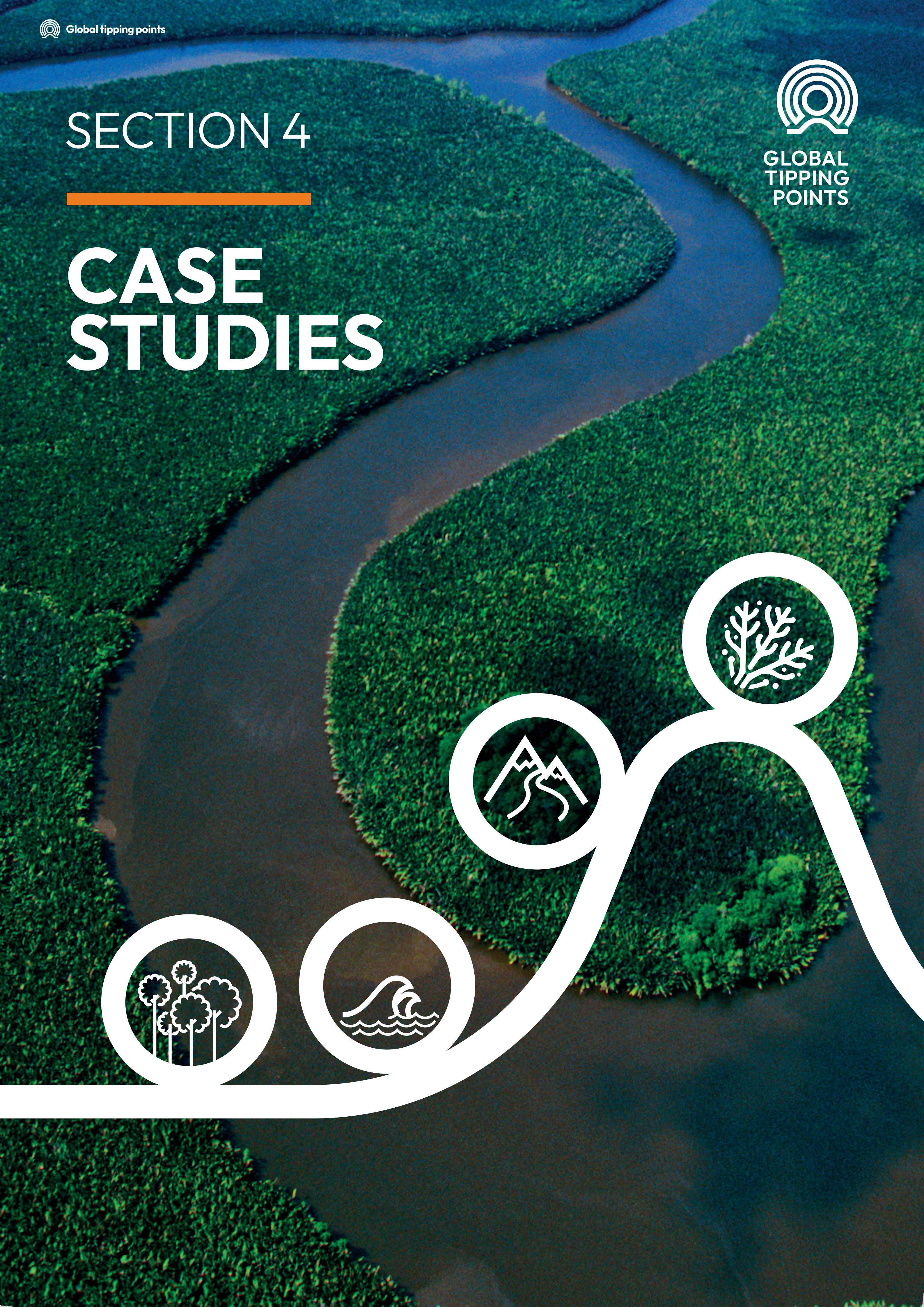

SECTION 4

CASE STUDIES

GLOBAL
TIPPING
POINTS

CASE STUDY 01

THE AMAZON RAINFOREST AT THE BRINK

4.1 The Amazon forest at the Brink: cascading risks of social-ecological tipping points and the opportunities to regeneration

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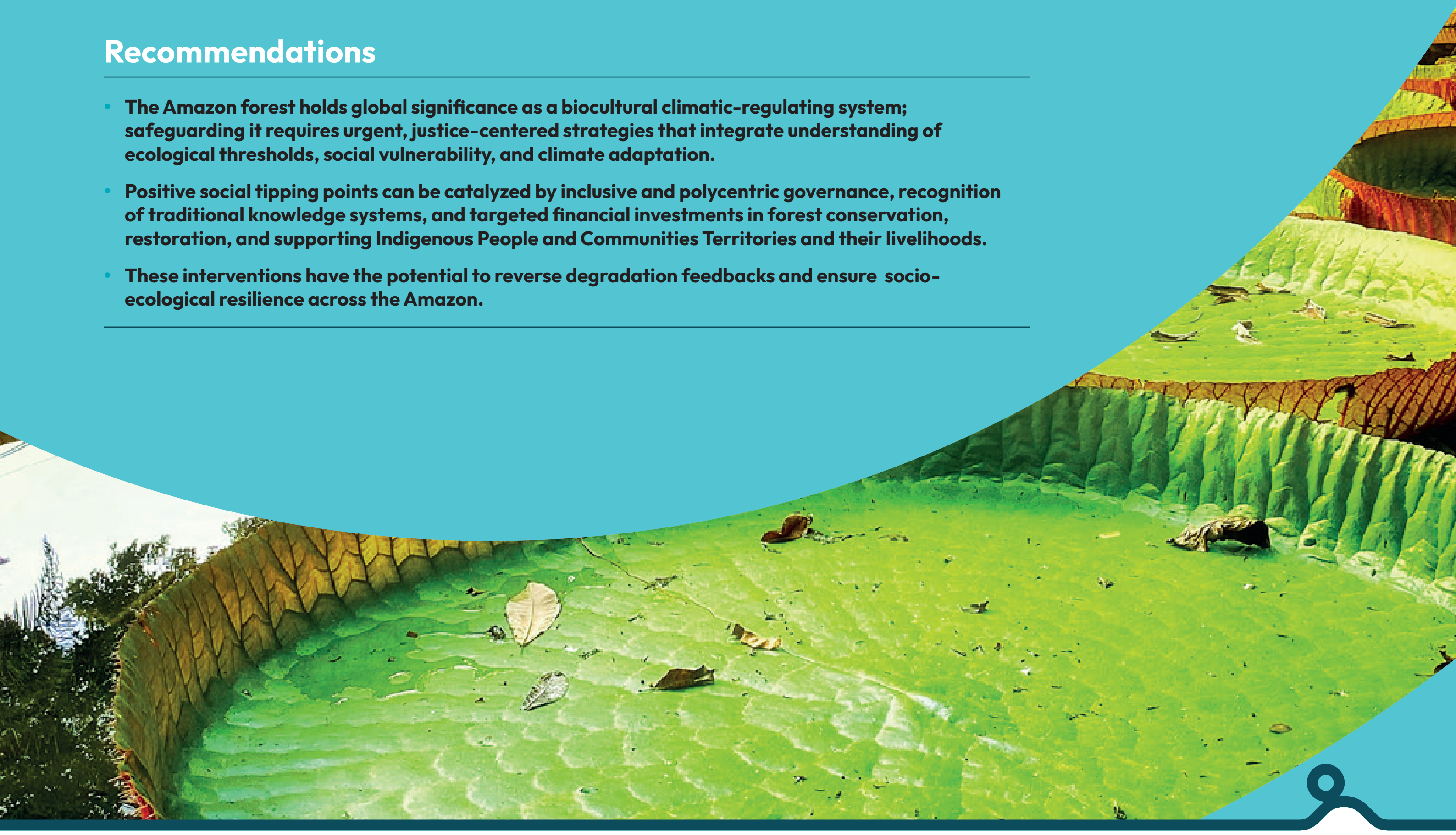
Risk assessment

