased virtual conferencing;
- develop warning systems for critical events, such as heat waves and pollution peaks;
- Reduce the commute of patients to clinics by expanding telehealth;
- Replace disposable medical devices with reusable ones.

In addition, medical education should include knowledge about environmental medicine and planetary health, preparing professionals to deal with the challenges of the twenty-first century. The incorporation of topics related to the consequences of climate change on health should be a mandatory part of undergraduate and graduate curricula. The Faculty of Medicine of the University of São Paulo has already included this topic for third-year medical students and for graduate students.

Interdisciplinary research is essential to understand and predict the cardiovascular impacts of climate emergencies. Longitudinal studies with integrated environmental and clinical data are needed. The use of technologies such as artificial intelligence and wearable sensors can enable real-time monitoring of vulnerable populations, supporting preventive health policies and sustainable urbanism.

REFERENCES

1. @coracaonatela. “Extrapolations, um futuro inquietante”. Instagram, 2023. https://www.instagram.com/reel/CszJg6xAiVH/?igsh=MXI0cmc0ZXNvcHdsMA%3D%3D

2. The Smithsonian Institution’s Human Origins Program. Climate Effects on Human Evolution. https://humanorigins.si.edu/research/climate-and-human-evolution/climate-effects-human-evolution, 2024.

3. D.S. Kazi DS, *et al*. Climate Change and Cardiovascular Health: A Systematic Review. *JAMA Cardiol*. 9, 748-757 (2024).

4. U.P. Santos, *et al*. Exposure to fine particles increases blood pressure of hypertensive outdoor workers: A panel study. *Environ Res.* 174, 88-94 (2019).

5. M.A. Pereira Filho, *et al*. Effect of air pollution on diabetes and cardiovascular diseases in São Paulo, Brazil. *Braz J Med Biol Res*. 41, 526-32 (2008).

6. Mudanças climáticas para profissionais da saúde: Guia de bolso. https://www.gov.br/saude/pt-br/centrais-de-conteudo/publicacoes/guias-e-manuais/2024/guia-mudancas-climaticas-para-profissionais-da-saude.pdf, 2024.

7. S.P. Ang, J.E. Chia. Climate change and cardiovascular risk. *Current Opinion in Cardiology* 40, 244-250 (2025).

8. Q. Hua, *et al*. Ozone exposure and cardiovascular disease: A narrative review of epidemiology evidence and underlying mechanisms. *Fundam Res* 5, 249-263 (2024).

9. E. Braunwald, Cardiovascular effects of climate change, *European Heart Journal* 45, 3006–3008 (2024).

10. I.T. Costa, *et al*. Extreme Weather Conditions and Cardiovascular Hospitalizations in Southern Brazil. *Sustainability* 13, 12194 (2021).

11. J.M. Robine, *et al*. Death toll exceeded 70,000 in Europe during the summer of 2003. *C R Biol* 331, 171-8 (2008).

12. D.L. Paterson, H. Wright, P.N.A. Harris. Health Risks of Flood Disasters. *Clin Infect Dis*. 67, 1450-1454 (2018).

13. R. Xu, *et al*. Socioeconomic level and associations between heat exposure and all-cause and cause-specific hospitalization in 1,814 Brazilian cities: A nationwide case-crossover study. *PLoS Med*. 17, e566-e576 (2020).

8.2 Climate Change and Health: An Urban Approach

Mariana Veras, Marie-Anne Van Sluys, Paulo Saldiva

INTRODUCTION: LIVING IN SOCIETY AS AN EVOLUTIONARY NECESSITY

During evolution, Homo sapiens took the path of favouring the development of the central nervous system rather than a body structure capable of competing physically with other animals of similar size. Consequently, survival for sapiens was reliant on hunting small animals and gathering fruits and carcasses left behind by other predators. Our physical limitations compared to other predators necessitated the survival of the human species through cooperation and solidarity via collaborations and partnerships, rather than individual strength. Hunter-gatherer communities generally comprised no more than a few hundred members, highly dependent on resource availability for group sustenance. The structure of their dwellings was simple enough to allow community migration upon the depletion of surrounding natural resources. The creativity embedded in the brain developed the capacity, through encephalic development, to use fire for food preparation, facilitating the intake of calories and proteins. The technology developed by hunters and gatherers provided them with tools for hunting, fishing, and cultivating some plant species, enhancing the group's survival capacity. In regions with greater scarcity of natural resources, there was a stimulus for the creative potential of brain neurons to increase food production, leading to population growth. For this reason, the first cities emerged in the arid or semi-arid regions of the Fertile Crescent in the Middle East and along the banks of the Nile. The increase in food quantity in the emerging cities also resulted in a loss of dietary diversity present in hunter-gatherer diets. Microorganisms that were in balance with domesticated animals found in humans a new, less adapted host. The population increase and lack of sanitation led city dwellers to exchange ideas, thoughts, and also microorganisms. Ultimately, excess production resulted in stockpiling and accumulation of wealth, creating the foundations of social and economic inequality present in cities to this day. In summary, in cities, we enrich the spirit, but also encounter new forms of illness, as outlined below.

UNPLANNED URBAN GROWTH FACING THE CHALLENGES OF CLIMATE CHANGE

Brazilian cities have undergone notable changes in land use and occupation. Generally, our cities have shifted economic activities to the central region, with residential housing consequently moving to the periphery. The significant construction density in the city centres leads to soil impermeabilization and loss of green areas, factors that contribute to the emergence of heat islands. In São Paulo, the surface temperature difference between the city centre and the periphery can reach up to ten degrees Celsius. A thermal gradient of this magnitude does not occur without consequences for urban climatic dynamics. The rainfall regime in the city has been significantly altered in recent decades. The existence of a warmer central core compared to the periphery creates upward air flows in the central region, much like the torches of a hot air balloon heat the air inside to rise. As a result, moist fronts approaching the city encounter a region of lower pressure, entering the central urban territory with greater speed. Upon reaching the centre, they arrive at a higher temperature area, resulting in more intense rainfall. In summary, rains are “sucked” into the central region, displacing intense rainfall to the centre, which has a higher level of soil impermeabilization. The change in the intensity and location of rainfall represents a health hazard, as it favours flooding and the transmission of waterborne infectious agents, as well as landslides in communities residing in risk areas for such events. The excess standing water and increased urban temperatures also promote the proliferation of dengue and Zika-carrying mosquitoes, among other urban fevers. The warming of cities and urban climate variability are significantly associated with illness and mortality from respiratory and cardiovascular diseases.

TEMPERATURE, ACCLIMATISATION, AND ILLNESS

The accelerated climate changes we are experiencing are much more than a basic comfort parameter. Extreme temperatures or their variability have direct and indirect effects on human health, and the changes in temperature patterns caused by climate change have raised concerns about their impacts on global health. By 2100, an increase of between 1.8 and 4 degrees in the average temperature is expected, and recent understanding of adaptation has shifted from bio-physiological factors to broader social and economic dimensions of vulnerability and people's and cities' capacity to respond to environmental challenges. The consequences of climate change can be analysed from different perspectives, such as economic impacts, social consequences, global food security, changes in the built environment, mitigation strategies, health impacts, minority vulnerabilities, changes in the distribution of vector-borne diseases, and many others. Regardless of the perspective from which the analysis is conducted, there is no doubt that human health will be affected, directly or indirectly (1).

TEMPERATURE AND PHYSIOLOGICAL ADAPTATION

Temperature is more than a basic comfort parameter. Extreme temperatures, or their variability, have direct and indirect effects on human health, and changes in temperature patterns caused by climate change have raised concern about their impacts on global health. Given the complexity of the topic, this article focuses on the direct effects of temperature on human health, leaving aside equally important aspects such as the spread of infectious diseases, food insecurity, and migration flows.

Adaptation to various environmental conditions has enabled the consolidation of the human species. We are homeothermic creatures, meaning we control our body temperature within a narrow range (35 °C to 37 °C). To cope with changes in external temperature, our bodies resort to adaptive adjustments which, in extreme situations, can overload the respiratory and cardiovascular systems. For instance, high temperatures activate the parasympathetic system, decreasing heart rate, cardiac output, blood pressure, and the secretion of cortisol and thyroid hormones. During periods of heat, there is a loss of circulating volume through sweating, which increases blood viscosity and predisposes to the formation of clots that can occlude arteries in the brain and heart, especially in individuals with pre-existing cardiovascular diseases. Conversely, low temperatures provoke opposite changes, elevating sympathetic tone. Peripheral vasoconstriction, increased metabolic rate, and elevated heart rate represent a greater workload for the heart. Low temperatures also challenge the respiratory system, reducing pulmonary defence mechanisms against infectious agents, predisposing individuals to pneumonia and exacerbating diseases such as chronic bronchitis and asthma. Age affects the primary mechanisms that maintain body temperature. Simplistically, one could say that children (still maturing their thermoregulation systems) and the elderly (whose systems lose efficiency) are the most vulnerable groups (references 2 to 4). In this context, the global demographic shift towards an ageing population should warrant attention in planning future climate policies. Numerous epidemiological studies conducted over the last decade in various parts of the world have supported the concept that temperature extremes—and their variability—are significantly associated with increased hospital admissions and mortality (1)

WHAT WE KNOW ABOUT THE IMPACTS OF TEMPERATURE VARIATIONS ON HUMAN HEALTH IN OUR COUNTRY

Below is a summarised presentation of the results of some large-scale epidemiological studies conducted in our country:

- Heatwaves cause a significant increase in hospital admissions among the elderly and children, accounting for about 6% of SUS admissions, or approximately 132 per hundred thousand inhabitants (5)
- There are geographical, demographic, cause-specific, and temporal variations in the associations between heatwaves and hospitalisation in the Brazilian population. Considering the projected increase in the frequency, duration, and intensity of heatwaves, future strategies should be developed, such as establishing early warning systems, to reduce health risks associated with heatwaves in Brazil (6)

- Individuals living in less developed cities in Brazil are more vulnerable to hospitalisation related to temperature variability. This disparity could exacerbate existing socioeconomic and health inequalities in Brazil, suggesting that more attention should be given to less developed areas to mitigate the adverse health effects of short-term temperature fluctuations (7)
- Exposure to ambient heat has been positively associated with hospitalisation for Chronic Obstructive Pulmonary Disease, particularly during the end of the hot season. These data add to the growing body of evidence implicating global warming as a significant contributor to the future burden of healthcare (8)
- Extreme temperatures are estimated to have led to a cumulative loss of $104.86 billion (95% CI: 65.95, 142.70) in economic costs related to productivity losses due to premature deaths between 2000 and 2019. Greater risks from extreme cold temperatures were observed in the southern region of Brazil, while extremely hot temperatures were noted in the Central-West and Northeast regions. In conclusion, non-ideal temperatures are associated with considerable work losses as well as economic costs in Brazil (9)

ADDITIONAL REFLECTIONS

Once objective and scientific information has been presented, we seek permission to speak as a scientists and citizens, focusing on cities, given our increasingly urbanised world. Climate change arises from conscious consumption choices of our species, not others, which suffer in threatened ecosystems. By shifting the discussion from distant biodiversity to our preferred habitat, we aim to place human health at the centre in order to accelerate policies for the sustainable use of natural resources. The time has passed when we were hunter-gatherers living in a world full of resources; today, a large population adopts practices that require enormous amounts of resources, causing planetary burnout. Our species is unlikely to disappear, but it remains uncertain who will survive. Will we be able to adapt physiology and urban infrastructure at the same pace as environmental changes, especially considering the global ageing population? Who will be selected to survive: the wealthiest or the most vulnerable? Will we abandon “The Origin of Species” to adopt “Forbes indicators”? Throughout evolution, we bet on the brain and creativity, not on physical strength. To survive, we needed group solidarity: compassion and collaboration were essential. Over time, we domesticated plants and animals and created cities, accelerating art, science — and inequalities. Human history dates back hundreds of thousands of years, but culture and socioeconomic disparity are relatively recent. "Today, cities reflect this duality: engines of innovation that also amplify vulnerability and exclusion. Megacities seem like open-air museums of human evolution, where high-tech centres coexist with medieval conditions in the peripheries. Inequality is not just social; it is a threat to urban health, an imbalance that weakens the "body" of the city. At this point, the humanities become essential. To improve urban health, cities must cultivate more than infrastructure: they need to nurture relationships. Ethics, history, philosophy, and the arts provide tools to mediate differences, humanise policies, and promote dignity in harmony with the environment. Otherness — the recognition of the other — and compassion are not abstract virtues; they are the foundations of coexistence. We conclude, daring to say that the climate crisis, given its magnitude, is an opportunity to revive ancestral dialogue. Technology is indispensable to confront this challenge, but it must engage with a sustainable economy based on fundamental rights — citizenship, equity, solidarity, and well-being. Much of this dialogue will be dedicated to building public policies that transform cities into healthier and more sustainable places.

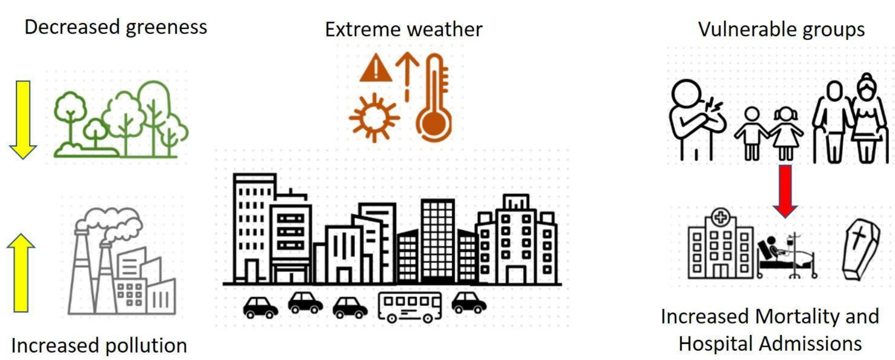


Figure 1: Illustrative diagram on climate change and urban health.

REFERENCES

1. A. Gasparrini et al., Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *Lancet*, v. 386, n. 9991, p. 369-375 (2015).

2. S. S. Cheung et al., The thermophysiology of uncompensable heat stress: physiological manipulations and individual characteristics. *Sports Medicine*, v. 29, p. 329-359. DOI: 10.2165/00007256-200029050-00004. (2000).

3. A. Bouchama et al., Heat stroke. *New England Journal of Medicine*, v. 346, p. 1978-1988. DOI: 10.1056/NEJMra011089. (2002).

4. C. A. Roncal-Jimenez et al., Climate change associated with elevated temperature and humidity is a risk factor for chronic kidney disease of unknown cause: a global hypothesis. *Kidney International*, v. 86, p. 509-517. DOI: 10.1038/ki.2015.88. (2015).

5. Q. Zhao et al., Geographic, demographic, and temporal variations in the association between heat exposure and hospitalization in Brazil: a nationwide study between 2000 and 2015. *Environmental Health Perspectives*, v. 127, n. 1, p. 017001. DOI: 10.1289/EHP3889. (2019).

6. Q. Zhao et al., Heatwaves and hospitalizations in Brazil: geographic, demographic, cause-specific, and temporal variations in risk. *PLOS Medicine*, v. 16, n. 2, e1002753 DOI: 10.1371/journal.pmed.1002753. (2019).

7. R. XU, et al., Socioeconomic inequality in vulnerability to all cause and cause specific hospitalization associated with temperature variability: a time series study in 1,814 Brazilian cities. *The Lancet Planetary Health,* v. 4, n. 12, e634–e642. DOI: 10.1016/S2542-5196(20)30251-5. (2020).

8. Q. Zhao et al., Ambient heat and hospitalization for COPD in Brazil: a nationwide case crossover study. *Thorax*, v. 74, n. 11, p. 1031-1036. DOI: 10.1136/thoraxjnl-2019-213486. (2019).

9. B. Wen et al., Productivity adjusted life years lost due to non-optimum temperatures in Brazil: a nationwide time series study. *Science of the Total Environment*, v. 873, p. 162368. DOI: 10.1016/j.scitotenv.2023.162368. (2023).

8.3 Impact of the Climate Crisis on Bacterial Infections and the Spread of Antibiotic Resistance

Evangelina Araújo, Marina Farrel Côrtes, Nazareno Scaccia, Thaís Guimarães, Silvia Figueiredo Costa

INTRODUCTION

Climate change may potentially be the greatest health threat of the 21st century. Among the key challenges in addressing the health effects of the climate crisis are the need for increased investment in research across various fields and the active involvement of decision-makers in public policy (1).

In Brazil, temperature increases have already exceeded the 2°C threshold in certain biomes and cities (2). Brazil is the seventh-largest emitter of greenhouse gases in the world and the fourth-largest per capita emitter (3). It is also expected to be among the countries most affected by climate change, with its population—especially the most vulnerable—facing significant health impacts as a result. In 2024, for example, Brazilians faced several extreme weather events across the country, such as heatwaves, flooding in the state of Rio Grande do Sul, and the loss of 22 million hectares of the Amazon rainforest due to fires, which resulted in air pollution levels higher than anywhere else in the world (4).

Lack of sanitation, environmental degradation, and the loss of biodiversity contribute substantially to the global burden of disease. The disruption of ecosystems leads to increased transmission of infectious diseases by expanding the presence of vectors and the spread of pathogens, which contributes to public health emergencies (1).

Climate change increases the risk of bacterial infections and the spread of pathogens, posing a serious challenge to public health. As a consequence, greater use of antibiotics in humans, animals, and agriculture can be expected, which would exacerbate the spread of antibiotic-resistant bacteria (5). By 2050, it is estimated that around 10 million people may die each year due to antibiotic-resistant bacterial infections, and these estimates could worsen under changing climate conditions (6). Studies have identified antibiotic resistance genes in polluted rivers of the Ilha Grande Bay in Rio de Janeiro, a region significantly affected by climate change (7), as well as the presence of carbapenem-resistant Gram-negative bacteria in the urine of dogs rescued from flood-affected areas in Rio Grande do Sul (8).

EMERGING AND RE-EMERGING BACTERIAL INFECTIONS

Settlements formed in the aftermath of disasters—particularly in low- and middle-income countries such as Brazil—are often characterized by unsafe conditions. This includes overcrowding, poor ventilation, inadequate shelter, lack of safe food and water, and reduced access to healthcare services, all of which contribute to an increased risk of bacterial infection (9). Waterborne and foodborne diseases (such as cholera, diarrhea, and typhoid fever), as well as diseases related to overcrowding (such as meningitis and tuberculosis, transmitted via respiratory secretions like droplets and aerosols), are the most commonly reported bacterial diseases in shelters (10).

The increasing frequency and intensity of heavy rains and flooding—phenomena associated with global warming—have created ideal conditions for the spread of bacterial zoonoses like *Leptospira spp.* In urban environments, particularly in tropical and subtropical regions such as Brazil, poor sanitation, high population density, and the presence of rodents are factors that, combined with flooding, contribute to leptospirosis outbreaks (9).

In Brazil, data from the Ministry of Health indicate that between 2001 and 2020, more than 70,000 cases of leptospirosis were reported, with an average case-fatality rate of around 9% in epidemic years such as 2011 and 2020—both marked by flooding events associated with the La Niña phenomenon and intense rainfall (11).

A recent example of the climate crisis' impact on the spread of bacterial diseases, particularly leptospirosis, was the major flood disaster that occurred in 2024 in Rio Grande do Sul, leaving large parts of the state underwater. The affected areas and number of people totaled 478 municipalities that experienced flooding, directly impacting around 2.4 million people—20% of the state's population. Among the causes of death was an outbreak of leptospirosis, caused by the bacterium *Leptospira spp.*, which can be found in contaminated water or soil (9).

IMPACT OF THE CLIMATE CRISIS ON BLOODSTREAM INFECTION RATES AND BACTERIAL RESISTANCE

Bloodstream infections (BSIs) are among the most serious infections affecting humans, with high morbidity and mortality rates that vary depending on the etiologic agent and the population studied. Recent studies have indicated an increase in the frequency of BSIs during the summer or in months with higher temperatures (12–14). A study conducted by Fisman et al. (2014) analyzed positive blood culture results from 2007 to 2011 along with geographic, climatic, and socioeconomic data sources from an international network of 23 centers across 22 cities (including two hospitals in São Paulo). Among the data sources analyzed, only the proportion of gross domestic product allocated to health care and the geographic distance from the equator were significantly associated with bloodstream infections caused by Gram-negative bacteria (12).

In an ecological study conducted in Botucatu from 2005 to 2010, Caldeira et al. evaluated the impact of temperature and humidity on the incidence and etiology of BSIs. The authors observed a higher incidence of BSIs caused by Gram-negative bacilli during warmer seasons. Temperature was positively associated with the recovery of Gram-negative bacilli (OR = 1.14; 95% CI 1.10–1.19) and *Acinetobacter baumannii* (OR = 1.26; 95% CI 1.16–1.37) (13).

IMPACT OF THE CLIMATE CRISIS ON BACTERIAL RESISTANCE MECHANISMS

Temperature changes can affect the cellular and physiological responses of bacteria, which in turn may influence the evolution and prevalence of antibiotic resistance genes. Physiological responses to temperature-induced stress may overlap with antibiotic stress responses, contributing to the evolution of resistance by altering gene expression (15,16). Consequently, the expression of resistance genes may be triggered by environmental stressors, as mutations that confer resistance to stress can also lead to cross-resistance to antibiotics (16). Similarly, pesticides, heavy metals, and other environmental pollutants can drive the selection of cross-resistance, promoting the survival of resistant strains in increasingly contaminated environments (5). Climate change facilitates horizontal gene transfer between bacteria, accelerating their spread—particularly in environments impacted by pollution and water scarcity (5). In vitro studies have shown that temperatures above 37 °C favor bacterial conjugation and transformation (17).

A recently published systematic review included 30 selected articles, most of which were published after 2019, and highlighted a lack of Brazilian data (18). Brazil contributed only one study. The review suggests that rising temperatures associated with climate change may contribute to the spread of antibiotic resistance across various ecosystems. This phenomenon has been observed in soil, glaciers, rivers, and clinical environments. The Brazilian study included in the review was an experimental analysis of 48 soil samples from the Amazon region (19). The study found that deforestation in the Amazon led to an increase in antibiotic resistance genes in the soil, and that anthropogenic changes may exert selective pressure on microbial communities, expanding the soil resistome. The authors observed that converting native forest into farmland and cattle pasture increased the abundance of genes encoding efflux pumps, target site modifications (e.g., ribosomal alterations), and enzymes such as β-lactamases (19).

CLIMATE CRISIS AND BASIC SANITATION

The climate crisis increases the risk of spreading antibiotic-resistant bacteria and antibiotic residues (Figure 1) through flooding and scarcity in drinking water—particularly in regions of Brazil with limited basic sanitation coverage. It is essential to note that currently, only about 55% of the sewage generated in Brazilian municipalities is collected, and of that, approximately 80% is treated (20). Recent estimates indicate that 24.3% of the Brazilian population—approximately 49 million people—do not have access to sewage collection, and untreated wastewater is discharged directly into rivers, streams, and oceans (21).

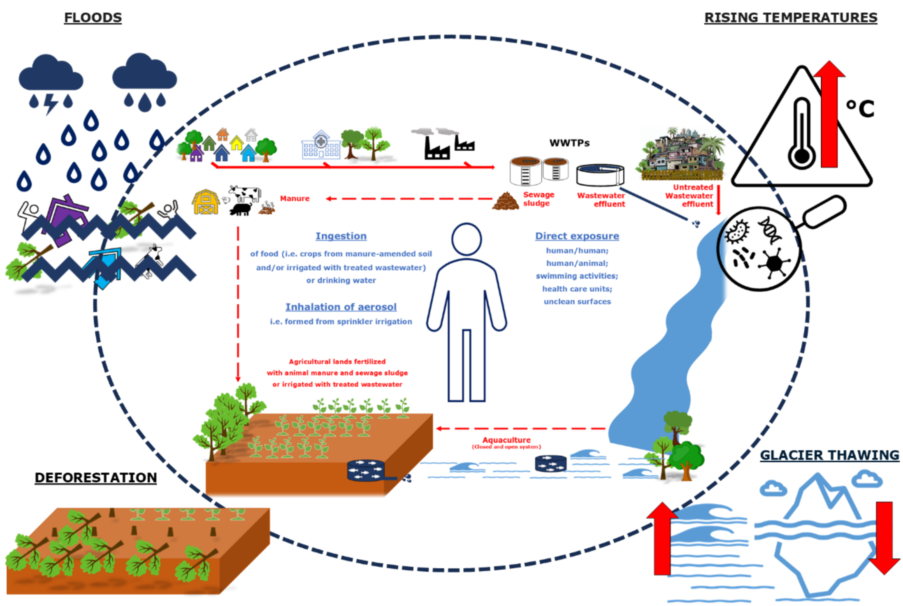


Figure 1: Climate change and antibiotic resistance. Inside the dashed black line, antibiotic resistance enters the environment from humans, livestock, and industry wastewater. WWTPs often fail to fully remove antimicrobial, ARB and ARGs releasing them into water and soil via sewage sludge. Manure and aquaculture waste further spread resistance in agriculture. Climate change (floods, rising temperatures, deforestation and glacier thawing) intensifies antibiotic resistance by dispersing pathogens and creating favorable conditions for ARB growth. This interconnected cycle heightens public health risks worldwide.

Wastewater from healthcare facilities, urban areas, agriculture, and industry serves as a major reservoir and route for the transmission of antibiotic resistance. Antibiotics and bacteria carrying resistance genes have been found in water sources worldwide, and antimicrobial pollution is expected to worsen in low- and upper-middle-income countries (22). Even in places where wastewater is collected and routed to treatment plants, if the treatment is inadequate, discharge into rivers can significantly increase the release of antimicrobial residues and resistant bacteria into natural water bodies.

A study conducted in Brazil detected 23 antibiotic residues in aquatic environments (e.g., effluents from wastewater treatment plants, hospital wastewater), with concentrations ranging from 0.13 to 37.30 µg/L (20). Residues from various antibiotic classes—including azithromycin, levofloxacin, ceftriaxone, and meropenem—have also been reported in hospital and urban wastewater in São Paulo (23). In some cases, concentrations exceeded Predicted No-Effect Concentrations (PNECs), suggesting a potential for selection pressure leading to antibiotic resistance.

REFERENCES

1. D. Campbell-Lendrum, T. Neville, C. Schweizer, and M. Neira, Climate Change and Health: Three Grand Challenges. *Nature Medicine* 29, 1631–1638. (2023).

2. P. Artaxo, As Três Emergências que Nossa Sociedade Enfrenta: Saúde, Biodiversidade e Mudanças Climáticas. Estudos Avançados 34, 100. (2020).

3. Climate Watch, *Historical GHG Emissions* [online], 2025, accessed 23 July 2025. Available at: https://www.climatewatchdata.org

4. Brasil. Ministério da Saúde. Secretaria de Vigilância em Saúde, *Programa Vigiar. Poluição Atmosférica e Saúde Humana* [online], 2025, accessed 23 July 2025. Available at: https://app.powerbi.com/view?r=eyJrIjoi.

5. P. Rzymski, W. Gwenzi, B. Poniedziałek, S. Mangul, and A. Fal, Climate Warming, Environmental Degradation and Pollution as Drivers of Antibiotic Resistance. *Environmental Pollution* 346, 123649. (2024).

6. J. O'Neill. Antimicrobial Resistance: Tackling a Crisis for the Health and Wealth of Nations [online], London: Review on Antimicrobial Resistance, 2014, accessed 23 July 2025. Available at: https://amr-review.org/sites/default/files/...

7. L.F. Bacha, M.A. P. Oliveira, F. Landuci , A. C. Vicente, P.H Paz, Antibiotic-resistance genes and metals increase in polluted tropical rivers of the Baia da Ilha Grande, Rio de Janeiro, Brazil. *Science of the Total Environment* 968,178778. (2025).

8. M.E.R.J. da Silva, G. M. Breyer, T. S. Weyh, S.D. de Oliveira , F. M. Siqueira, Carbapenem-resistant Gram-negative bacteria in urine of dogs rescued from southern Brazil floods. *Veterinary Research Communications* 49, 230 (2025).

9. H. Cena, M. Labra, and NBFC Collaborator Group, Biodiversity and Planetary Health: A Call for Integrated Action. *The Lancet* 403, 1985–1986.(2024).

10. F.V. Segala, G. Guido, G. Stroffolini , L. Masini, P. Cattaneo , Insights into the Ecological and Climate Crisis: Emerging Infections Threatening Human Health. *Acta Tropica*, vol. 262, (2025)

11. Brasil. Ministério da Saúde. Secretaria de Vigilância em Saúde, *Boletim Epidemiológico*: Leptospirose [online], Brasília: MS, 2021, accessed 23 July 2025. Available at: https://www.gov.br/saude/pt-br

12. D. Fisman, E. Patrozou ,Y.Carmeli, E. Perencevich, A.R. Tuite, Geographical Variability in the Likelihood of Bloodstream Infections Due to Gram-Negative Bacteria. *PLoS One* 12, e114548 (2014).

13. S.M. Caldeira, A.R. da Cunha, R. T. Akazawa, R.G. Moreira, L.R. de Souza, Weather Parameters and Nosocomial Bloodstream Infection: A Case-Referent Study. *Revista de Saúde Pública* 49, 19. (2015).

14. K. Blot, N. Hammami, S. Blot, D. Vogelaers, M. Lambert, Gram-Negative Central Line-Associated Bloodstream Infection Incidence Peak During the Summer: A National Seasonality Cohort Study. *Scientific Reports* 12, 5202. (2022).

15. M. Cruz-Loya, T. M. Kang, N. A. Lozano, R. Watanabe, E. Tekin . Stressor Interaction Networks Suggest Antibiotic Resistance Co-Opted from Stress Responses to Temperature. *The ISME Journal*. 13, 12–23. (2019).

16. Rodríguez-Verdugo, N.L. Huntelman, M. Cruz-Loya, V. Savage, P. Yeh, Compounding Effects of Climate Warming and Antibiotic Resistance. *iScience* 23, 101024.(2020).

17. L. Guigard, F. Nazaret, J. Almario, F. Bertolla, H. Boubakri, The Connections of Climate Change with Microbial Ecology and Their Consequences for Ecosystem, Human, and Plant Health. *Journal of Applied Microbiology* 12, lxaf168.(2025)

18. M.F. Salgueiro, J.A.C. Martínez, R.K. Gan, P.A. González, Climate Change and Antibiotic Resistanc,: A Scoping Review. *Environmental Microbiology* 16, e70008. (2024).

19. L.N. Lemos, A. Pedrinho, A.T. Ribeiro de Vasconcelos, S.M. Tsai, L.W. Mendes. Amazon Deforestation Enriches Antibiotic Resistance Genes. *Soil Biology and Biochemistry* 153, 108110 (2021).

20. K.V.L. Lima, J.H.F. Jesus, R.F.P, Nogueira, Occurrence of Antibiotics in Aqueous Matrices: An Outlook About the Situation in Brazil. *Journal of the Brazilian Chemical Society* 35, 1–14 (2023).

21. IBGE, *2022 Census* [online], 2022, accessed 26 May 2025. Available at: https://agenciadenoticias.ibge.gov.br/en/…

22. E.H. Macedo, B. Lehner, J.A. Nicell , U. Khan, E.Y. Klein, Antibiotics in the Global River System Arising from Human Consumption. *PNAS Nexus* 4, 096. (2025).

23. N. Scaccia, J. V. da Silva Fonseca, A. L. Megueya, G. L. de Aragão, T. Rasolofoarison, Analysis of Chlorhexidine, Antibiotics and Bacterial Community Composition in Water Environments from Brazil, Cameroon and Madagascar During the COVID-19 Pandemic. *Science of the Total Environment*, 932, 173016. (2024)

24. Intergovernmental Panel on Climate Change (IPCC), Synthesis Report (SYR): *Sixth Assessment Report (AR6)* [online], 2023, accessed 23 July 2025. ISBN 978-92-9169-164-7. Available at: https://www.ipcc.ch/report/ar6/syr/downloads/…

8.4 Arboviruses and Climate Change: Contemporary Challenges and Key Considerations

Maria Cassia Mendes-Correa, Ester Cerdeira Sabino

Arboviral infections pose major public health challenges, with dengue alone causing illness in an estimated 100 million people annually (1). The global risk is rising due to rapid urbanization, climate change, insecticide resistance, poverty, inadequate sanitation, increased human mobility, and other societal factors (2). Growth of mosquito populations and vector adaptability also contribute to arbovirus resurgence. Increased DENV cases are linked to reduced mosquito control and declining public health measures (3,4).

