

CORAL BLEACHING AND CLIMATE CHANGE



The cover of this report was created by Joana Lira

Joana Lira is a visual artist who authentically values and exalts Brazilian cultural roots, drawing on her Pernambuco essence in a contemporary and original way. Her identity is manifested in a multifaceted production, capable of creating and promoting relationships and experiences that provoke and engage the public. Often drawing inspiration from women, Joana conveys the strength, beauty, and diversity of Brazil through a unique and vibrant style. With a diverse portfolio, she has worked on projects that cross borders—from exhibitions in cultural centers in Brazil and abroad to collaborations with renowned brands and institutions. She works in areas such as set design, graphic design, illustration, and urban interventions, always with an aesthetic that pulsates with identity and emotion. Her projects occupy spaces, reinvent landscapes, and foster visual dialogues that stimulate reflection and deep connections.



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CORAL BLEACHING AND CLIMATE CHANGE

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Synthesis Report

Coral Bleaching and Climate Change

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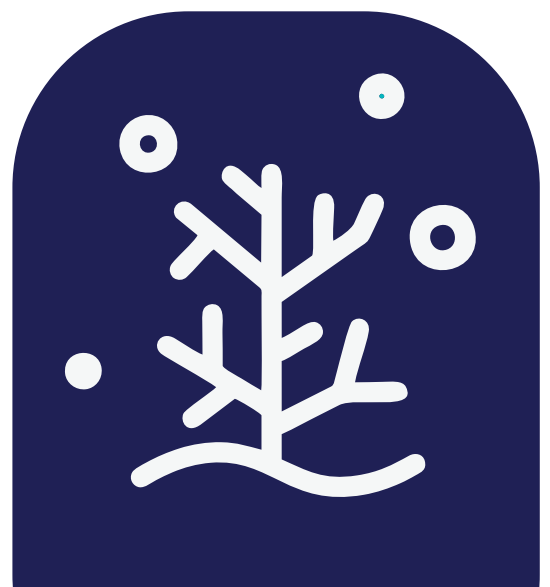
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1

INTRODUCTION



1. INTRODUCTION

The complexity of the effects of global environmental changes, including future climate projections, calls for novel approaches to counter the rapid decline of coral reefs, one of the first and most impacted megadiverse ecosystems that provide essential benefits to humankind. These inter and transdisciplinary approaches are essential for understanding the interactions between social, biophysical and ecological systems, characterizing impact risks, vulnerability and adaptation solutions.

The Synthesis Center on Environmental and Climate Change - SIMACLIM (<https://simaclim.com.br/>) is aligned with this mission, combining a close relationship to state policies and strong independence. It aims to integrate accumulated and ongoing research from various national and international networks and research groups, organizing information and assisting state planning to achieve goals set out in national plans and Climate Change agreements. The objectives of SIMACLIM are:

- (i) Integrate the accumulated and ongoing research of the Brazilian Research Network on Global Climate Change - Rede Clima (<https://redeclima.cemaden.gov.br/>) with the experiences developed by other national and international research networks and groups in a pioneering manner, organizing/synthesizing information and assisting in the planning of the Brazilian State regarding the fulfillment of the goals committed to in agreements related to climate and biodiversity changes, as well as in the processes of drafting and reviewing documents and treaties related to these topics.
- (ii) Support Brazilian Ministry of Science, Technology and Innovation (MCTI) strategies and initiatives related to the targets outlined in the United Nations' Sustainable Development Goals (SDGs).
- (iii) Identify opportunities for actions on climate change adaptation, for the economic valuing the ecological transition and the potential of renewable energy and Brazilian biodiversity as a central element of the bioeconomy, as well as strategies for the country's sustainable development, including future projections. This is justified by the complex effects of global climate and environmental change.

Of the 12 planned synthesis products, the first two themes chosen for separate development were the **Coral Reef Climate Crisis**—characterized by increasingly severe and prolonged bleaching events—and the **Amazon Rainforest Tipping Point**. Both Coral Reefs and the Amazon Rainforest are biodiversity hotspots, representing ecosystems that are both vulnerable to climate change and critical to global environmental stability.

While corals and other reef-building organisms have existed for over 200 million years, human-induced conditions now threaten their function and persistence. The potential loss associated with the destruction of coral reef systems is immense for most tropical countries that depend on them for physical, biological, economic and cultural benefits (Good and Bahr, 2021; Putnam et al., 2017). With coral reefs distributed along a vast expanse of its coast, Brazil is certainly among those.



1.1. About the Workshop

The **I Workshop on Coral Bleaching and Climate Change** was one of the two first synthesis workshops of SIMACLIM. It took place in Recife, Brazil, between May 6-8, 2024, and brought together academics and policymakers from different institutions and countries, including representatives from Brazil's ministries of the environment and of foreign affairs, and from UN Habitat.

The place and timing of the meeting couldn't be more emblematic. Recife, the capital of the Brazilian state of Pernambuco, whose name literally means "reef" in Portuguese, is a city named after one of its most prominent features: the reefs that lined along the coast have protected its low-lying shore and impressed voyagers with its rich marine life (Callcott, 1824).

Recife, however, is now among the country's most vulnerable coastal regions due to persistent challenges with flooding and coastal erosion (Costa et al., 2010). Situated on the Northeastern coast of Brazil, Recife has a low elevation, making it highly susceptible to rising sea levels. The city is built on a network of rivers and waterways, with large areas built over land reclamation, making it prone to flooding, especially during heavy rainfall events. Climate change is expected to increase the frequency and intensity of these events. Recife has an estimated population of approximately 1.6 million people, being one of the most populous Brazilian cities and a major cultural and economic hub. Increased coastal erosion threatens infrastructure, homes, and natural habitats, also causing the displacement of communities. The coral reefs that for centuries have provided natural protection against storm surges and erosion to coastal occupations, have been degraded by land runoff, pollution and overuse, and are now under threat from global warming and ocean acidification, which can dramatically exacerbate the impacts of storms and sea level rise.

The meeting was held while a major mass coral bleaching event was developing along most of Brazil's unique reefs. In 2024 NOAA (the National Oceanic and Atmospheric Administration) declared the 4th global mass coral bleaching event since 1998, following those in 2010 and 2014-2017. This event was triggered by elevated sea surface temperatures associated with climate change and the onset of an El Niño. The event affected coral reefs worldwide, with significant impacts in the Pacific, Indian, and Atlantic Oceans. As scientists and



policy makers discussed, the sea in the outside window was still warm, raging against a line of large rocks set as a barrier to protect the beachfront avenue at high tide. Beneath the waves, much of the remaining corals were either bleached or dead.

The workshop began with presentations on experiences at the regional level (Recife, Salvador and Abrolhos), as well as the National level. Given the ongoing severe warming event (Alert level 5¹ - near complete mortality >80% corals), a portrait of the situation of Brazilian reef environments and of the southern Atlantic was presented and discussed. Presenters also discussed global impacts, the global fourth mass bleaching event and the situation in the Atlantic ocean and the widespread bleaching phenomena in the region. Updated data from NOAA and ICRI show that one year after the official declaration of the fourth global coral bleaching event, from January 2023 to March 2025, the bleaching event has affected 84% of the world's reefs, with 82 countries and territories reporting damage².

The debates and data presented in this workshop unfortunately showed what seems like irreversible short- and medium-term impacts for reef environments, even when considering the best scenarios.

Thus, it is very important to consider issues like differences in resilience among coral reef species, and regions with distinct physical and chemical variables, which require constant, continuous monitoring in a variety of geographical locations and in different depths and climate conditions. In the specific case of Brazil, with its huge coastline, and broad distribution of coral reefs (over 2000 kms considering main reef formations) local differences are expected and meteorological and oceanographic processes vary from region to region. We also must understand past impacts and their socioeconomic repercussions in order to be able to improve our ability to predict and prepare for new disasters and their impacts on biodiversity and human communities. And above all, we may

¹ On December 15, 2023, NOAA Coral Reef Watch implemented a revised coral bleaching heat stress category system for its Bleaching Alert Area product. Extreme accumulations of coral bleaching heat stress in 2023, in multiple regions of the world, especially in the eastern tropical Pacific Ocean and Greater Caribbean, which were confirmed by in-water observations, necessitated the introduction of additional Bleaching Alert Levels. This development is a refinement of the original system that only used Bleaching Alert Levels 1 and 2. https://coralreefwatch.noaa.gov/product/5km/index_5km_baa-max-7d.php.

² <https://gcrmn.net/2025/04/23/global-bleaching-anniversary/>



understand and strengthen human resilience, particularly through empowerment of local communities.

This report is structured as follows: Chapter 1 introduces the theme, its background and importance. Chapter 2 discusses the present status of coral reefs and reef environments, especially in Brazil, as well as the existing monitoring initiatives. Chapter 3 presents scenarios for reef environments in Brazil in terms of socioeconomic and environmental impacts. Chapter 4 presents existing political instruments that directly and indirectly protect coral reefs, at the international level and within Brazil. Chapter 5 systematizes the public policy proposals discussed during the workshop for the Brazilian context, which include suggestions for strengthening institutions, instruments and mechanisms that are already in place; pathways to improve civil society's participation and representation; priority themes and pathways for financing research, communication and education initiatives; and suggestions for new policies. Chapter 6 closes the report with the main conclusions and takeaways.

1.2. Why Coral Reefs?

Coral reefs occur in more than 100 countries and territories throughout the tropics, covering just 0.2% of the ocean floor. Despite such a relatively small area, coral reefs support at least 25% of all marine species and present indisputable beauty and importance.

Recent estimates highlight the immense economic value of coral reefs, which are crucial to global ecosystems and economies. According to a 2024 report by the Coral Restoration Foundation, coral reefs contribute approximately US\$2.7 trillion annually to the global economy. This includes US\$36 billion from tourism, US\$10 billion from fisheries, and over US\$2 billion from the protection of coastal infrastructure (UNEP - UN Environment Programme) (UNEP - UN Environment Programme).

However, coral reefs are among the most vulnerable ecosystems to human-induced pressures. Historically, coral reefs have been degraded by local impacts from land-based sources of pollution, including nutrient and sediment runoff from agriculture, marine pollution, and harmful fishing practices like overfishing and destructive methods. Concern about the state of conservation of reefs led to the establishment in 1994 of the International Coral Reef



Initiative (ICRI), a global partnership between Nations and organizations which strives to preserve coral reefs and related ecosystems around the world. In 1997 the Global Coral Reef Monitoring Network (GCRMN) was created, to monitor reef health and promote their conservation. Since then, global reports have been published every two years, bringing together results from various countries around the world, organized into regional hubs (Wilkinson, 1998; 2000; 2002).