- **The Amazon is approaching ecological tipping points due to interacting climate and land-use feedbacks that threaten to trigger large-scale forest degradation and regime shifts in the range of 1.5-2 °C global warming.**
- **These changes risk transforming forested areas into altered ecosystems, weakening global climate regulation, altering regional climate, and accelerating biodiversity loss.**
- **Negative social tipping points, including displacement, health impacts, and cultural erosion are unfolding alongside ecological forest transitions, especially among Indigenous and traditional populations.**
- **These impacts and risks remain significantly under-addressed in climate policy and are intensified where governance fails to secure land rights, enforce protections, or support adaptation.**
- **Indigenous Territories and Protected Areas exhibit strong climate mitigation potential, underscoring their vital role in maintaining carbon stocks and resisting ecosystem collapse.**
- **In contrast, undesignated Public Forests account for the majority of carbon losses from degradation, reflecting the consequences of weak governance and land tenure insecurity.**
- **Without immediate action, cascading risks could result in irreversible losses to both ecosystems and communities, undermining regional and global sustainability.**

Recommendations

- **The Amazon forest holds global significance as a biocultural climatic-regulating system; safeguarding it requires urgent, justice-centered strategies that integrate understanding of ecological thresholds, social vulnerability, and climate adaptation.**
- **Positive social tipping points can be catalyzed by inclusive and polycentric governance, recognition of traditional knowledge systems, and targeted financial investments in forest conservation, restoration, and supporting Indigenous People and Communities Territories and their livelihoods.**
- **These interventions have the potential to reverse degradation feedbacks and ensure socio-ecological resilience across the Amazon.**



Executive Summary

This chapter explores tipping points in the Amazon as both a warning and a window of opportunity, revealing how the destabilization of forest and Earth systems is driving profound and often irreversible impacts on Indigenous Peoples traditional populations and local population in the region—their territories, rights, livelihoods, and cultures—while also accelerating the ecological and climate crisis. While the ecological tipping point of forest dieback has received global attention, the negative social tipping points unfolding across the region are overlooked despite their role in amplifying ecological risks and opportunities for transformative changes.

Failure to protect the remaining forested areas, Indigenous territories, cultural systems, and local governance structures is undermining forest resilience and climate stability, while also deepening health burdens, displacement, and social inequalities. Fire outbreaks now directly affect 24 million people in the Amazon, with severe health and economic consequences disproportionately borne by Indigenous Peoples, children, and the elderly who are up to 22 times more vulnerable to smoke and heat.

Yet the Amazon is also a place of resilience and innovation. Indigenous territories protected areas could prevent over 15 million respiratory and cardiovascular cases annually and save more than $2 billion USD in health-related costs. These territories also contribute an estimated $5 billion USD each year to the global economy through climate regulation, carbon storage, and food and energy production.

Protected areas are a vital investment for global climate and community stability because they protect forests from deforestation and fires. By preventing multiple threats such as deforestation, fire and land grabbing, they protect the communities living in these ecosystems.

Throughout the region, Indigenous Peoples and traditional communities are catalyzing positive social tipping points jointly articulated with multi-stakeholders both nationally and internationally through forest protection, sustainable livelihoods, and restoration-based economies. From agroforestry systems in the Brazilian Amazon such as Tomé-Açu to rubber-based “vegetable leather” industries in Acre, these efforts demonstrate that socially rooted and ecologically informed interventions can reverse destructive feedbacks and enable regenerative processes.

Governance plays a central role in tipping this balance. Brazil’s legal frameworks and deforestation monitoring systems, including Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm), jurisdictional REDD+, sustainability programs like Mato Grosso’s Produce, Conserve, and Include (PCI) strategy and Municípios Verdes (Green Municipalities) have helped reduce deforestation, but remain fragmented and often inequitable in terms of shared benefits with local communities, Indigenous and traditional populations. Scaling these initiatives can lead to positive tipping dynamics including polycentric governance models that secure land tenure, prioritize Indigenous and traditional knowledge, and promote inclusive benefit-sharing.

This case study provides key recommendations for catalyzing positive tipping points, including: establishing and strengthening protected areas, Indigenous and traditional populations territories, recognizing and supporting Indigenous and traditional knowledge systems; halting deforestation and forest degradation; and restoring degraded ecosystems. These interventions are not only essential to prevent irreversible changes in socio-ecological systems, but can catalyze a transformation toward climate justice, forest regeneration, and promoting earth stewardship.

Without a justice-centered approach, the Amazon’s tipping points will not only spell disaster for the region but will also accelerate global climate instability, reinforcing patterns of historical inequities and deepening socio-economic divides. The time for action is now, to prevent a crisis, build resilience, and ensure that the Amazon remains a thriving ecosystem for both its people and the planet.