Other factors contributing to the re-emergence are host genetic variations, viral evolution, the density of human and mosquito populations, mosquito species, and vector competence (5). Therefore, the emergence and re-emergence of arboviruses as a public health problem is a highly complex issue resulting from the convergence and reciprocal interactions of multiple factors.

It is estimated that climate change may interfere with arbovirus transmission globally primarily through two different mechanisms[6]:

1. Adaptation and expansion of arbovirus vectors into regions beyond their traditional geographic range (6);
2. Changes in transmission dynamics that modify the length of the transmission season (6).

ARBOVIRUS VECTOR ADAPTATIONS AND MODIFICATIONS IN DURATION OF THE TRANSMISSION SEASON

Variations in temperature, humidity, and precipitation associated with climate change affect the geographic distribution and population trends of these vectors, thereby influencing the transmission of diseases such as dengue, Zika, Chikungunya, and West Nile virus (3).

Temperature affects arbovirus transmission due to its nonlinear impact on mosquito physiology, altered development and mortality rates (3,7-9). Temperature also influences viral incubation in mosquitoes, with warmer conditions shortening the extrinsic incubation period (10,11).

The impact of rainfall on arbovirus transmission is multifaceted and influenced by the specific local social-ecological environment.

Aedes aegypti mosquitoes preferentially oviposit in water-containing containers commonly found in residential environments where the females obtain blood meals from humans. Elevated rainfall can contribute to increased vector populations by generating more water-filled breeding sites in proximity to dwellings (12).

However, drought conditions and water scarcity may also lead to an increase in vector populations when individuals store water in containers near their homes (13).

Warming temperatures likely enable vectors to settle in temperate regions that previously were mostly unsuitable. This includes expansion both north and south and to higher altitudes, resulting in increased disease transmission in many new regions as a consequence of climate change scenarios (14-18).

The geographic expansion of vector survival and reproduction puts new populations at risk of infection, and these naïve populations will either lack immunity or have a different immune profile compared to populations where arboviruses currently circulate. For example, changes in climate suitability for Aedes mosquitoes are predicted to increase the at-risk population between the 1980s and 2020 by approximately two billion people (19). An additional increase in susceptibility of more than two billion people is estimated between 2015 and 2080 (20).

CHALLENGES IN THE BRAZILIAN AMAZON

The Brazilian Amazon is recognized as being a large reservoir of arboviruses, with at least 180 different viruses identified so far (21).

Arboviruses persist in forests via a sylvatic cycle involving insect vectors and wild vertebrate hosts. Deforestation and mining bring humans closer to these environments, raising the risk of new and recurring zoonotic diseases (22).

Development in the Brazilian Amazon has led to the proliferation of settlements lacking basic infrastructure like piped water and waste collection, creating favorable conditions for Ae. aegypti breeding (22). Unplanned urban growth, land use changes, and increased human mobility enable invasive species and pathogens to spread further. These issues occur alongside rapid climate change and ongoing deforestation (22).

Over the past two decades, the Brazilian Amazon has experienced increased floods, droughts, and fires, largely due to strong El Niño and La Niña weather cycles. El Niño causes warmer, drier conditions in the basin, while La Niña results in cooler, wetter weather (23,24).

By 2060-80, the Amazon is projected to warm 1-2°C above the global average due to severe droughts and less cloud cover, leading to higher surface shortwave radiation. This could push the region past a tipping point toward a degraded, savanna-like ecosystem with more droughts, negatively impacting the global climate system (25,26).

Increased extreme weather due to climate change may boost the risk of arbovirus outbreak risk in Brazil's most vulnerable region with infrastructure deficiencies and a scarcity of prevention resources (22).

At a recent WHO event, Dr. Sylvie Briand, the WHO Director of Pandemic and Epidemic Diseases, said that the next pandemic could be due to emergence of a new arbovirus and that there are already indications that this risk is increasing (27).

Considering the factors mentioned, the Brazilian Amazon stands out as a worrying location for the emergence or worsening of arbovirus diseases, which pose serious threats to global health.

The Global Arbovirus Initiative, aligned with efforts such as the WHO Neglected Tropical Disease Roadmap, the Global Vector Control Response Initiative, and the EYE strategy, proposes coordinated international actions. These include enabling real-time global surveillance and supporting the development of diagnostics, treatments, and vaccines to address future outbreaks (28).

Control, and improved diagnostics, treatment, surveillance, and public health actions.

REFERENCES

1. Challenges in combating arboviral infections. *Nat Commun*. 15(1):3350 (2024). doi: 10.1038/s41467-024-47161-3.

2. E. Abbasi, Global expansion of Aedes mosquitoes and their role in the trans-boundary spread of emerging arboviral diseases: A comprehensive review. IJID. *One Health* 6, 100058. (2025). doi: 10.1016/j.ijidoh.2025.100058

3. M.A. Robert, A.M. Stewart-Ibarra, E.L. Estallo, Climate change and viral emergence: evidence from Aedes-borne arboviruses. *Curr Opin Virol*. 40:41-47 (2020). doi: 10.1016/j.coviro.2020.05.001.

4. D.J. Gubler, Dengue and dengue hemorrhagic fever. Clin. Microbiol. Rev. 11:480–496. (1998). doi: 10.1128/CMR.11.3.480.

5. H. Ketkar, D. Herman, P. Wang, Genetic Determinants of the Re-Emergence of Arboviral Diseases. Viruses. 11(2):150 (2019). doi: 10.3390/v11020150.

6. I. Dorigatti, K.A.M. Gaythorpe, V.M. Cox, F.A Windram, L. Cator, Priorities for modelling arbovirus transmission under climate change. *Trends Mol Med*. S1471-4914(25)00121-2 (2025). doi: 10.1016/j.molmed.2025.05.010

7. O.J. Brady et al., Modelling adult Aedes aegypti and Aedes albopictus survival at different temperatures in laboratory and field settings. *Parasites Vectors* 6:351. (2013).

8. L.M. Rueda, K.J. Patel, R.C. Axtell, R.E. Stinner, Temperature-dependent development and survival rates of Culex quinquefasciatus and Aedes aegypti (Diptera: Culicidae). J Med Entomol 27:892-898 (1990).

9. G.H. Samuel, Z.N. Adelman, K.M. Myles, Temperature-dependent effects on the replication and transmission of arthropod borne viruses in their insect hosts. Curr Opin Insect Sci 16:108-113 (2016).

10. M. Chan, M.A. Johansson, The incubation periods of dengue viruses. *PLoS One* 7(11): e50972 (2012).

11. B. Tesla, L.R. et al., Temperature drives Zika virus transmission: evidence from empirical and mathematical models. *Proc R Soc B Biol Sci*, 285:20180795 (2018).

12. R. Lowe *et al*. Nonlinear and delayed impacts of climate on dengue risk in-Barbados: a modelling study. *PLoS Med* 15: e1002613 (2018).

13. A.M. Stewart Ibarra et al., Dengue vector dynamics (Aedes aegypti) influenced by climate and social factors in Ecuador: implications for targeted control. *PLoS One* 8:e78263 (2013).

14. L. Gilbert, The impacts of climate change on ticks and tick-borne disease risk. *Annu. Rev. Entomol*. 66, 373–388 (2021).

15. C. Barcellos, et al., Climate change, thermal anomalies, and the recent progression of dengue in Brazil. *Sci. Rep.* 14, 1–9 (2024).

16. J. Alencar et al., Effects of seasonality on the oviposition activity of potential vector mosquitoes (Diptera: Culicidae) from the São João River Basin Environmental Protection Area of the state of Rio de Janeiro, Brazil. *Eur. Zool. J*. 89, 1018–1025 (2022).

17. S.J. Ryan et al., Global expansion and redistribution of Aedes-borne virus transmission risk with climate change. *PloS Negl. Trop. Dis.* 13, e0007213 1-20 (2019).

18. S.L. Li et al., Mapping environmental suitability of Haemagogus and Sabethes spp. mosquitoes to understand sylvatic transmission risk of yellow fever virus in Brazil. *PLoS Negl. Trop. Dis.* 16, e0010019 (2022).

19. T. Nakase et al., Population at risk of dengue virus transmission has increased due to coupled climate factors and population growth. Commun. *Earth Environ*. 5, 1–11 (2024).

20. J.P. Messina et al., The current and future global distribution and population at risk of dengue. *Nat. Microbiol.* 4,1508–1515. (2019).

21. N. Dégallier et al., Modifications of arbovirus transmission in relation to construction of dams in Brazilian Amazonia. *Cienc Cult* 44:124-35 (1992).

22. R. Lowe et al., *Emerging arboviruses in the urbanized Amazon rainforest*. BMJ. Nov 13;371:m4385. doi: 10.1136/bmj.m4385. (2020).

23. M.G. Fonseca et al., Climatic and anthropogenic drivers of northern Amazon fires during the 2015-2016 El Niño event. *Ecol Appl* 27:2514-27. doi:10.1002/eap.1628. (2017).

24. M.M. Moura et al., Relation of El Niño and La Niña phenomena to precipitation, evapotranspiration and temperature in the Amazon basin. *Sci Total Environ* 651:1639-51. doi: 10.1016/j.scitotenv.2018.09.242. (2019).

25. J.A. Marengo et al., Changes in climate and land use over the Amazon region: current and future variability and trends. *Front Earth Sci* 6:228. doi:10.3389/feart.2018.00228. (2018)

26. C.A. Nobre et al., Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. *Proc Natl Acad Sci U S A* 113:10759-68. doi:10.1073/pnas.1605516113 (2016).

27. V.S. Balakrishnan, WHO launches global initiative for arboviral diseases. *Lancet Microbe Jun*;3(6): e407. doi: 10.1016/S2666-5247(22)00130-6. (2022).

28. Report of the third meeting of the WHO Technical Advisory Group on Arboviruses (TAG-Arbovirus): hybrid meeting, Accra, Ghana, 20-22 June 2023. Geneva: World Health Organization; 2024. Licence: CC BY-NC-SA 3.0 IGO

8.5 Malaria, Climate Change, and Perspectives

Giselle Maria Rachid Viana, Carolina Aguiar, Nathália Nogueira Chamma Siqueira, Izis Mônica Carvalho Sucupira, Celia R. S. Garcia

INTRODUCTION

Malaria remains one of the main global public health challenges, particularly in tropical regions with deep socio-environmental vulnerabilities, such as South-East Asia, Africa, and the Amazon. Global malaria fatality in 2023 remained nearly the same as 2022 with approximately 597,000 people succumbed, with children and pregnant women being most vulnerable. The current trends show that malaria mortality has declined by half from 28.5 to 13.7 deaths per 100,000 in the past two decades. However, global incidence increased to 263 million cases in 2023, which is 11 million more than 2022 (1). In South American countries, Brazil accounts for a significant portion of malaria cases, with vast areas near the Amazon region contributing to 99% of these cases. In Brazil, the prevalence of *P. falciparum* and *P. vivax* cases was similar until the late 1980s. Since 1980, *P. falciparum*-related malaria has progressively declined while *P. vivax* increased and became predominant in the country, accounting for over 90% of malaria episodes in 2011 (2). Presently, more than 80% are caused by *P. vivax*, but over the years, trends are shifting to rising *P. falciparum* cases (1).

Over the past few decades, significant progress has been made in adopting control strategies that have led to a reduction in transmission, including important milestones in eliminating *P. falciparum* malaria in some areas of Brazil (1, 3). However, the predominance of *P vivax* cases poses unique challenges to malaria control, including relapses that occur weeks or months after the initial infection, greater genetic diversity compared to *P. falciparum*, and the feasibility of vector transmission across various temperature ranges. Combined with the growing impacts of climate change, these factors threaten the progress achieved (4).

Evidence accumulated over the years suggests that rising temperatures, shifts in rainfall patterns, deforestation, and extreme weather events — such as floods and prolonged droughts — have altered the distribution of *Anopheles* mosquitoes and influenced the seasonality of malaria transmission (5). Modeling studies from initiatives such as the *Malaria Atlas Project* and research led by Brazilian scientists suggest that Brazil may experience significant changes in vector ecology and an increased risk of outbreaks, particularly in the Amazon region, where a mosaic of ecosystems and anthropogenic pressures complicate the epidemiological landscape (6).

This text examines the impact of climate change on malaria patterns in Brazil, with a focus on the Amazon Basin. It highlights the need for an integrated malaria research agenda that combines genomic and entomological surveillance, climate-epidemiological modeling, and the identification of new therapeutic and vector control targets.

CLIMATIC AND ENVIRONMENTAL DETERMINANTS OF TRANSMISSION: VECTORS, ECOSYSTEMS, AND EXTREME EVENTS

Environmental and climatic factors, including temperature, relative humidity, rainfall, and land-use changes such as deforestation and forest fires, strongly influence malaria transmission dynamics in the Amazon. The increase in average temperatures, variability in rainfall patterns, and alteration of hydrological cycles are among the most observed effects in the Amazon, directly influencing the presence and development of the vector, especially *Anopheles darlingi,* the primary malaria vector in the region (9). These conditions enhance vectorial capacity and expand risk areas beyond historically endemic boundaries (6) (Figure 1).

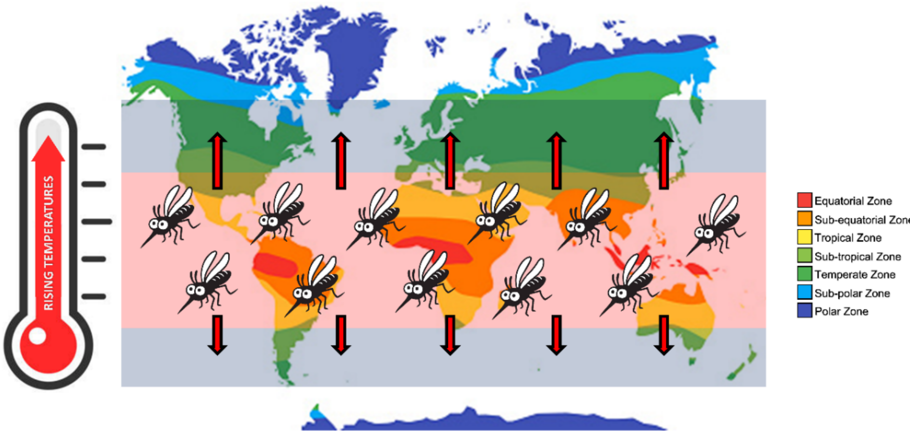


Figure 1: Expansion of *Anopheles* mosquito habitats into temperate regions under global warming. The primary malaria vectors (*Anopheles spp.*) are predominantly distributed in tropical and subtropical regions (shown in the red band). Rising global temperatures are enabling these vectors to survive and establish in previously unsuitable, colder climates, allowing a northward expansion into temperate regions (blue bands), as indicated by the red arrows.

The El Niño phenomenon often leads to higher temperatures and reduced rainfall, directly impacting the transmission dynamics of diseases such as malaria. These changes affect the ecological cycles of vectors and may increase human exposure, particularly in rural and fragmented forest areas where access to sanitation and healthcare services is limited (7).

Additionally, extreme weather events, such as floods and prolonged droughts, impact the ecology of vector breeding sites and human behavior, thereby altering patterns of exposure to infection (11, 12). The expansion of human settlements over forested areas, combined with intensive deforestation, increases human presence in high-risk zones and exposure to malaria vectors, which are highly sensitive to environmental changes (13). Deforestation alters the landscape, favoring the emergence of microenvironments that are conducive to vector proliferation (14). Vector adaptation to these environments, combined with insecticide resistance, contributes to intensified transmission and complicates the management of vector-borne diseases (8, 9).

Vegetation suppression disrupts ecological balance and increases human exposure to wild pathogen reservoirs, thereby favoring the emergence of zoonoses and the spread of known diseases. Habitat modification can also alter vector displacement patterns, leading to an increase in their presence in urban and peri-urban areas.

Given the complexity of epidemiological cycles and vector expansion associated with global warming, the development of integrated control strategies, spatial epidemiology tools such as remote sensing and predictive modeling, and the adoption of innovative technologies have become essential for anticipating changes in vector distribution and assessing the risk of outbreak emergence under different climate scenarios. This helps mitigate public health impacts. The integration of environmental, climatic, and epidemiological data enhances surveillance strategies and facilitates timely responses by Brazil's Unified Health System (SUS) (10, 11).

VULNERABILITY, HUMAN MOBILITY, AND HEALTH SYSTEM RESPONSES

Local surveillance must become increasingly strategic, considering the growing proportion of autochthonous cases reported outside major urban centers, underscoring the need to strengthen responses in peripheral and logistically hard-to-reach territories.

Brazil has made substantial progress toward achieving the goal of malaria elimination by 2035. Between 2021 and 2024, there was a 27% reduction in the number of municipalities with active transmission, from 288 to 211. Additionally, the number of priority municipalities — those responsible for 80% of the national malaria burden —decreased from 33 in 2021 to 25 in 2024 (Figure 2). This reduction in the territorial concentration of malaria reflects the positive effects of decentralized surveillance, expanded access to diagnostics, and improved integrated strategies in high-incidence municipalities (11).

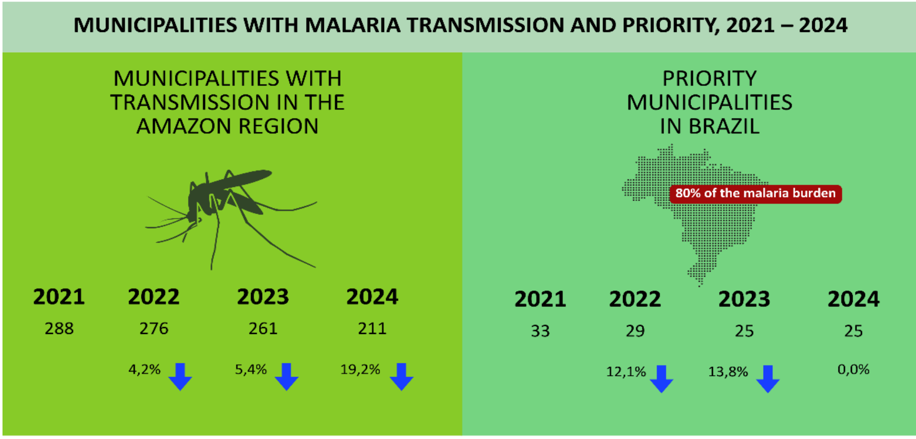


Figure 2: Evolution of municipalities with active malaria transmission and priority municipalities between 2021 and 2024. Source: Sivep-Malaria/SVSA/MS. Author's elaboration.

However, it is important to highlight the relevance of travel medicine, sentinel surveillance, and inter-institutional coordination in preventing transmission beyond endemic areas. It also calls for intersectoral responses and health communication strategies focused on transient populations. It is also relevant to avoid delays in clinical suspicion, given the overlapping symptoms with other febrile infectious diseases such as dengue, leptospirosis, acute Chagas disease, and visceral leishmaniasis.

In the specific case of *P. vivax* malaria, the parasite's ability to cause relapses and maintain asymptomatic infections poses an additional challenge. These biological characteristics are exacerbated by climate variability, which affects the vector's distribution, biting behavior, and breeding sites, particularly in areas with unstable transmission. Warmer temperatures and changes in precipitation patterns expand the window of seasonal transmission, facilitating the reintroduction of *P. vivax* in peri-urban and frontier areas, including those undergoing deforestation and hydrological disruption. Moreover, extreme climate events — such as prolonged droughts or floods — can displace communities and increase exposure among individuals who are non-immune or partially immune.

P. vivax infections often remain undiagnosed, contributing to the maintenance of hypnozoite reservoirs and silent transmission cycles. This makes elimination strategies particularly complex in remote areas. Surveillance systems must evolve to identify and respond to these hidden reservoirs by incorporating spatial and temporal modeling tools, expanding molecular and entomological monitoring, and strengthening community-based approaches aligned with local sociocultural dynamics and climate adaptation strategies (11).

Antimalarial Resistance and Therapeutic Innovations in Brazil: A Perspective on *P. vivax* and *P. falciparum*

Emerging resistance to antimalarial drugs remains a significant challenge for malaria control and elimination efforts worldwide. Although chloroquine (CQ) continues to be effective against *P. vivax* in many regions of Brazil, CQ-resistant *P. vivax* strains have been widely documented in Southeast Asia, Oceania, and parts of South America (12) (Figure 3).

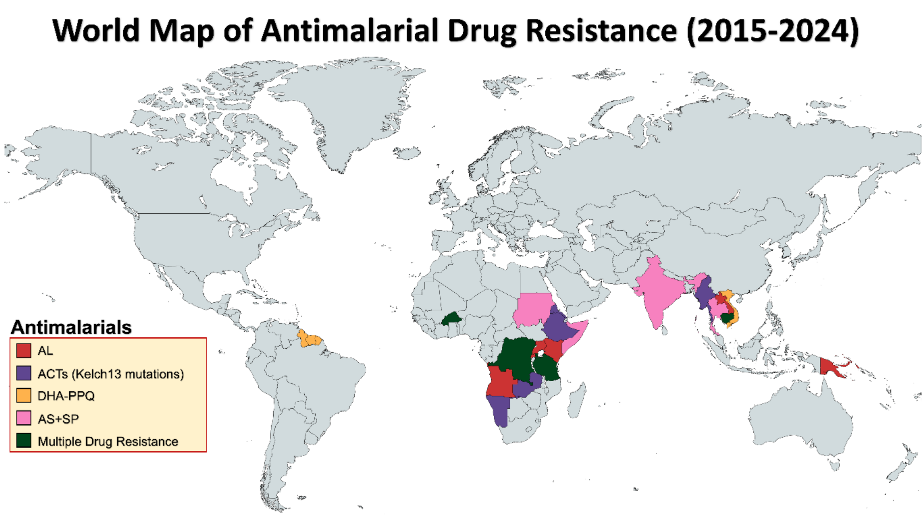


Figure 3: The map illustrates the geographic distribution of *P. falciparum* resistance to major antimalarial therapies, as reported in the WHO World Malaria Report 2024. Colors indicate the predominant drug or combination therapy for which resistance or treatment failure has been documented. ACT: artemisinin-based combination therapy; AL: artemether–lumefantrine; AS: artesunate; DHA-PPQ: dihydroartemisinin–piperaquine; SP: sulfadoxine–pyrimethamine.

In Brazil, the first confirmed case of CQ-resistant *P. vivax* was reported in 1999 in Manaus, Amazonas, and subsequent studies have confirmed its presence across several areas of the Amazon region. Nevertheless, the overall prevalence of CQ resistance in Brazil remains low and geographically restricted, which supports the continued use of CQ as the standard first-line treatment (13). A key limitation to the surveillance of *P. vivax* resistance is the lack of validated molecular markers. Currently, monitoring depends primarily on therapeutic efficacy studies, while *ex vivo* assays are still limited to specialized research settings, restricting their broader application in public health programs (14).

The genetic basis of CQ resistance in *P. vivax* remains poorly defined. Research has focused mainly on orthologs of *P. falciparum* resistance genes, particularly *pvcrt-o* and *pvmdr1*. The *pvcrt-o* gene, a homolog of *pfcrt*, has been tentatively associated with CQ treatment failure through increased gene expression. Copy number variation (CNV) in *pvcrt-o* has also been reported in Brazilian isolates and is related to the CQ-resistant phenotype (15). Additional regulatory polymorphisms have been explored; notably, Sá et al. (2019) demonstrated that an increased number of MS334 tandem repeats in CQ-resistant *P. vivax* progeny from the Sal-1 lineage led to elevated *pvcrt-o* expression and reduced susceptibility to CQ, supporting the functional relevance of this promoter region in resistance mechanisms (16).

Recent research on *P. vivax* (17) has enhanced our understanding of the infection. Studies indicate significant variation in total parasite biomass among patients, unrelated to peripheral parasitemia levels. Genetic analysis across Brazil and South America revealed high diversity, with South American isolates forming a unique global cluster. In Brazil, seven clades were identified, including a distinct lineage in the states of Amapá and Pará (18). Although these findings require validation in clinical studies, they highlight promising targets for the development of molecular tools for surveillance and emphasize the need to integrate genomic data into resistance monitoring strategies.

In parallel with genomic and molecular advances, there has also been progress in the development of vaccines and therapeutic innovations, which represent complementary strategies in malaria control. While Mosquirix™ (RTS,S/AS01), developed for *P. falciparum*, offers limited protection to children under 18 months of age, and R21-Matrix-M, also specifically designed for *P. falciparum*, offers up to 75% of protection against malaria in children under 36 months of age (19), a potential new vaccine for *P. vivax*, tested in non-clinical models, showed a safe profile with a strong immune response, supporting its progression for clinical trials (20).

Studies on antimalarial therapy are crucial. A long-acting 8-aminoquinoline, which was approved for treating *P. vivax malaria*, offers the advantage of single-dose administration, improving patient adherence and reducing the risk of relapses associated with hypnozoites (21). Notably, Brazil was one of the first countries in the world to implement tafenoquine in its national malaria treatment guidelines, underscoring the country's leadership and commitment to innovation in malaria control.

For *P. falciparum*, Brazil adopted artemisinin-based combination therapies (ACTs) as first-line treatment in 2006. The most widely used regimens include artemether–lumefantrine (AL) and artesunate–mefloquine (ASMQ), both combined with a single dose of primaquine to block transmission (22). Artemisinin resistance, first observed over a decade ago in the Greater Mekong Subregion (GMS), is primarily characterized by delayed parasite clearance following artesunate monotherapy or ACT. Clinically, this is often defined as a parasite clearance half-life greater than five hours or detectable parasitemia on day three. The primary molecular determinant of artemisinin resistance is the *pfkelch13* gene (also known as K13), with point mutations mainly located in the β-propeller domain shown to confer reduced drug susceptibility both in vitro and in vivo (23).

Despite the low prevalence of *pfkelch13* mutations associated with artemisinin resistance in the Brazilian Amazon (24, 25), the high transboundary mobility among mining populations, especially between Venezuela, Guyana, and the Brazilian state of Roraima, poses a considerable risk for the introduction and spread of artemisinin-resistant strains of *P. falciparum*.

In light of the challenges posed by emerging drug resistance, identifying new molecular targets has become a critical focus in malaria research. Martins and Daniel-Ribeiro (2024) (26) explored the mechanisms behind malaria-linked neurocognitive sequelae, suggesting that systemic inflammation and blood-brain barrier disruption during infection contribute to long-term neurological problems. G protein-coupled receptors (GPCRs) have emerged as promising targets in the *Plasmodium* parasite. For instance, in *P. falciparum*, the GPCR-like receptor PfSR25 functions as a potassium sensor, influencing calcium signaling; its removal increases parasite susceptibility to antimalarials (27). Similarly, the kinase PfeIK1 plays a central role in melatonin-driven synchronization of the parasite's cell cycle; we aim to block this pathway with melatonin derivatives to disrupt parasite growth (28). Furthermore, biliverdin, a byproduct of heme degradation, hinders parasite growth by targeting enolase and stress response pathways mediated by eIF2α (29).

Collectively, these findings highlight the current limitations in monitoring antimalarial drug resistance, particularly in *Plasmodium vivax*, and emphasize the need for specific validation of molecular markers. Despite the continued efficacy of chloroquine and ACTs in many areas of Brazil, the emergence and spread of resistant strains in neighboring regions and the high mobility of populations across borders underscore the fragility of existing treatment strategies. In this context, the search for new antimalarial compounds and the development of effective vaccines remain global priorities.

Finally, as mentioned earlier, it is essential to have an integrated malaria research agenda. Advancing research in vaccine and drug discovery is particularly crucial for developing effective interventions for vulnerable populations. Together, these efforts are essential for guiding evidence-based strategies to address both current and future public health challenges.

REFERENCES

1. World Health Organization (2024) World Malaria Report 2024. (World Health Organization, Geneva).

2. A.M. Siqueira, *et al*. Plasmodium vivax landscape in Brazil: Scenario and Challenges. *Am J Trop Med Hyg* 95:87 (2016).

3. N.J. Arisco, *et al*. Ecological change increases malaria risk in the Brazilian Amazon. *Proc Natl Acad Sci USA*. 121:e2409583121 (2024).

4. Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) – Impacts, Adaptation and Vulnerability. (IPCC, Geneva) (2023).

5. A.K.R. Galardo, *et al*. Seasonal abundance of anopheline mosquitoes and their association with rainfall and malaria along the Matapí River, Amapá, Brazil. *Med Vet Entomol.* 23:335–349 (2009).

6. Malaria Atlas Project Modelling the burden of climate-driven malaria transmission in Africa and the world. (Gates Foundation Report) (2023).

7. A.S. Silva, *et al*. Impact of El Niño on the dynamics of American cutaneous leishmaniasis in a municipality in the western Amazon. Acta Trop. 222:106032 (2021).
P.E.G. Coutinho, *et al*. An analysis of the influence of the local effects of climatic

and hydrological factors affecting new malaria cases in riverine areas along the Rio Negro and surrounding Puraquequara Lake, Amazonas, Brazil. *Robust decision making*. 190:311 (2018).

8. M.C. Castro, *et al*. Malaria risk on the Amazon frontier. *Proc Natl Acad Sci USA*. 103:2452–2457 (2006).

9. Ministério da Ciência, Tecnologia e Inovação (MCTI) (2023) Agenda Nacional de Ciência para o Clima e Saúde. (MCTI, Brasília).

10. Ministério da Saúde (Brazil), Secretaria de Vigilância em Saúde (2024) Boletim Epidemiológico da Malária. Disponível em: http://200.214.130.44/sivep_malaria/. Acessado em 6 de julho de 2025.

11. F.S. Santana Filho, *et al*. Chloroquine-resistant Plasmodium vivax, Brazilian Amazon. *Emerg Infect Dis.* 13(7):1125 (2007).

12. Silva SR, *et al*. Ex vivo susceptibility of Plasmodium vivax isolates from the Brazilian Amazon to commonly used antimalarial drugs and association with molecular markers. *Int J Parasitol Drugs Drug Resist.* 15:9–24 (2021).

13. Aguiar ACC, *et al*. Plasmodium vivax and Plasmodium falciparum ex vivo susceptibility to antimalarials and gene characterization in Rondônia, West Amazon, Brazil. *Malar J.* 13:73 (2014).

14. S.R. Silva, *et al*. Gene copy number variation and gene expression of Plasmodium vivax multidrug resistance (pvmdr1) and chloroquine resistance transporter (pvcrt-o) genes in Brazilian isolates. *Antimicrob Agents Chemother.* 62(1):e01806-17 (2018).

15. J.M. Sá, *et al*. Transcriptional profiling defines dynamics of parasite gene expression in response to chloroquine treatment in Plasmodium vivax. *Nat Commun.* 10:4300 (2019).

16. J.L. Silva-Filho, *et al*. Total parasite biomass but not peripheral parasitaemia is associated with endothelial and haematological perturbations in Plasmodium vivax patients. *eLife.* 10:e71351 (2021).

17. A. Ibrahim, *et al*. Population-based genomic study of Plasmodium vivax malaria in seven Brazilian states and across South America. *Lancet Reg Health Am*. 18:100420 (2023).

18. World Health Organization. WHO recommends R21/Matrix-M vaccine for malaria prevention in updated advice on immunization. (World Health Organization, Geneva) (2023).

19. R.F. Marques, *et al*. Non-clinical toxicity and immunogenicity evaluation of a Plasmodium vivax malaria vaccine using Poly-ICLC (Hiltonol®) as adjuvant. Vaccine 42(9), 2394–2406 (2024).