The year of 1997 was declared the first International Year of the Reef (IYOR), in response to the increasing threats on coral reefs and associated ecosystems, such as mangroves and sea grasses around the world. IYOR was a global effort to increase awareness and understanding of the values and threats to coral reefs, and to support related conservation, research and management efforts. In the following year the first global mass bleaching event occurred, caused by elevated temperatures prompted by a strong El Nino. This year of 2024 marks the fourth global bleaching event since 1998, and the second in the last decade. The third global bleaching event was the first that spread over multiple years, from 2014 to 2017, affecting 51% of the world's coral reefs with significant bleaching and 15% with significant mortality (Eakin et al., 2022). Repeated bleaching has contributed to an alarming trend. The world lost 16 percent of its coral cover during the first global bleaching event in 1998, then 14 percent of coral cover from 2009 to 2018 (Wilkinson et al., 2000, Souter et al., 2020). The loss may be even higher after the 2023-2024 event, pending reporting by the GCRMN currently in preparation.

Preserving the integrity and resilience of coral reef ecosystems is vital for the well-being of tropical coastal communities around the world. Protecting these ecosystems is a critical component of achieving the Sustainable Development Goals outlined in the 2030 Agenda for Sustainable Development.

Predictions indicate that up to 90% of coral reefs could be lost in the next 30 years without significant intervention (UNEP - UN Environment Programme), though significant local variation in bleaching, mortality and long-term loss make it difficult to apply broad-brush projections (McClanahan et al., 2025). Efforts to protect and restore coral reefs are crucial to maintaining their economic and ecological contributions.



Brazil is home to the only shallow coral reefs in the South Atlantic (Maida & Ferreira, 1997). Shallow reef formations (with depths of less than 20 meters) are found on oceanic islands and along the Brazilian coast from Maranhão to southern Bahia, with the Abrolhos formation being the most diverse and extensive in Brazil (Maida & Ferreira, 1997; Leão et al., 2016). Recent discoveries extend the occurrence of shallow formations to Espírito Santo (Mazzei et al., 2017). Deeper, mesophotic reefs, on the other hand, are present on the mid and outer continental shelves from the North region (Moura et al., 2016), the Northeast coast (Camargo et al., 2015; Fontes et al., 2019; Soares et al., 2019), and the East (Leão et al., 2016). These formations, which developed during the last glacial period, did not keep pace with the rising sea levels at the end of the Pleistocene, and are therefore referred to as "drowned" reefs (Maida & Ferreira, 1997; Camargo et al., 2015).

The reefs along the Brazilian coast exhibit low diversity but high levels of endemism — up to 50% — and unique forms that have gone extinct in other parts of the world, making them considered "relics" (Leão et al., 2016; Leão & Kikuchi, 2005). While in most modern reefs in the Caribbean and Indo-Pacific, corals are the dominant forms contributing to the rigid structure with their calcium carbonate skeletons, the formation of Brazilian reefs significantly involves other reef-building organisms, such as calcareous algae (Figueiredo et al., 2008). Recent studies have also revealed a surprising dominance of bryozoans in the Abrolhos Bank formation, further enhancing the uniqueness of Brazilian reef formations (Bastos et al., 2018).

Coral reefs generate up to R\$ 167 billion for Brazil through coastal protection and tourism services, as estimated by a recent study conducted by the Boticário Group Foundation for Nature Protection³. The value of ecosystem services provided by coral reefs in mitigating damage caused by storms, flooding, and erosion in coastal areas was calculated, as well as the economic impact of tourism in destinations with coral reefs in the Northeast, revealing that revenues from leisure and recreational activities reach R\$ 7 billion annually. In addition, coral reefs are a main source of food security for Brazilian dense coastal population⁴. Coral reef values however go beyond monetary values, providing food security and being part of the history, culture and

³ [https://www.fundacaogrupoboticario.org.br/pt/Biblioteca/OsM_outubro-3_leve\(31-10-23\).pdf](https://www.fundacaogrupoboticario.org.br/pt/Biblioteca/OsM_outubro-3_leve(31-10-23).pdf).

⁴ Estimate 18% of the Brazilian population live in coastal metropolises, and 13 of the 17 state capitals (Seixas et al, 2023. IPBES Summary for decision makers- Marine and Coastal Region. IPBES).



traditional livelihoods of coastal communities. Brazil has an estimated one million artisanal fishers that produce half of the country's fishery production, with coral reefs and associated environments such as mangroves and seagrasses as key ecosystems in maintaining productivity in tropical oligotrophic waters. The health of coral reefs directly affects fish populations, which in turn impacts the food security and economic and cultural stability of traditional coastal communities.

1.3. Acidification, Deoxygenation, Heating

The Sixth Climate assessment report from the Intergovernmental Panel on Climate Change (IPCC – AR6), emphasized that it is unequivocal that the current warming of around 1.1°C above the average of the pre-industrial period, has been caused by man (IPCC, 2021). The effects of climate change have also been detected in the ocean, and include rising mean sea levels, warming and marine heat waves (MHWs), acidification and deoxygenation (IPCC, 2021; Gruber, 2011).

These effects, present and future, documented by historical series of observations and predictions by numerical modeling, are irreversible on the scale of human life (Abram et al., 2019). This also means a loss of marine biodiversity, food insecurity and a cost of more than 1 trillion US dollars by 2100, if the greenhouse gas emission reduction scenarios from the Paris Agreement are not met (IPCC, 2019). In the same IPCC report, the interdependence of the Earth System compartments with the ocean was also mentioned, including regions far from the coast, due to changes in the global hydrological cycle (IPCC, 2019).

Among the effects of climate change on the oceans, warming and MHWs, acidification and deoxygenation have been the subject of studies for more than a decade (Riebesell, 2009; Keeling et al., 2010; Gruber, 2011; Gittings et al., 2018; Gruber et al., 2021; Arteaga & Rousseaux, 2023;). On a global scale, the three impacts affect the general circulation of the ocean, decrease the anthropogenic CO₂ ocean sink and promote the expansion of oxygen minimum zones in the ocean, with severe consequences for marine biodiversity and food security.

Climate change is also affecting organisms at the base of the trophic chain, and it is predicted that rising global temperatures will cause changes in species' thermal niches, nutrient availability and a sharp



decline in the diversity of tropical phytoplankton, compromising their population growth rates and primary productivity, with a consequent reduction in atmospheric carbon sequestration (Cooley et al., 2022).

In the same way that extreme precipitation, temperature and drought events in continental areas are directly related to climate change (Stott et al., 2016), MHWs, acidification and deoxygenation events have also been detected in the ocean and can occur simultaneously (Frölicher et al., 2018; Gruber et al., 2021).

What defines an extreme event in the ocean?

a) Marine heatwaves

Marine heatwaves (MHWs) are characterized as events where there is a prolonged and anomalously warm temperature at the ocean surface or subsurface (Xu et al., 2022). Generally, a MHW is declared when the temperature threshold exceeds the climatological 99th percentile (Gruber, 2011; Abram, 2019).

In the past decades, the frequency, duration and spatial extension of MHW are increasing (Gruber, 2011). From observations and model simulations, Frölicher et al. (2018) have detected a two-fold increase in the frequency of MHW between 1982 and 2016, and model scenarios predict a 16-fold increase in their frequency for a global warming within the Paris Agreement limits i.e. 1.5°C above the pre-industrial period, or a 23-fold increase for a global warming of 2.0°C.

b) Ocean acidification

Ocean acidification results from the increase in hydrogen ions (H⁺) concentration, driven by the dissolution of atmospheric anthropogenic CO₂ in the ocean. This leads to a decrease in the availability of carbonate ions in seawater, and consequently to the decrease in seawater saturation () of aragonite and calcite, two biologically essential calcium carbonate minerals (Feely et al., 2009) relevant to coral reef calcification. Ocean acidification trend is now detected on both surface and ocean interior, and the last IPCC climate assessment (AR6) considered that is now virtually certain that the pH on surface ocean waters has declined between -0.017 to -0.027 pH units/decade over the last four decades (Canadell et al., 2021).



In contrast to gradual ocean acidification, the ocean may also experience extreme acidification events, although the mechanisms triggering strong H^+ increase and decrease are not yet fully understood (Burger et al., 2020). Different from ocean surface temperature, there aren't available daily measurements of the carbon chemistry in the global ocean, thus this type of assessment is possible using biogeochemistry models and observations (Burger et al., 2020; Gruber et al. 2021). Hence, acidification extreme events are considered when the average H^+ exceeds its 99th percentile, and when decreases below the 1st percentile (Burger et al. 2020). In a model-based assessment, Gruber et al. (2021) suggest that strong upwelling may drive a surface ocean acidity event, as it brings upwards water masses with high H^+ concentrations, although all the drivers are not yet well understood. Burger et al. (2020) results suggest that in both low- and high-emission scenarios (RCP2.6 and RCP8.5), the ocean surface will experience an increase in H^+ , leading to a "near-permanent acidity extreme state" 2030.

c) Ocean deoxygenation

Ocean deoxygenation is caused by ocean warming: as temperature rises, dissolved oxygen becomes less soluble in seawater (Gruber et al., 2011). Simultaneously, ocean warming also increases upper ocean stratification, enhancing deoxygenation (Keeling et al. 2010). Depending on the levels of oxygen loss, denitrification in the water column is also at stake (Keeling et al., 2010).

Dissolved oxygen is fundamental to all aerobic organisms in the ocean, although different groups have different levels of sensitivity to deoxygenation, and benthic organisms are more vulnerable to its effects (Keeling et al., 2010; Stramma et al., 2008). Although low oxygen or even anoxic events occur relatively often in coastal areas (mainly due to eutrophication processes), any loss in ocean O_2 may further impact these ecosystems, as lateral exchanges with the open ocean are a source of oxygenated waters (Stramma et al., 2008; Gittings et al., 2018).

Observations are key to understanding the processes controlling O_2 loss, as models are not yet fully capable of reproducing the observed temporal variability and trends (Oschlies et al., 2018). The estimated trend in oxygen loss since 1960 is -0.09 to $-0.34 \mu\text{mol kg}^{-1} \text{yr}^{-1}$.

Stramma et al. (2008), and Schmidtke et al. (2017) estimated that the total ocean O₂ content has decreased by 2% since the 1960's decade.

Gruber et al. (2021) results suggest that in future warming scenarios, ocean deoxygenation extremes are more likely to occur in the tropical ocean and below the surface, slightly southwards from the MHW areas. The "compound" events (heat, acidity and low oxygen) studied by Gruber et al. (2021) may last, in these areas, for more than 200 days.

d) Tipping points:

When parts (or elements) of the Earth climate system reach a threshold that leads to a completely different state or functioning, one says a "tipping point" has been reached (Lenton et al., 2008). Ocean extreme temperatures, changes in circulation or water column stratification are listed as ocean tipping elements (IPCC Special report on Oceans and Cryosphere 2019), but changes in ocean biogeochemistry are also foreseen, such as acidification and deoxygenation (Heinze et al., 2021).

In the Atlantic ocean, climate change and other anthropogenic pressures are pushing key ecosystems towards "tipping points." Coral reef degradation is also one of them.