4.1.1 Introduction: The Amazon at the Crossroads of Climate and Social Tipping Points

The Amazon rainforest is a critical element of Earth's climate system (Malhi et al., 2021), the collapse of which has been highlighted as a tipping point which could be crossed under current climate projections (Armstong-McKay et al., 2022). Storing up to 200 Gt C shared between above- and below-ground biomass (Malhi et al., 2021), partial dieback of the rainforest in the most vulnerable 40% may cause emissions of ~30 Gt C, contributing to ~0.1°C of global warming and up to 2°C of regional warming (Armstong-McKay et al., 2022). While global climate changes that cause warming and drying in the region push the Amazon rainforest towards tipping (Armstong-McKay et al., 2022), this is further compounded by other concerns. Deforestation and forest degradation for example, can amplify regional water recycling feedbacks and fire feedbacks, which further push the system towards tipping (Salati et al. 1979, Brando et al. 2014, Betts et al. 2004, Pueyo et al. 2010, Zemp et al., 2017a,b).

The Amazon forest system is both a biodiversity hotspot and essential for regional and global climate stability, playing a central role in moisture recycling, cloud formation, and energy transport (Lovejoy & Nobre, 2018; Flores et al., 2024). The Amazon region is also culturally megadiverse, home to 1.7 million people from 375 Indigenous ethnic groups living across approximately 3,344 Indigenous territories, highlighting the profound and ancestral interdependence between cultural and ecological processes and resilience (Prist et al., 2023). It is where most staple crops were first domesticated and where the very disciplines of ecology and evolutionary biology took shape (Neves et al., 2021).

The risk of Amazon dieback has been predominantly documented in relation to climate change, deforestation and fire regimes (Lapola et al., 2018; Cox et al., 2004; Lapola et al., 2023; Wunderling et al., 2022; Hirota et al., 2011). The loss of resilience in the Amazon biome is increasingly evident, with local and regional-scale ecosystem transitions already occurring (Brando et al., 2025; Flores et al., 2024).

For instance, as climate change makes the Amazon rainforest hotter and drier, weak governance further amplifies fire risks, fueling uncontrolled burning that threatens ecosystems and the well-being of forest-dependent communities (Barlow et al., 2018). Some regions of the Amazon are now carbon sources rather than sinks, surpassing emissions from deforestation alone (Aragão et al., 2018; Gatti et al., 2021). Since the turn of the century, we have seen large amounts of deforestation within the basin, with an area ~3700km^2, mainly on the south-eastern edge, experiencing 50% or more deforestation (Figure 4.1.1a; Hansen et al., 2013), increasing multiple natural and social risks.

While uncertainties remain regarding the precise Amazon tipping threshold and timeline, it is clear that the social consequences of the current environmental degradation are already profound and will only intensify, becoming far-reaching and irreversible (Lapola et al., 2023; Lapola et al., 2018; Pinho et al., 2015). Extreme events of droughts are leading to disasters in the region by blocking navigability, access to food, water, health, education, and energy, thus affecting all dimensions of livelihoods and wellbeing (Santos et al., 2024; Lapola et al., 2018). These impacts when reaching Indigenous and traditional Peoples are driving migration and increasing poverty and inequalities in larger urban centers in the Brazilian Amazon (Brondizio, 2025). Both extreme floods and droughts deemed one-in-a-century-events have affected the Amazon basin recently (Barichivich et al., 2018, Marengo et al., 2021). However, these do not have homogenous effects across the basin. Using the Standardised Precipitation-Evapotranspiration Index (SPEI; Beguería et al., 2010), we show the percentage of the Amazon basin that has experienced very wet (SPEI > 2) or very dry (SPEI < -2) conditions at some time each year between 2001-2022 (Fig. 1b,c). With red (blue) points denoting significantly reported droughts (floods) in the media, it is clear that these do not necessarily correlate when looking across the full basin, highlighting the importance of viewing the Amazon as a complex and diverse system.

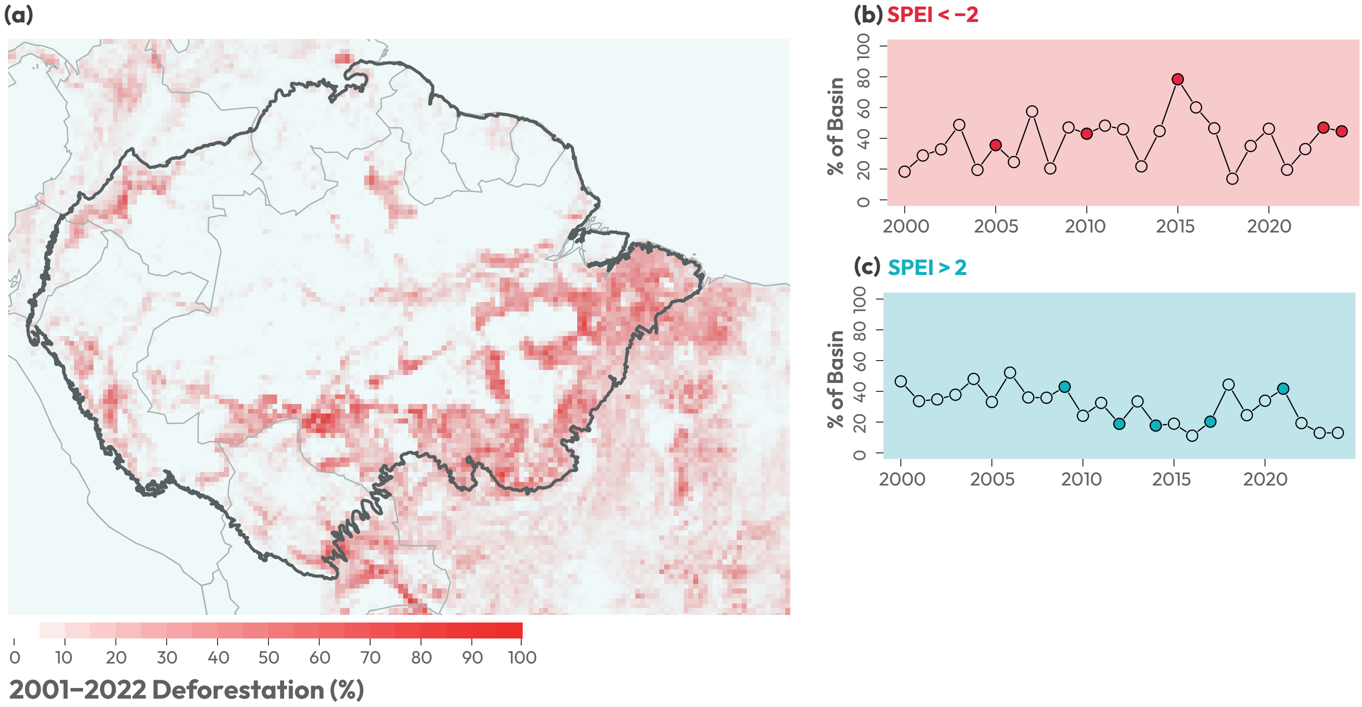


Figure 1: (a) Percentage of deforestation observed in each grid cell for the period 2001-2022 according to the Global Forest Watch database (Hansen et al., 2013), with the Amazon basin shown in a black outline. (b,c) Percentage of Amazon basin (black line in (a)) that experiences Standardised Precipitation-Evapotranspiration Index (Beguería et al., 2010) values (b) <-2 and (c) >2 at some point in the year, suggesting very dry or very wet conditions respectively. Points are coloured if a drought (red) or flood (blue) was widely reported that year.