20. M.V.G. Lacerda, *et al*. Single-Dose Tafenoquine to Prevent Relapse of Plasmodium vivax Malaria. *N Engl J Med*. 380(3):215. doi: 10.1056/NEJMoa1710775 (2019).

21. Ministério da Saúde. Guia de tratamento da malária. Disponível em: https://www.gov.br/saude/pt-br/centrais-de- conteudo/publicacoes/svsa/malaria/tratamento/guia_tratamento_malaria_2nov21_isbn_site.pdf/view

22. N.W. Lucchi, R. Abdallah, J. Louzada, V. Udhayakumar, J.Oliveira-Ferreira. Molecular Surveillance for Polymorphisms Associated with Artemisinin-Based Combination Therapy Resistance in Plasmodium falciparum Isolates Collected in the State of Roraima, Brazil. *Am J Trop Med Hyg*. 102(2):310 (2020).

23. J. de Aguiar-Barros, *et al*. Molecular Surveillance of Artemisinin-Resistant Plasmodium falciparum Parasites in Mining Areas of the Roraima Indigenous Territory in Brazil. *Int J Environ Res Public Health*. 21(6):679 (2024).

24. R.L.D. Machado, *et al*. Correlation between Plasmodium vivax variants in Belém, Pará State, Brazil and symptoms and clearance of parasitaemia. *Braz J Infect Dis*. 7:176–178 (2003).

25. Y.C. Martins, Daniel-Ribeiro CT A hypothesis to explain malaria-induced neurocognitive sequelae. *Trends Parasitol*. 40:1077 (2024).

26. M.S. Moraes, *et al*. Plasmodium falciparum GPCR-like receptor SR25 mediates extracellular K+ sensing coupled to Ca2+ signaling and stress survival. *Sci Rep*. 7:9545 (2017).

27. B.K.M. Dias, *et al*. The Plasmodium falciparum eIK1 kinase (PfeIK1) is central for melatonin synchronization in the human malaria parasite. Melatotosil blocks melatonin action on parasite cell cycle. *J Pineal Res*. 69:e12685 (2020).

28. E. Alves, *et al*. Biliverdin targets enolase and eukaryotic initiation factor 2 (eIF2α) to reduce the growth of intraerythrocytic development of the malaria parasite Plasmodium falciparum. *Sci Rep*. 6:22093 (2016).

8.6 Conclusion

The climate crisis is also a cardiovascular crisis. The effects of pollution and extreme temperatures are already reflected in mortality statistics and health services. The "summer heart" hypothesis reminds us that environmental impact starts early and can shape our biology in profound ways. Recognizing this connection and acting in an integrated way between science, public policies and civil society is imperative to ensure a healthier and more resilient future to the challenges posed by climate change.

The Intergovernmental Panel on Climate Change (IPCC) has already warned that Latin America, including Brazil, is likely to experience an increase in the occurrence of extreme events, such as torrential rains and floods, in the coming years. This suggests that, in the absence of structural interventions and effective public policies, the tendency is for cases of leptospirosis and other bacterial diseases to rise, especially in vulnerable urban areas. Brazil faces significant challenges from catastrophic flooding and high rates of deforestation that could amplify the growing prevalence of antibiotic resistance in the human-animal-environment compartments, posing a threat to public health.

Although there are vaccines available for some arbovirus infections, there are no specific antiviral treatment options, and the lack of diagnostic tests in several regions remains an unsolved problem. In addition, existing treatment methods for arbovirus-related diseases basically focus on symptomatic management. The relationship between climate change and arbovirus transmission is complex, involving factors such as land use, urbanization, and human behaviour. The fight against arboviruses requires a joint effort, with vaccines, vector control, and improved diagnostics, treatments, surveillance, and public health actions.

Malaria remains a serious public health problem, requiring integrated approaches in the face of its multiple ecological, social, and clinical dimensions. Climate change intensifies the risks of transmission, especially in the Amazon region, requiring increased vigilance and continuous adaptation of control strategies. The growing prevalence of P. vivax poses additional challenges, such as relapses and asymptomatic infections. Resistance to antimalarials, combined with population mobility, weakens the progress made, reinforcing the need for therapeutic innovation. Investments in research, vaccine development, and new molecular targets are essential to achieve the goal of elimination by 2035.

In conclusion, human health is deeply intertwined with environmental and urban transformations driven by climate change. The way we live in cities reveals both the advances of civilization and the structural weaknesses that increase inequalities and risks to life. Physiological adaptation has its limits, especially in an increasingly elderly and vulnerable global population. Faced with this scenario, it is urgent to align science, ethics, and public policies to rebuild fairer, more resilient, and healthier cities. In short, the climate crisis is also a call for solidarity and the reinvention of our collective pact for coexistence.

9. DISASTERS, IMPACTS AND VULNERABILITIES RELATED TO CLIMATE CHANGE IN BRAZIL

Osvaldo L. L. Moraes[40], Regina Alvalá[41], Pedro Camarinha[41], Ana Paula Cunha[41], Silvia Saito[41], Marcelo Seluchi[41], Rachel Trajber[41]

INTRODUCTION

According to the latest IPCC report on climate change, in particular on impacts, adaptation, and vulnerability (IPCC 2021), disasters caused by climate change are already more frequent and intense than predicted by scientists. Therefore, the risk of disasters could continue to increase, even if nations succeed in limiting greenhouse gas emissions that drive global warming. Although the report highlighted here explains the causes and effects directly, a more in-depth approach is needed, particularly for Brazil, which is prioritized in this chapter.

Climate change is expected to have a number of severe consequences, some of which will have long-term impacts, such as the spread of disease and sea level rise, while others will have more immediate impacts, such as heavy rainfall, flooding, and landslides. Although we recognize the importance of other predicted consequences of climate change, this chapter targets “extreme weather events” that are responsible for geo-hydroclimatic disasters.

---

40 Departamento para o Clima e Sustentabilidade, MCTI, Brasilia, DF.

41 Centro Nacional de Monitoramento e Alerta de Desastres Naturais, CEMADEN, São José dos Campos, SP.

corresponding author: osvaldo.moraes@gmail.com

The series of extreme weather events recorded in Brazil in recent years has challenged the scientific and academic communities to deepen and accelerate the link between climate change and disasters. However, climate change and its impacts are highly complex scientific issues, so there are no simple answers to this link. It is becoming increasingly important to understand what science can tell us, especially to inform policy decisions.

With an initial focus on natural threats and their inherent complexity, several lines of evidence have been brought together to create a panorama of the influence of climate change on extreme weather events (Drexler and Meisenzahl, 2024). In the case of heatwaves and heavy rainfall, for example, the impact is already clear. In other cases, such as hurricanes, the signs are only just beginning to emerge; in still other cases, there are no clear indications yet. In all cases, however, the future trend is worrying: model calculations have shown that global warming will reach a level where various types of extreme events will become much more likely if no serious action is taken. However, according to scientific rigor, it cannot, and perhaps will never be, said that a particular event can be directly attributed to climate change. Even if a particular event is more likely due to climate change, given the non-linearity of the climate system, there is always the possibility that it could have occurred under unchanged circumstances. Any scientific evidence for the link between climate-related disasters and climate change must therefore correlate with statistically significant trends, not specific events. For scientific reasons, it should be noted, that some trends in severe storms are easier to identify than others. However, the main obstacles to a thorough understanding are, firstly the statistics — the ability to distinguish the signal from the noise of natural variability — and, secondly the limited time period (in temporal context) over which the warming has occurred. Modeling scenarios that take into account new greenhouse gas emissions and, consequently, global warming suggests that the signal will unfortunately become much clearer in the future (Hamdan et al., 2023).

However, attributing causes between climate change and extreme events is only one link between climate change and disasters. A year with “n” more extreme events than average may have much less impact than another year with “n” fewer extreme events than average. In other words, apart from the random element in the impact of increasing extreme weather events, it is crucial to consider that some areas are also more vulnerable to damage, such as fragile ecosystems or urban areas in floodplains. An extreme event can lead to a disaster if vulnerable areas are affected.

Climate change certainly influences weather events. However, labeling climate and weather as the cause of disasters can be misleading, as disasters are caused by the combination of natural threats and the vulnerability of human action. Therefore, caution is needed when linking the causes of extreme weather events and associated disasters. Even if science can clearly attribute such events to climate change, the resulting damage is essentially the result of existing vulnerabilities combined with the threats that triggered the geo-hydrological events.

People know that the damage they suffer is due to their vulnerability. As Wisner et al. (2004) emphasize, there is no crisis without vulnerability. An extreme event may not cause damage in well-prepared communities. However, a vulnerable community may suffer damage even if the extreme event is not so extreme. Similarly, the impacts may expand and intensify in direct proportion to the intensity of the natural threat. A community may infer damage from its vulnerability even if the triggering climate event has a clear signature of climate change (Ribot et al., 2020). Therefore, attributing a disaster to a climate event alone is therefore inappropriate. On the other hand, attributing disasters to vulnerability alone diminishes the importance of the other triggering factor, especially climate events triggered or exacerbated by greenhouse gas emissions. In other words, it is scientifically challenging to combine local causes (vulnerabilities) with the global cause (increased greenhouse gas concentrations).

As already emphasized, a direct attribution of recorded disasters to climate change may not be entirely appropriate. Therefore, for an appropriate assessment, a correlation is sought by comparing the trend in extreme events and the trend in the number of disasters with the data. This requires not only reliable data, but also a significant sample data set for representative statistical analysis.

Data can be defined as facts that can be stored and analyzed (Hackman et al. 2024). It is often used synonymously with information, but it is important to note that there is a subtle difference between the two. The term data refers to the raw data from which information is subsequently derived. While the definitions of data seem clear, and refer to facts, figures, or observations, it is also clear that there is no homogeneity when it comes to the content, of data, which easily leads to confusion about how data is processed, interpreted, and presented.

The contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2021) included an analysis of the reality of climate change. According to this report, “we now have a much clearer view of the past, present, and possible future climate, and this information is important for understanding where we are heading, what can be done, and the multiple facets of a changing climate for which we need to prepare, in all regions.” The conclusions of Working Group I are based on the integration of various findings, including in-situ and remote observations, paleoclimate information, global and regional climate models, as well as advances in analytical methods and findings from the growing field of climate services.

From a pragmatic point of view, to conclude that the climate has changed, one must demonstrate that there has been a noticeable change in the long-term pattern of climate variability. Reports V and VI of the Intergovernmental Panel on Climate Change (IPCC), published in 2014 and 2023, respectively, show evidence of statistically significant fluctuations in the long-term mean climate state.

For the purposes of this chapter, i.e. to understand the relationship between climate change and disasters, we illustrate the increase in precipitation in Brazil using the indicator Rx1day. This indicator is calculated considering the maximum daily rainfall (in mm) during a given period. Figure 1 illustrates the fluctuations in the annual average of Rx1day, calculated for decadal intervals. The numbers in the center represent the difference of this index between decades. A simple inspection of the “Anomalies” map between the decades 2011-2020 and 2001-2010 shows that the average daily precipitation was mostly positive. This example certainly deserves careful consideration. From a meteorological point of view, the main issues in adopting an index relate to the definition of extreme events, changes in their distribution, and their intensity (Gimeno et al., 2022). Pandergas (2028) points out the many ways to define extreme precipitation, and how the choice of definition influences the response to global warming. According to this author, researchers should carefully choose and clearly articulate their definition of extreme precipitation, just as users should consider the definition of extreme precipitation when interpreting analyzes of its change with warming.

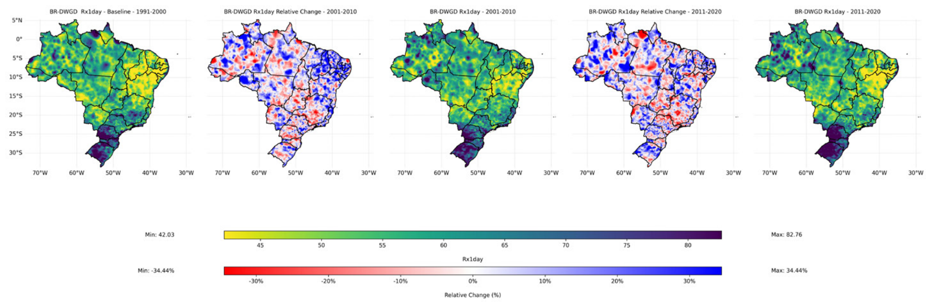


Figure 1: The Rx1day index. Maximum daily precipitation (in mm) for the last three decades. The intermediate values show the difference between the decades.

Although, from a meteorological point of view, there are undoubtedly objectives criteria to determine the various indices available for the defition of extrem wind; for disasters, however, there is no such equivalence.

Osuteye et al. (2017) assessed the limitations and bottlenecks of the available databases. The occurrence of disasters is increasingly documented and recorded in international disaster databases. The United Nations Development Program (UNDP) Global Hazards Information Platform (GRIP) website provides a comprehensive list of disaster databases classified as global, regional, or national. This website links to the availability of four global disaster databases: EM-DAT, Global Disaster Identification Number (GLIDE), College of Richmond Disaster Database Project, and NatCatService. In addition, the Dartmouth Flood Observatory maintains an archive of over 4,000 major flood events that can be searched by country. Another database is DesInventar, a catalog of national data that currently includes 89 countries and is constantly growing.

The databases have different thresholds for what they consider to be a disaster event. In EM-DAT, a disaster event must meet one of the following criteria to be registered: 10 or more deaths, 100 or more people affected/injured/displaced, or a national declaration of a state of emergency and/or a call for international assistance. While the DesInventar database definition considers one (1) or more human casualties or US$1 or more in economic losses, DesInventar uses national and local newspapers, police, and health reports as sources of information and includes as disaster events where there was any type of human or economic loss. The EM-DAT is compiled from various sources, including the UN, governmental and non-governmental organizations, insurance companies, research institutes, and news agencies, and has a wide range of other sources. As a result, these two databases can paint a very different picture of disaster losses in a country.

In Brazil, the official platform for disaster registration is S2iD (https://s2id.mi.gov.br/). This platform contains disaster records and the analysis of the federal recognition of the emergency situation or public emergency. In S2iD, municipalities must register the occurrence of events and apply for federal funds for local humanitarian assistance and the restoration of essential services in the event of disasters. The system categorizes disasters into two broad groups: Natural Disasters and Technical Disasters. The natural disaster group includes hydrologic disasters, such as floods, rainfall, and waterlogging; meteorological disasters, such as hurricanes, cold fronts, convergence zones, storms, and extreme temperatures; and climatological disasters such as drought, dry spells, wildfires, and low humidity; geological disasters include earthquakes, mass movements, and erosion; and finally, biological disasters, which include viral, bacterial, parasitic, and fungal infectious diseases, as well as animal, algal, and other pest infestations. S2iD has been recording disasters since 1991.

According to the Brazilian Atlas of Disasters, which compiles data from S2iD, there were 23,923 recognized disasters in Brazil between 1991 and 2020. In other words, 23,923 municipal decrees of emergency or disaster were recognized. These disasters caused 2,297 deaths, affected more than 77 million people, and had an economic impact of more than R$ 300 billion. This distribution can be broken down by typology and decade. For comparison with the figure below, we consider hydrological, meteorological, and geological disasters, especially mass movements. In these cases, the Atlas counts 8,998 disasters that caused 2,153 deaths, representing 93% of total deaths, affected 51 million people (66% of the total), and caused economic losses of more than R$100 billion (about 33% of the total). However, it is noteworthy, that no municipal decrees were recognized before 2003.

Figure 2 shows the ten-year total number of recognized hydrometeorological disasters, by region, for the decades 2001-2010 and 2011-2020. According to S2iD, no municipal decrees on public disasters or emergencies were recognized in the decade 1991-2000 (an explanatory sentence should be inserted here). Therefore, as highlighted, caution should be exercised when attributing the increase in the number of observed disasters to climate change, especially since, according to the S2iD, the number of disasters in the Northeast region in the decade 2011-2020 was lower than the number of disasters recognized in the decade 2002-2010. Nevertheless, the S2iD fulfills its purpose, which is to integrate different national civil protection products and improve the quality and transparency of risk and disaster management in Brazil. On the other hand, this platform has been restructured over the years, which means that the methodology for recognizing municipal decrees has changed over time. In other words, it is not possible to scientifically prove that the figures presented in this figure reflect the disasters that actually occurred in the country. Despite these limitations in the data source for disasters, there is also no doubt that disasters caused by extreme weather events are responsible for almost all deaths and the majority of people affected.

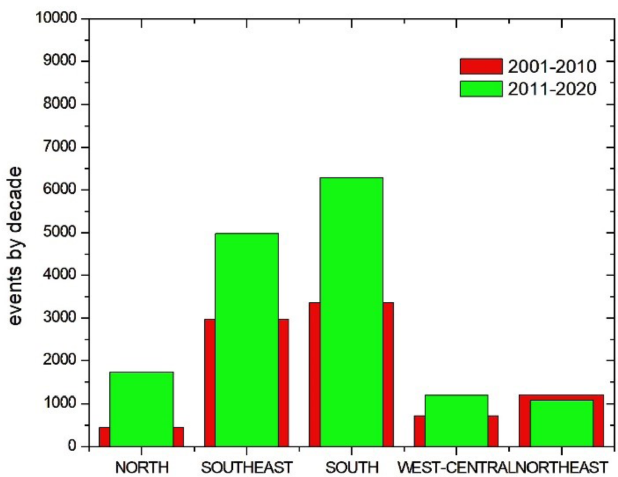


Figure 1: disasters by decade and region in Brazil

Considering the highlighted specificities and limited data sources, this chapter aims to assess what is known about climate change and the resulting disasters in Brazil. Therefore, this chapter highlights (i) the national overview of geohydrometeorological disasters in Brazil; (ii) droughts and their impacts on different biomes; (iii) progress and challenges in reducing vulnerability to disasters in the country; and (iv) education and disaster risk reduction with climate justice.

GEO-HYDROMETEOROLOGICAL DISASTERS

Concepts and scientific framework

The term "geohydrometeorological" used in this chapter is composed of three elements that represent the natural areas of natural phenomena that can lead to the disasters discussed in this topic:

- Geo-, derived from "geological" (from the Greek gê, "earth"), refers to processes related to soil, rocks, relief, and gravitational mass movements (e.g., landslides).
- Hydro-, derived from hydrological (from the Greek hydor, "water"), refers to the dynamics of water on the surface or underground (e.g., floods, inundations, downpours).
- Meteorological, refers to atmospheric processes that act as triggers or conditions for the above phenomena, especially precipitation.

The term thus attempts to summarize the multi-causal and interdependent nature of these events, which do not belong exclusively to a single physical domain, but result from the interaction between geological, hydrological, and meteorological conditions. In the Brazilian context, the definition used in this chapter includes events such as floods, inundations, flash floods, landslides, and other mass movements triggered by intense and/or heavy rainfall.

Contrary to the notion that these are purely natural events, it is important to understand that the catastrophic nature of these events depends essentially on human and territorial vulnerabilities. Although excessive rainfall is the triggering factor discussed in this chapter, the damage and losses are exacerbated by anthropogenic processes, such as disorderly urbanization, the occupation of hillsides and riverbanks, deficiencies in urban infrastructure, unsafe housing conditions, and the lack of effective planning and land management policies. Therefore, this topic analyzes disasters of geo-hydrometeorological origin and how they manifest themselves in Brazil. It highlights their peculiarities and main determinants given the country's regional diversity, against a background of scientific knowledge that helps to understand what transforms a natural event into a socio-environmental disaster.

National overview and observational evidence

Between 1991 and 2024, geo-hydrometeorological disasters accounted for just over a third (38.5%) of all events recorded in the Integrated Disaster Information System (S2iD). Although they do not account for the absolute majority of records, these events were responsible for most of the human impacts during this period, 83.5% of reported deaths (4,549 out of a total of 5,448) and 91% of displaced and homeless people (9.81 million out of a total of 10.77 million). These figures show that geo-hydrometeorological disasters, although relatively less frequent than other types of disasters, such as droughts, are notable for the scale of the social and humanitarian impact they often cause, in an intense way.

The above data show the high death and destruction potential of these events, especially when they affect urban areas, which are characterized by multiple dimensions of vulnerability, such as fragile and inadequate infrastructure, irregular settlement of slopes and floodplains, largely due to a lack of spatial planning and characterized by significant social inequality. Disasters of geological origin, especially landslides, are a prime example: they are much rarer than other types of disasters, but are among the deadliest, especially when they occur in densely populated areas on susceptible slopes or in their immediate vicinity. The Petrópolis tragedy on February 15, 2022, illustrates this dynamic well: an episode of extreme rainfall, highly concentrated in time and space, triggered 269 landslides (Alcântara et al., 2023), but a single large landslide on the Morro da Oficina destroyed dozens of houses and was responsible for most of the 230 deaths recorded in this event. On the other hand, hydrological disasters, such as floods, flashfloods and waterlogging, are very frequent, with 13,324 registered events (28.7% of all disasters reported to S2iD between 2001 and 2020), and affect practically all Brazilian municipalities to some extent. These events are primarily responsible for the displacement and homelessness of the affected population and also have a significant impact on urban infrastructure, mobility, public health, and the local economy. Take floods as an example, they accounted for 10% of all disasters registered in S2iD during the same period (4,822 out of a total of 46,423), but were responsible for 45.2% of all displaced and homeless people (3.28 million out of a total of 7.25 million), and caused 23% of total material losses (R$24.8 billion out of a total of R$107.8 billion), taking into account both public and private losses. These figures illustrate that hydrological events, even if they do not lead to fatalities, have a devastating impact on the living conditions of the affected population.

After this initial contextualization of the types of geohydrometeorological disasters that occur in Brazil, it is crucial to understand that the frequency and severity of these disasters present a significant territorial inequality, whether in terms of quantity or accumulated impacts over time, with a greater concentration in the eastern part of the Southeast, South, and Northeast regions. A superficial analysis could suggest that the explanation for this concentration lies in the climatic conditions of these regions, which are characterized by an increased occurrence of intense and heavy rainfall at certain times of the year, especially due to their proximity to the Atlantic Ocean and their proximity to cold fronts that collide with large warm air masses. Although the climatic factor is part of the problem, it is not sufficient to explain the spatial distribution of these disasters. When analyzing communities close to each other with almost identical climates, it becomes clear that not all of them have a significant history of disasters. Nor does the presence of physical elements, such as rugged terrain or extensive floodplains, provide a complete explanation, as there are areas with these characteristics that have experienced fewer disasters in the past.

Therefore, the decisive factors for the occurrence and extent of disasters only become clear through an analysis at the local level, resulting from the combination of natural threats and social and structural vulnerabilities. Disorganized urban growth, extensive soil sealing, the settlement of “risk areas” without adequate drainage or containment infrastructures and the lack of shelter and prevention measures are crucial factors in turning an extreme natural event into a major disaster. In this sense, the following topics of this session will aim to detail the main explanatory features for understanding the main geohydrometeorological disaster hotspots in Brazil, emphasizing the role of vulnerability as a key element in risk generation.

Regional Risk Scenarios related to Geohydrometeorological Disasters in Brazil

The risk of geo-hydrometeorological disasters in Brazil exhibits considerable regional variability, due to climatic, geological, geomorphological, hydrological, and, above all, socio-spatial factors. The most important risk scenarios by region and disaster type are presented below, as well as indications of the effects of climate change.

Southeast Region: conceptual and methodological deepening to elucidate the complexities of geo-hydrometeorological disaster risk

The southeastern region is home to about 40% of Brazil's population and is the region with the most geo-hydrometeorological disasters in the country (Avila et al., 2016; Saito et al., 2018), with landslides and flash floods being the most destructive and deadly. Due to this relevance, the risk scenarios in this region are analyzed in more detail. Although there are specific factors that cause and trigger geo-hydrometeorological disasters in this region, the considerations and analyzes developed for the Southeast provide a conceptual and methodological reference for understanding the other regions, whose characterization is briefly presented.

Accelerated and largely disorganized urban growth, combined with a lack of or inadequate spatial planning, has led to the expansion of many precarious settlements in areas with high geohydrometeorological vulnerability (Alves et al., 2023; Hirye et al., 2023). In these locations, extensive soil impermeability and inadequate micro- and macro-drainage systems impair rainwater infiltration and runoff (Altafini et al., 2023). This leads to the accumulation and concentration of surface and subsurface flows, which, when they reach steep slopes, can promote their instability and trigger landslides, especially in colluvial soils typical of the Serra do Mar and Serra da Mantiqueira regions (Oliveira et al., 2021; Vieira et al., 2016). The same factors (excessive impermeability, poor drainage, and rugged terrain) also favor the occurrence of violent flash floods, especially in densely populated urban areas. Under these conditions, the uncontrolled flow of water causes rapid and localized damage, often occurring simultaneously with landslides, and significantly amplifying the impact of these events.

Cities located in rugged terrain in these mountain ranges and adjacent mountainous regions, such as Petrópolis (RJ), Angra dos Reis (RJ), Santos (SP), Campos do Jordão (SP), and several municipalities in the Zona da Mata Mineira and Zona Serrana regions of Espírito Santo, present a high geohydrometeorological risk, as evidenced by their history of major disasters (Bonini et al, 2021; Alcântara et al., 2023; Souza et al., 2023). In addition, the Southeast is characterized by the metropolitan regions of São Paulo, Rio de Janeiro, Vitória, and Belo Horizonte, whose risks are exacerbated by population density, which increases the exposure of people in vulnerable areas (Saito et al., 2018), mainly due to socio-spatial inequalities and the colonization of vulnerable areas, by vulnerable communities. Anthropogenic changes, such as the irregular erosion of slopes, poorly designed landfills, and the discharge of wastewater or rainwater into slopes and natural channels, significantly increase environmental vulnerability and, thus disaster risk.

From a climatic perspective, the main mechanisms associated with intense rainfall in the Southeast are mesoscale convective systems (Siqueira & Marques, 2016), cold fronts, the orographic effect of coastal mountains, low pressure systems (Santana et al., 2013), and the transport of moisture from the Amazon region. The South Atlantic Convergence Zone (SACZ) is the second most important system, responsible for 47% of the intense rainfall in the Australian summer in the region, surpassed only by the cold fronts (53%) (Lima et al., 2010). According to studies by Aguiar and Cataldi (2021), the average probability of occurrence of a disaster in the presence of the SACZ in the Brazilian Southeast, is 24%, while the conditional probability of occurrence of the SACZ in the presence of a disaster in the Southeast, is 48%. This is the case of the major disaster in the mountainous region of Rio de Janeiro in January 2011, when heavy rains were triggered by the displacement of a cold front that joined the moisture convergence zone and organized the SACZ (Aires et al., 2020).

In many cases, the combination of the different climate systems and factors mentioned above can occur simultaneously, and generate even more extreme scenarios, such as the disaster that occurred in São Sebastião in February 2023. The confluence of an intense cold front, a low pressure area, an influx of oceanic moisture amplified by the warming of the seas, and the orographic impact of the Serra do Mar mountain range culminated in the heaviest rainfall recorded in Brazil in just 12 hours, with a cumulative rainfall of 683 mm, causing widespread landslides and killing 64 people (G1, 2023; Marengo et al. 2024).

This last disaster, in particular, clearly summarizes the main message we want to highlight in this topic. Although the extreme meteorological event that culminated in the São Sebastião disaster recorded its highest rainfall in the neighboring municipality of Bertioga, the impact in the latter municipality was of lesser magnitude and did not result in fatalities. The extreme rainfall (over 500 mm) affected the entire coastal strip between the two municipalities; however, the most severe impacts were concentrated in certain neighborhoods of São Sebastião, particularly Vila do Sahy. In this area, pre-existing socio-environmental vulnerabilities and a high level of exposure exacerbated the consequences of the event.

On the north coast of Bertioga, mid- and high-end condominiums predominate, mostly located on coastal plains with good natural drainage and adequate infrastructure. On the south coast of São Sebastião, a striking contrast can be observed: While the higher-value coastal areas, which are less prone to disasters, are inhabited by high-end homes and condominiums and benefit from better infrastructure in their surroundings, the sector located on the other side of the BR-101 highway is home to more vulnerable communities, with inadequate infrastructure and in areas that are highly prone to landslides, flash floods, inundations and flooding of small watercourses. A final reflection on this disaster: Bastos Moroz & Thieken (2024) show that urban settlement/exposure explains at least 46% of the physical and human damage in São Sebastião over the last two decades, which could have been avoided by spatial planning policies and curbing urban expansion in vulnerable areas.

In conclusion, it is worth emphasizing once again that extreme precipitation events per se are not, the main cause of geohydrometeorological disasters. Although they trigger geohydrometeorological phenomena, disasters are the result of a historical process of risk construction, conditioned by socio-economic inequalities, environmental degradation, and land use patterns. When these events occur, they therefore merely highlight and reinforce pre-existing vulnerabilities and structural problems, and transform risks into concrete impacts. This finding is all the more worrying considering that the frequency and intensity of these events has increased in recent decades, in the context of climate change and natural climate variability (IPCC, 2022; Marengo et al., 2020), as we will discuss below. These events could have far-reaching impacts if disaster risk reduction (DRR) and climate change adaptation measures are not taken immediately.

Climate Change and Geohydrometeorological Disasters in the Southeast Region

Before addressing climate change directly, it is important to clarify that the relationship between global warming and the intensification of extreme rainfall is based on a widely recognized thermodynamic principle, described by the Clausius-Clapeyron relationship. Simply put, this principle states that for every increase in air temperature of about 1°C, the ability of the atmosphere to store water vapor increases by about 7% (Trenberth et al., 2003; Allan & Soden, 2008). This increase in moisture storage capacity means that, in a warmer climate, the atmosphere has more "fuel" for the formation of deep clouds and precipitation systems. However, this additional moisture does not necessarily lead to more rainy days per year, but rather to more concentrated and intense precipitation events (Donat et al., 2016; Pendergrass & Knutti, 2018). It is precisely this characteristic that increases the risk of geo-hydrometeorological disasters.

In this regard, there is solid evidence that extreme precipitation events are increasing in southeastern Brazil, which is consistent with the planetary warming observed over the same period. This is underlined by the trend of increasing maximum daily precipitation and extremely wet days, especially in the state of Rio de Janeiro, where average daily extreme events increased by up to 5 mm per decade (Luiz-Silva & Oscar-Júnior, 2022). Based on the recent findings of Orlandi Simões et al. (2025), some areas in the southeast also show consistent signs of an increase in the frequency and intensity of extreme precipitation events, especially in summer, implying a reduction in the estimated return period. This applies to parts of Espírito Santo, south-central Rio de Janeiro (including the Serrana region), and areas in northern and central Minas Gerais, where positive trends in extreme rainfall indices indicate a greater likelihood of severe episodes in the near future. The study conducted by Ávila et al. (2016), which analyzed data from 1978 to 2014 and demonstrated statistically significant trends in the increase in extreme precipitation events in the Serra do Mar region in the state of Rio de Janeiro, points in the same direction.

It is worth noting that, in addition to these trends already observed in the past, more recent studies using climate modeling and risk analysis data suggest that southeastern Brazil may be further affected by events of geohydrometeorological origin as a result of ongoing global warming. These studies show an almost consistent trend towards an increase in the frequency and magnitude of extreme precipitation events concentrated in one and five days (Camarinha, 2016; Debortoli et al, 2016; Luiz-Silva & Oscar-Júnior, 2022; Santos, 2022). especially in scenarios where global warming exceeds 2°C (Marengo et al., 2021; Debortoli et al. 2016; Brazil, 2016; Marengo et al., 2021; Santos, 2022; Brazil, 2020).