There is very high confidence that rising sea temperatures are leading to more frequent and severe coral bleaching events in the Atlantic, as well as other parts of the world's ocean (Cooley et al., 2022). Coral reefs, already stressed by pollution and overfishing, are highly vulnerable to tipping points, where repeated bleaching can lead to the death of large reef systems (Armstrong-McKay et al., 2023; Pearce-Kelly et al., 2024). Once a reef collapses, the biodiversity and services it provides—such as fisheries and coastal protection—may not recover. Addressing these tipping points requires urgent global action to reduce greenhouse gas emissions, manage fisheries sustainably, and protect vital marine ecosystems (Armstrong-McKay et al., 2023; Pearce-Kelly et al., 2024).





2

ON THE PRESENT STATUS OF REEF HEALTH



ON THE PRESENT
STATUS OF REEF
HEALTH

2. ON THE PRESENT STATUS OF REEF HEALTH

2.1. The History of Coral Bleaching Events

The first documented large-scale, mass coral bleaching event driven by elevated ocean temperatures occurred > 40 years ago during the 1982–83 El Niño in the eastern tropical Pacific (Glynn, 1984). Coral mortality from this marine heatwave ranged from 75–85% in Panama to 95–99% in the Galapagos Islands (Glynn, 1994; Palacio-Castro et al., 2023). This single bleaching event eliminated coral reefs from the southern Galapagos, and only one living coral reef remaining today off the far northern Island of Darwin, as all other structural reefs were rapidly bioeroded in ~10 years after the 1982–83 El Niño (Manzello et al., 2014; Glynn et al., 2018). Conversely, reefs in Panama have shown notable recovery to pre-1982–83 coral cover, as well as increased tolerance to subsequent El Niño warming events in 1997–98 and 2015–16, and this has been attributed to an increased dominance of heat tolerant algal symbionts (Palacio-Castro et al., 2023).

Since the first heat-driven mass mortality event in the eastern Pacific, marine heatwaves and resultant coral bleaching events have increased in frequency, severity, and spatial scale (Baker et al., 2008; Skirving et al., 2019; Hoegh-Guldberg et al., 2023) few coral reefs remaining on planet Earth have not experienced a mass bleaching event (e.g., Rapa Ampat, Indonesia). Many locations that were hypothesized to be refugia, either owing to large distances from human population centers (Northern Great Barrier Reef, Dry Tortugas, Florida), or unique oceanography (i.e., Red Sea) have all experienced severe, heat-driven bleaching events within the past 8 years, with certain locations experiencing mass mortality (Hughes et al., 2017; Cardoso et al., 2024). The Great Barrier Reef has experienced seven mass bleaching events since 1998, five of these occurring within the past 9 years (Spady et al., in prep.).

Strong El Niño events have historically been the harbinger of severe bleaching events, but recently, large-scale and severe events have occurred during La Niña periods (Great Barrier Reef in 2022; Fiji and Vanuatu in early 2023) (Spady et al., 2022). This suggests that ocean temperatures may have increased to the point whereby large-scale bleaching events may now occur during any phase of ENSO, which is in line with what is expected on a rapidly warming planet.

2.2. Coral Reef Watch SST Monitoring, Including the Current Virtual Stations for Brazil

The monitoring of thermal anomalies in the oceans using satellite-derived sea surface temperatures (SSTs) by NOAA's Coral Reef Watch (CRW) has been very successful at predicting where and when coral bleaching is likely occurring (NOAA CRW 2024: <https://coralreefwatch.noaa.gov>). NOAA CRW has predicted all large-scale bleaching events since the late 1990s. NOAA's CRW can predict coral bleaching with high confidence by quantifying thermal anomalies in the ocean during the warmest part of the year. The primary algorithm (Degree Heating Weeks, DHWs) that NOAA CRW uses is based on: 1) observations of mass coral bleaching and mortality throughout the eastern tropical Pacific during the 1982/83 El Nino, and 2) the subsequent laboratory experiments that established cause-and-effect between elevated temperatures and bleaching (Glynn & D'Croz, 1990). DHWs are the standard metric utilized worldwide to estimate heat stress that is impacting coral reefs.

NOAA's CRW serves 214 Regional Virtual Stations, which consolidate all the key data products for the prediction and monitoring of coral bleaching for defined regions around the planet (NOAA CRW Regional Virtual Stations:

<https://coralreefwatch.noaa.gov/product/vs/map.php>).

NOAA CRW currently serves seven Regional Virtual Stations for Brazil's coral reefs. These include: Fernando de Noronha, Maracajaú, Costa dos Corais, Todos os Santos Bay, Abrolhos Reefs, Trindade and Martim Vaz, and Búzios.

2.3. Coral Bleaching and Global Bleaching Events and Predictions for the Future

On April 15th, 2024, the United States NOAA and the International Coral Reef Initiative announced that the world was experiencing its 4th Global Bleaching Event (GBE4). Since February 2023, mass coral bleaching has been documented across at least 75 different countries/territories spanning the northern and southern hemispheres of all ocean basins (as of December 31st, 2024). The GBE4 has been record-setting, as 79.7% of the world's reef area has experienced bleaching-level heat stress (BLHS) from January 1, 2023, to December 31, 2024, (BLHS is degree heating weeks - DHW > 4°C-weeks) exceeding the previous

record set during the 3rd Global Bleaching Event that spanned 2014-2017 (GBE3, cumulative reef area impacted = 65.7%). In fact, during the past 365 days alone, > 75% of the world's reef area has experienced BLHS, exceeding the previous record during GBE3 by 18.9% and increasing% (Table 1).

Table 1. Peak % of the Coral Reef Area that experienced bleaching-level heat stress during a 365-day period for each Global Coral Bleaching Event (GBE). GBE Index developed by Skirving et al. (2019) and provides a measure of % reef pixels experiencing bleaching-level heat stress within the past 365 days.

Event	Years	Peak % Reef Area Impacted
GBE1	1998	20%
GBE2	2010	35%
GBE3	2014-2017	56.1%
GBE4	2023-2025	84.0% and increasing (March 30 th , 2025)

Coral reef areas in both the northern and southern Atlantic Ocean have experienced the most extreme levels of heat stress during this event, with Degree Heating Week (DHW, °C-weeks) values 2-3 times greater than has ever occurred before in the satellite record. Most reef areas in the wider Caribbean and south Atlantic exceeded 16°C-weeks, with some regions surpassing 20°C-weeks; these extreme levels of heat stress have driven coral mortality ranging from 60-99% during past events. During this event, 99.9% of all reef areas in the Atlantic ocean have experienced bleaching level-heat stress. Record-setting heat stress has also occurred in the eastern tropical Pacific, southcentral Pacific (e.g., Western and American Samoa), southern Great Barrier Reef, and parts of the Western Indian Ocean. It is important to note that GBE4 has been updated here as per March 2025⁵.

Approximately, 8% of the world's corals died after GBE1 in 1998, with a further loss of 14% of the world's corals from 2009-18, spanning GBE2 and GBE3 (Souter et al. 2021). The full ecological impacts of GBE4 will not be fully realized for months-to-years, but preliminary reports have been alarming, and already shows that the current bleaching event has impacted 84% of the world's reefs, affecting 82 countries and

⁵ <https://gcrmn.net/2025/04/23/global-bleaching-anniversary/>



territories. The acroporid corals, which were the dominant, shallow-water, reef-building corals throughout the wider Caribbean for at least the past 250,000–500,000 years, were severely impacted, with reports of 90–100% mortality in Florida, Mexico, and Puerto Rico following the 2023 phase of this event (Manzello, in prep.).

As the oceans continue to rapidly warm due to climate change, it is estimated that most coral reefs systems will experience annual severe bleaching sometime between 2040–2050 (van Hooidonk et al. 2014; 2015). An analysis of in situ (versus satellite-derived) temperature trends from the Florida Keys predicted that annual bleaching could occur as soon as the early 2020s for these imperiled reefs (Manzello 2015). This suggests that the future of coral reefs beyond the next 20–30 years is in serious jeopardy.

2.4. State of the Art

Brazilian coral reefs

Brazilian coral reefs represent the most diverse reef systems in the southwestern Atlantic Ocean. Stretching along approximately 3,000 km of coastline, Brazilian reefs showcase a remarkable variety of shapes and sizes, ranging from fringing reefs and linear barriers to unique coral formations known as “chapeirões” or coral pinnacles (Leão et al., 2003; Ferreira & Maida, 2006; Rodriguez-Ramirez et al., 2008; Kikuchi et al., 2010; Bastos et al., 2018). Besides forming a continuum with mangroves and seagrass beds (e.g., Moura et al., 2011; Bastos et al., 2022), Brazilian coral reefs are closely associated with rhodolith beds (e.g., Amado-Filho et al., 2012; Moura et al., 2021), as well as with incised valleys, sinkholes and other mesoscale hardbottom features that occur in the continental shelf (Camargo et al., 2015; Castro et al. 2023). These mosaics form large reef meta-ecosystems connected by the exchange of energy, materials, and organisms across their boundaries (Loreau et al., 2003). Despite presenting a more incipient coral cover, drowned reefs are also common along the Brazilian continental shelf, in both shallow and deeper waters, and play important ecological roles in its larger reefal meta-ecosystems (e.g., Moura et al., 2013).

In the Status of Coral Reefs of the World: 2008, Rodriguez-Ramirez et al. identified six primary regions of coral reefs along the Brazilian coast and oceanic islands: 1) the islands and ocean banks of the Fernando de

Noronha chain; 2) Touros-Natal; 3) Pirangi-Maceió; 4) Baía de Todos os Santos-Camamú; 5) Porto Seguro-Cabrália; and 6) Abrolhos. Building on this foundation, Leão et al. (2016) expanded the geographical division and consolidated it into four major regions: 1) the Northern Region, including the Manuel Luiz Parcel; 2) the Northeast Region, encompassing the reefs from the Northeast coast to the São Francisco River; 3) the Eastern Region, which covers Bahia; and 4) the region of the Oceanic Islands. An updated typology of Brazilian reefs, as well as their distribution ranges, has been provided by Moura et al. (2021).

The Global Coral Reef Monitoring Network (GCRMN) adopted a classification based on Marine Ecoregions (MEOW) (SPALDING et al., 2007), which place Brazilian shallow water coral reefs into three Marine Ecoregions: 74 – Oceanic Islands; 75 – Northeast; and 76 – East.

Coral reef monitoring programs in Brazil and the Brazilian node on the GCRMN

Brazil has been reporting for the GCRMN since 1998, participating on the Reports of "Status of Coral Reefs of the World" as part of the Southern Tropical America Node, including five global reports between 1998 and 2008 (Wilkinson, 1998; 2000; 2002; 2004; 2008) with Brazilian effort led by Dra Zelinda Leão from Universidade Federal da Bahia, up until the 2008 report. The contributions were then based on accounts gathered from scientists that led local or regional monitoring efforts, organized to give a picture of the status of coral reefs health, as indicated by coral cover and fish abundance trends, main anthropogenic impacts and conservation initiatives.