In a scenario marked by deep social inequalities, violence, and accelerating forest degradation, what is at stake is not only the stability of the Amazon biome, but the future of its Indigenous and traditional Peoples—whose territories and ways of life are vital to global climate regulation, yet who face the risk of irreversible social collapse, deepening poverty, displacement, and the erosion of historical rights and cultural identities across the basin (Brondizio, 2025; Bowman et al., 2021). Nonetheless, Indigenous Protected Areas (IPAs) are critical buffers against escalating threats such as deforestation, fire, mining, and infrastructure development, which continue to undermine the ecological integrity of the Amazon Basin (Prist et al., 2023). Strengthening and expanding protected areas and Indigenous Peoples and traditional population territories not only safeguards biodiversity and Indigenous rights, but also reduces the risk of emerging zoonotic diseases and helps mitigate slow-onset climate impacts driven by forest degradation (Bowman et al., 2021).

The Overlooked Social Dimension of Tipping Points in the Amazon rainforest

Critical ecological transitions in the Amazon are already disrupting biodiversity, climate regulation services (Hirota et al., 2011; Flores et al., 2024; Brando et al., 2025), and livelihoods, health and cultural identities (Birkmann et al., 2023; Lapola et al., 2018; Pinho et al., 2015). Yet, despite the extensive research on biophysical tipping points, their social dimensions in terms of impacts, vulnerabilities, adaptation and limits to it, remain underexplored in the region (Brondizio et al., 2016; Spaiser et al., 2024; Birkmann et al., 2023). Despite their critical contributions to environmental stewardship and social resilience, the role of Indigenous, traditional, and community-based organizations remains largely invisible in dominant policy narratives and decision-making arenas (Brondizio et al., 2021).

Globally, the social dimension of impacts and vulnerabilities, adaptation, limits to adaptation and residual risks are disconnected from the discussion of ecological tipping points (Birkmann et al., 2023; Whyte, 2020), limiting full understanding of tipping points effects on livelihoods and culture (Parry et al., 2017; Brondizio et al., 2021; O'Neill et al., 2023).

This is an alarming oversight given that climate and ecological tipping points in the Amazon pose an existential threat to people, particularly Indigenous and traditional populations, as well as to economies, governance, and human rights. Associate loss and damage will disproportionately impact Indigenous and traditional Peoples whose livelihoods and cultural heritage are deeply intertwined with the forest, and may exceed their adaptive capacity (Birkmann et al., 2023; Lapola et al., 2023).

However, Indigenous Territories and Protected Natural Areas (PNAs) in the Amazon stored over 58% of the region's carbon stock in 2016 (41,991 MtC), yet accounted for only 10% (−130 MtC) of the net carbon loss, highlighting their critical role in climate stability (Walker et al., 2020). Despite this, nearly 434 MtC and 423 MtC of carbon were lost from Indigenous Territories and PNAs, respectively, due to forest degradation (Walker et al., 2020), pointing to the urgent need for increased political protection and financial support for Indigenous and local stewardship to meet the Paris Agreement targets. Although research is limited, growing evidence shows that Indigenous and traditional territories play a vital role in supporting human health and local economies, underscoring the need to fully recognize their ecological, social, and economic benefits in land tenure, conservation, and ecosystem service policies (Prist et al., 2023).

The Amazon's social tipping points present a major hurdle for achieving global sustainability in a socially just way under a rapidly changing climate. However, current global and public policies and governance mechanisms are shaped by historical inequalities and global legacies of exploitation (Birkmann et al., 2023, Box 8.5). They are failing to address the cascading socio-ecological impacts of Amazon degradation, particularly for Indigenous and traditional communities who are already suffering irreversible losses (Lapola et al., 2023). For instance, Indigenous territories are increasingly facing multiple pressures, including climate change and land-use change, while rising extremes such as severe droughts have intensified tree mortality and increased vulnerability to wildfires. These events have already been observed in Indigenous Territories like Xingu and Raposa Serra do Sol in the Brazilian Amazon, where climate-driven droughts are triggering cascading degradation and amplifying future risks (Walker et al., 2020; Brando et al. 2019). As these crises escalate, the window of opportunity for meaningful action is rapidly closing (Lenton et al., 2023). Without urgent and deliberate intervention, these communities will continue to face food and water insecurity, loss of health, displacement, and escalating violence, reinforcing cycles of vulnerability and exclusion in the context of global climate change. See chapter 1.4.8 of the report for more information on human rights and preventing regional tipping points.

We can, however, learn from some positive stories within the region. The local wellbeing benefits within the Amazon have been seen with the implementation of sustainable-use protected areas (Campos-Silva et al., 2021), and by reducing emissions (Walker et al., 2020).

Given the Amazon's essential role in global biodiversity and climate regulation, addressing its tipping points must be seen through a climate justice lens—locally, nationally and internationally. The Amazon is not only a regional concern but a critical solution providing climate regulation and an ecosystem where the societal costs of inaction will extend far beyond its borders. Safeguarding the Amazon requires a fundamental shift toward the adoption of policies that prioritize Indigenous and traditional Peoples' land rights, recognize traditional knowledge systems, and ensure equitable access to adaptation and resilience-building resources. The Indigenous territories have a large potential to mitigate climate change and deforestation in these areas, avoiding the Amazon tipping points from being reached (Brondizio 2025). Hence, international cooperation and financial mechanisms must acknowledge the Amazon's planetary significance, providing adequate support for conservation, restoration, regeneration and climate adaptation efforts as to reduce the risks of crossing irreversible tipping points.

This case study examines the Amazon's negative tipping points, analyzing the critical transitions already underway and the cascading socio-ecological risks they trigger. We explore how these processes can lead to impacts on food, water, and health security, promoting forced displacement, conflicts, governance breakdowns, and livelihood collapses, amplifying existing inequities and systemic vulnerabilities. The case study will then assess pathways for building Amazon resilience, highlighting opportunities for positive social tipping dynamics that can reduce socio-ecological risks, advance climate justice, and foster transformative change.