Despite the evidence presented so far, whether for Southeast Brazil or any other region, there is still a debate about the specific role of anthropogenic climate change in the occurrence of individual events, as it is difficult to isolate the anthropogenic contribution from natural variability and other regional or local meteorological factors (Stott et al., 2016). In this sense, “attribution studies” have emerged as a fundamental tool to reduce these uncertainties by using climate modeling, to compare the probability or intensity of an event in the current climate (with radiative forcing caused by human activities, especially greenhouse gas emissions) and in a counterfactual scenario without this forcing (Vincent et al., 2020). Although it is not possible to attribute absolute causality to a single event, this approach allows us to estimate how global warming changes the likelihood and severity of extremes (World Weather Attribution, 2023), which provides important information for assessing the amplification of impacts and targeting adaptation and risk management strategies.

To conclude this section, after selecting the Southeast of Brazil as a case study and moving on to brief analyzes of the other regions, we present recent scientific findings that illustrate the link between climate change and geo-hydrometeorological disasters of great magnitude. A prime example is the extreme event that occurred in Minas Gerais in January 2020, characterized by record rainfall that resulted in 56 deaths and estimated damages of R$ 1.3 billion. According to an attribution analysis conducted by Dalagnol (2021), about 41% of these impacts can be linked to man-made global warming. This underlines the anthropogenic influence on the intensification of precipitation extremes and the amplification of their socio-economic consequences.

Souza et al. (2023) came to similar conclusions in their study on the disaster that occurred in Baixada Santista (SP) in March 2020, triggered by rainfall amounts of up to 350 mm in 48 hours. These amounts were enough to trigger flash floods, flooding, and, above all, large-scale landslides that claimed 44 lives, affected around 2,800 people, and caused damage of more than 43 million US dollars. Analyzes on attribution showed that precipitation of this magnitude became 46% more likely, in the context of current warming and that between 20% and 42% of the observed impacts can be attributed to anthropogenic climate change.

Overview of Geohydrometeorological Disasters in the South Region and Associated Climate Change

The southern region of Brazil, characterized by its subtropical climate and diverse topography, has experienced a significant increase in extreme events in recent decades, particularly the major disasters that occurred in the Itajaí Valley (2008) and Rio Grande do Sul in 2023 (Alvalá et al, 2024) and, especially, April-May 2024, which is considered the most devastating disaster in the region, affecting more than 2.3 million people and causing 184 deaths and 42 missing persons (Reboita et al, 2024; Marengo et al., 2024). This topic examines the patterns of floods and landslides and their relationships with environmental, and socio-spatial factors, and climate change, thus providing a scientific basis for understanding the relationship between these phenomena and the occurrence of disasters, especially in recent decades. The southern region of Brazil has geomorphological features that significantly increase its vulnerability to climate-related disasters, as it is a highly populated region. The rugged terrain, characterized by extensive alluvial plains interspersed with plateaus and mountain ranges, creates natural conditions that favor both flooding and landslides (Marth et al., 2016). The steep slopes of the Serra Gaúcha and the Planalto Catarinense, combined with sedimentary soils that are easily eroded by climatic and anthropogenic influences, create scenarios with high geotechnical instability. The floodplains of the Taquari-Antas, Uruguai, and Iguaçu rivers, characterized by low gradients and alluvial soils, are naturally subject to periodic flooding. However, the width of the downstream relief, the steepness of the plains, and direct and indirect anthropogenic interventions have become decisive factors that increase vulnerability to disasters, especially during intense rains that quickly lead to high surface runoff.

The urbanization process in the southern region is characterized by the systematic settlement of areas considered unsuitable, including steep slopes, valley bottoms, and floodplains (Beltramin & Morais, 2024). The lack of adequate spatial planning has led to a concentration of the population in areas with high ecological vulnerability, exposed to geohydrological influences. In Blumenau, Santa Catarina, for example, the low-income population is systematically directed to areas of higher risk, including riverbanks, unstable slopes, and flood-prone areas, a situation that exponentially increases their vulnerability (Souza et al., 2021).

River adjustments due to inadequate channelization and improper urban drainage management have significantly altered runoff patterns, and created new risk areas in previously stable areas (Beltramin & Morais, 2024). The straightening of watercourses without taking into account natural geomorphological processes has also led to accelerated erosion and bank instability, accelerating the silting of rivers and streams, and increasing their vulnerability to flooding. In addition to these factors, environmental degradation has contributed significantly to the increased risk of geo-hydrometeorological disasters. The removal of native vegetation cover, especially on slopes and in permanent protected areas, has led to a loss of geotechnical stability and increased surface erosion (Silva et al., 2022), accelerating the aforementioned erosion processes. The conversion of forest areas to agricultural and urban land has also significantly altered infiltration and runoff patterns, such that studies in some river basins in the southern region show a direct link between the loss of forest cover and the increased frequency and intensity of floods and landslides (Canil et al., 2020). In addition to these factors, anthropogenic changes to regional water systems include the straightening of channels, the construction of dykes, the filling, of floodplains and the alteration of natural drainage patterns (Beltramin & Morais, 2024). These interventions have led to altered drainage regimes, altered sedimentation patterns, and the creation of new points of geomorphological instability.

Thus, these factors of vulnerability and high exposure prove to be components that favor the occurrence of disasters during heavy and intense rainfall. From a climatic point of view, the southern region is characterized by a subtropical climate, characterized by frequent episodes of prolonged and heavy rainfall, which contribute to soil saturation and the triggering of extreme geohydrological events (Oliveira et al., 2019).

The main meteorological systems associated with geohydrometeorological disasters are generally synoptic in nature, with a focus on frontal systems, extratropical cyclones, depressions, SACZs, and the subtropical anticyclones of the South Atlantic and Pacific (Pugas et al., 2024). Oceanic systems such as the Brazil Current and the Falkland Current (Stramma et al., 1990), and low-frequency oscillations such as the Pacific Decadal Oscillation and the Southern Oscillation associated with the El Niño–Southern Oscillation (ENSO) phenomenon also exert a significant influence. The latter plays a prominent role in regional climate variability, as El Niño and La Niña phases significantly modulate the spatial distribution and intensity of precipitation as well as the frequency of extreme events (Fernandes & Rodrigues, 2018). El Niño events are closely linked to the occurrence of landslides in the region (Emberson et al., 2021). This modulation is partly related to the influence on the regional atmospheric circulation, especially the variability and intensity of the low pressure systems responsible for transporting moisture to the region. In fact, studies conducted after the major disaster of 2024 have shown that the probability of El Niño events in southern Brazil has increased by 2 to 5 times and the intensity by 3 to 10%, while human-induced climate change has doubled their frequency and increased their intensity by up to 9%, amplifying the geohydrological risk in the region. (Clark et al., 2024).

Regarding the main observed climate changes, precipitation data from 1961 to 2020 show a significant increase in the intensity and frequency of extreme events in the southern region of Brazil (Martini, 2022; Fernandes & Rodrigues, 2018). In a more recent study, Dunn et al. (2024) showed that the southern region of Brazil has exhibited a consistent trend of increasing precipitation extremes since 1950. Using observational and reanalysis data for the period from 1950 to 2018, the authors analyzed several indicators of extreme precipitation events, and identified the region as one of the areas with the largest contiguous extents in the world, showing a systematic increase, in both the frequency and magnitude of these events per decade. Climate projections for the coming decades indicate that this will be the most critical region in the country in terms of intensification of precipitation extremes, with high reliability due to the convergence between different climate models (Pillar & Overbeck, 2024; Gomes et al., 2022; Marengo et al., 2021).

The Third National Communication on Climate Change (Brazil, 2016) had already identified this high climate risk, highlighting the vulnerability to geohydrological disasters and predicting a worsening in the following decades with the progression of global warming (Camarinha et al. 2016, Debortoli et al. 2016; Debortoli et al. 2017). These conclusions were reiterated in Brazil's Fourth National Communication to the United Nations Framework Convention on Climate Change (Brazil, 2020) and confirmed by subsequent studies, such as that of Marengo et al. (2021), which maintain the consistency of the diagnosis and projection in terms of regional criticality. In addition, the projections indicate an increase in interannual variability, with alternating periods of more severe droughts and extreme rainfall, which increase the risk of flooding and mass movements (Gomes et al., 2022; Martini, 2022).

Overview of Geohydrometeorological Disasters in the Northeast Region and Associated Climate Change

Although the Northeast region is generally associated with drought, it offers a significant risk of rainfall-induced disasters, especially in coastal areas and areas with a humid tropical climate. Capital cities such as Recife (PE), Salvador (BA), Maceió (AL), and Fortaleza (CE), as well as neighboring cities within their metropolitan areas, face recurrent flooding caused by the combination of high water, sewerage failure and intense, short-duration rainfall. These cities are also exposed to the risk of landslides in densely populated areas located on hills and coastal slopes where soils are highly susceptible to instability, exacerbated by human intervention during their often irregular settlement. The vulnerability of cities, characterized by social inequality and poor infrastructure, amplifies the impact of these events, even if they are not extreme.

An extremely important factor in understanding geo-hydrometeorological disasters is the high vulnerability of the population, especially in urban areas. Saito et al. (2018) found that in the Northeast region, about 15% of the Brazilian population lives in recognized risk areas, a total of more than 2.7 million people. This is particularly true for the metropolitan regions of Salvador (BA), Recife (PE), Fortaleza (CE), and eastern Alagoas, which are characterized by high social vulnerability. In absolute terms, the Southeast region has the largest population exposed to geohydrological risks. However, in the Northeast region, around 15 out of every 100 inhabitants live in areas prone to landslides or flooding. In addition, other cities in the Northeast also show similar patterns, where high population density in irregular settlements, without adequate infrastructure, increases vulnerability to landslides, as observed by Almeida et al. (2014) in the municipality of São Luís (MA).

Among the main natural factors responsible for the most significant disasters in the northeastern region is the Barreiras Formation, a geological formation widely distributed along the coast of northeastern Brazil, and characterized by poorly consolidated sandy and clayey sedimentary deposits (Arai, 2006). The low cohesion and high permeability, combined with steep slopes and intense rainfall at certain times of the year, make it highly susceptible to slope instability, which often causes landslides. This situation is exacerbated by disorganized urban development and the lack of adequate surface drainage systems, factors that favor infiltration and increased neutral pressure in the soil. In municipalities such as Salvador and Lauro de Freitas (BA), Recife and Jaboatão dos Guararapes (PE) and Natal (RN), such events have occurred repeatedly in the past. There are records of significant disasters associated with periods of intense rainfall, generally related to the disorganized human settlement associated with the Barreiras Formation (Coutinho & Silva, 2005).

From a climatic point of view, the Brazilian Northeast is subject to a complex system of climatic and meteorological factors that favor the occurrence of geohydrometeorological disasters. Eastern waves are the main atmospheric mechanism, responsible for 50% of heavy rainfall events and 60% of precipitation in the eastern part of the region (Seigerman et al., 2024). These systems usually last 3–8 days and interact with mesoscale convective systems that propagate over the equatorial South Atlantic, and intensify convective activity near the Brazilian coast (Seigerman et al., 2024), mainly affecting coastal communities in the eastern part of the Northeast, precisely where the majority of the population is concentrated.

The Intertropical Convergence Zone (ITCZ) also exerts a decisive influence on interannual and interdecadal precipitation, especially in the Agreste, Sertão, and Meio-Norte regions (dos Santos et al., 2023), but is less relevant in explaining major historical disasters. Oceanic conditions, especially positive sea surface temperature anomalies over the equatorial South Atlantic and the intensification of trade winds, favor the excessive transport of moisture from West Africa to South America, contributing to extreme events (Seigerman et al., 2024).

Recent studies using climate projection models indicate that climate change in northeastern Brazil tends to increase the variability of extreme precipitation. It is estimated that the number of days with intense rainfall will increase by up to 140 %, while the number of dry days will decrease by up to 15 %, increasing geohydrological risks in the region (Medeiros & Oliveira, 2023). This increase is most pronounced under moderate and intermediate global warming scenarios, which are considered the most likely for the coming decades. In contrast, under an extreme warming scenario of 4°C, the trend is towards a drier climate, with a decrease in the frequency of intense precipitation events. However, the extent of extreme precipitation events increases significantly with the increasing intensity of global warming (Marengo et al., 2021; dos Santos et al., 2020), especially along the coastal strip in the far east of the northeastern region, between Pernambuco and Natal, during the summer months (dos Santos et al., 2020).

However, in contrast to the above-mentioned regions in the south and southeast, the findings on climate change in the northeast are subject to a higher degree of uncertainty, both under current conditions and in future projections. For example, the study by Avila-Diaz et al. (2020), states that the predominant signal in the eastern part of the region indicates a reduction in annual precipitation totals and lower intensity precipitation events, accompanied by an increase in the frequency of days with extreme precipitation, but without conclusive evidence of intensification or attenuation of the magnitude of these events.

Overview of Geohydrometeorological Disasters in the North Region and Associated Climate Change

In the northern region, geohydrometeorological disasters are dominated by long-lasting seasonal floods associated with the flood pulse of the major Amazonian rivers (e.g., Amazonas, Solimões, Madeira, and Acre). These hydrological patterns are determined by rainfall fluctuations in large catchment areas and the propagation of the flood wave along the main channel. These prolonged floods cause floodplains and paleofloodplains, inundate production areas and riverside settlements, and disrupt transportation infrastructure and urban services for weeks to months, increasing health, logistical, and socioeconomic risks in the cities of Manaus, Porto Velho, Rio Branco, and Santarém (Pinel et al., 2019). Recent monitoring and reanalysis studies show that extreme flooding in the Amazon basin has increased in frequency and duration in recent decades. This is partly due to changes in tropical atmospheric circulation and the balance between precipitation and runoff, which has increased the vulnerability of the population living along rivers and in cities (Barichivich et al., 2018; Pinel et al., 2019).

In addition to flooding in lowlands, erosion processes and landslides in riparian areas are important processes that are often linked to river dynamics. Bank erosion can lead to bank failures, and meander migration favors an abrupt loss of soil resistance, leading to the phenomenon locally known as "terras caidas"," especially when soil cohesion is reduced by prolonged saturation or stress reduction during drought periods.

In urban areas of the Amazon, such as Manaus, the risk of landslides is exacerbated by anthropogenic factors, even in regions with moderate natural susceptibility. Irregular slope cuts, poorly constructed embankments, loss of vegetation cover, and inadequate drainage systems alter local geomorphological and hydrological conditions, favoring the occurrence of landslides even during moderate rainfall (Ramos et al., 2019).

Regarding climate change and its relationship with the main geohydrometeorological disasters in the region, there is evidence that the significant warming of the tropical Atlantic since the 1990s is a key factor in the intensification of the hydrological cycle in the Amazon. This warming increases the atmospheric water vapor, transported by the trade winds into the northern Amazon basin, which increases precipitation and river runoff, especially during the rainy season (Gloor et al. 2013; Barichivich et al. 2018; Wang et al. 2018). Marengo et al. (2024) show that these changes have been reflected in a fivefold increase in severe flooding events in central Amazonia in recent decades (2001–2021), with the total duration in Manaus being 20% longer than during the entire 20th century. Precipitation trends vary between northern and southern Amazonia, with an increase in convective activity and precipitation in the north, in contrast to the decrease in the southern part.

A study by Pinho et al. (2024) clearly shows the socio-economic effects associated with these climate changes, albeit only partially. Between 2006 and 2010, an annual average of around 540,000 people was affected by hydrological events in the region. In the most recent period, from 2018 to 2022, this number jumped to around 1.78 million people per year, an increase of 229%. During the same period, economic losses also increased significantly, from an average of USD 132.8 million per year (2006–2010) to USD 634.2 million (2018–2022) — an increase of 377%.

Studies analyzing climate projections for the northern region of Brazil indicate that the observed trends of increased occurrence of extreme events persist and even intensify in some scenarios, albeit with a higher degree of uncertainty compared to the south and southeast regions (Debortoli et al., 2016; Marengo et al., 2021). In general, climate models indicate a decrease in total annual precipitation, which is accompanied by an increase in the frequency and magnitude of heavy rainfall events. The intensity of these changes varies from slight to moderate, depending on the global warming scenario and is more pronounced under a stronger warming (Avila-Diaz et al., 2020; Debortoli et al., 2016; Marengo et al., 2021). These results highlight the importance of considering climate projections derived from multiple models and scenarios when formulating adaptation strategies, given both the region's sensitivity to hydrological variability and its high socio-ecological vulnerability. At the same time, the need to expand and deepen observational studies is emphasized in order to reduce the uncertainties associated with the projections and improve the scientific basis for decision-making.

Overview of Geohydrometeorological Disasters in the Central West Region and Associated Climate Change

The Central-West region has the fewest historical records of geohydrometeorological disasters. This is mainly due to the topographical features, which are predominantly of gentle relief, the low population density and the climate, which favors fewer episodes of very heavy rainfall compared to other regions.

Nevertheless, the occurrence of flash floods and urban flooding has increased in the major cities of the Brazilian Central West. This phenomenon is explained by a combination of changing land use patterns, characterized by an accelerated expansion of the urban fringe and soil impermeability, and recent fluctuations in the intensity of short-duration rainfall. In cities such as Goiânia, Cuiabá, and Campo Grande, the rapid conversion of permeable surfaces into paved and built-up areas, accompanied by inadequate updating and maintenance of drainage systems, leads to a reduction in local storage and infiltration capacity and an increase in surface runoff, resulting in high-energy, flash flood events of short duration that cause significant, individual damage (Souza et al., 2021). Studies on urban vulnerability and flood indices applied to urban catchments in the Central-West region show that local hydrogeomorphological units and micro-slopes control the concentration of runoff, meaning that even moderate rainfall can cause severe flooding and inundation in areas with under-drainage and valley floor occupation (Mattos et al., 2021; Moraes & Gonçalves, 2024).

In addition, analyzes of regional precipitation series and trend studies indicate heterogeneous signals in the Central-West region. While total annual precipitation does not show a consistent increase in all sub-regions, there is evidence of an increase in the frequency and intensity of short-term extreme events (analyzes based on indicators RX1day, R95p, etc.), especially in Goiás and the Federal District (Debortoli et al., 2016), which, together with the settlement factors described above, exacerbates current urban risks (Valverde & Marengo, 2014; Battisti et al., 2025).

The results of studies that incorporate future climate projections are inconclusive regarding the patterns of increasing extreme precipitation events in the near future, although the general trend is a slight increase in both frequency and magnitude (Debortoli et al., 2016; Marengo et al. 2021; Avila-Diaz et al., 2020). However, for the second half of the 21st century and/or in scenarios where global warming exceeds 2°C, the results are more consistent, and indicate a significant increase in extreme precipitation events (Debortoli et al., 2016; Marengo et al. 2021; Avila-Diaz et al., 2020).

To a certain extent, these above-mentioned patterns and uncertainties were also found in analyzes based on observational data, as in the study by dos Santos et al. (2021). Using historical precipitation series from 1979 to 2019, the study evaluated standardized extreme indices and found that the number of days with very heavy precipitation (R20mm) showed no statistically significant changes at most of the analyzed stations. However, a positive trend for the occurrence of days with more than 50 mm of precipitation was observed at around 25 of the locations. In addition, both the maximum precipitation on a single day (Rx1day) and the maximum precipitation on five consecutive days (Rx5day) showed predominantly increasing trends. In contrast, total annual precipitation showed negative trends in much of the eastern part of the Central-West region, suggesting a possible intra-annual redistribution of precipitation with more concentrated and intense events, favoring the occurrence of hydrological events. Finally, integrated modeling combining land-use changes and more intense precipitation scenarios show that the combined effect of changes in runoff due to the high imperviousness of urban areas and increased precipitation intensity is likely to multiply the depth and return period of urban flooding and inundation, increasing the likelihood of failures in drainage systems designed for historical climates and increasing the risk of hydrological disasters (Mattos et al., 2021).

DROUGHTS IN BRAZILIAN BIOMES

Drought is a climatic extreme related to low water availability caused by the deficit of precipitation compared to normal conditions and often enhanced by the increase in atmospheric water demand after high temperatures or intense winds (UNDRR, 2021). It is important to note that the effects of drought accumulate slowly over time and can last for months or years after rainfall returns to its average values.

Drought events can result in disasters when the demand for water is no longer supplied, causing water imbalance for different human activities (Wilhite and Glantz, 1987, UNDRR, 2021). Thus, drought is configured as a risk when there is a decrease in the capacity of the different systems to deal with the water deficit (Cunha et. al. 2018, 2019). This risk can result in impacts on people's livelihoods, productive sectors, the health of ecosystems, and even the lives of humans and animals (Cunha et al., 2019; Marengo et al., 2021; Cuartas et al., 2022).

In less developed countries, impacts on human livelihoods are often associated with the level of poverty, further intensifying existing vulnerabilities. In addition, more recurrent and intense droughts can also accelerate land degradation processes, resulting in the long-term loss of ecosystem services when tipping points are exceeded (Vogt et al., 2011; Spinoni et al., 2015).

Brazil has faced drought events of great magnitude since the beginning of the 21st century, which have caused significant impacts on several biomes, including the Amazon, the Pantanal, the Cerrado and the Caatinga. These extreme events not only affect the biodiversity of these ecosystems but also compromise the living conditions of human populations (Cunha et al., 2019; Cuartas et al., 2022).

The time series of the drought index, called SPEI (Standardized Precipitation Evapotranspiration Index (Vicente-Serrano et al., 2010) show that from the 90s onwards, droughts in Brazil became more frequent and intense (more negative and consecutive SPEI values, Figure 3a). The SPEI is an index that considers both precipitation and potential evapotranspiration (estimated based on air temperature), providing an integrated measure of water availability and climatic conditions in a region, being a simple way to account for deviations from the water balance of a given region.

According to SPEI data (Figure 3a), the country faced three major droughts (negative and consecutive peaks of SPEI, below -1.0): the first between 1997 and 1998, the second between 2015 and 2016, and the last in 2023 and 2024. It is worth mentioning that the drought of 2015-2016 surpassed that of 1997-1998, but the last one of 2023-2024 presented more negative SPEI values, indicating that it is the most intense in the historical series. This scenario was due not only to the deficit of rainfall, but to the simultaneous occurrence of drought events and heat extremes, especially between the years 2023 and 2024. In different parts of the globe, the simultaneous occurrence of multiple climate hazards such as drought and heat (compound drought-heat) has also increased and is projected to further increase in this century (Zscheischler et al. 2018, 2020; Vogel et al. 2020; IPCC 2021).

Compared to past decades, in the last ten years (2014 to 2024), droughts have been more recurrent and more intense in the Cerrado, Amazonia, and Pantanal biomes (persistently more negative SPEI values, Figures 3b, c, d, and g), therefore biomes outside the limit of the Brazilian semi-arid region, a region where droughts used to be more recurrent than in the rest of the country.

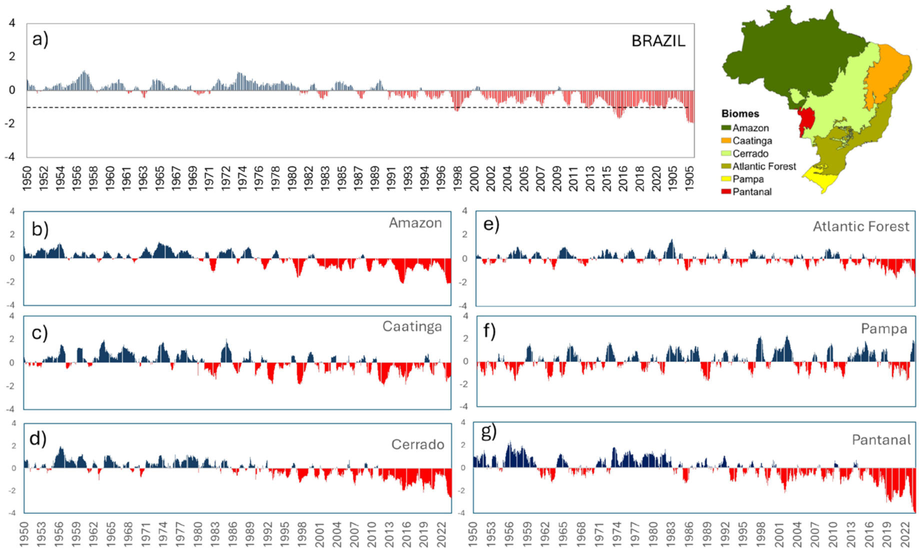


Figure 3: Temporal evolution of droughts in Brazil considering the Standardized Precipitation and Evapotranspiration Index (SPEI) from 1951 to 2024. The blue bars indicate years in which precipitation was greater than evapotranspiration (positive water balance), indicating wetter periods, with greater water availability, while the red bars indicate years in which evapotranspiration was greater than precipitation (negative water balance), resulting in drier conditions, with less water availability. (Source of SPEI data: Vicente-Serrano et al., 2010; post-processing and analysis: CEMADEN/MCTI).

According to data from the Integrated Drought Index - IDI (Cunha et al., 2019, Zeri et al., 2024), an operational index for drought monitoring provided by the Brazilian National Center for Monitoring and Early Warning of Natural Disasters - CEMADEN/MCTI, in terms of extent, the 2023-2024 drought leads, covering about 5 million km^2, which corresponds to approximately 59% of the Brazilian territory. Secondly, the drought of 2015-2016 affected about 4.6 million km^2 (approximately 54% of the country). The drought of 1997-1998 reached about 3.6 million km^2, equivalent to 42% of the national territory.

Data from CEMADEN (Monitoramento de Seca para o Brasil — Centro Nacional de Monitoramento e Alertas de Desastres Naturais - Cemaden/MCTI) show that in 2024 more than half of Brazil suffered the direct impacts of the climate crisis, in which the Amazon, Cerrado and Pantanal biomes faced the worst drought in the last 70 years. As of September 2024, approximately 1200 municipalities in Brazil have faced severe drought conditions. In a situation of extreme drought, there were 263 Brazilian municipalities. The rainfall deficit observed since the spring of 2023 in such an extensive area of Brazil (covering the northern to southeastern regions of the country), and the occurrence of high temperatures, heat waves, and low relative humidity, reaching values close to 7% in part of the Central-west region, drove the spread of fires.

Although historically droughts are more recurrent in the semi-arid region, in recent years, droughts have been quite severe, causing impacts in different regions of Brazil.

In the Amazon Biome, the droughts that occurred in 1982-83, 1997-98, 2005, 2010, 2015-16 and more recently in 2023-24 stand out (Marengo, 2013; Jiménez-Muñoz et al., 2016; CEMADEN, 2023; Espinoza et al., 2024, Anderson et al., 2018). Each drought event has a different pattern in terms of physical causes and geographic distribution of the water deficit (Cunha et al., 2023). The droughts of 1982-83, 1997-98, 2010 and 2015-16 were associated with El Niño, while the 2005 drought was associated with warmer North Tropical Atlantic (NTA) (Marengo, 2013; Aragão et. al, 2018). During the 2005 drought, much of the southwestern Amazon experienced rainfall deficiency; in 2010, the areas that experienced drought were the central and eastern part of the Amazon, and in 1983 and 1998, almost all of the northern, central and eastern Amazon experienced rainfall deficiency (Marengo and Espinoza, 2016). In turn, the drought of 2015-16 occurred due to one of the strongest El Niño events ever recorded associated with NTA warming, exceeding the spatial extent of the impacts that occurred in 2005 and 2010, particularly in the eastern and southern part of the Amazon (Erfanian et al., 2017; Jiménez-Muñoz et al., 2016; Jiménez et al.; 2018; Anderson et al, 2018).

Recently, in 2023-24, Amazon faced another historic drought event added to extreme heat events (Figure 4). According to IDI data, the 2023-2024 droughts, in addition to being the largest in terms of territorial extension, was also characterized by the longest drought ever to occur outside the semi-arid region. Part of the biome recorded a water deficit for 18 to 20 consecutive months.

The effects of the drought were visible in most of the main rivers of Amazonia, including the Negro, Solimões, Purus, Juruá and Madeira, severely impacting waterway transport, compromising the transport of water, food, and isolating indigenous communities. In October 2023, the water level in the port of Manaus reached 12.70 m, the lowest level recorded since 1902 (Espinoza et al., 2024).

The southern region of the country, which mostly covers the Atlantic Forest and Pampa biomes, has also recorded recurrent drought events, especially in the years 2004-05, 2012-13 and 2019-22 (Berlato, 2005; Brazet al., 2017; Cardoso et al., 2020). According to Fernandes et al. (2021), this last event may be associated with the negative phase of the Pacific Decadal Oscillation (PDO) and neutrality conditions in the Equatorial Pacific.

As a result of the 2012 drought, most of the South region suffered a substantial depletion of surface and groundwater, affecting the water supply in rural properties and agricultural and livestock production. In the drought event from 2019 to 2020, the first quarter of 2020 was the most critical in terms of intensity and expansion, since 100% of the municipalities in the entire region were classified as having a severe to exceptional drought condition (Fernandes et al., 2021 and CEMADEN/MCTI, 2024). The impact of this drought could also be observed by the drop in the flow of the reservoir of the Itaipu Hydroelectric Power Plant.

It is important to note that, until shortly before the historic flood that occurred in Rio Grande do Sul, in May 2024, a state that has about 68.8% of its territory covered by the Pampa biome, the region was facing a severe and prolonged drought. Governments were still carrying out drought response actions when they were surprised by the great flood, which imposed an additional challenge on the management of disaster risks related to extreme events. In a short period of time, it was necessary to move from responding to a water crisis to facing the impacts caused by a hydrological event of large proportions.

In the Southeast region, composed mostly of the Atlantic Forest (about 60% of the territory) and Cerrado (approximately 30%) biomes, during the summers of 2013-14 and 2014-15, the region faced drought conditions and a critical water crisis with impacts on several sectors of society, including human supply, agriculture, and hydroelectric power generation (Coelho et al., 2015; Nobre et al., 2016). The main cause of this atmospheric condition was due to the presence of a high-pressure system known as “blockages”, anomalously intense and persistent, thus preventing the passage of frontal systems (Marengo et al., 2015; Coelho et al., 2015). The watersheds in the Southeast region, both for hydroelectric power generation and supply, once again presented critical conditions between the years 2022 and 2024 (Cuartas et al., 2022; 2024; WMO, 2022).

The volume of water reservoirs has reached its most critical levels. In particular, the Cantareira Water Supply System, located on the border between the states of São Paulo and Minas Gerais, faced its worst water shortage, having to use the dead volume between July 12, 2014 and December 30, 2015 (537 days). At the time, water scarcity affected more than 8.8 million people (Deusdará Leal et al.; 2020; Cunha et al.; 2019).