The GCRMN then went through a transition period from the last global report in 2008 until the sixth 2020 report (released in 2021), the first based on the quantitative analysis of a global dataset compiled from monitoring data contributed by more than 300 members of the network. In February 2020, in the early Covid 19 pandemic days, the GCRMN Steering Committee called for a data assembling meeting when data collected during the National Coral Reef monitoring Program/Reef Check Brazil from 2002-2018 was presented and supported the writing of the first Brazil Node chapter on the "Status of Coral Reefs of the World: 2020" report (Ferreira et al., 2020).

From 2023 onwards, Brazil resumed its active ICRI (International Coral Reef Initiative) membership (see section 4.2). In order to contribute to



the organization of the 6th GCRMN Status of the Reefs Report, due in 2026, the Department of Ocean and Coastal Management of the Ministry of the Environment and Climate Change, conducted a survey of existing coral reef monitoring initiatives, aiming to expand the incorporation of existing data not included in the fifth report and at the establishment of a network for the Brazil node of GCRMN. According to this 2024 survey, nine coral reef monitoring projects are presently in progress. These projects cover 21 Marine protected Areas (MPAs), distributed across seven states, with a remarkable contribution from the Programa de Pesquisas Ecológicas de Longa Duração (PELD), which is sponsored by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and affiliated to the International Long-Term Ecological Research (ILTER) Network.

Coastal and oceanic reefs are monitored and the projects have national (Reef Check, Coral Vivo, and Monitora), regional (PELD ILOC, PELD Abrolhos), and local (PELD TAMS, PELD UFAL, PELD Semiárido, Projeto Conservação Recifal) coverage. Regarding length of duration, two projects have been monitoring for over 20 years (Reef Check 2002, PELD TAMS 2002), two for more than 10 years (PELD Abrolhos 2006 and PELD ILOC 2012), two for five years (PELD UFAL 2018) or less (Coral Vivo 2020), while Monitora, an initiative led by Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio) and aimed largely at Federal MPAs, is still being implemented.

Seven different monitoring protocols are used, with four being adaptations of the Reef Check protocol, that includes citizen science involvement. Monitoring is mainly conducted annually, with occasional discontinuities. The projects are primarily funded by government agencies (PELD, Monitora), Petrobras (e.g., Coral Vivo) and are mostly executed/coordinated by universities, with some NGOs initiatives.

Bleaching events in Brazil: a brief history

The registered history of bleaching in Brazil began in 1993, with scattered opportunistic findings. The first coral bleaching records at the Brazilian coast were made in the 1993/1994 El Niño, during the Southern Hemisphere summer. Bleaching was recorded in São Paulo rocky reefs (Migotto, 1997), at the Abrolhos reefs (Castro and Pires, 1999) and at Tamandaré reefs (Ferreira and Maida, 2006). Still during the 1990's, other events were recorded for Pernambuco (Costa et al., 2001) and Bahia reefs, in Abrolhos (Leão et al., 2003) and coastal reefs



in Northern Bahia (Kikuchi et al., 2003; Kelmo et al., 2003), again related to the 1997/1998 El Niño. During these events, most colonies had a bleaching frequency of less than 60%, with a few species like *Agaricia humilis* and *Porites branneri* presenting more than 90% of bleached colonies (Leão et al., 2003).

During this same El Niño phase a mass bleaching episode was observed at the Parcel Manuel Luís, a reef located 86 miles offshore in Maranhão state, Northern Brazil (Moura et al. 1999). Almost all scleractinians and *Milleporidae* hydrocorals were bleached, with several colonies presenting severe mortality (Amaral et al., 2006).

From this decade on, there was a significant rise in bleaching records along the coast and oceanic islands. In 2003, 2005, and 2010 bleaching events coincided with sea surface temperature anomalies due to El Niño (Ferreira et. al., 2006; Leão et al., 2008; Miranda et al., 2013; Teixeira et. al., 2019). Recovery was reported when further monitoring was carried out (e.g., Leão et al., 2008; Krug et al., 2012; 2013).

At the coastal reefs of northern Bahia, a monitoring effort between 1998 and 2005 indicated more severe bleaching prevalence for some species such as *Favia gravida*, *Millepora nitida* (with 100% bleached colonies), *Agaricia humilis* and *Siderastrea stellata* (circa 80% bleached colonies), while prevalences for the other monitored species varied from 1 to 65% (Leão et. al., 2008).

From 2010 on, bleaching records increased in frequency and spatial scale, including further reports for the Northern coast (Ceará state) (Soares and Rabelo, 2014), but no mass mortality episodes have so far been recorded in the Brazilian coast (Leão et al., 2008, 2010; Kikuchi et al., 2010; Krug et al., 2012, Miranda et al., 2013; Kikuchi et al., 2013; Ferreira et al., 2013).

During the Third Global Bleaching Event (TGBE), between 2016–2017, extensive and prolonged bleaching was observed in the Abrolhos reefs (Teixeira et al., 2019), but mortality was relatively low, akin to the rates recorded in oligotrophic reefs of the Pacific Ocean (Eakin et al., 2019). These relatively short-term trends led to the interpretation that the low-richness Brazilian reefs dominated by massive forms, and largely thriving in turbid waters, could present higher resistance to climatic stress than high diversity oligotrophic reefs, and therefore the SWA would function as a climate change refugia (Mies et. al., 2020).



However, between 2019 and 2020, the most dramatic bleaching events – possibly even stronger than the previous global events of 2010 and 2014-2017 events – were recorded at the Brazilian coast and oceanic islands (Teixeira et al., 2019; Gaspar et al., 2019; Banha et al., 2020; Gomes et al., 2021), this time with extensive mortality recorded in different reefs (Duarte et al., 2020; Ferreira et al., 2021; Pereira et al., 2022; Cardoso et al., 2024; Vidal et al., 2025). Two messages became very clear: 1) Brazilian reefs are neither climate refugia or resistant to bleaching; and 2) there are great differences in the timing, intensity and duration of bleaching events among regions.

Since then, thermal anomalies have intensified, and 2024 was an especially critical year according to NOAA CWP. In April 2024, NOAA and ICRI declared the 4th Fourth Global Coral Reef Bleaching Event. During the ICRI press conference, an update on the current bleaching situation in Brazil was presented, based on preliminary results from key coral reef monitoring programs across the country. For the entire Northeast Region (Ecoregion 75) and the Oceanic Islands (Ecoregion 74), the intensity and persistence of the anomaly, as indicated by the DHW (Degree Heating Weeks) index, surpassed 18 weeks. Bleaching was reported at rates close to or exceeding 90% across both regions. The Eastern Region (Ecoregion 76), which includes Abrolhos, experienced significant anomalies and persistence, though at lower levels than the other regions. Preliminary assessments indicate extremely high mortality rates in the Northeastern coastal areas, where key reef-building species, such as the hydrocorals *Millepora* spp. and the endemic *Mussismilia harttii*, are among the most vulnerable and have suffered the heavier losses.

In contrast, the Abrolhos region was largely spared from a mass bleaching episode in 2024, presenting a stark difference from 2019, when it was the most affected (Teixeira et al., 2019; Duarte et al., 2020). This preliminary scenario is still under review, as monitoring teams continue to analyze data for upcoming reports and publications. There is growing evidence that mortality rates increase after heatwaves events during several months or even years, even when the coral colonies did not bleach (Cardoso et al., 2024). Nevertheless, the 2024 event is already being considered the most severe bleaching ever recorded for the Northeast Region and possibly for the Oceanic Islands too.



Regarding mortality rates, the role of other factors may vary at the local scale. Cardoso et al. (2024) showed that bleaching and mortality levels are not related with protection regime and distance offshore in the Abrolhos reefs. Indeed, mortality levels of the iconic brain-coral *Mussismillia brasiliensis*, endemic to Bahia, have been higher in the offshore protected reefs than in nearshore unprotected reefs sites, where higher macroalgal cover hinder alleopathic contacts with filamentous cyanobacteria that benefit from higher seawater temperatures and elicit coral tissue necrosis (Ribeiro et al., 2018; 2022). At a finer scale, spatial variables such as distance from the coast and depth shaped mortality patterns in the coastal reefs of Tamandaré, as well as herbivory rates, inferred by protection levels, seem to have favored recovery of the hydrocoral *Millepora alcicornis* after bleaching events (Vidal et al., 2025). Unfortunately, there is growing evidence that the impacts so far recorded on Brazilian reef ecosystems may be irreversible, even under the most optimistic projections, with projected warming scenarios calling for urgent global and local actions in order to prevent extreme losses and retain some of the essential services derived from coral reefs.

It is equally important to address variations in resilience among species and regions with distinct physical and chemical conditions. For instance, in the last decade, the coral cover of reefs submitted to sediment plumes from dredging operations in the Abrolhos region have declined faster than that of nearby reefs, even those subjected to intense fishing pressure (Teixeira et al., 2021). This highlights the need for continuous, systematic monitoring across a variety of geographical locations, depths, and climate conditions, and an especial attention from licensing agencies (e.g., IBAMA, ICMBio) when dealing with the implementation of businesses near coral reef areas. In Brazil, with its vast coastline, significant gaps remain – even for fundamental oceanic variables such as coral and algal cover.

Coral bleaching occurs largely under thermal and light stress during anomalous periods that trigger the breakdown of the symbiosis between cnidarian hosts and microscopic dinoflagellate photosynthesizers. This intracellular process ensues pigment reduction and overall physiological stress due to lowered autotrophic carbon translocation to the coral host, increasing tissue degradation and lesions, as well as the susceptibility of coral holobionts to microbial diseases (Cardoso et al., 2024). Despite such relevance, the responses of coral microbiomes to changing seawater conditions in



the tropical Southwestern Atlantic, including ocean acidification (e.g., Hill et al., 2019), remain a significant knowledge gap that impedes the development of targeted restoration programs (Peixoto & Voolstra, 2023; Peixoto et al., 2024). Microbial assemblages associated with corals shift as water conditions and coral health change (e.g., Garcia et al., 2013; Fernando et al., 2015), but coral diseases remain among the most severe and yet poorly understood drivers of coral decline in the Southwestern Atlantic (Francini-Filho et al., 2008). Moreover, even the structure and dynamics of the elusive zooxanthellae (*Symbiodinacea*) endosymbiont assemblages remain poorly assessed in Southwestern Atlantic corals (but see recent progress in the reports by Garrido et al., 2022; 2024; Amario et al., 2023; Cardoso et al., 2024; Villela et al., 2024, and references therein). These gaps, alongside shifting ecological baselines must be addressed, and microbiomes need to be explicitly incorporated in at least some coral reef monitoring initiatives. The same can be said about several coral photophysiology variables, which can be rapidly assessed *in situ* and without harming the corals, with use of Pulse Amplitude Modulated (PAM) fluorometry (e.g., Cardoso et al., 2024).

Understanding the cumulative impacts and their socioeconomic consequences is also crucial. This knowledge can enhance our ability to predict and prepare for future disasters and mitigate their effects on both biodiversity and the human communities that depend on these ecosystems.