As COP 30 unfolds in Belém, within the Amazon rainforest, this topic takes on unprecedented global relevance. The Amazon's fate is a defining issue for climate stability, biodiversity conservation, and global equity. Preventing its tipping points from becoming cascading crises is not just an environmental imperative, it must become a human rights and climate justice priority.

4.1.2 Climate and Ecological Feedback Loops in the Amazon rainforest System

The Amazon rainforest system is under increasing pressure from interacting climate and ecological feedbacks that push it closer to a tipping point (Flores et al., 2024). These feedbacks, driven by both climate-driven stressors and human-induced disturbances, threaten to destabilize the rainforest's ability to sustain its natural equilibrium. Understanding these processes is critical to assessing the conditions that accelerate degradation and determining how their effects are distributed across the basin.

The interplay of climate change, deforestation, and forest degradation is reshaping the Amazon through both short- and long-term stressors. Extreme droughts have become more frequent and severe over the last 20 years with record droughts in the years 2005, 2010, 2014-2015 and 2023-2024 (Marengo et al., 2021). Many of them were triggered by anomalous warming of sea surface temperatures (SSTs) in the tropical Atlantic and Pacific, often intensified by El Niño events (Marengo et al., 2008; Jiménez-Muñoz et al., 2016). Meanwhile, the dry season has lengthened significantly over southern Amazonia since 1979 (Fu et al., 2013; Marengo et al., 2021), exposing large forest areas to prolonged water deficits. These shifts disrupt key biophysical feedback loops, such as the forest-rainfall feedback, which regulates Amazonian precipitation patterns.

Amazon forest ecosystems play a major role in moisture recycling, with up to an estimated 30% of rainfall in South American cities originating from evapotranspiration (Beveridge et al., 2024). As moisture moves westward across the basin, it becomes almost entirely recycled by the forest itself. The release of latent heat when this moisture condenses in the atmosphere also helps drive the monsoon circulation that draws more moisture into the Amazon basin (Boers et al. 2017). However, deforestation, particularly along the eastern Amazon, can disrupt both processes, reducing rainfall further into the basin (Staal et al., 2018). This positive feedback loop of drying and tree loss contributes to widespread forest dieback, further intensifying regional water deficits and leading to a degraded state.

At smaller scales, fire-vegetation feedback loops drive local forest mortality. As droughts become more severe, forests become drier and increasingly prone to wildfires (Brando et al., 2014). Fire frequency has surged in recent years (Aragão et al., 2018; Gatti et al., 2021), often leading to the replacement of burned areas with highly flammable grasses, which further desiccate the landscape, dry the atmosphere above, and increase future fire risks (Higgins et al., 2000). These dynamics create self-reinforcing degradation cycles, making it difficult for forests to naturally recover over time.

Beyond regional climate feedback, the Amazon is also influenced by large-scale atmospheric and oceanic circulation shifts. The Atlantic Meridional Overturning Circulation (AMOC) has weakened since the 1950s, likely due to anthropogenic emissions (Caesar et al., 2018), which could alter Amazon rainfall patterns; a southward shift in the Intertropical Convergence Zone (ITCZ) can increase precipitation in the southern Amazon while intensifying drying trends in the north (Akabane et al., 2024; Nian et al., 2023). These divergent patterns could stabilize forests in some regions while pushing others toward a degraded or savanna-like state (Ciemer et al., 2021).

Currently, up to 47% of Amazonian ecosystems are exposed to compounding stressors that increase the likelihood of reaching localized or basin-wide tipping points (Flores et al., 2024). Locally, tippings could result in three possible future states across different regions, depending on the location: degraded forest, degraded open-canopy ecosystems, or savanna type of ecosystems. Each has different levels of irreversibility, depending on the persistence and intensity of disturbances.

Recent modeling results, in agreement with earlier expert assessments (Lovejoy & Nobre, 2018), suggest that if deforestation reaches more than 20% of the current forest extent, combined with 1.5–2°C of global warming, over two-thirds of the Amazon could cross a tipping point (Wunderling et al., 2025), changing state within decades (Cooper et al. 2020). However, other modelling studies suggest a smaller change in rainfall response to deforestation than previously thought (Yoon & Hohenegger, 2025). Flores et al. (2024) suggest precautionary limits of 1.5°C and 10% deforestation (requiring restoration of 5% of the biome) to avoid broad-scale ecosystem transitions. These findings underscore the urgent need for strong, effective governance, climate action, and conservation policies to safeguard the Amazon forest system from irreversible transformations.

4.1.3 Societal impacts in the Amazon rainforest system

The Amazon rainforest is facing profound social and economic vulnerabilities due to ecological and climate tipping points. Historically, Indigenous and traditional populations were well-adapted to natural seasonal patterns (Harris 1998), but increasingly frequent and severe extreme climate events, such as droughts and floods are overwhelming these communities' ability to cope (Maru et al. 2014; Lapola et al. 2018; Kreibich et al., 2022; Pinho et al., 2025 in review). Losses in food production, infrastructure, and health services are becoming commonplace, with extreme flooding now occurring every four years instead of once every two decades (Marengo et al. 2024). These disruptions are directly tied to shifts in the hydrological cycle and climate feedback loops (Zemp et al. 2017a,b; Garcia et al. 2018), which are not only degrading ecosystems but also undermining basic human needs like food and water security (Nobre et al. 2025, Padilha et al. 2025).

Applying the risk framework, adapted from the IPCC AR6 and discussed in Section 2.1, highlights the interconnected nature of climate-related hazards, exposure, and vulnerabilities in the Amazon. Should the Amazon rainforest reach its bio-physical tipping point, immediate hazards, including extreme climate events and wildfires, will severely affect health, livelihoods, infrastructure, and culture particularly among rural and Indigenous communities. The combination of extreme droughts, degradation of forests and aquatic ecosystems is likely to lead to a collapse in biodiversity and commercial fish stocks (Birkmann et al., 2023; Lapola et al., 2023), while water shortages would further destabilize hydropower and river transport (Lapola et al., 2018; Lenton et al., 2023; Costa & Marengo, 2023). These cascading ecological failures are leading to increased food prices and reduced access to essential resources , creating acute risks for marginalized populations who lack the resources and infrastructure to adapt effectively (Monteverde et al., 2024; Begazo-Curie & Vranken, 2025). Already the Brazilian government is bringing in food and water to the Amazon during droughts (Kelly & Grattan 2023), and under a tipping scenario such a crisis situation would become chronic.