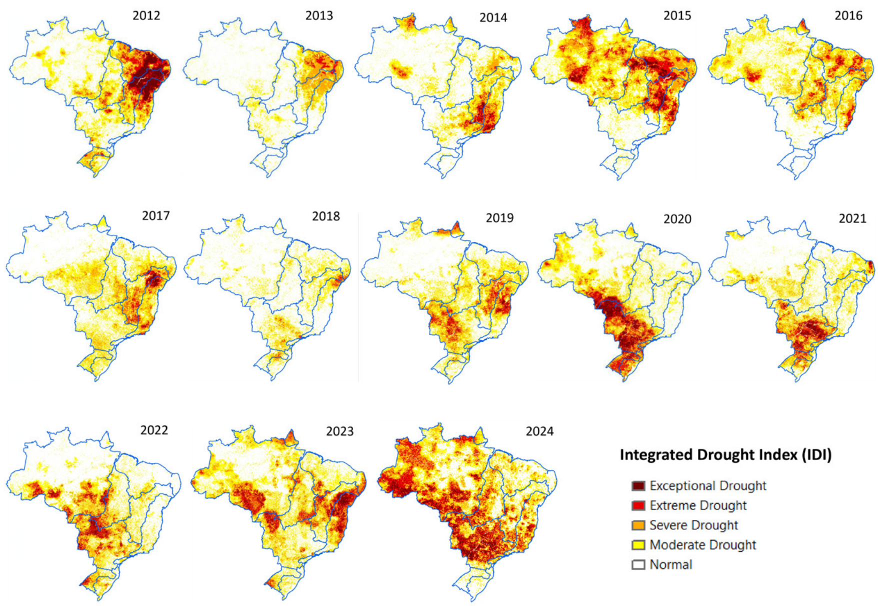


Figure 4: Annual maps of the Integrated Drought Index (IDI, Source: CEMADEN/MCTI)

Concerning the Caatinga biome, predominant in the Brazilian semi-arid region, it is an area known to be vulnerable to climatic factors, especially due to low water availability and high socioeconomic vulnerability (Marengo et al., 2018; Gomes and Willegaignon, 2021). The main drought events in the region were 1982-1983, 1986-87, 1992-1993, 1997-

1998, 2001-2002, 2005, 2010 and 2012-2017 (Gutiérrez et al. 2014, Wilhite et al. 2014, Marengo et al. 2016). During the extreme drought years of 1982-83 and 1997-98, both El Niño and the influence of warmer waters in the North Tropical Atlantic (ATN) were responsible for circulation changes that reduced rainfall in the region (Nobre et al. 2016, Marengo et al. 2013). On the other hand, the onset of the 2012 drought was due to a La Niña event, in which the cooling of the waters of the central Pacific together with the warming of the ATN, favored the position of the ITCZ further north of its climatological position (Rodrigues and McPhaden 2014). In 2015, with the characterization of El Niño, the drought conditions that had occurred since 2012 ended up intensifying and the drought between 2012 and 2017 in the semi-arid region was defined as the most intense "event" in the last 30 years (Brito et al., 2017; Cunha et al., 2018b). Considering the cumulative impacts between 2012 and 2017, about 1,100 municipalities were affected (33.4 million people affected per year), especially in relation to water supply and losses in agro-production systems, with impacts estimated at approximately R$ 104 billion (Marengo et al., 2017). In 2023, a large part of the Caatinga was again affected by another drought event, less intense in terms of impacts, but causing severe drought conditions in some municipalities in western Bahia, affecting agricultural areas and pastures (CEMADEN, 2023, October Bulletin). The climatic factors attributed to this event were again due to the action of El Nino and the warming of NTA (CEMADEN, 2023).

Although droughts are increasingly recurrent throughout the country, the semi-arid Northeast still concentrates the most intense (exceptional) events in Brazil's recent history.

As indicated by Figures 3 and 4, in recent years, among all Brazilian biomes, drought has been more intense, especially in the Pantanal and Cerrado Biomes, which comprise the central region of the country. The Pantanal Biomes faced a severe drought between 2019 and 2024, contributing to the spread of fires and affecting natural biodiversity and the agribusiness and livestock sectors. This prolonged drought has severely impacted water resources in the Pantanal. In 2020, the river level reached extremely low values and, in some stretches of the river, transport had to be restricted. Very low river levels affected the mobility of people and the transport of soybeans and minerals to the Atlantic Ocean via the Paraná-Paraguay Waterway (Marengo et al., 2021). In the 2023-24 rainy season, the Paraguay Basin (Pantanal biome basin) recorded precipitation deficits of around 300 mm, which indicates that only 60% of the expected rainfall for the rainy season, which began in October 2023, was observed, thus prolonging the impacts of droughts.

The Pantanal has drawn particular attention because it is one of the most threatened Brazilian ecosystems from direct anthropogenic pressures and climate change. Cunha et al., 2023 showed that drought and heat compound events have been more recurrent and widespread since 2000 in the Pantanal. In addition, there has been a pattern of change to hotter and drier conditions in the last 40 years, also contributing to the reduction of water availability and to the widespread fire in Pantanal. Tomasella et al. (2022) using drought indices (SPI and SPEI) derived from weather station data showed a significant trend toward a drier and hotter condition across central Brazil (including Pantanal) for different time scales, especially for time scales of 12 months and larger.

According to Municipal Agricultural Production data from the Brazilian Institute of Geography and Statistics (https:// sidra. ibge. gov. br/ tabela/ 1612), the maize yields were 50% less in the 2020 season compared with the previous year, in adtion, the severe drought in 2020 caused losses of at least 1 million tons of grains in the soybean harvest. Faced with this situation, the government declared an emergency to facilitate agricultural insurance access (Cunha et al., 2023).

In addition to the impacts on agricultural productivity, droughts associated with heat extremes are also related to increased fire risk, especially in tropical regions. The Pantanal is predicted to become more flammable in a future drier and warmer climate, in combination with human-modified landscapes, and therefore particularly vulnerable to increased fire risk (Ribeiro et al. 2022; Afroz et al. 2023). While small fires are historically used for land clearance for subsistence (agricultural activities), the exceptionally long drought of 2019 and 2020 encouraged many people to set arson for area and land expansion (Libonati et al. 2020, 2022; Ribeiro et al. 2022). This situation culminated in almost 30% of the Biome burned, killing 17 million vertebrates (Ribeiro et al. 2022).

Most of the last major drought events in the Central region of the country were mainly caused by the occurrence of atmospheric blockages that prevented the passage of rain-causing meteorological systems (Marengo et al., 2021). Some studies indicate that atmospheric blockages are occurring more frequently globally since the beginning of the century (Lupo et al., 2021).

The increasing frequency of extreme events, such as heat waves and prolonged droughts, has contributed significantly to changes in weather patterns over time, intensifying the phenomenon of aridity. This, in turn, is characterized as a long-term climatic condition, resulting from a water deficit. This deficit is due to insufficient average precipitation combined with a high rate of evapotranspiration, which consists of the loss of water to the atmosphere due to heat.

Tomasella et al., (2025) analyzing a time series of the Aridity Index from 1961 to 2020 indicated a trend towards drier conditions in the center and northeast of the country, while the southern region showed changes to wetter conditions (Figure 5). The expansion of semi-arid areas was also observed to the detriment of dry, subhumid and humid regions in the Caatinga Biome. The authors also showed that these trends accelerated in the period from 1991 to 2020, indicating intensification. During this period, an area of > 4200 km^2 within the arid category was observed for the first time, according to the convention classification . In addition, new areas, with sizes ranging from 1,200 to 11,500 km^2, included in the dry subhumid category, were detected in central Brazil (part of the Cerrado and Pantanal). In addition to the Aridity Index, the authors also analyzed a time series of the Vegetation Health Index (VHI, Kogan et al., 1997) also indicating negative trends in all Brazilian biomes, suggesting an increase in vegetation stress over the years.

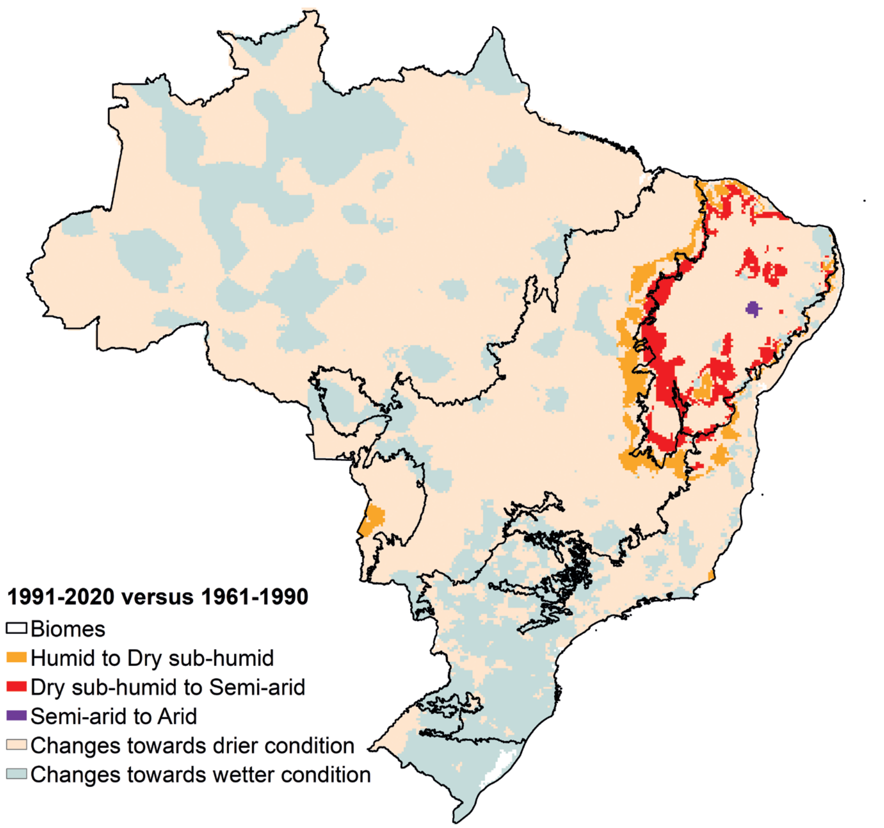


Figure 5: Changes in AI classes between the periods 1991–2020 and 1961–1990 (Fonte: Tomasella et al., 2025).

Several studies already indicate that there is strong evidence that climate change will increase the risk and intensity of droughts across the globe (IPCC, 2021, Williams et al., 2020, Marengo et al., 2021). In Brazil, studies show that such changes may cause significant impacts on agricultural production through increased frequency of droughts in Brazil (Assad et al., 2013; Marengo et al., 2017, 2020, 2021). According to Marengo et al., (2021), especially in the semi-arid region of Brazil, where rainfed family farming predominates and high socioeconomic vulnerability (Figure 6), productivity losses can lead to increased poverty, land conflicts, and mass migration to overpopulated urban centers.

In general, all municipalities that have a higher socioeconomic vulnerability may be more affected when a scenario of greater frequency, intensity and duration of drought occurs. In addition to the municipalities located in the Caatinga, municipalities located in the Northwest portion of the Amazon (Figure 6) may also be more impacted, since they are municipalities characterized by lower development indexes, poverty, less technical assistance, and, in short, less response capacity.

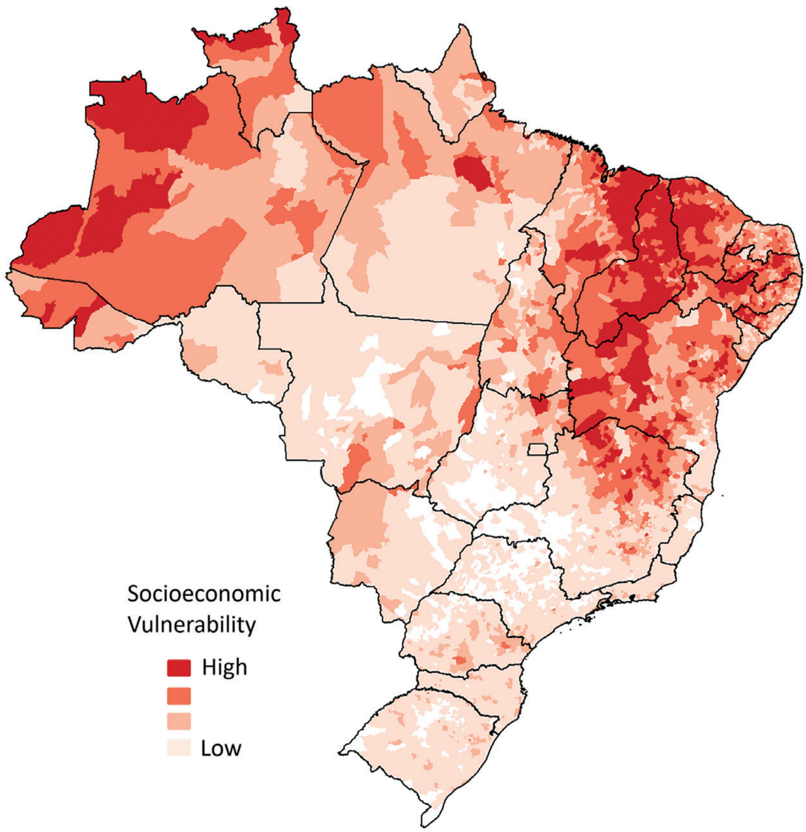


Figure 6: Socioeconomic vulnerabilityrelated to drought in Brazil. Darker shades of red indicate higher vulnerability; lighter shades indicate lower vulnerability. (Source: CEMADEN/MCTI).

In addition, it should be noted that the Brazilian energy matrix, although considered clean and diversified, still has a high dependence on hydroelectric energy, which represents a large portion of the matrix, however, it exposes the country to water crises caused by intense and prolonged droughts, which reduce energy generation and can lead to the activation of thermoelectric plants, more expensive and polluting.

The projected intensification of droughts and heat extremes in Brazil accentuates the pressure on the country's food, water, and energy security, making it even more urgent to implement public policies aimed at reducing socioeconomic vulnerabilities and strengthening the resilience of production systems in the country.

ADVANCES AND CHALLENGES FOR REDUCING VULNERABILITIES TO DISASTERS IN BRAZIL

Vulnerability has been explored in different conceptual frameworks, from those that link it directly to the direct damage of disasters to those that understand it as a result of indirect factors such as the extent of exposure, the degree of susceptibility, and the adaptive capacity of the affected population (Kim et al., 2021). It is also important to emphasize conceptual approaches to vulnerability that take into account its multidimensional (Birkmann and Wisner, 2006) and global composition, composed of different types of interconnected vulnerabilities, such as social, economic, physical, institutional, ideological, and others (Wilchex-Chaux, 1993). Regardless of the approach taken, there is a consensus that high levels of vulnerability to disasters can lead to greater damage or longer recovery times for the affected systems. Therefore, vulnerability is understood as a progressive process, whose structure relates to causes, dynamic stresses and uncertain conditions (Wisner et al. 2004). The need for a multidisciplinary analysis of human settlement in areas prone to natural hazards has been emphasized in studies since the 1940s (White, 1945). In the current context of climate change, this call is even more urgent when considering the multiple factors that play a role in vulnerability and adaptation. This increasing complexity is exacerbated by the inappropriateness of human actions on the land, such as the colonization of slopes or floodplains in disregard of natural conditions. Globally, the extent of human settlements in flood-prone areas exceeds that in safe zones, meaning that countries are increasingly increasing their exposure to extreme events (Rentschler et al. 2023).

Vulnerability is a key element in defining disaster risk, which is why the development of disaster risk management strategies has been prioritized. Global agendas, such as the Sendai Framework for Action (SFA) and the 2030 Agenda, include approaches to disaster risk reduction. For example, signatory countries commit to achieving the targets proposed in these agendas, to reduce the losses caused by disasters, focusing on the vulnerability of the population. Among the MAS priorities for action, understanding disaster risk in all its dimensions stands out: vulnerability, capacity, exposure of people and assets, risk characteristics, and environment.

Knowledge about at-risk population in areas suscetible to landslides, floods and flash floods

In Brazil in particular, information on the living conditions of the population living in disaster risk areas at the national level was first obtained through the creation of a new database, the Base Territorial Estatística de Risco (BATER), whose graphic boundaries contain the census data associated with the mapped risk areas. This method was initially used to characterize three pilot municipalities in the state of Rio de Janeiro (Petrópolis, Teresópolis, and Nova Friburgo) and is the result of technical cooperation between CEMADEN and IBGE. The results of the study show that it is estimated that around 155,000 people in 1,357 high-risk areas are exposed to the risk of landslides and/or flooding (Assis Dias et al., 2018).

It is worth noting that the mapping of census data to high-risk areas could not be done directly and automatically due to the different geometries between high-risk areas and census areas. Therefore, the methodology developed was groundbreaking and represented an important milestone in understanding the exposed population (Assis Dias et al., 2018). Several studies have been produced using BATER data, providing a new perspective on the topic. Alvalá et al. (2019), for example, looking at the living conditions of the population in high-risk areas at the inner-city level and the potential application of such information in the Brazilian early warning system, found that in 825 municipalities affected by past disasters in Brazil, there were an estimated 8,266,566 people living in 27,660 risk areas and 2,470,506 households. This result indicates that, for every 100 inhabitants, 9 lived in disaster risk areas in Brazil. In turn, Saito et al. (2019) show that the population living in disaster risk areas is concentrated in the country's main cities and small towns, which are densely populated even in small towns, suggesting that this is a reality that not only large cities face, just as there are disaster risk areas even in municipalities with a high level of human development. The results contributed to the understanding of the spatialization of disaster risk in Brazil. This is a fundamental step towards reducing loss of life and highlights a current problem faced by all municipalities, regardless of their size classification and level of human development.

Vulnerability indicators, indexes and scenarios

Many studies have been conducted to examine disaster vulnerability and identify indicators for better understanding. Rufat et al. (2015) analyzed social vulnerability factors in 67 case studies of flood-related disasters and concluded that the influence of indicators varied according to the stage of the disaster and the national context. Therefore, they highlighted the need for further research and provided recommendations for adapting indicators contextually.

Studies focusing on the effects of disaster vulnerability show that damages differ depending on specific elements of the study design, including regions, disaster types, and spatial units of analysis (Choo and Yoon, 2024). Based on this premise, these authors conducted a meta-analysis to analyze the connections between various studies to reveal the common trend in the relationship between vulnerability and disaster damage, including material damage and human losses. They examined the common effects of socioeconomic factors (population density, GDP, low-income households, and elderly population) on disaster damages based on 38 studies. In this context, they considered a subgroup analysis to identify the heterogeneity of effects by disaster type and spatial unit of analysis of the included studies. The results showed that the elderly population and low-income households were positively associated with disaster damage. At the community level, population density, the elderly population, and low-income households were positively associated with disaster damage, while GDP tended to reduce disaster damage at the national level.

In the Brazilian context, Assis Dias et al. (2020) developed the InOV (Operational Vulnerability Index) to support monitoring and early warning of disaster risks in Brazil. BATER data were crucial in identifying areas with large population concentrations exposed to landslide risk areas. The InOV, based on indicators that characterize residents' physical exposure conditions as well as the population's response capacity to recover after a disaster, was developed for 443 Brazilian municipalities, allowing for a relational analysis of risk areas within each municipality. Therefore, the InOV can support the identification of priority areas by providing additional information on vulnerable populations, as well as assist in identifying critical areas within the municipality that are at risk of hydrometeorological disasters when critical precipitation thresholds are exceeded.

In terms of risk scenarios, the majority of the global urban population lives in small cities, while in Brazil, approximately 45% resides in municipalities with up to 100,000 inhabitants—many of which are exposed to risks such as landslides and floods. A study conducted by Ribeiro et al. (2023) involving 234 cities in the South and Southeast regions analyzed the vulnerability and coping capacity of these municipalities, divided into two population groups: 20,000 to 50,000 inhabitants (Class A4) and 50,000 to 100,000 (Class A5). Based on statistical analysis of a set of 30 quantitative and 40 qualitative indicators, it was revealed that, although the municipalities presented high human development indices and the availability of master plans, vulnerabilities were associated with: i) Dependence on the agricultural sector or external resources; ii) Low education and income (Class A4); and poor infrastructure due to accelerated population growth (Class A5). The analysis concluded that the city's size, economic structure, and public policies directly influence vulnerability. Furthermore, existing legal instruments are insufficient to ensure adequate infrastructure or effective risk management in small cities.

Inclusion of vulnerability in regulations

More recently, Law 14.750/2023 amended the National Policy for Civil Protection and Defense (Law 12.608/2012) with the aim of "improving the tools for the prevention of accidents or disasters and the recovery of affected areas, the monitoring of accident and disaster risks, and the generation of early warnings." This law included several concepts, including vulnerability as "the physical, social, economic, or environmental vulnerability of a population or ecosystem in the face of an adverse event of natural or human origin" (Brasil, 2023).

The inclusion of this concept in the PNPDEC is an important step forward, as it can serve as a guideline for vulnerability reduction measures. On the other hand, the association of vulnerability with fragility deserves special attention, indicating a strong socio-economic orientation of this concept. The disasters in Brazil have shown that the population is severely affected by disasters even if it does not exhibit such vulnerability. Therefore, it is important to understand that vulnerability requires the interaction of several factors, such as the lack of coordination of public policies and poor urban infrastructure, which contribute to people's exposure to risk. Ensuring the safety of the population will only be effective if it is included in its entirety, regardless of its economic status, especially in the context of current and future coexistence with extreme conditions.

Reduction of institutional vulnerabilities

The Elos project, led by CEMADEN in collaboration with the National Secretariat for Civil Defense (Sedec/MDR) and the United Nations Development Program (UNDP), was a strategic initiative to strengthen disaster risk management in Brazilian municipalities. The project made a diagnosis of the capabilities and needs of municipal civil defense authorities, taking into account three axes (structuring, training, and management), with the aim of supporting the implementation of the National Civil Defense Policy (PNPDEC) in Brazilian municipalities.

The scientific component of the Elos project was fundamental to the robustness of the results obtained, especially in the adoption of the methodological procedures used. Three research tools were used: i) an online questionnaire, completed by 1,993 municipalities; ii) in-depth interviews, conducted with 31 municipalities from 26 Brazilian states, as well as the Federal District (DF); and iii) virtual focus groups with 190 municipalities, to create spaces for collective discussion. The triangulation of the data obtained through the research highlighted the structural and institutional weakness of municipal civil protection agencies, from the lack of basic equipment such as computers and vehicles to the lack of professional recognition (Brasil, 2021). All of these aspects ultimately have a direct impact on disaster preparedness, response, and recovery at the municipal level.

The resulting diagnosis constitutes a fundamental tool to support the reduction of institutional vulnerability. In this sense, another relevant result was the identification of the challenges faced by civil protection authorities in strengthening the PNPDEC, such as i) the demand for professionalization and upgrading of civil protection activities; ii) the scarcity of financial resources to implement the PNPDEC at the municipal level; iii) training initiatives that take into account the specificities of the five regions of the country; iv) the improvement of internal and institutional communication processes regarding risks and disasters; and v) the strengthening of social and intersectoral participation (Marchezini et al, 2025).

Challenges

Brazilian scientific production has contributed significantly to the consolidation of theoretical frameworks, the construction of databases, and the development of indicators and methodologies to assess the multiple dimensions of vulnerability in the country. These advances contribute to the development of more meaningful disaster risk scenarios, e.g. in the context of monitoring and early warnings, and guide actions to strengthen institutions and reduce their vulnerability. However, given the growing consensus that the causes of vulnerability are multifactorial, and interrelated between root causes, uncertain conditions, and dynamic pressures (Wisner et al., 2004), working to reduce them always requires a departure from conventional approaches.

Even if concrete efforts have been made so far, it is an ongoing process, and vulnerability reduction requires the coordination of different public policies, such as environmental, urbanization, economic, educational, climate change, and others. In addition, the notion that vulnerability is limited to poverty, must be overcome so that actions reach all populations exposed to climate change, in an equitable approach.

BETWEEN KNOWLEDGE AND RESILIENCE: DISASTER RISK REDUCTION EDUCATION

As already mentioned, extreme weather events are becoming more frequent and have deadly consequences that affect populations and ecosystems unevenly. Floods, severe droughts, mass movements, heat waves, and forest fires not only endanger the environment, but also society. In this context of climate emergency, Disaster Risk Reduction Education (DRRE) becomes an important tool to improve risk perception, promote citizen participation, and formulate multi-level responses. Based on Environmental Climate Education (ECA), DRRE promotes a critical and transformative worldview by bringing together scientific, traditional, and local knowledge to strengthen risk prevention, adaptive capacity, and community resilience in the face of climate change.

The scope of this chapter assumes that education must represent a coherent analysis of the model that guides global development decisions and requires the consideration of multiple dimensions — economic, political, technical, historical, ethical, social, cultural, moral, esthetic, and environmental. From this perspective, the EAC and ERRD take on the role of stimulating questions about systemic (un)sustainability, and relying on observation, investigation, reflection, and action alongside individuals and communities to find ways to change reality. This includes addressing the root causes of the climate emergency: Denial, lack of policy choices, and the false solutions of green capitalism and environmental marketing (greenwashing), aimed at maintaining the unsustainable practices of the current economic model.

The educational challenge is clearly visible on the planetary horizon. The planetary boundaries framework (Rosckström et al., 2009) show that six of the nine safety boundaries have probably already been crossed, including climate, biosphere integrity, and biogeochemical flows (Richardson et al., 2023). Overcoming these boundaries converges with social boundaries (health, equality, peace, and, of course, education), as environmental violations and inequalities are mutually dependent. Therefore, education, as a political act in the broadest sense, is essential to balance the pressure on the Earth system and mitigate climate injustice. It is crucial to act in a coordinated manner from the perspective of a paradigm shift based on regenerative concepts and values, in order to strive for a secure future with climate justice. We need to change the system, not the climate!

Although the recent Intergovernmental Panel on Climate Change Assessment Reports (IPCC, 2023) recognize education as a factor inversely proportional to social vulnerability— - be it through empowering local actors, social learning, or strengthening institutional arrangements — they maintain a functionalist perspective on education, viewing it as a vector of mitigation and adaptation. Similarly, the Hyogo Framework for Action (2005-2015) recommended the inclusion of disaster risk reduction in formal and non-formal education, and capacity building activities" (UNISDR, 2005), but reduced the role of education to raising awareness of prevention and safety culture.

The Sendai Framework for Action (2015-2030) goes further by emphasizing the importance of various measures for managing and coping with disaster risk — including education measures, "that prevent and reduce exposure to hazards and vulnerability to disasters, enhance response and recovery preparedness, and thus strengthen resilience" (UNRRD 2015, p. 12). The Sendai Framework for Action therefore emphasizes "understanding disaster risk" as a priority "and recommends education, sharing experiences, lessons and best practices, and training on disaster risk reduction, “including the use of existing training and peer-learning mechanisms” (UNRRD, 2015, p. 15). The 2030 Agenda, with its 17 Sustainable Development Goals (SDGs), is a “global call to action to end poverty, protect the environment and climate, and ensure that people everywhere can enjoy peace and prosperity” and includes in SDG 13.3 “improving education, awareness and human and institutional capacity to mitigate, adapt, reduce impacts and provide early warning of climate change” (UN, 2015, p.32).

Analysis of the documents shows that, although they are well-intentioned and advance international agendas, they have limitations in their approach to education. In all cases, education is seen in a generic and reductionist way as a complementary tool aimed primarily at raising awareness, disseminating information, or providing technical training— and not as an emancipatory and political practice capable of challenging the current model of civilization and creating truly transformative pathways. This approach, while relevant, proves to be uncritical and incapable of addressing the roots of the climate and socio-ecological emergency, as it ignores the socio-economic, political, and cultural structures that generate risks and vulnerabilities.

In Brazil, the fragility of the ERRD and the EAC reproduces these features in the legal framework, but society is speaking out. If, on the one hand, the broad inclusion of the ERRD in formal education — previously proposed by the National Policy for Civil Protection and Defense (Law No. 12.608/2012) through an amendment to the Law on Guidelines and Bases of Education - LDB (Law No. 9394/1996) — LDB (Law No. 9394/1996), which culminated in the National Common Curricular Base (BNCC, 2018) with rare and specific references to learning objectives related to risks, disasters, and climate change (Matsuo and Silva, 2021). On the other hand, the mobilization of civil society, with the support of government agencies, led to the elaboration of the Climate-Environmental Education Guidelines (2022-2023). This document was created in a participatory manner to address the climate emergency and includes 10 guidelines that address the need for a national climate-environmental education program that provides scale, continuity, synergy, access to resources, and quality for transformative processes, and prioritizes climate justice with actions based on equity, inclusion, and well-being.

Recently, Law No. 14.926/2024 was enacted, which focuses on climate change, biodiversity conservation and risks and vulnerabilities to socio-environmental disasters within the framework of the National Environmental Education Policy (Law No. 9.795/1999). However, it does not provide the necessary depth or guidelines for implementation in formal and informal education.

EAC/ERRD contributions to territorial resilience

The ERRD "should focus primarily on preventing disasters, promoting an understanding of their causes, reducing vulnerable situations and populations, and encouraging society to cooperate in prevention. As pointed by Sulaiman et al. (2021), it should also contribute in the preparation of self-protection exercises for emergencies which cannot be avoided. The integration of EAC and ERRD, through the mobilization of citizen science and co-risk management, therefore becomes a critical component of any national adaptation strategy (Branco et al, 2025), and contributes to (i) broadening risk perception: citizen science tools (home rain gages, monitoring apps) transform local data into actionable knowledge, and catalyze early responses; (ii) empowerment and social cohesion: participatory education processes strengthen support networks, that are essential for safe evacuations and post-event recovery; (iii) multilevel governance: by linking schools, civil defense agencies, universities, and local governments, education creates horizontal communication channels that strengthen national adaptation policies; (iv) Promoting climate justice: critical curricula address inequalities based on ethnicity, gender, and territory, and inform decisions to protect the most vulnerable groups (children, elderly, black and indigenous populations).

The following specific scenarios are organized by type of impact and are described with location, actions, and outcomes. The practices listed do not claim to be exhaustive, but are intended to demonstrate that disaster risk reduction education has measurable impacts on changing attitudes, building knowledge, formulating strategies and even saving lives. Despite their scattered nature, the scenarios provide solid evidence to advocate for the expansion of these approaches in school curricula, teacher training, and cross-sectoral interventions across the country.

Scaling Up Disaster Risk Awareness: A National Challenge

In recent years, many Brazilian communities across different regions have experienced firsthand the impacts of increasingly intense socio-environmental disasters. Floods, landslides, wildfires, and heatwaves have affected daily life and exposed vulnerabilities that, until recently, were not even recognized as real risks. In this context, education has proven to be a powerful tool for transforming fear into preparedness, vulnerability into collective care, and information into preventive action.

In schools across the country, teachers, students, and families have been developing activities that bring science closer to everyday life: workshops to map risk areas, educational games, rainfall-monitoring apps, comic books, and public awareness campaigns. These initiatives, connected through collaborative networks, have reached thousands of people and created a movement of awareness that now spans hundreds of municipalities.

The results are tangible. In communities heavily affected by extreme rainfall, the previous work of students alongside local Civil Defense agencies was decisive in saving lives. In coastal regions, traditional knowledge from caiçara populations was combined with monitoring technologies, giving rise to community-based emergency protocols. In urban peripheries, schools became spaces for listening and planning, where residents and youth jointly built community plans for risk reduction and climate adaptation.

This transformative power of education is also evident in broader actions. In several municipalities, local managers, technicians, and teachers have been trained to strengthen contingency plans, reduce emergency response times, and design public policies more closely aligned with community realities. In Amazonian schools, for example, activities on fire and territory have engaged youth in wildfire prevention and in defending the forest as an essential part of their way of life. In large cities, educommunication has helped students confront misinformation by producing podcasts, campaigns, and other media content that reinforce climate justice and amplify the voices of local communities.

All of this shows that education goes far beyond the classroom: it creates networks of care, builds trust among people, and strengthens youth and community leadership. Schools are becoming spaces of protection and hope, capable of bringing together scientific knowledge and local wisdom to confront climate challenges.

Final Remarks

Whether facing floods in urban areas, landslide risks on hillsides, wildfires in the forest, or heatwaves in the cities, education has proven to be essential for saving lives, reducing damage, and building more resilient communities. By uniting science, culture, and social participation, it paves the way for different generations to face disaster risks together and to cultivate new ways of living in times of climate change—with solidarity, resilience, sustentability, justice, and care for life.

REFERENCES

AFROZ, M.; CHEN, G.; ANANDHI, A. Drought- and heatwave-associated compound extremes: a review of hotspots, variables, parameters, drivers, impacts, and analysis frameworks. Frontiers in Earth Science (Lausanne), v. 10, art. 914437, 2023. doi:10.3389/feart.2022.914437.

AGUIAR, L. D. F., CATALDI, M. (2021). Social and environmental vulnerability in Southeast Brazil associated with the South Atlantic Convergence Zone. Natural Hazards, 109(1), 481-503. https://doi.org/10.1007/S11069-021-04926-Z

AIRES, M.; MARTINS, C. L. F.; CURY, G. S. A.; FERNANDES, P. J. F.; OLIVEIRA, J. L. F. Simulação numérica do desastre de origem natural ocorrido em janeiro de 2011 no município de Nova Friburgo, RJ, utilizando o modelo BRAMS. Revista Brasileira de Geografia, v. 65, n. 2, p. 217-235, 2020. DOI: https://doi.org/10.14393/RCG217449994.