There is no doubt that Brazilian reefs have entered the global map of coral reefs mass bleaching events. There is an urgent need for the unification of efforts towards local and global actions to mitigate the problem. Since this last unprecedented 2024 event it is imperative and urgent to establish a wide and connected network, able not only to evaluate impacts but also to indicate and monitor effective responses.

2.5. Projections for Coral Reef Status in Brazil

Projections of temperature across Brazilian reefs

Despite being spread across more than 15 degrees of latitude, from 1°S near the mouth of the Amazon River to 18°S at the Abrolhos Islands, the full extent of Brazilian coral reefs has experienced severe bleaching and high mortality, as described in previous paragraphs. Thus, while more southern locations experience lower overall temperatures, corals in



these locations also experience severe stress from warming due to their adaptation to local contexts. Projections of the onset of severe bleaching conditions (NOAA CRW⁶) do not show any later onset of catastrophic bleaching for southern locations. Conversely, some of the earliest onsets of twice-per-decade bleaching under RCP4.5 (a mid-range warming scenario) is shown for Abrolhos reefs in the south. By contrast, coastal reefs extending from Natal (5°S) to Salvador (13°S) show the latest onset of twice-per-decade bleaching indicating a greater influence of coastal turbidity than latitude in affecting bleaching susceptibility of reefs.

The high levels of bleaching and mortality already shown indicate a very significant prognosis for Brazil's corals. Climate model projections (CMIP6) of the onset of catastrophic bleaching (whether rated at annual severe bleaching or twice per decade, which are only distinguished by a few years to up to ten years) have been used by the IPCC to state that 70-90% of global reefs are anticipated to be lost at 1.5°C warming, and 90-99% lost at 2°C warming (Frieler et al., 2013; IPCC 1.5 Report 2018; Cooley et al., 2022). A range of research papers have elaborated on these projections, e.g. in the context of loss of thermal refugia (Dixon et al., 2022), and multiple interacting stressors (Setter et al., 2022), reaffirming the findings that severe bleaching is expected to impact all coral reefs globally within a few decades.

This is particularly so as many reef regions may have already experienced the equivalent of 1.5°C warming in recent summer seasons or over a year, and globally, temperatures are projected to cross the 1.5°C threshold (calculated over a 20-year period) by 2034 (see Copernicus projection⁷). Current committed temperatures are projected at > 2.7°C warming, far above the thermal tolerance limits of corals. However, these scenarios are ameliorated by caution that the high degree of averaging of GCMs fails to take into account local to regional nuances in thermal exposure of reefs, variability in environmental conditions and in biotic responses of corals (McClanahan et al. 2025), which may be particularly relevant for Brazilian reefs given their inshore location and exposure to turbid conditions and cooler ocean waters from the South Atlantic. This could mean that while the full extent of coral reefs may be severely impacted across the Brazilian coast, there may be multiple refuge locations with

⁶ https://coralreefwatch.noaa.gov/climate/projections/downscaled_bleaching_4km/

⁷ <https://climate.copernicus.eu/how-close-are-we-reaching-global-warming-15degc>



healthy corals remaining – though this will depend greatly on the absence of local stressors.

Tipping point for coral reefs?

Coral reefs are identified among the first global ecosystems to cross a climate tipping threshold, alongside the ice-dominated systems in the Arctic region (Armstrong-McKay et al., 2022), adopting the range 1.5°-2°C identified by the IPCC (see above). However, the global range of impacts on coral reefs already documented has resulted in a lowering of the expected range for tipping to 1.0-1.5°C (with a median of 1.2°C, crossed during the third global Bleaching Event in 2014-2017) (Lenton et al., 2023).

This revised range for tipping of coral reef ecosystems, and the observations of widespread bleaching across Brazilian reefs in the last 2 decades suggest the threshold has likely been crossed, at least for part of their distribution. The low species diversity of Brazilian coral reefs, and the high vulnerability of the dominant reef-builders and their endemism, indicates a very high importance of addressing this climatic threat, and investment in research and management (see section 5.2).



3

SOCIAL, ECONÓMIC AND ENVIRONMENTAL SCENARIOS



**SOCIAL,
ECONÓMIC AND
ENVIRONMENTAL
SCENARIOS**

3. SOCIAL, ECONOMIC AND ENVIRONMENTAL SCENARIOS

Humanity faces what has been called the “triple planetary crisis”, three interconnected global environmental challenges: climate change, biodiversity loss, and pollution. These issues are deeply interlinked and pose significant threats to the planet's ecosystems and human well-being. The costs of climate change induced losses are tremendous, and it has been lately clear that they may be more rapid and severe than predicted.

Although the response timescale to mitigation actions of the ocean is longer than the average human life, and the deep ocean timescale spans thousands of years, the Sixth IPCC Assessment Report (Group 2 - 2022), Heinze et al. (2021) and Muelbert et al. (2021) suggest that i) the identification of hotspots for abrupt changes; ii) the knowledge of the mitigation targets, based on greenhouse gas emission scenarios ; iii) the consideration of efficient and ocean-safe carbon dioxide removal strategies, and iv) interaction and communication between multiple stakeholders, including indigenous and traditional communities, are key to be applied concomitantly to adaptation strategies.

This scenario points to the urgency of policies that enhance coral resilience, and the political path to protect reef environments includes the full implementation of existing environmental policies. In practice that means the reduction of human activities that directly impact coral reefs, as well as funding new research, monitoring, and short- and long-term solutions.

3.1. Resilience of Socio Ecological Coral Reef Systems

Socio-ecological resilience in coral reef systems refers to the capacity of these interconnected human and natural systems to absorb disturbances, such as climate-induced coral bleaching or overfishing, while maintaining essential functions and structures. Coral reefs provide critical ecosystem services, including coastal protection, fisheries, and tourism, which in turn support human livelihoods. Resilience in these systems not only depends on the ecological capacity of coral reefs to regenerate after stress, but also on the human communities' ability to adapt through sustainable management practices, governance, and policy interventions. When resilience is strengthened, coral reef systems are better able to tolerate stressors without transitioning into a degraded state, marked by biodiversity

loss and economic decline. Additionally, the human dimension of resilience brings an ability to anticipate and influence future pathways, fostering proactive measures to mitigate future impacts and promote long-term sustainability (Holling, 1973; Gunderson & Holling, 2002; Walker et al., 2004). The integration of continuous monitoring, adaptive management, and local community engagement is critical to enhancing resilience in coral reef ecosystems, ensuring that both the ecological and social components of the system remain intact.



The question is: given the present status and trends, and the utmost importance of coral reefs for human societies in the densely populated Brazilian coast, are the government and society prepared and aware of the risks and losses ahead?

3.2. Local and Regional Impacts

One of the greatest challenges to coral reef resilience related to ongoing global changes lies in management of local impacts that continuously erode ecosystem and social resilience. Among these influences it is important to highlight:

- Land based impacts in its several sources, such as polluted agricultural run-off, incipient sewage treatment, industrial waste, oil spills and plastic residuals entering the marine food web, among several other coastal sources of contamination;
- Habitat destruction and sedimentation from seaport construction and navigation channels' dredging;
- Overfishing with impacts on key ecosystem processes such as herbivory and control of opportunistic populations; illegal fishing



activities; abandoned, lost or discarded fishing gear that capture non-target species and impact coral reefs with lost fishing nets;

- Exotic invasive species that negatively impact local ecological interactions and ecosystem processes;
- Uncontrolled tourism, that also promotes the demand for local reef fishery resources;
- Increasing pollution, structural damage, sedimentation and smothering of reef structures, - Artificial reefs that function only as reef fish attractors and stepping-stones for harmful invasive species, such as sun-corals and lionfish.
- Lack of or unsuitable public policies and legal setbacks, such as the absence of a sound program for a national energy transition, and the recent proposition of constitutional amendment to allow the privatization of coastal public areas, the so-called marine/navy belt (PEC 03/2022), respectively.
- Interaction with other climatic events, such as the increase in cyclones and above average rainfall, which enhance pollution in coastal reefs due to increased terrigenous sediments runoff.

3.3. Impacts on Biodiversity

Reef fish studies in coastal areas of southwestern Atlantic have shown changes in distribution and intensity of reef trophic interactions in scenarios projected for the near future (2050 and 2100), which indicate disequilibrium in ecosystem functions. The important role of herbivores in shallow tropical reefs is predicted to reduce. Tropicalization of higher latitudes are more likely to occur at northern hemisphere reefs, but not along the Brazilian coast. Therefore, in the southern hemisphere it is predicted that there is a loss in important trophic links such as herbivory and invertivory, leading to a change in trophic links that can critically affect the reefs and promote new kinds of environments with different structures and functioning (Inagaki et al., 2020).

The increase in temperature in tropical reefs is predicted to negatively impact fish biomass, with changes in the role of fish in the system. These predicted changes favor an increase in invertivorous fish biomass, suspension-feeding zooplankton, and turf algae, while corals tend to collapse (Capitani et al., 2022).

Martello et al. (2023), based on a modelling study, predicted increased losses of endemic coral species such as the reef builders *Mussismilia*

braziliensis and *M. harttii*, while other widely distributed coral species would tend to expand their range towards higher latitudes. These predictions indicate the need for conservation strategies such as ecological corridors, but the velocity of losses versus gains in novel ecosystems are a major concern, together with the conservation status of coastal areas that would accommodate the putative migration processes associated with climate change. Another aspect that must be considered for gaining more predictability in projected scenarios is the availability of up-to-date environmental variables, especially accurate and comprehensive reef habitat maps over which potential future distributions can be more reliably projected. In addition, as climate changes are occurring extremely fast, it is remarkable that some of these modelling studies used oceanographical predictors spanning from 2000 to 2014, a time frame that does not comprise recent changes in climate and oceanographic parameters.



Therefore, we need to address these uncertainties with well-structured datasets and continuous monitoring of key biotic and abiotic features at large geographical scales and with adequate spatiotemporal resolution. Habitat mapping, which is a long-standing impediment to spatial planning, represents another relevant additional caveat to modelling studies, once predicted distribution shifts must be coupled with the actual ranges and the patchy nature of reef frameworks. The Abrolhos shelf is a remarkable example of the importance of continued efforts toward coral reef mapping with a combination of different approaches. Following *in situ* acoustic surveys and validation, Moura et al (2013) increased the known reef area of the largest and most biodiverse reef complex in the South Atlantic from 500 km² (Prates 2006, based on remote sensing) to 8,800 km². Despite recent progress with coral reef mapping with remote sensing (e.g., Silveira et al., 2021;



Zoffolli et al., 2022), the overall turbid waters of the Southwestern Atlantic often impede large scale, rapid and relatively cheap coral reef detection with remote sensing, even for large reef structures that may span across hundreds of kilometers (e.g., Moura et al., 2016).

Furthermore, precaution principles may guide local conservation initiatives to prevent impacts that reduce reef systems resilience and ability to cope with changes and adapt in a reasonable time frame.