Fire outbreaks in the Amazon Basin directly affect Indigenous Peoples, traditional communities, and among these, children, and the elderly are up to 22 times more vulnerable to smoke and heat exposure (Machado-Silva et al. 2020; Campanharo et al. 2019, Urrutia-Pereira et al. 2021). Burning a single hectare of Amazon forest can release 760.5 kg of PM2.5 (fine particulate matter in the air with a diameter of 2.5 micrometres or less), resulting in public health costs exceeding $2.1 million USD, and up to $7.5 million in severe cases, highlighting the profound societal and economic toll of fires in the region (Prist et al. 2023).

Vulnerabilities in the Amazon forest are heterogeneous; they are shaped by deep-rooted inequalities and historical injustices such as land dispossession and marginalization of Indigenous Peoples and traditional communities (Birkmann et al., 2023; Pinho et al. 2015, Sultana, 2021, Parry et al., 2017). Unequal access to capital, healthcare, education, and basic infrastructure compounds the impact of climate shocks, particularly if the Amazon region suffers from ecological tipping points. As these stressors intensify under a tipping scenario, so too would the risks of economic decline, social unrest and forced migration (Pinho et al., 2015; Lapola et al., 2018; Birkmann et al., 2023). The Amazon's social tipping points such as migration and conflict, would be increasingly triggered not only by actual environmental degradation but also by perceived climate risks (De Longueville et al., 2020), undermining community stability and deepening socio-economic disparities (Spaiser et al. 2024). However, the further into the cascading chain of socioeconomic impacts we move in anticipating scenarios under Amazon systemic tipping, the more uncertainty we face. Still, the transition from sporadic climate shocks to permanent large-scale ecological regime change, will likely result at least temporarily in large-scale impoverishment and loss of social cohesion that would further erode adaptive capacity and accelerate displacement and systemic instability (Lenton et al., 2023).

Self-reinforcing cycles of decline can emerge, involving food insecurity, displacement, violence, and physical and mental health deterioration (Spaiser et al. 2024). Cascading risks, which cannot be mitigated through adaptation strategies (Thompson et al. 2024, de Carvalho 2025), represent irreversible losses in biodiversity, livelihoods and cultural identity. The erosion of traditional knowledge and social cohesion would further accelerate these declines (Birkmann et al., 2022, Pearson et al. 2023).

The societal impacts of climate and land-use change in the Amazon, ranging from escalating health crises and economic losses to the erosion of traditional knowledge, rights and cultural identities, are already deeply felt, particularly among Indigenous and traditional communities. Overcoming these interconnected risks requires confronting historical asymmetries in power, capacity, and voice. Moving forward, effective responses must be rooted in inclusive governance arrangements that bridge public and private sectors, science and policy, and, most critically, the lived knowledge and leadership of Indigenous Peoples and local communities (Garnett et al., 2018).

4.1.4 Governance to avoid socio-ecological tipping points in the Amazon

As highlighted in the previous section, the Amazon faces imminent socio-ecological tipping points driven by land-use change, environmental degradation, and deep-rooted inequalities. Avoiding collapse and fostering resilience requires strengthening governance systems that are inclusive, territorially grounded, and capable of integrating Indigenous knowledge and science into policies for conservation, climate adaptation, and sustainable livelihoods (see Chapter 1.2).

In the absence of robust governance, crises can escalate, straining state capacity, undermining democratic institutions, and increasing the risk of climate-induced social unrest and authoritarian backsliding (Spaiser et al., 2024; Urzedo & Chatterjee, 2022). Just responses must center the rights and agency of Indigenous Peoples and Local Communities, prioritizing land tenure security, participation in decision-making, and access to sustainable finance (Pereira et al., 2024; see Chapter 1.4).

Brazil and other Pan-Amazonian countries have developed legal frameworks, monitoring systems, and institutional arrangements to curb deforestation and safeguard ecosystems. Brazil's Action Plan for the Prevention and Control of Deforestation in the Legal Amazon PPCDAm, reinstated in 2023, combines enforcement tools such as DETER and PRODES with territorial strategies like the demarcation of Indigenous Lands and Protected Areas, which remain among the most effective barriers to deforestation (Nolte et al., 2013; Walker et al., 2020). Recent reductions in deforestation alerts by 50% in 2023, compared to the previous year, and the lowest since 2018, show the impact of renewed governance efforts (Reuters, 2024).

Regional governance for protected areas in the Amazon has also evolved beyond extractivist models, increasingly embracing participatory approaches that recognize the interdependence between forest conservation and social equity (Brondizio 2025). For instance, extractivist and Sustainable Development Reserves, supported by grassroots mobilization and international cooperation (e.g., UN Rio 92, PPG-7), have helped link biodiversity protection to poverty reduction and local empowerment (Pinho et al., 2014). Programs such as Bolsa Floresta, SDR Mamirauá, and Proambiente are incentive-based policies, e.g., payment for ecosystem services (PES), that promote capacity building, local participation and generate socio-ecological co-benefits in the Brazilian Amazon. The co-management of pirarucu fisheries -one of the largest freshwater fisheries in the world- in Mamirauá at the Juruá River exemplifies how community-led governance can improve well-being while protecting biodiversity (Campos-Silva et al., 2021).

Hybrid governance arrangements, blending national policy, international partners and funding, and strong local institutions have enabled innovations such as in freshwater management agreements and sustainable practices for fisheries (Brondizio 2025). For instance, along a 2,000-km stretch of the Amazon, co-managed protected areas involving over 100 communities have delivered improved health, education, and livelihoods while restoring wildlife populations (Campos-Silva et al., 2021). The 2006 Soy Moratorium (also summarised in Box 3.5.2 of the report), catalyzed by civil society pressure and corporate accountability, became a landmark governance intervention, proving that market-driven agreements can effectively curb deforestation by making environmental compliance a condition for market access (Nepstad et al., 2014). The Amazon Fund and state-led REDD (Reduction Emissions from Deforestation and Forest Degradation) programs exemplify how performance-based partnerships, combining international donor funding, national and subnational strengthening and local implementation can align incentives across scales to reduce deforestation and strengthen forest governance in the Amazon (Nepstad et al., 2014; Garret et al., 2021).

A range of innovative governance instruments has gained force recently to curb deforestation in the Brazilian Amazon. Jurisdictional REDD+ programs in states like Acre, Amazonas, Amapá, Pará, and Mato Grosso offer performance-based incentives for reducing emissions while promoting sustainable development associated with the carbon market (Gueiros, 2023). Locally driven initiatives such as Mato Grosso's Produce, Conserve, and Include (PCI) strategy and Pará's Municípios Verdes Program link land-use planning, environmental licensing, and inclusive rural development, demonstrating how subnational and municipal leadership can drive effective forest governance (Garret et al., 2021). Yet, these market-based instruments still face implementation challenges, including insecure land tenure and unstable funding that must be addressed to ensure sustainability and justice. The finance subchapter (1.2.3) of Chapter 1.2 delves into more detail about this.