ALCÂNTARA, E.; MARENGO, J. A.; MANTOVANI, J. E.; LONDE, L. R.; SAN, R. L. Y.; PARK, E.; LIN, Y. N.; WANG, J.; MENDES, T.; CUNHA, A. P.; PAMPUCH, L.; SELUCHI, M.; SIMÕES, S.; CUARTAS, L. A.; GONCALVES, D.; MASSI, K.; ALVALÁ, R.; MORAES, O.; SOUZA FILHO, C.; MENDES, R.; NOBRE, C. A. (2023). Deadly disasters in southeastern South America: flash floods and landslides of February 2022 in Petrópolis, Rio de Janeiro. Natural Hazards and Earth System Sciences, 23(3), 1157-1188.

ALLAN, R. P.; SODEN, B. J. Atmospheric warming and the amplification of precipitation extremes. Science, v. 321, n. 5895, p. 1481-1484, 2008. DOI: https://doi.org/10.1126/science.1160787.

ALTAFINI, D.; BRAGA, A. C.; UGALDE, C. Mapping Urban Flood-Prone Areas' Spatial Structure and Their Tendencies of Change: A Network Study for Brazil's Porto Alegre Metropolitan Region. Cartographica, v. 58, n. 4, p. 258-275, 2023.

ALVALÁ, R. C. S.; ASSIS DIAS, M. C.; SAITO, S. M.; STENNER, C.; FRANCO, C.; AMADEU, P.; RIBEIRO, J.; SANTANA, R. A. S. M.; NOBRE, C. A. Mapping characteristics of at-risk population to disasters in the context of Brazilian early warning system. Mendeley data, v1, (2019). http://dx.doi.org/10.17632/36zkrpjs7z.1

ALVES, L. M.; MARENGO, J. A.; CUNHA, A. P.; FISCH, G. F. Climate patterns in the Amazon region in 2013: drought in eastern Amazon and floods in southwestern Amazon. *Bulletin of the American Meteorological Society (State of the Climate 2013)*, v. 95, n. 7, p. S155–S156, 2014. doi:10.1175/2014BAMSStateoftheClimate.1.

ALVES, L. G. S.; REIS, F. A. G. V.; GIORDANO, L. C.; NUMMER, A. V. Analysis of the 2022 Petrópolis landslide disaster. Landslides, v. 20, n. 10, p. 2287-2307, 2023.

ANDERSON, L. O.; RIBEIRO NETO, G.; CUNHA, A. P. M. A.; FONSECA, M. G.; MENDES DE MOURA, Y.; DALAGNOL, R.; WAGNER, F. H.; ARAGÃO, L. E. O. Vulnerability of Amazonian forests to repeated droughts. *Philosophical Transactions of the Royal Society B: Biological Sciences*, v. 373, n. 1760, 2018, 20170411. doi:10.1098/rstb.2017.0411.

ANGELINE G. Pendergrass, What precipitation is extreme?.*Science***360**,1072-1073(2018).DOI:10.1126/science.aat1871

ARAI, M. (2006). A grande elevação eustática do mioceno e sua influência na origem do Grupo Barreiras. Revista do Instituto de Geociências – USP. Série Científica, v. 6, n. 2, 1 – 6.

ARAGÃO, L. E. O. C.; ANDERSON, L. O.; FONSECA, M. G.; ROSAN, T. M.; VEDOVATO, L. B.; WAGNER, F. H.; SILVA, C. V. J.; SILVA JUNIOR, C. H. L.; AZEVEDO, C. R.; BROWN, F. I.; et al. 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. Nature Communications, v. 9, n. 536, 2018. doi:10.1038/s41467-017-02771-y.

ASSAD, E.; et al**.** Impacts of climate change on Brazilian agricultural production. Brasília: LCSAR – The World Bank / Central Bank of Brazil, 2013. Accessed at: https://periodicos.unb.br/index.php/sust/article/download/33814/28556/92699.

AVILA, A.; JUSTINO, F.; WILSON, A. B.; BROMWICH, D. H.; AMORIM, M. C. Recent precipitation trends, flash floods and landslides in southern Brazil. Environmental Research Letters, v. 11, n. 11, 114029, 2016.

AVILA-DIAZ, A.; BENEZOLI, V. H.; JUSTINO, F.; TORRES, R. R.; WILSON, A. B. Assessing current and future trends of climate extremes across Brazil based on reanalyses and earth system model projections. Climate Dynamics, [S. l.], v. 55, n. 5-6, p. 1403, 2020DOI: https://doi.org/10.1007/s00382-020-05333-z

BALLARIN, A.; WENDLAND, E., ZAERPOUR; M.; HATAMI, S.; NETO, A. A. M.; PAPALEXIOU, S. M. (2024). Frequency Rather Than Intensity Drives Projected Changes of Rainfall Events in Brazil. Earth's Future, 12(1)

BARICHIVICH, J.; GLOOR, E.; PEYLIN, P.; BRIENEN, R. J. W.; SCHÖNGART, J.; ESPINOZA, J. C.; PATTNAYAK, K. C. Recent intensification of Amazon flooding extremes driven by strengthened Walker circulation. *Science Advances*, [S. l.], v. 4, n. eaat8785, p. 1-7, set. 2018. DOI: 10.1126/sciadv.aat8785

BATTISTI, R.; DAPPER, F. P.; SILVA, A. C. S.; MESQUITA, M.; SILVA, M. V. da; ANDRADE, R. R.; LOPES, A. G. C. Assessing Precipitation Trends Between 1960 and 2021 Using Multiple Trend Indexes in the Goiás State and Federal District, Brazil. International Journal of Climatology, [S. l.], v. 45, n. 5, p. e8750, abr. 2025. DOI: 10.1002/joc.8750

BERLATO, M. A. A estiagem 2004-2005. Porto Alegre: Secretaria da Agricultura e Abastecimento do Rio Grande do Sul, 2005. Disponível em: http://www.agrometeorologia.rs.gov.br/uploads/1184350382A_Estiagem_2004_2005_Relatorio_.pdf.

BELTRAMIN, K. K.; MORAIS, E. S. Fluvial adjustments due to straightening and inadequate management of urban drainage: the Maringá Stream catchment, Southern Brazil. Revista Brasileira de Geomorfologia, v. 25, n. 3, p. 45-62, 2024.

BONINI, J. E.; ROSS, J. L. S.; MARTINS, T. D.; VIEIRA, B. C. (2021). Escorregamentos rasos em São Luiz do Paraitinga (SP, Brasil) (2009-2010). Physisterrae, 2(1), 187-217.

Branco, Evandro Albiach; Jesus, Fernanda Santos Mota De; Paz, Mariana Gutierres Arteiro Da; Raymundo, Maria Henriqueta Andrade. Educação Ambiental e Sustentabilidades Outras. Revista Territorial, Goiás, outras, p. 26–55, 2025. Dossiê: Educação Ambiental e Sustentabilidades Outras. ISSN: 2317-0360.

BRAZ, D. F.; PINTO, L. B.; CAMPOS, C. R. J. de. Ocorrência de eventos severos em regiões agrícolas do Rio Grande do Sul. *Geociências*, v. 36, n. 1, p. 89–99, 2017. doi:10.5016/geociencias.v36i1.12298

Brasil. (2021a). *Diagnóstico de capacidades e necessidades municipais em proteção e defesa civil: Brasil* (Coord. V. Marchezini). Ministério do Desenvolvimento Regional. Secretaria Nacional de Proteção e Defesa Civil. https://www.gov.br/mdr/pt-br/assuntos/protecao-e-defesa-civil/diagnostico-de-capacidades-e-necessidade-municipais-em-protecao-e-defesa-civil

BRASIL. Educação em clima de riscos de desastres / Centro Nacional de Monitoramento e Alertas de Desastres Naturais. – reimpr. rev. – São José dos Campos, SP: Cemaden, 2024.

BRASIL. Lei nº 14.750, de 12 de dezembro de 2023. Altera as Leis nºs 12.608, de 10 de abril de 2012, e 12.340, de 1º de dezembro de 2010, para aprimorar os instrumentos de prevenção de acidentes ou desastres e de recuperação de áreas por eles atingidas. Diário Oficial da União: seção 1, Brasília, DF, 13 dez. 2023. Disponível em: https://www.planalto.gov.br/ccivil_03/_Ato2023-2026/2023/Lei/L14750.htm. Acesso em: 09 de ago. 2025.

BRASIL. Ministério da Ciência, Tecnologia e Inovação (MCTI). Terceira comunicação nacional do Brasil à Convenção-Quadro das Nações Unidas sobre

Mudança do Clima. Brasília, DF: MCTI, 2016. Disponível em: https://repositorio.mctic.gov.br/handle/mctic/4312.

BRASIL. Ministério da Ciência, Tecnologia e Inovações (MCTI). Quarta comunicação nacional do Brasil à Convenção-Quadro das Nações Unidas sobre Mudança do Clima. Brasília, DF: MCTI, 2020. 57 p. Disponível em: https://repositorio.mcti.gov.br/handle/mctic/4782. Acesso em: 01 ago. 2025

BRASIL. Ministério do Meio Ambiente. Plano Nacional de Adaptação à Mudança do Clima. Brasília, DF: MMA, 2016.

BRASIL. Presidência da República. Ministério da Educação. Base Nacional Comum Curricular . São Paulo: Fundação Carlos Alberto Vanzolini, 2018

BRITO, S. S. B.; CUNHA, A. P. M. A.; CUNNINGHAM, C. C.; ALVALÁ, R. C.; MARENGO, J. A.; ARAUJO, M. Frequency, duration and severity of drought in the Brazilian semiarid. International Journal of Climatology, v. 38, n. 2, p. 517–529, 2018. doi:10.1002/joc.5225.

CAMARINHA, P. I. M. ; DEBORTOLI, N. S. ; RODRIGUES, R. . Natural Disasters Caused by Water. In: MCTI - Ministry of Science, Technology and Innovation. (Org.). Third National Communication of Brazil to the United Nations Framework Convention on Climate Change. 1ed. 2016, v. 2, p. 145-159.

CAMARINHA, P. I. M. Vulnerabilidade aos desastres naturais decorrentes de deslizamentos de terra em cenários de mudanças climáticas na porção paulista da Serra do Mar. 2016. 162 f. Tese (Doutorado em Ciência do Sistema Terrestre) – Instituto Nacional de Pesquisas Espaciais, São José dos Campos, 2016. Disponível em: http://mtc-m21b.sid.inpe.br/col/sid.inpe.br/mtc-m21b/2016/06.19.03.49/doc/publicacaquarta comuo.pdf. Acesso em: 9 ago. 2025.

CANIL, K.; LAMPIS, A.; SANTOS, K. L. Vulnerability and the social construction of risk: a contribution to planning in the São Paulo Macrometropolis. Environmental Science & Policy, v. 108, p. 55-64, 2020.

CARDOSO, L. S.; JUNGES, A. H.; TAZZO, I. F.; VERONE, F.; TAROUCO, A. K.; OLIVEIRA, A. M. R.; BREMM, C. (2020). Análise da estiagem na safra 2019/2020 e impactos na agropecuária do Rio Grande do Sul. Circular técnica SEAPDR/DDPA, v. 6, p. 8–57

CENTRO NACIONAL DE MONITORAMENTO E ALERTAS DE DESASTRES NATURAIS – CEMADEN. *Monitoramento de Secas e Impactos no Brasil em 2023*. Disponível em: https://www.gov.br/cemaden/pt-br/assuntos/monitoramento/monitoramento-de-seca-para-o-brasil. Acesso em: August 2025.

CENTRO NACIONAL DE MONITORAMENTO E ALERTAS DE DESASTRES NATURAIS – CEMADEN. *Monitoramento de Secas e Impactos no Brasil em 2024*. Disponível em: https://www.gov.br/cemaden/pt-br/assuntos/monitoramento/monitoramento-de-seca-para-o-brasil. Acesso em: August 2025.

CHOO, M.; YOON, D. K. A meta-analysis of the relationship between disaster vulnerability and disaster damage. International Journal of Disaster Risk Reduction, Vol. 102, Februry 2024. https://doi.org/10.1016/j.ijdrr.2024.104302.

CINTI, T. M.; MARQUES, M. L. Associação entre suscetibilidade à inundação e desenvolvimento da área urbanizada de Campinas-SP. Seminário Internacional de Investigação em Urbanismo, v. 12, n. 2, 2020.

CLARKE, B.; BARNES, C.; RODRIGUES, R.; ZACHARIAH, M.; ALVES, L. M.; HAARSMA, R.; PINTO, I.; YANG, W.; VAHLBERG, M.; VECCHI, G.; IZQUIERDO, K.; KIMUTAI, J.; OTTO, F. E. L. Climate change, El Niño and infrastructure failures behind massive floods in southern Brazil. London: Grantham Institute, Imperial College London, 2024. Disponível em: https://www.worldweatherattribution.org/climate-change-made-the-floods-in-southern-brazil-twice-as-likely/. Acesso em: 07 ago. 2025.

COELHO, C. A. S.; CARDOSO, D. H. F.; FIRPO, M. A. F. Precipitation diagnostics of an exceptionally dry event in São Paulo, Brazil. Theoretical and Applied Climatology, v. 125, n. 3–4, p. 769–784, 2015. doi:10.1007/s00704-015-1540-9.

COSTA, J. J. et al. Vulnerabilidades socioambientais à ocupação urbana: uma análise de Blumenau (SC) e Aracaju (SE). Revista Geográfica Acadêmica, v. 14, n. 4, p. 56-75, 2020.

COUTINHO, R.Q.; SILVA, M.M. (2005). “Classificação e Mecanismos de Movimento de Massa”. Conferência. IV COBRAE – Conferência Brasileira sobre Estabilidade de Encostas. Salvador, Bahia.

CUARTAS, L. A; CUNHA, A. P. M. A.; ALVES, J. A.; PARRA, L. M. P.; DEUSDARÁ-LEAL, K.; COSTA, L. C. O.; MOLINA, R. D.; AMORE, D.; BROEDEL, E.; SELUCHI, M. E.; CUNNINGHAM, C.; ALVALÁ, R. C. S.; MARENGO, J. A. Recent hydrological droughts in Brazil and their impact on hydropower generation. Water, Switzerland, v. 14, n. 4, 601, 2022.

CUARTAS, L. A.; FUJITA, T.; ANDRADE CAMPOS, J.; UVO, C. B.; NIKRAVESH, G.; OLSSON, J.; SÖRENSEN, J.; MARENGO, J. A.; AMORE, D.; BROEDEL, E.; PEIXOTO, J. Hydrometeorological drought analysis through Two-variate Standardized Index for the Paraná River Basin, Brazil. Journal of Hydrology: Regional Studies, v. 54, article 101886, 2024. doi:10.1016/j.ejrh.2024.101886.

CUNHA, A.P.M.A.; ZERI, M.; DEUSDARÁ LEAL, K.; COSTA, L.; CUARTAS, L.A.; MARENGO, J.A.; TOMASELLA, J.; VIEIRA, R.M.; BARBOSA, A.A.; CUNNINGHAM, C.; CAL GARCIA, J.V.; BROEDEL, E.; ALVALÁ, R.; RIBEIRO-NETO, G. Extreme Drought Events over Brazil from 2011 to 2019. ATMOSPHERE 2019, 10, 642. https://doi.org/10.3390/atmos10110642.

CUNHA, A.P.M.A; MARCHEZINI, V.; LINDOSO, D. P.; SAITO, S. M.; ALVALÁ, R. C. DOS SANTOS. The challenges of Consolidation of a Drought-Related Disaster

Risk Warning System to Brazil. SUSTAINABILITY IN DEBATE, v. 10, p. 43-76, 2018. https://doi.org/10.18472/SustDeb.v10n1.2019.19380.

CUNHA, A. P. M. A.; TOMASELLA, J.; RIBEIRO-NETO, G. G.; BROWN, M.; GARCIA, S. R.; et al. Changes in the spatial–temporal patterns of droughts in the Brazilian Northeast. Atmospheric Science Letters, v. 19, art. e855, 2018b. doi:10.1002/asl.855.

CUNHA, A. P. M. A.; BUERMANN, W.; MARENGO, J. A**.** Changes in compound drought-heat events over Brazil's Pantanal wetland: an assessment using remote sensing data and multiple drought indicators. *Climate Dynamics*, v. 62, n. 1, p. 739–757, 2023. doi:10.1007/s00382-023-06937-x.

CUTTER, S. L.; BORUFF, B. J.; SHIRLEY, W. L. Social vulnerability to environmental hazards. Social Science Quarterly, v. 84, n. 2, p. 242–261, 2003. DOI: https://doi.org/10.1111/1540-6237.8402002.

DALAGNOL, R.; GRAMCIANINOV, C. B.; CRESPO, N. M.; LUIZ, R.; CHIQUETTO, J. B.; MARQUES, M. T. A.; et al. Extreme rainfall and its impacts in the Brazilian Minas Gerais state in January 2020: Can we blame climate change? Climate Resilience and Sustainability, v. 1, n. 1, e15, 2021. DOI: https://doi.org/10.1002/CLI2.15.

DEBORTOLI, N. S. ; CAMARINHA, P. I. M. ; RODRIGUES, R. ; MARENGO, J. A. . Índice de Vulnerabilidade aos Desastres Naturais no Brasil, no contexto das Mudanças Climáticas. In: Breno Simonini Teixeira; Jose Antonio Marengo Orsini; Márcio Rojas da Cruz. (Org.). Modelagem Climática e Vulnerabilidades Setoriais à Mudança do Clima no Brasil. 1ed.Brasília: MCTI, 2016, v. 1, p. 321-386.

DEBORTOLI, N. S.; CAMARINHA, P. I. M.; MARENGO, J. A. ; RODRIGUES, R. . An index of Brazil's vulnerability to expected increases in natural flash flooding and landslide disasters in the context of climate change. Natural Hazards (Dordrecht), v. 85, p. 1-25, 2017.

DONAT, M. G.; LOWE, T. R.; ALEXANDER, L. V.; FISCHER, E. M. More extreme precipitation in the world's dry and wet regions. Nature Climate Change, v. 6, p. 508–513, 2016. DOI: https://doi.org/10.1038/nclimate2941.

DOS SANTOS L. O. F.; MACHADO, N. G.; BIUDES, M. S.; GELI, H. M. E.; QUERINO, C. A. S.; RUHOFF, A. L.; IVO, I. O.; NETO, N. L. Trends in Precipitation and Air Temperature Extremes and Their Relationship with Sea Surface Temperature in the Brazilian Midwest. Atmosphere, [S. l.], v. 14, n. 3, p. 426, 2023. DOI: 10.3390/atmos14030426.

DOS SANTOS, D. C., SANTOS, C. A. G., BRASIL NETO, R. M., DA SILVA, R. M., & DOS SANTOS, C. A. C. (2023). Precipitation variability using GPCC data and its relationship with atmospheric teleconnections in Northeast Brazil. Climate Dynamics, 61(5-6), 2717-2738. https://doi.org/10.1007/s00382-023-06838-z

DREXLER, A. H., & MEISENZAHL, R. (2024). Special issue on climate change and natural disasters. *Journal of Risk and Insurance*, *91*(2), 255-261. https://doi.org/10.1111/jori.12474

DUNN, R. J. H.; HEROLD, N.; ALEXANDER, L. V.; DONAT, M. G.; ALLAN, R.; BADOR, M.; BRUNET, M.; CHENG, V.; Ibadullah, W. M. W.; Ibrahim, M. K. I. B.; KRUGER, A.; KUBOTA, H.; LIPPMANN, T. J. R.; MARENGO, J.; MBATHA, S.; MCGREE, S.; NGWENYA, S.; CAICEDO, J. D. P.; RAMOS, A.; SALINGER, J.; VAN DER SCHRIER, G.; SRIVASTAVA, A.; TREWIN, B.; YÁÑEZ, R. V.; VAZQUEZ-AGUIRRE, J.; JIMÉNEZ, C. V.; VOSE, R.; YUSSOF, M. N. A. B. H.; ZHANG, X. Observed global changes in sector￾relevant climate extremes indices: An extension to HadEX3. Earth and Space Science, [S. l.], v. 11, p. e2023EA003279, 2024. https://doi.org/10.1029/2023EA003279.

ERFANIAN, A.; WANG, G.; FU, R. Droughts and floods in Amazonia: The role of sea surface temperature anomalies. *Science Advances*, v. 3, e1703014, 2017. doi:10.1126/sciadv.1703014.

EMBERSON, R., KIRSCHBAUM, D., & STANLEY, T. (2021). Global connections between El Niño and landslide impacts. Nature Communications, 12(1), 2262.

ESPINOZA, J.-C.; JIMÉNEZ, J. C.; MARENGO, J. A.; SCHONGART, J.; RONCHAIL, J.; LAVADO-CASIMIRO, W.; RIBEIRO, J. V. M. The new record of drought and warmth in the Amazon in 2023 related to regional and global climatic features. *Scientific Reports*, v. 14, art. 8107, 2024. doi:10.1038/s41598-024-58782-5.FERNANDES, L.G.; RODRIGUES, R. R. Changes in the patterns of extreme rainfall events in southern Brazil. International Journal of Climatology, 38(4), 1337-1350. 2018

FERNANDES, V. R.; CUNHA, A. P. M. A.; PINEDA, L. A. C.; LEAL, K. R. D.; COSTA, L. C.; BROEDEL, E.; MARENGO, J. A. Droughts and impacts in Southern Brazil. *Revista Brasileira de Climatologia*, v. 28, p. 561–584, 2021. Available at: https://ojs.ufgd.edu.br/rbclima/article/view/14748

FERREIRA, K.; ABIKO, A. K. Urban Resilience and Landslide Risk Management: The Case of Santos (Brazil). In: Resilience and Urban Disasters, p. 245-264. Springer, 2019.

G1. Chuva que caiu em 24 horas no Litoral Norte foi o maior registro da história do Brasil. G1 Globo, 20 fev. 2023. Disponível em: https://g1.globo.com/sp/vale-do-paraiba-regiao/noticia/2023/02/20/chuva-que-caiu-em-24-horas-no-litoral-norte-foi-o-maior-registro-da-historia-diz-governo-de-sao-paulo.ghtml Acesso em: 9 ago. 2025.

GIMENO, L., SORÍ, R., VÁZQUEZ, M., STOJANOVIC, M., ALGARRA, I., EIRAS-BARCA, J., GIMENO-SOTELO, L., & NIETO, R. (2022). Extreme precipitation events. *Wiley Interdisciplinary Reviews: Water*, *9*(6), e1611. https://doi.org/10.1002/wat2.1611

GLOOR, M.; BRIENEN, R.J.W.; GALBRAITH, D.; FELDPAUSCH, T.R.; SCHÖNGART, J.; GUYOT, J.-L.; ESPINOZA, J.C.; LLOYD, J.; PHILIPS, O.L. 2013. Intensification of the Amazon hydrological cycle over the last two decades. Geophysical Research Letters 40: 1729-1733.

GOMES, A. Y. da S.; WILLEGAIGNON, H. R. C. F. Efeitos da seca na Região Nordeste do Brasil / Effects of drought in the Northeast Region of Brazil. Brazilian Journal of Development, v. 7, n. 8, p. 80608-80618, 2021. doi:10.34117/bjdv7n8-561.

GUTIÉRREZ, A. P. A.; ENGLE, N. L.; DE NYS, E.; MOLEJÓN, C.; MARTINS, E. S. P. R. Drought Preparedness in Brazil. Weather and Climate Extremes, v. 3, p. 95–106, 2014. doi:10.1016/j.wace.2013.12.001.

HACKMAN, L., MACK, P., MÉNARD, H., Behind every good research there are data. What are they and their importance to forensic science, Forensic Science International: Synergy, Volume 8, 2024, 100456, ISSN 2589-871X, https://doi.org/10.1016/j.fsisyn.2024.100456.

HAMDAN, A., ALHAMAD, I. M., IKEMBA, S., & EWIM, D. R. (2023). Predicting future global temperature and greenhouse gas emissions via LSTM model. *Sustainable Energy Research*, *10*(1), 1-13. https://doi.org/10.1186/s40807-023-00092-x

HIRYE, M. C. M.; ALVES, D. S.; FILARDO, A. S.; MCPHEARSON, T.; WAGNER, F. Assessing Landslide Drivers in Social-Ecological-Technological Systems: The Case of Metropolitan Region of São Paulo, Brazil. Remote Sensing, v. 15, n. 12, 3048, 2023.

HUMMELL, B. M. L.; CUTTER, S. L.; EMRICH, C. T. Social Vulnerability to Natural Hazards in Brazil. International Journal of Disaster Risk Science, v. 7, n. 2, p. 111-122, 2016.

IMA, K. C.; SATYAMURTY, P.; FERNANDEZ, J. P. R. Large-scale atmospheric conditions associated with heavy rainfall episodes in Southeast Brazil. Theoretical and Applied Climatology, v. 101, n. 1-2, p. 121-135, 2010. DOI: https://doi.org/10.1007/S00704-009-0207-9.

IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2021. DOI: https://doi.org/10.1017/9781009157896.

IPCC. Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2022. DOI: https://doi.org/10.1017/9781009325844.

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell,

E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

JIMÉNEZMUÑOZ, J. C.; MATTAR, C.; BARICHIVICH, J.; SANTAMARÍAARTIGAS, A.; TAKAHASHI, K.; MALHI, Y.; SOBRINO, J. A.; VAN DER SCHRIER, G.; et al. Recordbreaking warming and extreme drought in the Amazon rainforest during the course of El Niño 2015–2016. *Scientific Reports*, v. 6, Article 33130, 2016. doi:10.1038/srep33130

JIMÉNEZ, J. C.; ESPINOZA, J. C.; MOREIRA, D.; CARDOZO, F.; MARENGO, J. A. The role of ENSO flavors and TNA on recent droughts over Amazon forests and the Northeast Brazil region. *International Journal of Climatology*, v. 38, n. 12, p. 5177–5189, 2018. doi:10.1002/joc.5725.

KIM, B. JE; JEONG, S.; CHUNG, JI-B. Research trends in vulnerability studies from 2000 to 2019: Findings from a bibliometric analysis. *International Journal of Disaster Risk Reduction,* v. 56, p. 102141, 2021.

KOGAN, F. N. Global drought watch from space. Bulletin of the American Meteorological Society, v. 78, n. 4, p. 621–636, 1997. doi:10.1175/1520-0477(1997)078<0621:GDWFS>2.0.CO;2.

LEAL, K. R. D.; CUARTAS, L. A.; ZHANG, R.; MOHOR, G. S.; CARVALHO, L. V. de C.; NOBRE, C. A.; MENDIONDO, E. M.; BROEDEL, E.; SELUCHI, M. E.; ALVALÁ, R. C. dos S. Implications of the New Operational Rules for Cantareira Water System: Re-Reading the 2014–2016 Water Crisis. Journal of Water Resource and Protection, v. 12, p. 261–274, 2020. doi:10.4236/jwarp.2020.124016.

LIBONATI, R.; DACAMARA, C. C.; PERES, L. F.; TRIGO, R. M.; KIPPEL, B. Rescue Brazil's burning Pantanal wetlands. Nature, v. 588, n. 7837, p. 217–219, 2020. doi:10.1038/d41586-020-03464-1.

LIBONATI, R.; GEIRINHAS, J. L.; SILVA, P. S.; RODRIGUEZ, D. A.; NOBRE, P.; FERNANDES, K.; FERNANDES, L. C. M.; DACAMARA, C. C. Assessing the role of compound drought and heatwave events on unprecedented 2020 wildfires in the Pantanal. Environmental Research Letters, v. 17, art. 015005, 2022. doi:10.1088/1748-9326/ac462e.

LUIZ-SILVA, W.; OSCAR-JÚNIOR, A. C. Climate extremes related with rainfall in the State of Rio de Janeiro, Brazil: a review of climatological characteristics and recorded trends. Natural Hazards, v. 113, n. 2, p. 1165-1198, 2022. DOI: https://doi.org/10.1007/s11069-022-05409-5.

LUPO, A. R.; JENSEN, A. D.; MOKHOV, I. I.; et al. Atmospheric blocking events: a review. Annals of the New York Academy of Sciences, v. 1504, p. 5–24, 2021. doi:10.1111/nyas.14557. MARCHEZINI, V., SAITO, S. M., LONDE, L. DE R., DAMACENA, F. D. L., & LOOSE, E. B. (2025). Coprodução de propostas para catalisar a implementação da Política Nacional de Proteção e Defesa Civil nos municípios brasileiros. Derbyana, 46. https://doi.org/10.69469/derb.v46.840

MARCHEZINI, V., SAITO, S. M., LONDE, L. R., & DAMACENA, F. D. L. (2025). Implementation challenges of disaster risk management policies: The organizational capacities of municipal civil defense units. *International Journal of Disaster Risk Reduction*, *119*, 105291.

MARENGO, J. A.; et al. Recent Extremes of Drought and Flooding in Amazonia: Vulnerabilities and Human Adaptation. *American Journal of Climate Change*, v. 2, p. 87–96, 2013. doi:10.4236/ajcc.2013.22009

MARENGO, J. A.; NOBRE, C. A.; SELUCHI, M. E.; CUARTAS, L. A.; ALVES, L. M.; MARENGO, N. A drought in southern Brazil in 2014: characterization, impacts and lessons. Weather and Climate Extremes, v. 8, p. 27–36, 2015. doi:10.1016/j.wace.2015.06.001.

MARENGO, J. A.; ESPINOZA, J. C. Extreme seasonal droughts and floods in Amazonia: causes, trends and impacts. *International Journal of Climatology*, v. 36, n. 3, p. 1033-1050, 2016. doi:10.1002/joc.4420.

MARENGO, J. A.; CAMARINHA, P. I.; ALVES, L. M.; DINIZ, F.; BETTS, R. A. Extreme Rainfall and Hydro-Geo-Meteorological Disaster Risk in 1.5, 2.0, and 4.0°C Global Warming Scenarios: An Analysis for Brazil. *Frontiers in Climate*, [S. l.], v. 3, p. 610433, mar. 2021. DOI: 10.3389/fclim.2021.610433.

MARENGO, J. A.; CUNHA, A. P. M. A.; CUARTAS, L. A.; DEUSDÁRA LEAL, K. R.; BROEDEL, E.; SELUCHI, M. E.; MICHELIN, C. M.; DE PRAGA BAIÃO, C. F.; CHUCHÓN ANGULO, E.; ALMEIDA, E. K.; KAZMIERCZAK, M. L.; MATEUS, N. P. A.; SILVA, R. C.; BENDER, F. *E*xtreme Drought in the Brazilian Pantanal in 2019–2020: Characterization, Causes, and Impacts. Frontiers in Water, v. 3, art. 639204, fev. 2021. doi:10.3389/frwa.2021.639204MARENGO, J. A.; CUNHA, A. P.; SELUCHI, M. E.; CAMARINHA, P. I.; DOLIF, G.; SPERLING, V. B.; ALCÂNTARA, E. H.; RAMOS, A. M.; ANDRADE, M. M.; STABILE, R. A. & JOSÉ. Heavy rains and hydrogeological disasters on February 18th–19th, 2023, in the city of São Sebastião, São Paulo, Brazil: from meteorological causes to early warnings. *Natural Hazards: Journal of the International Society for the Prevention and Mitigation of Natural Hazards*, [S. l.], v. 120, n. 8, p. 7997-8024, jun. 2024. DOI: 10.1007/s11069-024-06558-5

MARENGO, J. A.; DOLIF, G.; CUARTAS, A.; CAMARINHA, P.; GONÇALVES, D.; LUIZ, R.; SILVA, L.; ALVALÁ, R. C. S.; SELUCHII, M. E.; MORAES, O. L.; SOARES, W. R.; NOBRE, C. (2024) O maior desastre climático do Brasil: Chuvas e inundações no estado do Rio Grande do Sul em abril-maio 2024. Estudos Avançados, 38(112), 203-228.