4

EXISTING POLITICAL INSTRUMENTS TO PROTECT REEF ENVIRONMENTS

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This scenario points to the urgency of policies that enhance coral reef resilience, and the political path to protect reef environments includes the full implementation of existing environmental policies. In practice that means the reduction of human activities that directly impact on coral reefs, as well as funding new research and short- and long-term solutions.

4.1. National Participation in International Instruments

Brazil is a signatory to more than 35 International and Regional Conventions and Agreements and 28 Bilateral Agreements, as well as having actively hosted the drafting of Agenda 21 during Rio 92. Among these conventions, those relating to protected areas and wild flora and fauna in the coastal and marine zone stand out as the ones most directly connected to coral reef conservation. The following table shows these highlights.



TABLE 2. International Conventions and Treaties to which Brazil is a signatory, with an interface with the coastal and marine environment. Fonte: Atualizado de Prates (2003).

Act	Place	Entry into force	Entry into force in Brazil
World Natural Heritage Convention	Paris	1972	1972
Treaty on the prohibition of the emplacement of nuclear weapons and other weapons of mass destruction on the seabed and ocean floor and in its subsoil	London	1972	1988
Convention on International Trade in Endangered Species of Wild Fauna and Flora – CITES	Washington	1973	1975
Convention on Wetlands of International Importance – Ramsar Convention	Ramsar	1975	1993
Convention on Civil Liability for Oil Pollution Damage	Brussels	1975	1977
London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter	London	1975	1982
Convention on the Conservation of Migratory Species of Wild Animals – CMS	Bonn	1983	2013
Convention on Biological Diversity – CBD	Rio de Janeiro	1993	1994
United Nations Framework Convention on Climate Change– UNFCCC	Rio de Janeiro	1994	1994
Paris Agreement (legally binding international treaty on climate change, under the UNFCCC)	Paris	2015	2016
United Nations Convention on the Law of the Sea – UNCLOS	Montego Bay	1994	1994
International Seabed Authority (1994 Agreement on Part XI of UNCLOS)	Montego Bay	1994	2008
United Nations agreement on Biodiversity Beyond National Jurisdiction (BBNJ Agreement)	New York	2023	in progress

In 2006, during the 8th Conference of the Parties to the Convention on Biological Diversity, Brazil officially joined the International Coral Reef



Initiative (ICRI), bringing attention to its reef environments in international forums. Since then, Brazil has also been a part of the Global Coral Reef Monitoring Network (GCRMN) and has contributed to periodic publications like the "Status of Coral Reefs of the World". In 2017, Brazil participated in the International Coral Reef Policy Advisory Committee, invited by UNEP to draft the document "The Analysis of Global and Regional Policy Instruments and Governance Mechanisms Related to the Protection and Sustainable Management of Coral Reefs." The document was approved during UNEA-4 in March 2019.

Rio 92, known as the Earth Summit, marked the origin of the conventions: the Convention on Biological Diversity (CBD), the United Nations Framework Convention on Climate Change (UNFCCC) and the United Nations Convention to Combat Desertification (UNCCD). Considering that we're living through humanity's worst crises: pollution, loss of biodiversity and the climate emergency recently, a decision by the sixth session of the UN Environment Assembly (UNEA-6) in 2024, registered the "Rio Trio" initiative to promote collaboration between the Presidencies of the next Conferences of the Parties to the CBD, the UNFCCC and the Paris Agreement and the UNCCD.

It is worth highlighting that, since 2017 with the holding of the first Ocean Conference of the United Nations, has represented a unique and invaluable opportunity for the world to reverse the precipitous decline of the health of the oceans and seas through concrete solutions. The Conference will also promote progress in the implementation of Sustainable Development Goal 14, which is part of the 2030 Agenda adopted by all 193 UN Member States in 2015. The goal calls for efforts to conserve and sustainably use the oceans, seas and marine resources for sustainable development. The Third UN Ocean Conference (UNOC3), which will take place in Nice in June 2025. The conference aims to support further and urgent action to conserve and sustainably use the oceans, seas and marine resources for sustainable development.

In September 2019, the Intergovernmental Panel on Climate Change (IPCC), Scientific Panel subsidiary for UNFCCC, published a special report on the relationship between the ocean and climate change (IPCC, 2019)⁸, which presented alarming data both on the health of marine ecosystems due to warming, acidification, deoxygenation and

⁸ <https://www.ipcc.ch/srocc/>.



rising sea levels, and on the risks to their potential to continue to act decisively in regulating the climate. The report highlights that since 1993, the rate of ocean warming has more than doubled. Coral reef environments stand out because they are the main ones directly affected by global climate change. Coral reefs could be the first ecosystem to become functionally extinct. Some of these areas are doomed to disappear. IPCC forecasts show that with a 1.5°C rise in temperature, 70-90% of corals will disappear (50% of these environments have already been lost worldwide) and if the average temperature rise is 2.0°C, up to 99% of these environments are expected to be lost.

In 2018, a High-Level Panel for a Sustainable Ocean Economy was launched, comprising 14 heads of state, presenting a commitment for the next ten years⁹. Today there are 19 world leaders who have joined together to realize the mission of sustainably managing the ocean area under national jurisdictions. The commitment covers five areas that aim to protect the ocean (and the planet) while harnessing its potential to deal with global challenges such as climate change, food security and maintaining biodiversity. Brazil is not part yet of this Panel.

And in January 2021 was launched the United Nations Decade of Ocean Science for Sustainable Development (2021-2030), the ‘Ocean Decade’, provides a convening framework for a wide range of stakeholders across the world to engage and collaborate outside their traditional communities to trigger nothing less than a revolution in ocean science

In 2022, Heads of State, Ministers of environment and other representatives from UN Member States endorsed a historic resolution at the UN Environment Assembly (UNEA-5) today in Nairobi to End Plastic Pollution and forge an international legally binding agreement by 2024. The resolution calls for an Intergovernmental Negotiating Committee (INC) to develop “the instrument”, which should be based on a comprehensive approach that addresses the complete life cycle of plastic, including its production, design and disposal. The INC began its work in the second half of 2022, with the ambition of concluding negotiations by the end of 2024. However, the negotiations for a binding treaty have been discussed between the countries, with no significant progress so far and with each meeting of the

⁹ <https://oceanpanel.org/about-ocean-panel/>.



Intergovernmental Negotiating Committee on Plastic Pollution (INC) being postponed.

During 2024, Brazil assumed the presidency of the G20, and the Ministry of the Environment and Climate Change coordinated the Environment and Climate Sustainability Working Group (ECSWG). In the context of environmental and climate issues, Brazil stood out in several areas: Oceans, Payment for Ecosystem Services, Enhancing Adaptation Action and Finance in the context of Climate Change, and Waste and Circular Economy. Recognizing the urgent need to address the conservation and sustainable use of marine biodiversity, as well as the key role oceans play in ensuring climate stability and mitigating the adverse effects of climate change, G20 countries agreed on the importance of including ocean-based actions in their nationally determined climate targets (NDCs) and biodiversity plans (NBSAPs).

The final declaration adopted during the G20 Summit also committed to robust marine conservation targets and sustainable resource management, which will form a foundation for discussions at COP30¹⁰. And during the G20 summit in Rio de Janeiro, Presidents Lula and Macron of France committed to making the protection of the oceans and marine and coastal ecosystems a strategic priority in their bilateral and multilateral commitment to protecting biodiversity and combating climate change. The joint declaration highlights 20 points of convergence, among them the strengthening of cooperation on ocean issues, establishing spaces for debate on topics of mutual interest during UNOC3, to be held in Nice, and its continuation during COP30 of UNFCCC, to be held in Belém in November 2025.

In October of 2024, at the COP16 of CBD, 3 resolutions of importance to marine biodiversity were approved, with the highlight being the resolution 16/22 - Biodiversity and Climate Change which emphasizes to be “*Deeply concerned* that the increasing anthropogenic emissions of carbon dioxide leading to increased carbon dioxide concentrations in the atmosphere are causing ocean acidification and elevated temperatures, including marine heatwaves and deoxygenation, with severe consequences for marine life, in particular coral reefs and other sensitive marine ecosystems, species and life histories” and

¹⁰ <https://www.gov.br/planalto/pt-br/media/18-11-2024-declaracao-de-lideres-g20.pdf>.

Recognizing the crucial role and capacity of the ocean in regulating the climate¹¹.

Considerable progress was also made on the issue of the participation of traditional peoples and communities in the COPs and the agreement on a global levy on products made using genetic data from nature, potentially creating one of the world's largest biodiversity conservation funds.

Despite these resolutions COP16 failed to reach its conclusion. There was no agreement or quorum on the funding needed to fulfil the goals of the Kunming-Montreal Global Biodiversity Framework by 2030 to stop the human-caused destruction of biodiversity raising fears that this lack of progress on finance will hold back efforts to halt and reverse nature losses,

Also in 2024, at COP29 of UNFCCC, held in Baku, Azerbaijan, Brazil launched its updated Nationally Determined Contribution (NDC), ambitious and aligned to the 1,50 target which, for the first time, includes ocean-based measures as a central component. These actions are aligned with the National Climate Plan and integrated to the National Biodiversity Strategy and Action Plan (NBSAP). This ensures synergy between our climate adaptation and mitigation efforts and biodiversity goals. Also, at COP29, Brazil was nominated as the next co-chair of the Ocean Dialogue in preparation for COP30. This will be an opportunity to raise the urgency of the ocean issue in the negotiations for the next UNFCCC COPs.

The ocean-based actions included in Brazil's NDC include specific strategies for mitigation and adaptation, such as Marine Spatial Planning (MSP), highlighted as an important tool for decarbonization, along with initiatives such as the creation of marine protected areas (MPAs), and conservation programs and the restoration of climate-vulnerable ecosystems such as mangroves and coral reefs.

However, COP29 ended with mixed results and progress. The New Quantified Collective Goal (NCQG), the centerpiece of the negotiations, was formally established, marking progress, albeit limited, towards securing the climate finance needed by developing countries. Despite this, the promise of financial commitments remains

¹¹ <https://www.cbd.int/conferences/2024/cop-16/documents>.

insufficient to tackle the climate emergency¹². And there was no decision of an energy transition or the expected end to fossil fuels.

It will therefore be up to Brazil, the next president of COP30, to resolve several pending issues in multilateralism. It is already known that COP30 will be one of the most important meetings of the UNFCCC, on the one hand because it marks 10 years since the Paris Agreement and when all countries will have to present their new NDCs with ambitious targets that demonstrate their real intention to hold the average global temperature rise to 1.5°C, on the other hand climate finance, climate justice and the energy transition still need to be addressed.

4.2. National Instruments

Main conservation policies for reef environments.