Despite advances, governance of the Amazon remains fragmented. Policies have largely focused on Indigenous and traditional territories, often neglecting smallholders, colonists, and urban populations leaving structural vulnerabilities unaddressed (Pinho et al., 2014; Birkmann et al., 2022). Unequal representation, combined with ongoing development pressures, contributes to rural-urban migration and the emergence of new social risks (Brondizio, 2025).

To enable positive social tipping dynamics, governance must be polycentric and inclusive and nested across scales and sectors (Lenton et al. 2022). This includes reinforcing territorial governance, financing community-led solutions, integrating biodiversity and ecosystem services into social policy, and protecting biocultural heritage.

The Amazon forest holds many opportunities for transformation. Mobilizing its governance innovations can shift the region's trajectory away from collapse and toward building resilience, offering promising pathways towards global climate justice and sustainability. Halting deforestation and forest degradation, while securing sustainable, equitable livelihoods for Indigenous Peoples, is central to this shift. Building on this section, the next section outlines concrete pathways to activate positive social tipping points—recommendations that harness local agency, institutional innovation, and territorial integrity to drive transformative change across the Amazon.

4.1.5 Positive Tipping Points for Conservation and Restoration

Feedback mechanisms that risk triggering irreversible ecological tipping points in the Amazon also offer opportunities to catalyze positive social tipping points, transformative shifts in behaviors, institutions, and land use that reinforce forest regeneration, climate stability, and community resilience (see also the Prevention Chapter 1.2 of the report). Nowhere is this synergy more striking than in the Amazon, whose unmatched ecological and cultural wealth makes its protection central to planetary climate stability and human wellbeing (Barlow et al., 2018).

By investing in locally rooted solutions, restoring forest health, and advancing inclusive governance, it is possible to reverse negative trajectories and activate regenerative cascades across the region.

While the cascading social impacts of forest degradation may be difficult to reverse, positive social-ecological feedback, rooted in local agency and institutional transformation can slow, halt, or even shift these dynamics toward resilience. For instance, the development of vegetable leather in Acre exemplifies how accumulated social capital, collaborative networks, and place-based innovation—driven by rubber-tapping communities, women's groups, governments, and national/international donors can trigger lasting socio-economic transformation and diversified micro-industries such as art-crafts and medicinal oils (Brondizio et al., 2021). Similarly, the agroforestry systems led by local communities in Tomé-Açu provide a compelling alternative to widespread forest-to-pasture conversion, enhancing carbon sequestration, sustaining livelihoods, and redirecting land-use trajectories toward climate-resilient futures (Batistella et al., 2013).

Despite these contributions, Indigenous Peoples, traditional populations, and smallholders often receive only a fraction of the benefits. This has prompted initiatives focused on value aggregation, bioprospecting, and certification to increase equity within forest-based economies (Brondizio et al., 2023). State-led programs in Amapá, Acre, and Pará have also promoted inclusive forest economies, while the emerging bioeconomy paradigm seeks to reframe development through the diversification of production methods, the enhancement and protection of biodiversity, and the recognition of traditional knowledge and equitable benefit-sharing (Bergamo et al., 2022). Interventions that reinforce mutually beneficial relationships between restoring forest health and improving livelihoods can trigger locally positive cascades, generating both ecological protection and socio-economic well-being. These dynamics are central to activating the kinds of positive tipping points needed to shift the Amazon away from collapse and toward a just, climate-resilient future.

To shift from risk to building resilience, we propose five pathways to prevention, interventions capable of fostering positive tipping dynamics and transforming the Amazon into a global model of socio-ecological sustainability. Figure 4.1.2 shows where these pathways can prevent tipping and its cascading effects from occurring.

Commitment to Halt Deforestation and Biodiversity Loss

Building on Brazil's pledge to end deforestation by 2030 and its NDC under the Paris Agreement, transparent enforcement mechanisms must ensure real implementation. These actions align with global goals, including the Convention on Biological Diversity (CBD)'s 30×30 target. Multi-stakeholder platforms—like MapBiomas, the Climate Observatory, and the Amazon Trade and Environment Observatory, enhance accountability, are present among higher levels of governments such as public ministry and offer public pressure (Moutinho & de Azevedo, 2023). If all deforestation in the Amazon is curbed, emissions from land-use change could fall by 96%, reducing Brazil's total GHG emissions by 44% (Zimbres et al., 2024).

Strengthen Protection for Forest Conservation

Protecting intact forests, Indigenous Territories and Protected Areas is critical to tenure rights, culture, biodiversity and climate stability. These areas show the lowest deforestation and degradation rates and consistently safeguard carbon stocks (Walker et al., 2020; Josse et al., 2024). Protected areas in the Amazon reduce fire occurrence by up to 12% per year, with subnational reserves showing the strongest protective effect, underscoring their critical role in curbing fire-related environmental damage and the urgent need to expand and enforce these territories (Pêssoa et al., 2023). In contrast, Undesignated Public Forests account for 82% of degradation-driven emissions, and 44% of total forest carbon losses between 2003 and 2019 within the Brazilian Amazon (Bullock et al., 2020; Kruid et al., 2021). Prioritizing the protection of centuries-old forests and transferring non-designed public forests to Indigenous and traditional communities is vital for safeguarding ecological services and cultural integrity (Almada et al., 2024; Moutinho & Azevedo, 2023).

Territorial Protection and Empowerment of Indigenous Peoples and Local communities

Indigenous Peoples and Local Communities (IPLCs) manage over 58% of Brazil's protected lands and 59% of its forest carbon stocks (Walker et al., 2020). Their stewardship is essential for climate mitigation, biodiversity conservation, and health protection. Indigenous Territories in the Brazilian Amazon contribute to over US $5 billion annually to the global economy through food, energy, and vital climate regulation services (Siqueira-Gay et al. 2020). Protecting Indigenous Territories could prevent more than 15 million pollution-related illnesses annually and save $2 billion in health costs of population to fire (and particulate matter) exposure (Prist et al. 2023). Securing land rights, enhancing forest monitoring capacity, and recognizing ancestral knowledge are key to enabling IPLCs' continued role in safeguarding the Amazon and promoting intercultural and transdisciplinary solutions (Levis et al., 2024).