MARENGO, J. A.; ESPINOZA, J.-C.; FU, R.; JIMENEZ MUÑOZ, J. C.; ALVES, L. M.; DA ROCHA, H. R.; SCHÖNGART, J. Long-term variability, extremes and changes in temperature and hydrometeorology in the Amazon region: A review. Acta

Amazonica, [S. l.], v. 54, p. e54es22098, 2024. https://doi.org/10.1590/1809-4392202200980

MARTH, J. D.; MOURA, N. S. V.; KOESTER, E. Estudo da suscetibilidade à inundação com base em análise geomorfológica, bacia hidrográfica do Arroio Santa Isabel, região costeira do Rio Grande do Sul, Brasil. Revista Brasileira de Geomorfologia, v. 17, n. 1, p. 27-42, 2016.

MARTINI, L. C. P. Changes in rainfall patterns in southern Brazil over 1961-2020 period detected by rain gauge data. International Journal of Climatology, [S. l.], v. 42, n. 2, p. 1195-1208, fev. 2022. DOI: 10.1002/joc.7804.

MATSUO, P. M. (2023). Muito além da chuva: práticas educativas na era dos desastres. Coimbra: RISCOS – Associação Portuguesa de Riscos, Prevenção e Segurança, 159 p. DOI: https://doi.org/10.34037/978-989-9053-17-5_04

MATSUO, P. M., & SILVA, R. L. F. (2021). Desastres no Brasil? Práticas e abordagens em educação em redução de riscos e desastres. Educar em Revista, 37. DOI: http://dx.doi.org/10.1590/0104-4060.78161.

MATTOS, T. S.; OLIVEIRA, P. T. S.; BRUNO, L. S.; OLIVEIRA, N. D.; VASCONCELOS JÚNIOR, J. G.; LUCAS, M. C. Improving Urban Flood Resilience under Climate Change Scenarios in a Tropical Watershed Using Low-Impact Development Practices. Journal of Hydrologic Engineering, [S. l.], v. 26, n. 12, p. 5021031, dez. 2021. DOI: 10.1061/(ASCE)HE.1943-5584.0002143.

MEDEIROS, F. J. de; OLIVEIRA, C. P. de. Assessment of dry and heavy rainfall days and their projected changes over Northeast Brazil in Coupled Model Intercomparison Project Phase 6 models. International Journal of Climatology, v. 43, n. 9, p. 3927-3948, 2023. DOI: https://doi.org/10.1002/joc.7759.

MORAES, R. B. F. de; GONÇALVES, F. V. Development, Application, and Validation of the Urban Flood Susceptibility Index. Water Resources Management, [S. l.], v. 38, p. 2511-2525, 2024. DOI: 10.1007/s11269-024-03782-3

NOBRE, C. A.; MARENGO, J. A.; SELUCHI, M. E.; CUARTAS, L. A.; ALVES, L. M. Some characteristics and impacts of the drought and water crisis in Southeastern Brazil during 2014 and 2015. Journal of Water Resource and Protection, v. 8, p. 252–262, 2016. doi:10.4236/jwarp.2016.82022.

OLIVEIRA, T. G.; FIORI, A. P.; SILVEIRA, R. M. Propriedades geológico-geotécnicas de um solo coluvionar em encosta natural cortada por uma dutovia. Geociências, v. 38, n. 4, p. 1013-1028, 2020.

ONU - Organização das Nações Unidas. (2015). Transformando nosso mundo: a Agenda 2030 para o Desenvolvimento Sustentável. Disponível em: https://brasil.un.org/sites/default/files/2020-09/agenda2030-pt-br.pdf. Acesso em: 07 Ago. 2025.

ORLANDI SIMÕES, J. V.; ALVES, L. M.; PEDRA, G. U.; et al. Spatio-temporal assessment of extreme precipitation events in southeastern Brazil. Modeling Earth Systems and Environment, v. 11, p. 212, 2025. DOI: https://doi.org/10.1007/s40808-025-02396-x.

OSUTEYE, E., JOHNSON, C., & BROWN, D. (2017). The data gap: An analysis of data availability on disaster losses in sub-Saharan African cities. *International Journal of Disaster Risk Reduction*, *26*, 24-33. https://doi.org/10.1016/j.ijdrr.2017.09.026

PICANÇO, J. L.; MESQUITA, M. J. M.; SOARES, L. F. The Hydrological Disasters Through Historical Survey in the Serra do Mar Range, Southern Brazil. In: Advancing Culture of Living with Landslides, p. 1007-1014. Springer, 2017.

PILLAR, V. D.; OVERBECK, G. E. A diversidade da vegetação no Sul do Brasil: padrões e processos. In: SIMPÓSIO SOBRE A VEGETAÇÃO DO SUL DO BRASIL, 2024, Curitiba. Anais... Curitiba: UFPR, 2024. p. 100-115.

PINHO, P.; SILVESTRINI; R. A.; FELLOWS; M.; PEREZ; L. P.; ALENCAR; A.; GUYOT; C.; MOUTINHO; P.; LAPOLA; D. M.; STRINGER, L. C. (2024). Escalating Climate Disasters in the Amazon (2006-2022): Vulnerabilities and Compound Risks. Research Square. https://doi.org/10.21203/rs.3.rs-5045887/v1

PINTO, T. A. C.; MATTOS, E. V.; REBOITA, M. S.; SOUZA, D. O. D.; ODA, P. S. S.; MARTINS, F. B.; BISCARO, T.; FERREIRA, G. W. D. S. Synoptic and mesoscale atmospheric patterns that triggered the natural disasters in the Metropolitan Region of Belo Horizonte, Brazil, in January 2020. Atmosphere, v. 16, n. 1, p. 102, 2025. DOI: https://doi.org/10.3390/atmos16010102.

PUGAS, A. F.; SILVA, A. P. B.; SILVA, E. B.; ROLDAO, H. P.; QUADRO, M. F. L.; VITOR, A.; MUZA, M. N. Analysis of Temporal Precipitation Variability in the State of Santa Catarina-Brazil. Revista Brasileira de Climatologia, v. 34, p. 51-78, 2024. DOI: https://doi.org/10.55761/abclima.v34i20.17164.

RAMOS, C. M.; TORRES, A. P.; PEREIRA, I. N. A.; FROTA, C. A. Geotechnical Characteristics of Mass Movements in Manaus - AM. International Journal for Innovation Education and Research, [S. l.], v. 7, n. 12, p. 15-25, 2019. http://dx.doi.org/10.31686/ijier.Vol7.Iss12.1838

RENTSCHLER, J., AVNER, P., MARCONCINI, M. *ET AL*. Global evidence of rapid urban growth in flood zones since 1985. *Nature* **622**, 87–92 (2023). https://doi.org/10.1038/s41586-023-06468-9

RIBEIRO, D. F., SAITO, S. M., DOS SANTOS ALVALÁ, R. C. (2021). Disaster vulnerability analysis of small towns in Brazil. International Journal of Disaster Risk Reduction, 102726. https://doi.org/10.1016/j.ijdrr.2021.102726

RIBEIRO, A. F. S.; BRANDO, P. M.; SANTOS, L.; RATTIS, L.; HIRSCHI, M.; HAUSER, M.; SENEVIRATNE, S. I.; ZSCHEISCHLER, J. A compound event-oriented framework to tropical fire risk assessment in a changing climate. *Environmental Research Letters*, v. 17, n. 6, art. 065015, 2022. doi:10.1088/1748-9326/ac7342.

RICHARDSON, K., STEFFEN, W., LUCHT, W., BENDTSEN, J., CORNELL, S. E., DONGES, J. F., ... & ROCKSTRÖM, J. (2023). Earth beyond six of nine planetary boundaries. Science advances, 9(37), eadh2458.

RIO GRANDE DO SUL. Comitê Gestor do Plano Rio Grande. Resolução nº 05/2025, de 1º de julho de 2025. Dispõe sobre as iniciativas encaminhadas pelas secretarias finalísticas à Secretaria da Reconstrução Gaúcha, visando a inclusão na carteira do Plano Rio Grande, Programa de Reconstrução, Adaptação e Resiliência Climática do Estado do Rio Grande do Sul. Diário Oficial do Estado do Rio Grande do Sul: Caderno do Governo, Porto Alegre, p. 13, 1 jul. 2025. Disponível em: <https://www.diariooficial.rs.gov.br/materia?id=1286178>. Acesso em: 9 ago. 2025.

RIO GRANDE DO SUL. Lei Complementar Nº 16.263, de 27 de Dezembro de 2024. Institui a Política Estadual de Proteção e Defesa Civil - PEPDEC. 2024. Disponível em: https://www.diariooficial.rs.gov.br/materia?id=1181541. Acesso em: 30 jul. 2025.

ROCKSTRÖM, J., STEFFEN, W., NOONE, K., PERSSON, Å., CHAPIN III, F. S., LAMBIN, E., ... & FOLEY, J. (2009). Planetary boundaries: exploring the safe operating space for humanity. Ecology and society, 14(2).

RODRIGUES, R. R.; McPHADEN, M. J. Why did the 2011–2012 La Niña cause a severe drought in the Brazilian Northeast? Geophysical Research Letters, v. 41, n. 3, p. 1012–1018, 2014. doi:10.1002/2013GL058703

RODRIGUES, R. R.; MARINHO, D. F.; MATTOS, M. L. A. Impactos climáticos e variabilidade dos eventos extremos no Sul do Brasil. Climatologia Brasileira, v. 34, n. 2, p. 45-60, 2018.

SAITO, S. M. População urbana exposta aos riscos de deslizamentos, inundações e enxurradas no Brasil. Sociedade & Natureza, v. 30, n. 2, p. 227-251, 2018.

SAMUEL RUFAT, S.; TATE , E.; , BURTON, C. G.; MAROOF, A. S. Social vulnerability to floods: Review of case studies and implications for measurement. International Journal of Disaster Risk Reduction, Vol. 102, Februry 2024. https://doi.org/10.1016/j.ijdrr.2015.09.013

SANTANA, R. A.; TOTA, J.; SANTOS, R. M.; VALE, R. S. Jatos de baixos níveis no sudoeste da Amazônia. Ciência e Natura, v. 35, n. 2, p. 57-66, 2013. DOI: https://doi.org/10.5902/2179460X11684.

SANTOS, D. J. dos; PEDRA, G. U.; SILVA, M. G. B. da; JÚNIOR, C. A. G.; ALVES, L. M.; SAMPAIO, G.; MARENGO, J. A. Mudanças futuras de precipitação e temperatura no Brasil a partir dos níveis de aquecimento global de 1,5ºC, 2ºC e 4ºC.

Sustainability in Debate-Brasilia, Brasília, v. 11, n. 3, p. 57-73, dez. 2020. DOI: 10.18472/SustDeb.v11n3.2020.33933

SANTOS. Plano de Ação Climática de Santos (PACS). Santos, SP: Prefeitura Municipal de Santos, 2022. Disponível em: https://www.adaptacao.eco.br/_biblioteca/plano-de-acao-climatica-de-santos-pacs-relatorio-completo/. Acesso em: 25 jul. 2025.

SEIGERMAN, C. K., LEITE, N. S., MARTINS, E. S. P. R., & NELSON, D. R. At the extremes: Assessing interrelations among the impacts of and responses to extreme hydroclimatic events in Ceará, Northeast Brazil. Journal of Hydrology, 630, 130850. 2024. https://doi.org/10.1016/j.jhydrol.2024.130850

SILVA, J. F. M.; OBESO, M. P.; MAKRAKIS, M. C.; MAKRAKIS, S. Environmental analysis of land use and occupation in nine watersheds contributing to the Iguaçu River, Brazil. Research, Society and Development, v. 11, n. 13, e34868, 2022.

SIQUEIRA, J. R.; MARQUES, V. S. Case study of intense mesoscale convective systems occurred between 02 and 03 January 2013 in the state of Rio de Janeiro: Structural and thermodynamic characteristics. Revista Brasileira de Meteorologia, v. 31, n. 2, p. 57-76, 2016. DOI: https://doi.org/10.11137/2016_2_57_76.

SOUZA, C. M. M. et al. Social environmental vulnerability approach on the COVID-19 epoch: a case study in Blumenau (SC), Brazil. Research, Society and Development, v. 10, n. 10, e239101018739, 2021.

SOUZA, D. C.; CRESPO, N. M.; SILVA, D. V.; HARADA, L. M.; GODOY, R. M. P.; DOMINGUES, L. M.; LUIZ, R.; BORTOLOZO, C. A.; METODIEV, D.; ANDRADE, M. R. M.; HARTLEY, A. J.; ABREU, R. C.; LI, S.; LOTT, F. C.; SPARROW, S. (2023). Extreme rainfall and landslides as a response to human-induced climate change: a case study at Baixada Santista, Brazil, 2020. Research Square. https://doi.org/10.1007/s11069-024-06621-1

SPINONI, J., NAUMANN, G., & VOGT, J. (2015). Global drought frequency, duration, and severity for 1951–2010. *International Journal of Climatology, 35*(13), 4171–4186. https://doi.org/10.1002/joc.4039

STOTT, Peter A.; CHRISTIDIS, Nikolaos; OTTO, Friederike E. L.; SUN, Ying; VANDERLINDEN, Jean-Paul; VAN OLDENBORGH, Geert Jan; VAUTARD, Robert; VON STORCH, Hans; WALTON, Peter; YIOU, Pascal; ZWIERS, Francis W. Attribution of extreme weather and climate-related events. Wiley Interdisciplinary Reviews: Climate Change, v. 7, n. 1, p. 23-41, 2016. DOI: 10.1002/wcc.380.

STRAMMA, L.; IKEDA, Y.; PETERSON, R. G. Geostrophic transport in the Brazil Current region north of 20°S. Deep-Sea Research, v. 37, n. 12, p. 1875-1886, 1990. DOI: 10.1016/0198-0149(90)90083-8.

SULAIMAN, S. N.; TRAJBER, R.; MATSUO, P. M.; FERREIRA, K. UM CAMINHO ESTRATÉGICO Educação e engajamento social na construção de comunidades e cidades resilientes. GIRD+10: Caderno Técnico de Gestão Integrada de Riscos e Desastres. Ministério do Desenvolvimento Regional, 2021(143-151p.)

TOMASELLA, J.; CUNHA, A. M. A.; ZERI, M.; COSTA, L. C. O. Changes in the aridity index across Brazilian biomes. Science of the Total Environment, v. 989, art. 179869, 2025. doi:10.1016/j.scitotenv.2025.179869.

TRAJBER, R.; BRIANEZI, T.; BIASOLI, S. (Coord.). Diretrizes de Educação Ambiental Climática. FunBEA, ICS - Instituto Clima e Sociedade, Cemaden Educação. 2024 (versão eletrônica). Disponível em: https://educacao.cemaden.gov.br/midiateca/diretrizes-de-educacao-ambiental-climatica/. Acesso em: 14 ago. 2024.

TRENBERTH, K. E.; FASULLO, J.; SMITH, L. Trends and variability in column￾integrated atmospheric water vapor. Climate Dynamics, v. 20, n. 7, p. 741–758, 2003. DOI: https://doi.org/10.1007/s00382-002-0300-7.

UNDRR Marco de Sendai para Redução do Risco de Desastres 2015-2030 https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030

United Nations Office for Disaster Risk Reduction (UNDRR). GAR Special Report on Drought 2021. Geneva: UNDRR, 2021. ISBN 978-92-123202-7-4 .

UNISDR, Marco de Ação de Hyogo 2005-2015: aumento da resiliência das nações e das comunidades frente aos desastres.

VIEIRA, B. C.; SOUZA, L. M.; ALCALDE, A. L.; DIAS, V. C.; BATEIRA, C.; MARTINS, T. D. Debris flows in southeast Brazil: susceptibility assessment for watersheds and vulnerability assessment of buildings. Universidade de Lisboa, 2019.

VINCENT, L. A. et al. Observed trends in indices of daily and extreme temperature and precipitation for the countries of South America 1960–2014. Journal of Climate, v. 33, n. 21, p. 9499-9513, 2020. DOI: 10.1175/JCLI-D-19-1012.1.

VICENTE-SERRANO, S. M., BEGUERÍA, S., & LÓPEZ-MORENO, J. I. (2010). A multiscalar drought index sensitive to global warming: The Standardized Precipitation Evapotranspiration Index – SPEI. *Journal of Climate, 23*(7), 1696–1718. https://doi.org/10.1175/2009JCLI2909.1

VOGEL, M. M. et al. Identifying meteorological drivers of extreme impacts: an application to simulated crop yields. *Earth System Dynamics*, v. 11, n. 1, p. 223–243, 2020. doi:10.5194/esd-11-223-2020.

VOGT, J., SOTERIOU, A., STAHL, K., LÓPEZ-PAREDES, A., ABDALLA, S., POZO, J. T., & VOGT, S. (2011). *Monitoring drought globally and regionally: The European Drought Observatory (EDO).* Luxembourg: Publications Office of the European Union. https://doi.org/10.2788/80242

WANG, X.-Y.; LI, X.; ZHU, J.; TANAJURA, C.A.S. 2018. The strengthening of Amazonian precipitation during the wet season driven by tropical sea surface temperature forcing. Environmental Research Letters 13: 94015. doi:10.1088/1748-9326/aadbb9

WILCHES-CHAUX, G. (1993). La vulnerabilidad global. *Los desastres no son naturales*, *1144*(1.31).

WISNER, B.; BLAIKIE, P.; CANNON, T.; DAVIS, I. (2004). At Risk: Natural Hazards.

WILHITE, D. A., & GLANTZ, M. H. (1987). Understanding the drought phenomenon: The role of definitions. *Water International, 10*(3), 111–120. https://doi.org/10.1080/02508068708686328

WILHITE, D. A.; SIVAKUMAR, M. V. K.; PULWARTY, R. S. Managing drought risk in a changing climate: the role of national drought policy. WeatherClimExtrem, v. 3, p. 4-13, 2014.

WILLIAMS, A. P.; COOK, E. R.; SMERDON, J. E.; COOK, B. I.; ABAZOGLOU, J. T.; BOLLES, K.; BAEK, S. H.; BADGER, A. M.; LIVNEH, B. Large contribution from anthropogenic warming to an emerging North American megadrought. *Science*, v. 368, n. 6488, p. 314–318, 2020. doi:10.1126/science.aaz9600.

WORLD METEOROLOGICAL ORGANIZATION – WMO**.** State of the Climate in Latin America and the Caribbean 2021. Geneva: WMO, 2022. Available at: https://library.wmo.int/index.php?lvl=notice_display&id=21964.

WORLD WEATHER ATTRIBUTION. Rapid attribution analysis of extreme weather events. 2023. Disponível em: https://www.worldweatherattribution.org/. Acesso em: 01 ago. 2025.

ZERI, M.; CUNHA, A. P.; CUNNINGHAM, C.; GUEDES, M.; COSTA, L**.** A long-term database of the Integrated Drought Index for Brazil from 2003 to 2023 [dataset]. Mendeley Data, 08 jul. 2024. DOI:10.17632/dd95bhn7mh.1.

ZSCHEISCHLER, J. et al. Future climate risk from compound events. *Nature Climate Change*, v. 8, p. 469–477, 2018. doi:10.1038/s41558-018-0156-3.

ZSCHEISCHLER, J. et al. A typology of compound weather and climate events. *Nature Reviews Earth & Environment*, v. 1, p. 333–347, 2020. doi:10.1038/s43017-020-0060-z.

10. CLIMATE CHANGE: RECOGNIZED AND PROJECTED ECONOMIC IMPACTS IN BRAZIL

Eduardo Amaral Haddad[42], Andréa Bento Carvalho[43], Jaqueline Coelho Visentin[42]

INTRODUCTION

Climate change is one of the greatest current challenges for sustainable development, and requires responses based on scientific knowledge and cooperation between different disciplines. The projected impacts on Brazil, a country of continental size with significant socio-economic and environmental heterogeneity, increase the urgency to develop technical and institutional capacities for mitigation, and adaptation, as well as the formulation of effective climate policies.

In this context, two Brazilian scientific initiatives have played a fundamental role: the Brazilian Research Network on Global Climate Change (Rede Clima) and the National Institute of Science and Technology on Climate Change (INCT-MC2). Both have established themselves as strategic platforms for the generation and dissemination of knowledge, structured through collaborative and interdisciplinary networks involving dozens of research institutions in all regions of the country. With complementary approaches, these initiatives have contributed decisively to the understanding of the economic impact of climate change in Brazil

42 Universidade de São Paulo. USP, São Paulo, SP.
43 Universidade Federal do Rio Grande. FURG, Rio Grande, RS
corresponding author: ehaddad@usp.br

and to the formulation of public policy instruments for the transition to a low-carbon economy.

This chapter summarizes the scientific progress made within the Rede Clima's Economics subnetwork and the economic subcomponent of INCT-MC2. We present the methods developed, the main results , and the implications for the Brazilian climate agenda, focusing on regional economic impacts, mitigation tools, socio-environmental vulnerabilities, and the development of evidence-based public policies.

The text is organized as follows: The second section presents the role of the economy in climate change and the institutional contribution of the Climate Network and INCT-MC2. The third section explains the methodological approaches and analytical models used, focusing on the complementarity between predictive simulations (ex-ante) and empirical measurements (ex-post). It then discusses the main thematic results, which are divided into the areas of agriculture, water, energy, emissions, and regional inequalities, among others. The chapter concludes with a discussion on the future direction of climate economics in Brazil, followed by a conclusion.

THE ROLE OF ECONOMIC SCIENCE IN CLIMATE CHANGE

Climate change is not just an environmental phenomenon: its impacts permeate economic, productive, and social systems, affecting consumption patterns, production, investment, trade, and public policy. Therefore, its analysis requires tools that link the physical complexity of the climate system with the institutional, technological, and distributive structures of the economy.

In Brazil, the establishment of research networks such as Rede Clima and INCT-MC2 has been fundamental in structuring this integrated response. Founded in 2007, Rede Clima's mission is to generate and disseminate scientific knowledge on the causes and impacts of global and regional climate change, as well as to support Brazilian climate diplomacy, public policy formulation, and the adaptation of social, economic, and natural systems.

The Economics sub-network of Rede Clima, currently coordinated by Edson Paulo Domingues (UFMG) and Eduardo Haddad (USP), has been working since its inception on the development of applied methodologies for the analysis of socio-economic impacts, focusing on integrated modeling, simulations of climate change mitigation measures and the assessment of the distributional effects of climate change.

Furthermore, in its phase 2 (2016-2025), INCT-MC2 has developed a program structured around thematic axes with strong interdisciplinary links (Marengo et al., 2025). The Economics sub-component, coordinated by Eduardo Haddad (USP) and José Féres (Institute for Applied Economic Research - IPEA), has established itself as a center of methodological and analytical excellence, developing robust tools for economic impact measurement, risk modeling, and the design of adaptation and mitigation instruments.

Key contributions of the two networks include the first robust estimates of the economic impacts of climate change in Brazil based on computable general equilibrium (CGE) models, the development of regional and sectoral simulations for different types of extreme weather events, the integration of economics with topics such as agriculture, water availability, energy, health, and demography, and the formulation of proposals for carbon markets, emissions pricing instruments, and risk-based adaptation measures.

This work has enabled the development of public debate, supported national sustainable development strategies, and enhanced Brazil's ability to strategically position itself in international negotiations, such as the United Nations Framework Convention on Climate Change (UNFCCC).

METHODOLOGICAL APPROACHES: FROM STRUCTURAL MODELING TO EMPIRICAL EVIDENCE

Understanding the economic impacts of climate change requires the coordination of various analytical tools. The economics sub-network of the Rede Clima and the economics component of INCT-MC2 have structured their research agendas on the basis of two major methodological axes: Ex-ante assessments, which focus on structural modeling, and ex-post assessments, which focus on empirical analysis with causal identification. The integration of these two axes has strengthened the ability to diagnose, simulate and design public policies at different levels, from local to global.

Ex-ante Assessments: Simulation Models

The ex-ante assessments were based on the creation of computer models to anticipate the direct and indirect economic impacts of climate change. Using frameworks such as interregional input-output matrices, CGE models, and integrated assessment models (IAMs), it was possible to project the impacts on productive sectors and specific regions, analyze the effects of mitigation and adaptation measures, simulate scenarios of water scarcity, natural disasters, and technological changes, and estimate the distributional and regional impacts of climate events and economic instruments.

These models have been applied at different scales: from the creation of interregional systems for the 27 Brazilian states and over 5,500 municipalities (using the IIOAS method – Interregional Input-Output Adjustment System) , to the adaptation of tools for international contexts such as Angola, Chile, Colombia, Egypt, Lebanon, Morocco, and Mexico. The ability to calibrate models based on scarce or incomplete data, using statistical and accounting procedures, was a significant methodological advantage.

Among the innovations, the inclusion of specific modules for water, agriculture, carbon, and energy stands out, such as in the BMARIA-H2O model, which aims to assess the impact of climate change on water availability in the twelve river basins of Brazil.

Ex-post Assessments: Causal Identification and Empirical Evidence

In addition, advanced econometric tools were used within the ex-post axis to measure the observed impact of extreme weather events and public interventions on economic variables. Techniques such as Difference-in-Differences (DID), Synthetic Control, Regression Discontinuity, and Instrumental Variables were used extensively.

These methods made it possible to quantify the impact of droughts, floods, and heat waves on gross domestic product (GDP), employment, and prices, to assess the impact of public policies to mitigate climate change and environmental regulation, to identify the population groups and regions most affected by climate change, and to estimate response elasticities to the scarcity of natural resources, such as water.

Integrating the Axes and Generating Evidence for Public Policies

The analytical strength of research networks lies in the integration of these two axes. The link between the predictive power of structural models and the realism of empirical data enables the validation of scenarios and the calibration of models based on observations, the incorporation of uncertainties and risks in public policy simulations, the translation of economic results into actionable statistics for public administration and diplomacy, and the response to different temporal and spatial scales, from long-term impacts to short-term shocks.

This model of applied science reinforces the role of economics as a link between natural and social systems, and provides critical technical inputs for the formulation of national and sub-national climate change strategies.

ECONOMIC IMPACTS OF CLIMATE CHANGE: THEMATIC EVIDENCE

The effects of climate change on the Brazilian economy are diverse and heterogeneous. Several studies conducted within the Rede Clima and INCT-MC2 show that the impacts vary widely across sectors and regions, reflecting structural inequalities, land use patterns, dependence on natural resources, and socio-economic vulnerabilities. In this section, we organize the results by key themes.

Agriculture: Vulnerability and Production Transformations

Agriculture is one of the sectors most affected by the impacts of climate change in Brazil, both because of its economic importance and because of its strong dependence on variables such as temperature, rainfall patterns, and water availability. This vulnerability is exacerbated by the heterogeneous structure of the sector, which combines large, highly mechanized enterprises with traditional forms of family farming.

Recent studies (Tanure, 2020; Souza and Haddad, 2022) show that the impact on agricultural productivity is not uniform. Regions such as the north and northeast, where family farming predominates, tend to experience greater losses, especially for crops such as cassava, maize and beans. In contrast, crops such as soybeans and sugarcane, which have greater technological adaptability and irrigation infrastructure, are more resilient to climate change.

Projections show that, by the end of the century, GDP losses due to climate impacts on agriculture could be between 0.4% and 1.8% per year, depending on the emissions scenario (RCP 2.6 or RCP 8.5). Indirect impacts transmitted through production chains and cross-sectoral linkages, tend to amplify direct losses, increasing the urgency of adaptation measures with a systemic approach.

In this context, Visentin et al. (2025) proposed an integrated approach to assess the economic impacts of droughts on irrigated agriculture under climate change scenarios. The framework combines different models (econometric, hydrological, CGE, and risk transfer models) to capture everything from the sensitivity of agricultural productivity to blue water reductions to regional economic impacts and the cost of climate insurance premiums. The results suggest that even a moderate reduction in water availability can trigger significant ripple effects, affecting not only agricultural production but also national food security.

Another important aspect in the debate on agricultural resilience is the use of chemical inputs. A study by Rodrigues et al. (2023) examined the productivity and side effects of pesticide use in Brazil, applying damage control and statistical regression models. The results indicate an excessive use of these products, with doses above the optimal level already being used in more than 4,000 municipalities in 2006. This not only leads to economic inefficiencies, but also increases environmental risks, such as biodiversity loss, the emergence of resistant pests, and the pollution of natural resources. These findings underscore the need for public policies that focus on the rational use of pesticides and the promotion of sustainable alternatives to pest control.

Although most studies on the effects of climate change on agriculture focus on rural areas, increasing attention is being paid to the effects of climate change in urban contexts. Research by Oliveira, Palialol, and Pereda (2021) shows that temperature shocks have a negative impact on urban labor productivity, as measured by wages. These results pave the way for new studies on the economic impact of heat waves in Brazilian cities, which has direct implications for the formulation of public policies in the areas of health, urban planning, and the reduction of socio-spatial inequalities.

Water: Scarcity, Flooding, Vulnerability and Resilience

Water occupies a strategic position at the interface between climate, economy, and society. Of all the means through which the impacts of climate change are spread, it is probably the most immediate and tangible, as it is central to human well-being, agricultural production, energy production and ecosystem conservation. In Brazil, changes in the hydrological system are already being observed, and projections indicate that extreme events, such as prolonged droughts and severe flooding are likely to become more frequent and severe over the course of the 21st century.

Water scarcity is becoming one of the most important factors for economic impact in the context of climate change. The BMARIA-H2O model, developed as part of INCT-MC2, simulates the impact of reduced water availability on Brazil's river basins and estimates cumulative economic losses of up to R$ 29.7 billion by 2099 in the most critical scenarios. The impacts are particularly intense in the eastern and western basins of the Northeast Atlantic, the Parnaíba, and the São Francisco basin and have a significant impact on water-intensive sectors such as irrigated agriculture, livestock farming, the pulp and paper, industry and on water and wastewater services themselves.

Studies such as that by Rocha (2022) show that the low price elasticity of water demand hinders spontaneous adjustments to supply shocks, and makes scarcity a trigger for abrupt economic imbalances. The recommendation is clear: strengthen water policy with measures that combine infrastructure, reuse, efficient technologies, and fair pricing mechanisms, such as progressive tariffs and environmental offsets.

The vulnerability of urban water supplies also requires attention. In the case of the São Paulo metropolitan region, Vieira and Haddad (2020) developed the Weighted Travel Time Index (TTI), to measure the impact of flooding on urban mobility and, thus also on economic productivity. By combining data from the Uber Movement platform and household mobility surveys, the index proves to be a valuable tool for managing public transport and climate adaptation policies in large urban centers.

In addition, the interactions between climate, water, and agricultural production are particularly sensitive. Simões (2025) used interregional input-output and computable general equilibrium models to estimate the direct and indirect economic impacts of agricultural productivity losses caused by the recent hydrological events in Rio Grande do Sul. His results show that direct losses of R$8.5 billion in crops such as soybeans, corn, and rice can trigger systemic impacts of up to 0.14% of national output, with average multipliers of 3.5 times. These impacts are concentrated in the interior of the state economy, and highlight the importance of territorial public policies focused on water and production resilience.

Emissions, Consumption and Mitigation Policies

Brazil has a unique greenhouse gas (GHG) emissions trajectory, with a strong concentration in the land use, agriculture, and transportation sectors. This composition poses a particular challenge for the formulation of mitigation measures, which must take into account not only the quantities of emissions, but also the sectoral and regional distribution of the associated economic impacts.

Studies conducted in the research networks associated with INCT-MC2 suggest that there is scope for introducing economic instruments, such as carbon markets and emissions taxation, as more efficient alternatives to traditional governance and control. Carvalho's (2022) dissertation shows that, market mechanisms for compliance with Brazil's Nationally Determined Contributions (NDCs), have lower macroeconomic costs, although they entail distributional effects that need to be considered.

Three policy scenarios were tested: (i) a broad carbon market, that includes all sectors, (ii) a market limited to subsectors, and (iii) an inflexible policy based on binding targets. The results show that the broad market is environmentally more effective but has a greater redistributive effect. The narrow market, on the other hand, requires higher carbon prices, which affects sectors such as livestock farming and road transport more.