Main conservation policies for reef environments Brazilian public policies directed at coral reefs can be traced back to the late seventies, when a few no-take MPAs were declared in some of the country's most iconic reef sites. This phase started in 1979, with the declaration of the Atol das Rocas Biological Reserve in the only atoll in the South Atlantic and was followed by the declaration of the Abrolhos National Marine National Park in 1983, covering part of one of the most biologically diverse marine ecosystems in the South Atlantic, which hosts most of its coral species. Five years later, in 1988, the Fernando de Noronha Marine National Park was declared, encompassing part of the Fernando de Noronha Archipelago. Following this initial phase of no-take MPA declaration, with very low implementation levels, there were virtually no public policies addressing coral reefs up until the late 1990s.

In 1997, during the first International Year of the Reefs- IYOR, Brazilian scientists organized the "Workshop on Brazilian Coral Reefs: Research, Integrated Management, and Conservation" (March 9th-15th), which brought together researchers and environmental managers from Brazil and around the world. This workshop highlighted the importance of coral reefs and provided several recommendations for public policies. Six months later, these efforts resulted in the declaration of the country's largest coastal-marine protected area at the time, the Environmental Protection Area (APA) Costa dos Corais, along the coasts of Pernambuco and Alagoas states. This multiple-use MPA -

¹² <https://politicaporinteiro.org/2024/11/24/resultado-final-da-cop-29-incrementalismo-versus-urgencia/>



where certain extractive uses are allowed - was created to regulate the use of and protect the reef formations, as well as endangered species such as the manatee *Trichechus manatus* and the goliath grouper *Epinephelus itajara*.

The workshop was held at the Center for Research and Conservation of Marine Biodiversity of the Northeast (CEPENE), then linked to IBAMA and currently to ICMBio. In partnership with the Federal University of Pernambuco (UFPE), CEPENE remains a leader in actions for coral reefs. The workshop results laid the foundation for public policy formulation and setting priorities in research, management, and conservation of Brazilian coral reefs. It was also crucial to organizing sustainable use and conservation efforts for these ecosystems.

The discussions held at this historic event are captured in a nearly 100-page report, still a reference in the field. The document warns of the current threats to coral reefs: “Several factors are responsible for the degradation of these environments, including direct coral removal, overfishing, unregulated tourism, sedimentation from soil erosion due to deforestation for agriculture and construction, and domestic and chemical pollution. This degradation compromises the productivity and biodiversity of these ecosystems, threatening food security and the well-being of populations that depend on the reefs.”.

Another recommendation from the workshop contributed to the Environmental Crimes Law of 1998, which addressed coral banks. Article 33 of Law No. 9,605 imposes penalties and/or fines for those who “exploit natural fields of aquatic invertebrates and algae without a license, permission, or authorization from the competent authority” or for those who “anchor vessels or dispose of debris of any kind on mollusk or coral banks marked on nautical charts.” In 1999, State Decree No. 21,972 prohibited coral extraction on the southern coast of Pernambuco. On February 7th, 2002, State Decree No. 24,017 extended this rule to the northern coast of Pernambuco. In 1999, APA Costa dos Corais also pioneered the establishment of the first “exclusion zone” within a sustainable-use conservation unit in Brazil. A Reef Recovery Area was established through an IBAMA ordinance, limiting tourism and fishing activities to create a refuge for marine life, allowing species to develop without human interference. This area remains closed today and inspired similar measures in other municipalities within APA Costa dos Corais, as outlined in its Management Plan.



In 1999, the issue was incorporated by the Secretariat of Biodiversity and Forests of the Ministry of the Environment, which worked on establishing a Coral Reef Protection Network. Key actions include (Prates et al., 2003):

- Mapping of shallow coral reefs, leading to the first Coral Reef Atlas in Marine Protected Areas in Brazil (Prates. The project "Studies on Brazilian Coral Reefs: Training and Application of Remote Sensing Mapping Techniques," in partnership with INPE and the Coastal Reefs Project (UFPE/BID/IBAMA), aimed to map reefs within Brazil's MPAs. The first edition of the atlas was published in 2001, with a revised version in 2006 during COP8, covering nine Conservation Units;
- The "Conscious Conduct in Reef Environments" campaign was launched in 2002 to raise awareness about coral reef conservation among tourists. This campaign was relaunched in 2018 with the support of the Terramar Project (Brazil/Germany Cooperation, GIZ);
- The National Coral Reef Monitoring Program in Brazil began with the Coral Reef Monitoring Pilot Project, coordinated by UFPE and supported financially by the Ministry of the Environment. The Reef Check Brazil program has been monitoring representative coral reefs since 2002, using a participatory methodology to monitor four to twelve Conservation Units.

The declaration of a multiple-use and co-managed Marine Extractive Reserve (RESEX) in Corumbau, in 2000 was an additional landmark in Brazil's coral reef conservation. Born in the Amazonia, Extractive Reserves are areas where access and use rights, including natural resource extraction, are allocated to local groups or communities. Game changers in the MPA arena, they aim at the integration of conservation and livelihoods by empowering traditional communities in the complex decision-making processes and unbalanced disputes over coastal and marine territories. At this time, the First long-term monitoring initiative began in the Abrolhos reefs (2000), following RAP - Conservation International and partners, and the Corumbau Extractive Reserve also declared a no-take area, with a BACI assessment of reserve effects developed on fishery resources (Prates & Blanc, 2007).

In addition to the creation and establishment of conservation units, Brazil has also developed National Action Plans for the Conservation of Threatened Species (PAN). These plans, developed with societal input, identify and guide priority actions to combat the threats endangering



species and their environments. For example, the National Action Plan for Coral Reef Environments (PAN Corais), launched in 2014, addressed 52 endangered species. The plan concluded its implementation in 2021, and preparations began for the second cycle in 2024.

In 2023, under the Ministry of Environment and Climate Change (Decree No. 11,349/2023), the Department of Ocean and Coastal Management was created. Its responsibilities include coordinating plans and projects for the conservation of marine environments, mitigating environmental impacts, and implementing international agreements like ICRI, UNCLOS and BBNJ. The department has since worked to continue previous policies and promote conservation actions for ecosystems vulnerable to climate change, such as coral reefs and mangroves.

In 2024, the ProManguezal Program was created (Decree No. 12,045, of June 5th, 2024) and Brazil resumed its participation in ICRI. A national coral reef conservation strategy was also developed and recently signed as a Decree establishing ProCoral (Decree no. 12,486, of June 3rd, 2025) and launched internationally during the 3rd United Nations Ocean Conference, UNOC3, held in Nice, France in June 2025. Furthermore, a call for conservation projects for coral reefs was opened with BNDES, the Brazilian National Bank of Development, with funding totaling 90 million reais. An updated Coral Reef Atlas for 2025 is underway through a technical cooperation agreement between the Ministry of the Environment and MapBiomias.

The country's new Climate Plan is in the final stages of public consultation. The new Climate Plan is the main instrument of the National Policy on Climate Change (Law No. 12,187/2009) and agrees to build a long-term sustainable development path. In development since 2023, it will be the guide for actions to tackle climate change in Brazil until 2035. In its adaptation component, the Climate Plan's main challenge is to increase the country's resilience to climate change, while tackling inequalities in pursuit of climate justice. The plan will have a National Adaptation Strategy, which will define guidelines for drawing up sectoral and thematic adaptation plans at national level, as well as state and municipal adaptation plans. In the adaptation component, the plan is made up of 16 sectoral and thematic plans, including 'Ocean and Coastal Zone', in which one of the goals was the publication of a National Strategy for the conservation of coral reefs ProCoralProCoral aims to promote the resilience of these ecosystems



and the maintenance of their ecological functions and their benefits to human populations in the face of the pressures to which they are subjected, especially with regard to climate change. The Decree establishes guidelines and provides axes for implementation with respective lines of action, the first time that the country has had a specific public policy for coral reefs.

In the National Congress, the Law of the Sea (PL 6,969/2013) was recently approved by the Chamber of Deputies, after 13 years of discussion, as a small drop in the ocean of hope for environmental progress in the midst of various proposals that threaten historic environmental achievements, such as the Licensing Bill Proposal, being proposed in the National Congress, also known as the “Devastation Bill”, which would end the current environmental licensing procedures, and PEC 3, which aims to amend the Federal Constitution to extinguish “marine lands”, transferring these areas to states, municipalities and private individuals.

On the other hand, several new laws are being proposed in the National Congress, threatening historic environmental gains such as the Licensing Law Proposal, which would end current environmental licensing procedures, and PEC 3, which aims to amend the Federal Constitution to extinguish “terrenos de marinha” (marine lands), transferring these areas to states, municipalities and private individuals.

4.3. Political and Institutional Challenges

The federal government has been working on public policies for the conservation of coral reefs since the 1990s, but in a discontinuous way and with gaps in its actions.

In Brazil, the ups and downs of government bring about challenges of policy continuity and integration, as the protection of reef environments involves multiple scales, stakeholders and institutions. For instance, in recent years there have been many attempts, in Brazil and elsewhere, to dismantle existing environmental policies, and many have unfortunately been successful. Yet, the multitude of actors can be exactly what makes continuity possible, as there are more stakeholders to fill in the gaps that are left. Coral bleaching also brings opportunities due to its disaster-orientation and different sectors affected and also because it requires both small and large actions. Coral reefs also

provide the opportunity to bring together multiple interests through common ocean conservation goals. Perhaps precisely because of the climate emergency we are experiencing, it is important to recognize that for the first time we are seeing a public policy aimed at these environments. The challenge is to implement the policy and ensure that these actions continue.

Parallel to these issues, we must also deal with the broader and competing socio environmental challenges brought about by climate change, such as how to mitigate impacts and adapt to new scenarios such as a warmer ocean and its consequences. One path to this can be using nature-based solutions, although with care to complex conceptual issues in which this term can sometimes be used as a form of greenwashing. The development of such solutions should be pursued at the coastal territories through learning from local ecological knowledge. Successful initiatives from traditional people territories should be promoted and disseminated.





5

THE WAY AHEAD



THE WAY
AHEAD

5. THE WAY AHEAD

5.1. Need for Knowledge

Discussions during the seminar highlighted the growing severity of coral bleaching events and the increasing mortality rates in coral ecosystems, with a strong consensus on the impact of climate change, but beyond that, on the uncertainties derived from new and many times unpredictable scenarios. Participants emphasized the need for more comprehensive and long-term research to address knowledge gaps. The complexity of coral resilience, influenced by variables like ocean acidification, deoxygenation, and regional differences in species adaptation, was a key point. Monitoring programs need to be expanded geographically and temporally, to fill the significant gaps that persist in Brazil. Researchers also discussed the necessity of integrating socio-economic impacts into the study of coral reef decline, focusing on how local communities and ecosystems are affected and respond to adapt changes.

There was also a call for improved monitoring systems, better organized and consistent long-term studies, and a shift towards interdisciplinary approaches that include legal, economic, and ecological aspects. Proposals included using ocean essential variables for policy development, conducting multi-year laboratory experiments, and strengthening the existing networking culture in Brazil to improve data integration and research efforts. In conclusion, the discussions pointed to the urgency of addressing the gaps in monitoring and the need for a more holistic approach to understanding and mitigating the impacts of coral bleaching on the coastal socio-ecological system.