At the same time, demographic changes and changing consumption patterns also influence the dynamics of emissions. Research by Carvalho, Santiago, and Perobelli (2017, 2018) and Carvalho et al. (2021) shows that population aging and income growth tend to reduce per capita carbon intensity, although they can trigger sectoral changes that require continuous monitoring to reconcile economic growth and environmental objectives.

The literature has also focused on analyzing the distributional effects of carbon pricing policies. Moz-Christofoletti and Pereda (2021) assessed the socioeconomic impact of a hypothetical carbon tax in Brazil, based on a hybrid input-output model and a censored system of demand equations (QUAIDS). Considering two tax scenarios (40 USD/tCO_2 and 80 USD/tCO_2), the results indicate that the measure would be effective in reducing emissions, with a potential reduction of up to 4.2%, but would be slightly regressive, even when applying offset transfers. The welfare loss ranges from 0.06% for the richest households to 0.10% for the poorest. This shows how important it is to calibrate policies with redistributive mechanisms that mitigate their negative impact on equity.

The historical analysis of Brazilian emissions, conducted by Albuquerque et al. (2020), underlines the need for action. The study, based on data from the Greenhouse Gas Emissions and Removals Estimation System (SEEG), shows that, after a period of decline between 2004 and 2010, emissions began to rise again, reaching 2.17 billion tons of CO_2e in 2019, an increase of 9.6% over the previous year. Deforestation accounted for 44% of total emissions, followed by agriculture (28%) and the energy sector (19%). The authors emphasize the growing carbon intensity of the Brazilian economy and the difficulty of achieving agreed targets, as set out in the National Policy on Climate Change (PNMC).

In this context, strategies to increase energy efficiency appear to be promising alternatives. Magalhães and Domingues (2016), use a computable general equilibrium model, to show that energy efficiency strategies can reconcile environmental goals with economic development and the reduction of inequality. The results indicate simultaneous social and environmental benefits, highlighting the potential of these strategies as part of a just transition to a low-carbon economy.

In addition, Souza, Ribeiro, and Perobelli (2016) estimate the economic impact of different levels of emission reductions based on a national input-output matrix. The results show that a 1% reduction in total emissions can lead to a reduction in total production of up to 0.60%, depending on the stringency of the measures implemented. These results reinforce the recommendation for calibrated sectoral policies capable of minimizing transition costs in the short term while promoting long-term structural change consistent with Brazil's climate commitments.

Regional Growth and Inequalities

Climate change is exacerbating the historically grown regional inequalities in Brazil. The North and Northeast regions are particularly vulnerable, both because of the direct impact on sensitive sectors, such as agriculture and water resources, and because of limited institutional, financial, and technological responses.

Recent studies such as those by Tanure (2020) and Rocha (2022) show that potential overall losses in national GDP can be partially offset by gains in states in the south and southeast, such as São Paulo, Paraná, and Rio Grande do Sul. However, this apparent compensation masks serious losses of wealth in less developed regions, indicating that climate change has significant redistributive effects on the national territory.

A study by Sass (2021) highlights this type of vulnerability in the urban context by assessing the impact of droughts on industrial activity in the metropolitan region of São Paulo. By combining an econometric model and a spatial general equilibrium model (based on the BMARIA framework), the author finds greater vulnerability in capital- and technology-intensive sectors, such as chemicals, pharmaceuticals, and electronics. Water scarcity has a direct impact on the productivity of these sectors, with negative effects on income and employment in metropolitan communities and indirect effects on transportation, construction, and personal services. The sub-basin analysis highlights thateconomic losses are higher where water availability is more constrained and emphasizes the urgency of integrated strategies to mitigate climate risks in urban areas.

The importance of regional asymmetries was also highlighted in the first National Assessment Report of the Brazilian Panel on Climate Change, published in 2014. In its economic chapter on impacts, vulnerability and adaptation, the report summarizes empirical evidence from the first decade of the 21st century, based on econometric and general equilibrium models and climate simulations from the IPCC (2007). The summary shows that the impacts of climate change vary widely across sectors and regions, with agriculture and livestock among the most vulnerable sectors, particularly in the North, Northeast, and Central-West regions. In contrast, the South region experiences relative gains in certain scenarios, with a projected growth in regional GDP of up to 2% by 2050, in addition to the migration of crops such as coffee, cassava, and sugarcane. These geo-economic shifts would also be accompanied by an increase in poverty, internal migration, and economic concentration in the Center-South region of the country, requiring policy responses focused on territorial and social justice.

The role of natural resources in regional development plays a central role in this debate. Haddad and Araújo (2025) make an important contribution by quantifying the importance of the blue economy in Brazil, and using an interstate input-output model to map the interdependencies between coastal and inland regions. The results show that activities directly related to the maritime economy accounted for 2.91% of national GDP and 1.07% of employment in 2019, especially in the states of Rio de Janeiro, São Paulo, and Espírito Santo. If indirect effects are taken into account, these figures rise to 6.39% of GDP and 4.45% of employment, with significant multipliers for GDP (2.20) and employment (4.16). The study also shows that landlocked states, such as Minas Gerais, also benefit from productive linkages, underlining the importance of coordinated interregional policies for the sustainable development of coastal economies.

In light of these findings, the research networks recommend that public climate adaptation policies incorporate distributional, territorial, and intergenerational criteria. Instruments such as compensation funds, targeted investments in more vulnerable regions, and resilient social safety nets should be part of a broader just transition strategy capable of reducing inequalities exacerbated by the climate crisis.

Contributions to Public Policy Formulation and Climate Adaptation

The role of economics is not limited to analyzing impacts or developing scenarios. One of its central tasks, especially in the context of the climate crisis, is to provide qualified input for the formulation and evaluation of public policies. Both the economic sub-network of the Rede Clima and the economic sub-component of INCT-MC2 have worked directly in this regard, contributing to the design of mitigation and adaptation instruments, guiding sectoral policies, and providing technical support to Brazilian climate diplomacy.

Since ratifying the Paris Agreement in 2016, Brazil has made progressive climate commitments through its NDCs. The latest targets call for a 59% to 67% reduction in net GHG emissions by 2035, compared to 2005 levels (BRASIL, 2024). To achieve these targets responsibly and efficiently, analytical tools are needed to assess the costs, benefits, and distributional effects of policy alternatives.

In this context, the research networks supported by Brazilian climate science have played a fundamental role. Studies conducted within these networks have examined the economic impact of different carbon market formats (Carvalho, 2022), simulated industrial policies based on clean technologies (Tanure, Porsse, and Domingues, 2021), analyzed the sectoral impact of environmental taxes and subsidies, and assessed the expected impact on welfare, employment, and economic growth.

The results provide valuable insights for guiding public policy by highlighting the trade-offs between environmental sustainability, social equity and economic viability. By informing decision-makers about the differentiated impacts of climate policy, these studies promote greater transparency, predictability, and social acceptance of the measures adopted.

These findings stress the importance of careful institutional design of carbon pricing instruments. By combining environmental efficiency with appropriate social compensation, it is possible to achieve an ecological transition that is also just and inclusive.

Tax Reforms and Economic Instruments

A new research front focuses on the intersection of tax policy and environmental sustainability. A new project, launched in 2024 with support from the Bezos Earth Fund and the Climate and Society Institute, is investigating the potential impact of Brazil's tax reform on land use, deforestation, and sectoral resource allocation, from an ecological transition perspective. The aim is to identify mechanisms that combine economic efficiency with environmental justice, through instruments such as tax incentives for low-carbon sectors, tax breaks for clean technologies, and targeted penalties for carbon-intensive activities or those associated with deforestation.

This agenda is a response to the growing demand for tax policies that are consistent with national climate goals, while strengthening the role of economics in designing regulatory instruments that promote innovation, transparency, and equity.

In this context, Araújo and Féres (2024) analyzed the impact of a specific regulatory measure: the elimination of the requirement of prior authorization for the export of domestic wood in February 2020, promoted by an interpretative decree of Ibama (Brazilian Institute of Environment and Renewable Natural Resources). With this change, physical inspections of export shipments were also suspended. Using regression models with panel data, the authors estimated a 10.5% increase in timber export volumes in 2020, even after controlling for prices and destination markets. The results suggest that the relaxation of regulations may have favored the intensification of (possibly illegal) trade in domestic timber, which has an impact on deforestation.

Furthermore, Haddad et al. (2024) quantified the economic drivers of pressure on forest area in the legal Amazon, focusing on domestic, regional, and international demand. Using an interregional input-output matrix broken down into 27 regions of the Legal Amazon, and combining it with sectoral emissions and deforestation data, the study shows that about 60% of the deforested area meets the demand of the rest of the country, especially in the Center-South. International demand accounts for about 23%, while local demand accounts for only 17%. Beef production appears to be the main cause of tree cover loss. It is responsible for more than 93% of the estimated deforestation, mainly for domestic consumption. The authors argue that fiscal and regulatory measures aimed at traceability of production and changes in the structure of national demand may be crucial to slow the progression of deforestation.

In the area of market instruments, Neto and Remígio (2019) analyzed the legal, fiscal and financial aspects related to certified emission reductions (CERs) under the Clean Development Mechanism (CDM) in Brazil. The study shows that high transaction costs and the lack of clarity about the legal nature of CERs are obstacles to the expansion of these instruments. In particular, the authors emphasize that proponents often expect to sell the credits at a high discount, given the uncertainty of revenues and the high interest rates charged by financial institutions. In addition, the tax burden on trading and receiving CERs contributes to reducing their economic effectiveness. Given this situation, the authors recommend the development of a clear legal framework that provides legal certainty and fiscal stability as an essential step towards consolidating market mechanisms aimed at the transition to a low-carbon economy.

Finally, the analysis by Ruggiero et al. (2022) offers an innovative perspective on the impact of decentralized environmental tax incentives. The authors evaluated the impact of the Ecological ICMS — a tax transfer mechanism that rewards communities for conserving protected areas — on the creation of new protected areas in the Atlantic Forest. Using a difference-in-differences (DiD) econometric approach with data from 1,467 municipalities between 1987 and 2016, the study found positive effects, particularly in the creation of less restrictive and cost-effective protected areas, especially when proposed at the municipal level. The results highlight the potential role of intergovernmental fiscal instruments in inducing desirable environmental behaviors in subnational contexts, provided they are designed with institutional capacity and local incentives in mind.

Climate Diplomacy and International Negotiations

The research networks have also provided qualified technical support for Brazil's presence in multilateral forums. The models developed, especially those with regional detail, make it possible to assess the impact of international climate policies on the Brazilian economy, anticipate risks to production chains and identify opportunities related to the transition to more sustainable markets.

In addition, the data and evidence generated by the researchers have supported technical reports, developed negotiating positions, and provided arguments for the UNFCCC processes, expanding Brazil's strategic capacity in the diplomatic arena.

The inclusion of economic models tailored to the Brazilian reality strengthens the legitimacy of Brazilian participation in international negotiations, while helping to technically align domestic decisions with the commitments made in the Paris Agreement.

In this context, Luedemann, Marengo, and Klug (2016) emphasize the central role of cities as strategic actors in climate change mitigation and adaptation efforts. The authors analyze the development of national public policies such as the National Plan for Disaster Risk Management and Response and the establishment of the National Center for Natural Disaster Monitoring and Early Warning (Cemaden), both launched in 2011, as examples of integrated and multi-scalar approaches. These initiatives strengthen the resilience of cities and provide a technical basis for Brazil's international action on adaptation issues.

Calegari et al. (2023) added to this debate by examining how Brazilian municipalities are increasingly recognized as key actors in confronting climate change through locally grounded strategies. Their study highlights the interplay between national policy frameworks and municipal-level initiatives, showing that effective climate governance requires vertical coordination and institutional capacity at the local scale. By mapping the evolution of municipal climate action in Brazil, the authors demonstrate both the opportunities and constraints faced by cities in implementing adaptation and mitigation measures. The contribution of this paper lies in its systematic analysis of subnational climate governance, which complements earlier work on national institutions by emphasizing how urban actors translate broader policy frameworks into practical, place-specific responses. This perspective enriches the literature by connecting urban resilience with multi-level governance, shedding light on the scalar interdependencies that shape Brazil's capacity to address climate risks.In this sense, the Brazilian experience is highlighted as an important reference for developing countries, especially those with similar urbanization patterns. The study also highlights the transformative potential of international cooperation between cities in Latin America, Asia, and Africa, where social and environmental vulnerabilities intertwine. This South-South cooperation is seen as a promising way to strengthen local capacities and develop climate solutions that focus on reducing inequalities.

Integration with the financial sector and development banks

Another important step forward was the inclusion of climate criteria in the credit and investment analysis processes, in cooperation with public financial institutions such as Banco do Nordeste. Tools have been developed to estimate the carbon footprint, water consumption, and energy intensity by production chain, as well as to assess climate risks in financed projects and integrate environmental, social, and governance (ESG) criteria into financial decisions (Haddad et al., 2024d).

These innovations are a direct response to Article 2.1.c of the Paris Agreement, which states that financial flows must be aligned with a low-emission and climate-resilient development pathway. By translating climate risks and opportunities into operational metrics, these tools bring the financial system closer to the commitments of the green transition.

Tozato et al. (2019) discuss the methodological and institutional challenges of identifying and tracking climate-related public spending in Brazil, in the context of commitments made under international agreements such as Nationally Appropriate Mitigation Actions (NAMAs) and NDCs. Based on a document analysis and interviews with key stakeholders, the authors highlight the fragmentation of budget information and the lack of systematic mechanisms to track climate spending.

The study shows that, although the country has developed specific initiatives, such as the "climate agenda" in the 2012-2015 multi-year plan and partnerships with the Inter-American Development Bank (IDB), it remains difficult to distinguish and classify climate spending in the public budget. This restriction impairs transparency, long-term planning, and the coherence of climate measures. The authors also warn against the coexistence of fossil fuel subsidies and climate change initiatives, which can undermine progress towards a low-carbon economy.

These findings point to the importance of a budget classification system that enables the identification of positive and negative climate action, as well as clear regulatory frameworks that guide public investment. Strengthening fiscal governance of climate action is essential for mobilizing resources in a way that is consistent with national and international commitments.

PATHWAYS TO THE NOW: INNOVATION, CLIMATE JUSTICE, AND INTERDISCIPLINARY INTEGRATION

The consolidation of the climate economy in Brazil over the last two decades is a great success. However, future challenges require even more ambitious progress, both methodologically and institutionally. Research networks play a fundamental role not only in generating knowledge, but also in connecting science, policy, and society. In this section, we highlight three strategic vectors to strengthen this agenda: methodological innovation, climate justice, and interdisciplinary integration.

Methodological Innovation: Data, Models, and Technologies

The deepening of climate impacts and the complexity of economic dynamics require continuous improvement of analytical models. Priority areas include: Multi-level integration, with models that combine different geographic levels — such as municipalities, states, river basins, and economic regions — while retaining sectoral detail; Coupled modeling, through IAM, that links economic, hydrological, climatic, and ecological systems — as in the BMARIA-H2O model and simulations developed by Visentin et al. (2025), which aim to formulate multi-year insurance policies against extreme hydrological events; the use of big data and machine learning techniques to enrich databases, detect non-linear patterns, and improve the predictive capacity of models; and, finally, the explicit inclusion of uncertainties and risks through probabilistic simulations, stochastic scenarios, and sensitivity analyzes, that increase the robustness of public policy recommendations.

In addition, it is important to strengthen and expand open data platforms and accessible simulation tools that equip public administrations, policy makers and civil society organizations. Democratizing access to these tools means expanding society's potential to address climate challenges, by encouraging local appropriation of science and collective development of solutions.

The "Economics of Climate" study (Margulis and Dubeux, 2011) is considered a national reference for the use of integrated, multisectoral modeling to analyze the economic impacts of climate change. At the international level, innovative methodological initiatives such as that of León et al. (2022) stand out. Although applied to the context of geological disasters and not to Brazil, it presents a coupled framework that can capture the cascading impacts of extreme events on the economy, and shows the potential for adaptation to climate scenarios. The combined use of multi-sectoral, inter-regional models and complex shock propagation networks demonstrates how hybrid approaches can push the boundaries of knowledge and serve as a basis for adaptation measures such as insurance schemes and socio-economic safety nets.

Climate Justice: Inequality, Inclusion, and Responsibility

The effects of climate change are not neutral: they disproportionately affect the poorest, marginalized regions, and historically vulnerable groups. Economics must, therefore, contribute to a climate justice approach by analyzing the distributional impacts of climate policies, taking into account variables such as income, ethnicity, gender, geographic location, and access to public goods; by developing compensatory instruments, such as conditional transfers, adaptation funds, and safety mechanisms that target vulnerable populations; and by paying attention to the informal economy and local production chains, which are often not considered in traditional models but are essential for the resilience of communities.

Incorporating climate justice as a structuring principle expands the legitimacy of public policy and ensures that the transition to a low-carbon economy occurs in a fair and inclusive manner.

Interdisciplinary Integration: A New Research Architecture

The experiences of the Rede Clima and INCT-MC2 show that the greatest scientific progress comes from collaboration between different fields of knowledge. Overcoming disciplinary silos is an essential prerequisite for tackling the complexity of today's climate challenges.

Training a new generation of researchers requires collaborative research environments, with access to different methods, participation in international networks, and a focus on solving concrete problems. Initiatives such as the National Observatory for Water Security and Adaptive Management (ONSEAdapta) point the way to the future by integrating engineering, natural sciences, economics, and public policy.

Building this new interdisciplinary architecture also requires a strengthening of scientific communication. Data and models must be understandable, accessible, and applicable for public administration, private actors, and civil society organizations. An emblematic example is the work of Zatz (2025), which combines communication and economics by presenting, in a journalistic format, indicators for the marine economy in Brazil in combination with local narratives, such as that of the municipality of Caiçara. Another relevant example is the study by Tafarello et al. (2025), which combines education and economics in the analysis of educational practices focused on the adaptive management of freshwater and coastal waters. The work explores how Sustainable Development Goals (SDGs) 14 and 15 can be integrated into basic education, and proposes didactic and pedagogical strategies aligned with marine spatial planning (MSP), the Blue Curriculum, and economic tools to promote conservation.

These experiences emphasize that climate economics needs to be developed in dialog with other fields of knowledge and social sectors, to create a common, action-oriented knowledge base.

CONCLUSION: THE ROLE OF THE ECONOMY IN THE BRAZILIAN CLIMATE TRANSITION

The climate emergency is a civilizational challenge. To meet it, we must align productive, institutional, and financial systems with a new paradigm of sustainable and inclusive development. Economics, as an applied social science, has powerful tools to identify the causes, map the impacts, and propose solutions to the climate crisis, provided it is mobilized with technical rigor, social sensitivity, and a commitment to the common good.

In this chapter, we provided an overview of the main contributions of the Rede Clima and INCT-MC2, two key initiatives in building a robust and action-oriented Brazilian climate science. We showed how these networks have developed sophisticated analytical models capable of anticipating economic impacts, evaluating public policies, and simulating climate scenarios. They have highlighted regional and sectoral inequalities in the impacts of climate change on Brazil, provided concrete support for the formulation of NDCs and for Brazil's diplomatic engagement in international forums, promoted integration between science, government, the productive sector, and civil society, and generated a new generation of researchers and tools capable of responding to new challenges with innovation and ethical engagement.

The data presented shows that Brazil has the technical, institutional, and scientific capacity to lead ambitious climate change solutions. However, these capacities need to be translated into consistent public policies, adequate financing strategies, and a social pact that places environmental sustainability at the center of the national agenda.

The 30th Conference of the Parties to the UNFCCC (COP-30), which will take place in Brazil, represents a historic opportunity to reposition the country as a global leader in the fight against climate change. Economics can and should be one of the pillars of this leadership with its data, models and arguments.

REFERENCES

ALBUQUERQUE *et al*. Análise das emissões brasileiras de gases de efeito estufa e suas implicações para as metas de clima do Brasil 1970-2019. 2020. Observatório do Clima. Disponível em: http://seeg.eco.br. Acesso em: 10/07/2025.

ANDRADE, Israel.; CARVALHO, Andrea B. Planejamento Espacial Marinho como ferramenta de gestão de política pública para a Amazônia Azul. Textos para Discussão. IPEA. Brasília, 2025. Disponível em: https://repositorio.ipea.gov.br/server/api/core/bitstreams/3dcdd7d5-9978-4b0f-8627-127b8811afa5/contente. Acesso em: 10/07/2025.

ARAÚJO, Cláudio; FÉRES, José Gustavo. Passando a boiada: efeitos da suspensão da inspeção de exportações de produtos de madeira nativa. Radar: tecnologia, produção e comércio exterior: n. 75.: Instituto de Pesquisa Econômica Aplicada - IPEA, 29 abr. 2024.

BRANCO, Danyelle; FÉRES, José. Weather shocks and labor allocation: evidence from Northeastern Brazil. Anais do 45° Encontro Nacional de Economia ANPEC. 2017. Disponível em: https://en.anpec.org.br/previous-editions.php?r=encontro-2017. Acesso em: 19/07/2025.

BRASIL. Ministério do Meio Ambiente e Mudança do Clima (MMA). "Nova NDC do Brasil representa paradigma para o desenvolvimento do país", diz Marina na COP29. Brasília: MMA, 14 nov. 2024. Disponível em: https://www.gov.br/mma/pt-br/assuntos/noticias/nova-ndc-do-brasil-representa-paradigma-para-o-desenvolvimento-do-pais-diz-marina-na-cop29.BRASIL. *Plano Nacional de Adaptação à Mudança do Clima: estratégias setoriais e temáticas*. Vol. II. Brasília: Ministério do Meio Ambiente, 2016.

CALLEGARI, Camila et al. The Role of Cities: Linking Integrated Assessment Models to Urban Solutions. Sustainability, v. 15, n. 6, p. 4766, 2023.

CARVALHO, Terciane S; SANTIAGO, Flaviane S; PEROBELLI, Fernando S. Mudanças demográficas no Brasil e seus impactos sobre as emissões de gases de efeito estufa: uma análise de insumo-produto. Anais do 45º Encontro Nacional de Economia ANPEC. 2017. Disponível em: https://www.anpec.org.br/encontro/2017/submissao/files_I/i11-1fc8b5b5cceac736c4b048ab2f193dca.pdf. Acesso em: 19/07/2025.

CARVALHO, Terciane Sabadini; SANTIAGO, Flaviane; PEROBELLI, Fernando Salgueiro. Demographic changes and its impacts on consumption and greenhouse gas emissions in Brazil: a computable general equilibrium model approach. 2018. Disponível em: https://ageconsearch.umn.edu/record/332970/files/8948.pdf

CARVALHO, Terciane S.; SANTIAGO, Flaviane S.; PEROBELLI, Fernando S. Demographic change in Brazil and its impacts on CO_2 emissions. Economic Systems Research, v. 33, n. 2, p. 197-213, 2021.

CARVALHO, Micaele M. de. Efetividade econômica, social e ambiental da precificação de carbono na economia brasileira para o alcance de metas de redução de emissões de gases de efeito estufa. Tese de Doutorado. Centro de Desenvolvimento e Planejamento Regional. Universidade Federal de Minas Gerais. Belo Horizonte, 2022.

COI-UNESCO. 2022. Um Novo Currículo Azul – Um guia prático para formuladores de políticas, Paris (Manuais e Guias da COI, 90).

HADDAD, Eduardo A. Trade and Interdependence in Lebanon: An Interregional Input-Output Perspective. Journal of Development and Economic Policies, v. 16, n. 1, p. 5–45, 2014.

HADDAD, Eduardo A. *et al*. The economic impacts of flooding in Egyptian port cities. Policy Paper. PP02/25. Jan, 2025. Disponível em: https://www.policycenter.ma/publications/economic-impacts-flooding-egyptian-port-cities. Acesso em: 19/07/2025.

HADDAD, Eduardo A. *et al.* Assessing the economic impacts of Al-Haouz earthquake: damages and recovery strategy. 2024a.

HADDAD, Eduardo A. *et al.* Economic impacts of the 2023 earthquake in Morocco. 2024b.

HADDAD, Eduardo A. *et al.* Economic drivers of deforestation in the Brazilian Legal Amazon. Nature Sustainability, 1 set. 2024c.

HADDAD, Eduardo Amaral et al. (org.). A matriz de insumo-produto e a estrutura produtiva da região nordeste. Fortaleza: BNB, 2024d.

HADDAD, Eduardo et al. Impactos multissetoriais, riscos, vulnerabilidades e oportunidades. In: PAINEL BRASILEIRO DE MUDANÇAS CLIMÁTICAS (PBMC). Primeiro Relatório de Avaliação Nacional – Volume 2: Impactos, Vulnerabilidades e Adaptação. Brasília: UNESCO, 2014.

HADDAD, Eduardo A.; ARAÚJO, Inácio F. Shades of blue: the regional structure of the ocean economy in Brazil. npj Ocean Sustainability, v. 4, n. 1, p. 15, 23 abr. 2025.

HADDAD, Eduardo A. *et al*. Uneven integration: the case of Angola. 2020a. Disponível em: <www.policycenter.ma>.

HADDAD, Eduardo A. et al. Interstate input-output model for Mexico, 2013. Análisis Económico, n. 90, p. 7–43, 2020b.

HADDAD, Eduardo A. *et al*. Interregional Input-Output Matrix for Colombia, 2012. Bogotá: 2016.

HADDAD, Eduardo Amaral; BONET, Jaime; HEWINGS, Geoffrey J. D. The Colombian Economy and Its Regional Structural Challenges: A Linkages Approach.: Springer, 2023.

LEÓN, J. A. *et al*. Risk caused by the propagation of earthquake losses through the economy. Nature Communications, v. 13, n. 1, 1 dez. 2022.

LUEDEMANN, Gustavo; MARENGO, José A.; KLUG Letícia B. International Agreements, Climate Change and Urban Challenges. In: BALBIM, Renato (Ed.). The geopolitics of cities: old challenges, new issues. Chapter: 11. Ipea, 2016

MAGALHAES, Aline; DOMINGUES, Edson Paulo. Aumento da eficiência energética no Brasil: uma opção para uma economia de baixo carbono? Economia Aplicada, v. 20, n. 3, 2016, pp. 273-310.

MARGULIS, Sergio; DUBEUX, Carolina Burle Schmidt. Economia da mudança do clima no Brasil. 2011.

MOHOR, Guilherme S; MENDIONDO, Eduardo Mario. Economic indicators of hydrologic drought insurance under water demand and climate change scenarios in a Brazilian context. Ecological Economics, v. 140, p. 66–78, 1 out. 2017.

MOZ-CHRISTOFOLETTI, Maria Alice; PEREDA, Paula Carvalho. Winners and Losers: the distributional impacts of a carbon tax in Brazil. Ecological Economics 183 (2021) 106945.

NETO, Habib Jorge, F; REMIGIO, Hipolito G. Legal nature and credit and tax issues of certified emission reductions. In: Legacy of the CDM: lessons learned and impacts from the Clean Development Mechanism in Brazil as insights for new mechanisms. FRANGETTO & LUEDEMANN, G.; VEIGA, ANA PAULA (Orgs.). Ipea. Brasília, 2019. Disponível em: https://repositorio.ipea.gov.br/handle/11058/9534 . Acesso em 05/07/2025.

OLIVEIRA, Jaqueline; PALIALOL, Bruno; PEREDA, Paula. Do temperature shocks affect non-agriculture wages in Brazil? Evidence from individual-level panel data. Environment and Development Economics, v. 26, n. 5–6, p. 450–465, 5 out. 2021.

ROCHA, Ademir. Climate Change, Water Resources and Economic Impacts: An Analysis of Brazilian Hydrographic Regions. Tese de Doutorado. Faculdade de Economia, Administração e Contabilidade, Universidade de São Paulo. São Paulo, 2022.

RODRIGUES, Loredany C. C.; FÉRES, José Gustavo; COELHO, Alexandre Bragança. Pesticide use in Brazil: virtuous or vicious cycle? Anais do 51º Encontro Nacional de Economia (ANPEC). Rio de Janeiro, 2023.

RUGGIERO, P. G. C. et al. The Brazilian intergovernmental fiscal transfer for conservation: A successful but self-limiting incentive program. Ecological Economics, v. 191, 1 jan. 2022.

SASS, Karine. Mudanças climáticas, secas e impactos econômicos: uma análise para a Região Metropolitana de São Paulo. Tese de Doutorado. Faculdade de Economia, Administração e Contabilidade, Universidade de São Paulo. São Paulo, 2021.

SIMÕES, Marcelo P. Avaliação do impacto sistêmico da perda de produtividade agrícola no Rio Grande do Sul via Insumo-Produto e Equilíbrio Geral Computável: Universidade de São Paulo, 2025.

SOUZA, Bruno; HADDAD, Eduardo. Climate change in Brazil: dealing with uncertainty in agricultural productivity models and the implications for economy-wide impacts. Spatial Economic Analysis, v. 17, n. 1, p. 83–100, 2022.

SOUZA, Kenia B; RIBEIRO, Luiz Carlos de S; PEROBELLI, Fernando S. Reducing Brazilian greenhouse gas emissions: scenario simulations of targets and policies. Economic Systems Research, 2016.

TAFARELLO, Denise.; CARVALHO, Andrea B.; GOMES, Ana Paula A.; BENSO, Marcos Roberto.; CALIJURI, Maria do Carmo.; MEDIONDO, Mario Eduardo. Como práticas de educação ambiental climática contribuem para segurança hídrica e gestão adaptativa? XXVI Simpósio Brasileiro de Recursos Hídricos. Vitória. 2025.

TANURE, Tarik M. do P. Mudanças climáticas e agricultura no Brasil: impactos econômicos regionais e por cultivo familiar e patronal. Tese de Doutorado. Centro de Desenvolvimento e Planejamento Regional. Universidade Federal de Minas Gerais. Belo Horizonte, 2020.

TANURE, Tarciane Marques do Prado; PORSSE, Alexandre Alves; DOMINGUES, Edson Paulo. Política industrial verde no Brasil: impactos econômicos de opções de mitigação de gases de efeito estufa – uma análise através de equilíbrio geral computável (EGC). Anais do XXIV Encontro de Economia da Região Sul – ANPEC Sul, 2021.

TOZATO, Heloisa; LUEDEMANN, Gustavo; FRANGETTO, Flavia W. & MOREIRA, Carmen T.C. Abordagens metodológicas para a identificação dos gastos com mudança do clima: desafios para o Brasil. Boletim regional, urbano e ambiental, 21, 149-162, Julh-dez, 2019. Disponível em: http://repositorio.ipea.gov.br/handle/11058/9683 . Acesso em: 22/07/2025.

VIEIRA, Renato S.; HADDAD, Eduardo A. A weighted travel time index based on data from Uber Movement. EPJ Data Science, v. 9, n. 1, 1 dez. 2020.

VISENTIN, Jaqueline C. et al. Insurance for adaptation to hydrological anomalies: analysis using Computable General Equilibrium Models for Brazilian hydrographic regions: INCT para Mudanças Climáticas Fase 2. Conferência de resultados. Caderno de resumos, 2025.

ZATZ, Diana. (2025). Economia do mar. Revista Climacon. 2025. No prelo.

ZHOU, Lei; CHEN, Zhenhua. Are CGE models reliable for disaster impact analyses? Economic Systems Research, v. 33, n. 1, p. 20–46, 2021.

Aloisio Lopes P. de Melo

National Secretary for Climate Change at the Ministry of Environment and Climate Change. He holds a degree in Agricultural Engineering from ESALQ/USP, a specialization in Climate Change Economics from Cambridge University, and a master's degree in Development and Agriculture from UFRRJ. He is a civil servant specializing in Public Policy and Government Management.

COP30
BRASIL
AMAZÔNIA
BELÉM 2025

MINISTRY OF
SCIENCE, TECHNOLOGY AND INNOVATION

BRAZILIAN GOVERNMENT
BRASIL
STANDING WITH THE BRAZILIAN PEOPLE

ISBN: 978-85-7013-244-4
CBL
9 788570 132444