One of the recurring themes in the discussion was the growing realization that the severity of coral bleaching events has exceeded expectations. Participants highlighted that current knowledge does not fully account for the new scenarios emerging from these increasingly intense disturbances. There was a consensus that the frequency, intensity, and persistence of these events have escalated faster than previously anticipated, creating uncertainty about what lies ahead for coral reef systems.

The unpredictability of future impacts, combined with the lack of comprehensive long-term studies, leaves significant gaps in

understanding how ecosystems and associated human communities will adapt. This highlights the need for more robust scenario modeling, integrated monitoring, and multi-disciplinary research to better anticipate and manage the challenges coral reefs and their dependent systems will face in the coming years.

Community and societal engagement are essential for success particularly at local scales. Partnerships with Artisanal Fishers, who are often on the front lines of coral reef interactions, can rescue traditions and knowledge, enhance sustainable fishing practices and contribute to habitat protection efforts. Engagement of young people in environmental stewardship and coral restoration can empower future leaders to take active roles in conservation. Youth engagement programs are critical for ensuring the next generation is equipped to tackle the challenges reefs face.

5.2. Priority Research Themes for Coral Reef Conservation

In the context of the ongoing challenges facing coral reefs, there are priority research themes that are crucial to increasing understanding and developing strategies for sustainable coral reef management and conservation (Table 3). These themes address both the ecological complexities and the socioeconomic realities that shape the future of coral ecosystems.



Table 3. Priority research themes for sustainable coral reef management and conservation.

Restoration Techniques	Coral restoration efforts have gained momentum worldwide. Research into effective restoration techniques, such as coral gardening and artificial reefs, is essential to rehabilitate damaged ecosystems. Identifying species and methods that yield the highest success rates is critical for long-term conservation
Bleaching Events Across Depths: Oceanic Seamounts and Canyons	Studying coral bleaching across different depths provides valuable insights into how various reef zones are affected by thermal stress. This research can reveal depth-related resilience and inform targeted mitigation strategies for vulnerable areas
Community perception, governance arrangements, and socio-ecological adaptation.	Understanding how local populations perceive coral reefs as the climate impacts and respond to the changes is essential for fostering community engagement in conservation. Research in this area can guide policy development and improve communication strategies for coral protection
Engaging Tourists and the Hospitality Sector (Educação para Turistas e Setor Hoteleiro/Ciência Cidadã)	Strengthen citizen science programs to leverage local and tourist involvement in monitoring efforts. Engaging tourists and hospitality workers on coral observation and conservation can promote more responsible behaviors, reducing negative human impacts on reefs.
Prioritizing Areas for Conservation	Identifying and prioritizing key areas for conservation based on ecological importance and vulnerability is essential for maximizing conservation efforts. Research in this area helps to focus limited resources on the most critical habitats
Impact of Marine Debris	Research on the impacts of marine debris, especially plastics, on coral reefs is increasingly important. Studies in this area can help identify sources of pollution and develop effective mitigation strategies
Artificial Wrecks	Understanding the impacts of sinking artificial FAD-like structures to attract fish and thus improve catchability and how it differs from initiatives to provide substrate for coral and reef growth is a crucial but often overlooked and unregulated aspect of coral conservation.
Improving Predictability of Coral Stress Events (Melhorar Previsibilidade)	Research aimed at improving the predictability of coral stress events, like bleaching, is key for proactive conservation strategies. Developing more accurate predictive models can help inform real-time management decisions

5.3. Elements of Public Policy

Climate change impacts in the ocean are expected in many geographical regions. However, there is still an asymmetry when comparing the funds for climate, marine and ecological research in the Global North and South (Pettorelli et al., 2021; Rodrigues, 2021). This is also reflected in the present assessments for endangered coral reefs, where, in a recent review, Klein et al (2024) pointed out the lack of regional scale models for the tropical western Atlantic reefs. Despite that, there are studies already predicting a "tropicalization" of southern latitudes with coral colonization up to 27°S in the Atlantic, a decrease in the temperature-refugia, and the detected vulnerability areas correspond to the highly biodiverse area of Abrolhos.



Furthermore, coral reefs are an integrated part of the seascape and particularly coastal reefs are severely impacted by land-based activities. Thus, **firstly**, public policies directed at reef environments depend directly on the implementation of broader instruments, such as the Brazilian Forest Code, that protects native vegetation from damaging agricultural practices, and the National Plan for Basic Sanitation, to decrease pollution and other anthropic pressures. **Second**, the government must act strategically to decarbonize the economy and reduce carbon related pressures on the ocean. **Third**, due to reef environments' complex links to other ecosystems, key biomes like the Atlantic Forest and related ecosystems (mangroves, *restinga*, phanerogam banks, etc.) must be restored. This can be done within a framework of protected areas, but other areas must also be observed.



Fourth, society must comprehend the close link between climate and healthy ocean and the need to put pressure on governments while also implementing necessary changes in attitudes and behavior, and that requires a joint effort between social and behavioral scientists and the education sector.

In this case it is crucial that citizens also understand that protecting the environment and promoting human development does not need to be an either/or situation. In **fifth** place, as a prioritized action, the participation of different sectors of society, including traditional coastal populations, must be ensured and equalized in decision making processes. And **finally**, the ocean must be fully integrated into coastal and marine spatial planning and climate policy and for that it is urgent to explore ways to integrate ocean-based activities into mitigation and adaptation efforts as well in climate targets and policy.



6

CONCLUSIONS



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Coral reefs are long known to be affected by climate change as corals react to temperature anomalies by expelling their algae symbionts. The dramatic effect, known as coral bleaching, has been occurring, on a global scale, more often and more intensely than predicted for this decade. Projections indicated that, by 2040-2050, annual marine heatwaves will become the norm, with lethal effects on coral reefs biodiversity and structure. Solutions include achieving net-zero greenhouse gas emissions and promoting carbon sequestration through ecosystem restoration, enhancing local conditions and minimizing chronic deleterious impacts from local pressures; creating and maintaining accountable environmental laws; and implementing restoration initiatives aimed to improve both functions and resilience of local reefs and communities.

There was a shared consensus that even with rigorous mitigation measures, the ocean cannot return to its pre-industrial state. The focus must shift to understanding the varying vulnerabilities of different regions and applying site-specific adaptive strategies. These adaptations should also incorporate the knowledge and practices of indigenous communities, whose interactions with nature offer valuable insights for conservation efforts.

Several key themes emerged regarding coral bleaching, its impacts, and adaptive strategies. Coral bleaching patterns are highly variable, with some species bleaching instantly while others take longer. The restoration efforts need to be carefully mapped to ensure that practices are applied efficiently in areas most affected by coral loss and popular fishing grounds. Local techniques to mitigate environmental impacts were emphasized.

In terms of socio-economic impacts, the costs of addressing coral degradation, along with issues like overfishing, biological invasions, and insufficient environmental protection measures, are critical. The conclusion was clear: the situation may already be irreversible in some regions, and it is crucial to understand the broader ecosystems - beyond corals and algae - to assess the full socio-economic consequences for coastal communities, such as fishers, whose livelihoods are closely tied to these ecosystems, and the implications of transitions to non-coral ecosystems.



Overview: Integrating Coral and Ocean Topics into Brazilian Federal Government Policy and Global Multilateral Discussions

Coral reef ecosystems, vital for both biodiversity and human livelihoods, are under increasing pressure from climate change, overfishing and coastal development, making their preservation a crucial aspect of broader sustainability goals. Reducing carbon emissions is the biggest and most urgent challenge to be faced in this crisis, which is climatic, biodiversity and also humanitarian. Local action is also urgently needed to maintain or increase the resilience of coral reefs. In Brazil, although there have been many local conservation gains, with the creation of Marine Protection Areas (MPAs) and specific protection laws, there have also been losses in other areas, with a clear tendency for environmental licensing to become more flexible to enable the accelerated occupation of strategic coastal areas. Local and recurring impacts such as sewage pollution, widely recognized as extremely impactful for coral reefs, remain one of the biggest challenges for resilience and survival, especially after bleaching.

Rising ocean temperatures and recent high coral mortality highlight the need to strengthen resilience in marine environments through global action, just as effective local action is urgently needed. Federal environmental efforts alone are not enough to establish new MPAs, as this requires the consent of state governments, which together with municipalities need to cooperate for the effective management of MPAs along the coast.

Therefore, effective cooperation and communication strategies are needed to create cooperation between federal, state and municipal or local authorities, strengthening their involvement in conservation initiatives.

The need to enable the participation of local and indigenous communities in decision-making processes stands out, recognizing their knowledge, rights and allowing their active involvement in conservation efforts. Recognizing the need to create and implement MPAs (including extractive reserves) and traditional territories, such as the delimitation of indigenous lands, is urgent.

Another highlight is the importance of environmental education, especially for the younger generation. This is seen as a crucial measure to deal with the urgency of climate change, with growing recognition

of the need to integrate environmental education into school curricula to promote awareness and action from an early age. The country's recent signing of a Protocol of Intent with UNESCO to make ocean culture a school subject has raised the issue of including ocean education as part of the school curriculum in Brazil to an international level. The inclusion of climate literacy in the school curriculum, through scientific learning tools, is extremely important and is in line with Sustainable Development Goals 4 (Quality Education) and 13 (Climate Action).

Recently, coral reefs, as primary indicators of climate impacts and ocean health, have gained ground in the environmental discussions of the Brazilian federal government, which has led important initiatives during the last Conferences of the Parties to the Biodiversity and Climate Conventions and at UNOC3, with the highlight being the voluntary commitments presented and the launch of important public policies such as ProCoral. The climate emergency carries significant weight in international forums and platforms, such as the Conventions and Brazil's recent presidency of the G20, where the global community is actively seeking solutions to the urgent environmental challenges of the 21st century. During the workshop to prepare this summary, the Brazilian government's recent efforts to put the ocean on the global agenda were discussed and presented, especially the importance of the ocean-climate relationship, a role that is expected to be consolidated in concrete actions at COP30.





The bleaching events between 2014/2020 (global and regional) and the subsequent global bleaching events of 2023/2025 have together brought unprecedented impacts affecting all Brazilian coral reefs. Coral bleaching and death are obvious and readily measurable impacts, but they are also an indicator of many impacts, both for biodiversity and for humans, as consequences of climate change and a possible change in the state of the ocean and human life on Earth.

The Brazilian Federal government as well as state and municipal governments, together with global efforts, have a responsibility to take a leading role in protecting these ecosystems. This involves not only the development of policies and scientific research, but also active community involvement and education to ensure adaptation and long-term ecological and socio-economic sustainability.

The national strengthening of conservation policies and the development of scientific research alongside education at different levels and the active involvement of the community is mandatory. **We are at a decisive moment, where the crisis is already present and the forecasts make it clear that we are facing a last window of opportunity.**

7

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

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Centro de Síntese em Mudanças Ambientais e Climáticas

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