Restoration of Forest Ecosystems

Restoring degraded and abandoned lands can stabilize rainfall patterns and recover forest resilience. The Science Panel for the Amazon estimates restoration could help sequester 15–30 billion tonnes of CO_2 by 2050 (Gatti et al., 2023). Programs like Restaura Amazônia and the National Plan for the Recovery of Native Vegetation (PLANAVEG) aim to restore 12 million hectares by 2030 in the region and country. However, priorities must align across actors and sectors to avoid undermining restoration goals that need to be attentive to biodiversity (Barlow et al., 2021a,b). Restoration strategies should protect secondary forests (Jakovac et al., 2024), enhance connectivity, support seed and seedling supply chains, and engage Indigenous and local knowledge (Jakovac et al., 2024; Levis et al., 2024; Heinrich et al., 2021). Agroforestry systems rooted in Indigenous practices offer a scalable solution for restoration, food security, and livelihood income generation (Brondizio et al., 2021;. See also the Prevention chapter of the report (Chapter 1.2)

Cross-Sector Collaboration for Polycentric Governance

Transversal to all these initiatives is the imperative of cross-sector collaboration. Effective transformation requires coordination across governance levels: international, national, regional, and local. It needs collaboration between science and policy, and with Indigenous Peoples and Local Communities. Brazil's history of polycentric models, such as co-managed protected areas and sustainable-use reserves (Campos-Silva et al., 2021), and landmark international governance innovations like the Soy Moratorium, illustrate how the integration of science, monitoring, local participation, economic incentives, and secure tenure can generate lasting socio-ecological co-benefits. Multi-stakeholder coalitions must go beyond isolated projects and actively integrate biodiversity, climate, and social equity goals to enable resilient and just territorial governance.

Equitable climate and biodiversity finance, particularly through Payment for Ecosystem Services (PES) and jurisdictional REDD+ mechanisms, must directly reach Indigenous Peoples and Local Communities, and be backed by safeguards that ensure social inclusion, accountability, and long-term sustainability (Brondizio, 2025). Beyond financial flows, this demands institutional support for IPLC-led monitoring, territorial management, and innovation systems.

Despite the Amazon's extraordinary socio-biodiversity crucial to global ecosystem services, cultural diversity, and scientific innovation, at least in Brazil it remains one of the most under-researched and underfunded regions (Barlow et al., 2018). Unlocking its full potential for resilience and sustainability demands urgent, equitable, and cross-sectoral investment in knowledge, innovation, and local capacity.

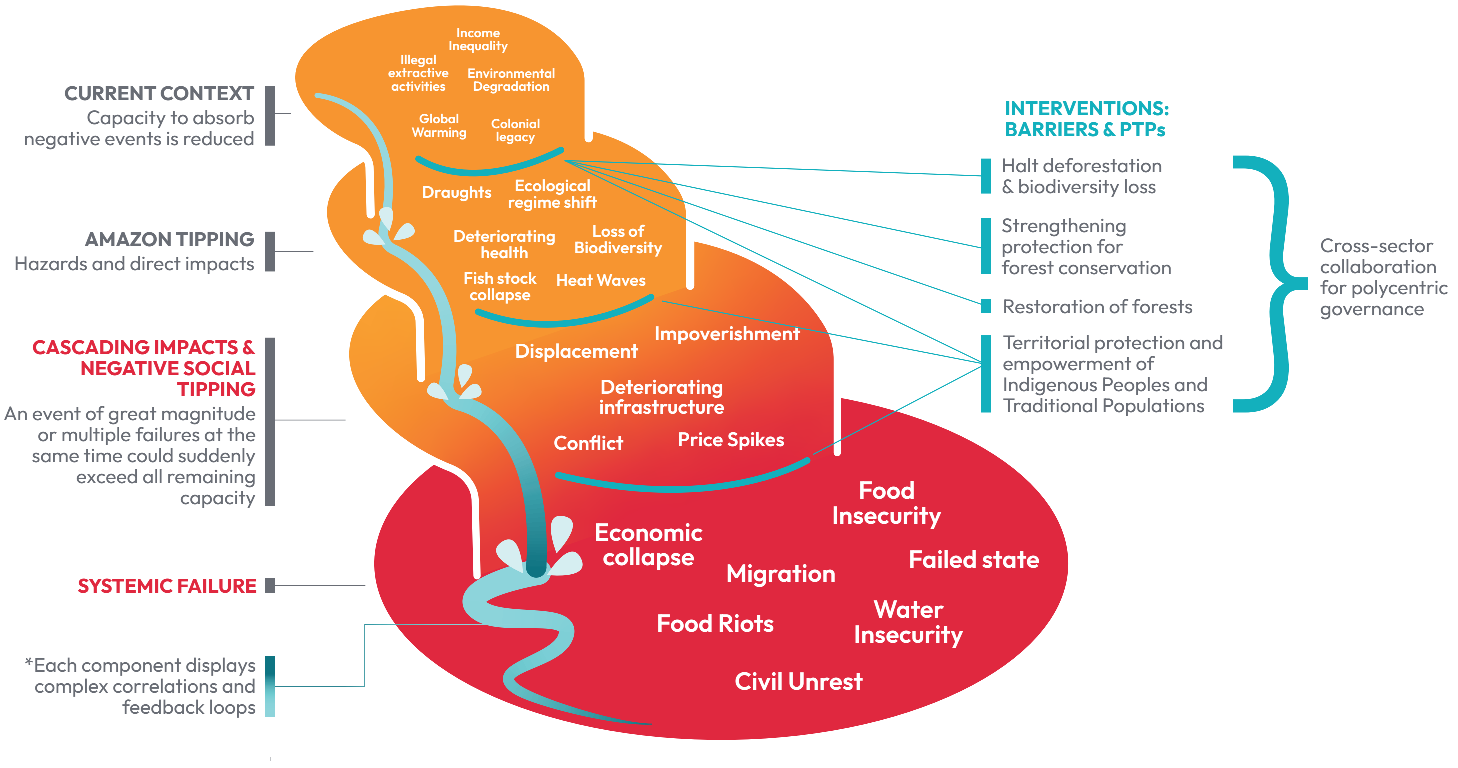


Figure 4.1.2: The cascading impacts of the Amazon rainforest tipping point, flowing from current context through the effects of tipping, and the social tipping points that could also be crossed, culminating in systemic failure. The 5 pathways recommended here act as barriers and offer potential for positive tipping against this cascade. Adapted from Laybourn et al., 2024.

CASE STUDY 02

ATLANTIC OCEAN CIRCULATION

4.2 Atlantic Ocean Circulation Case Study

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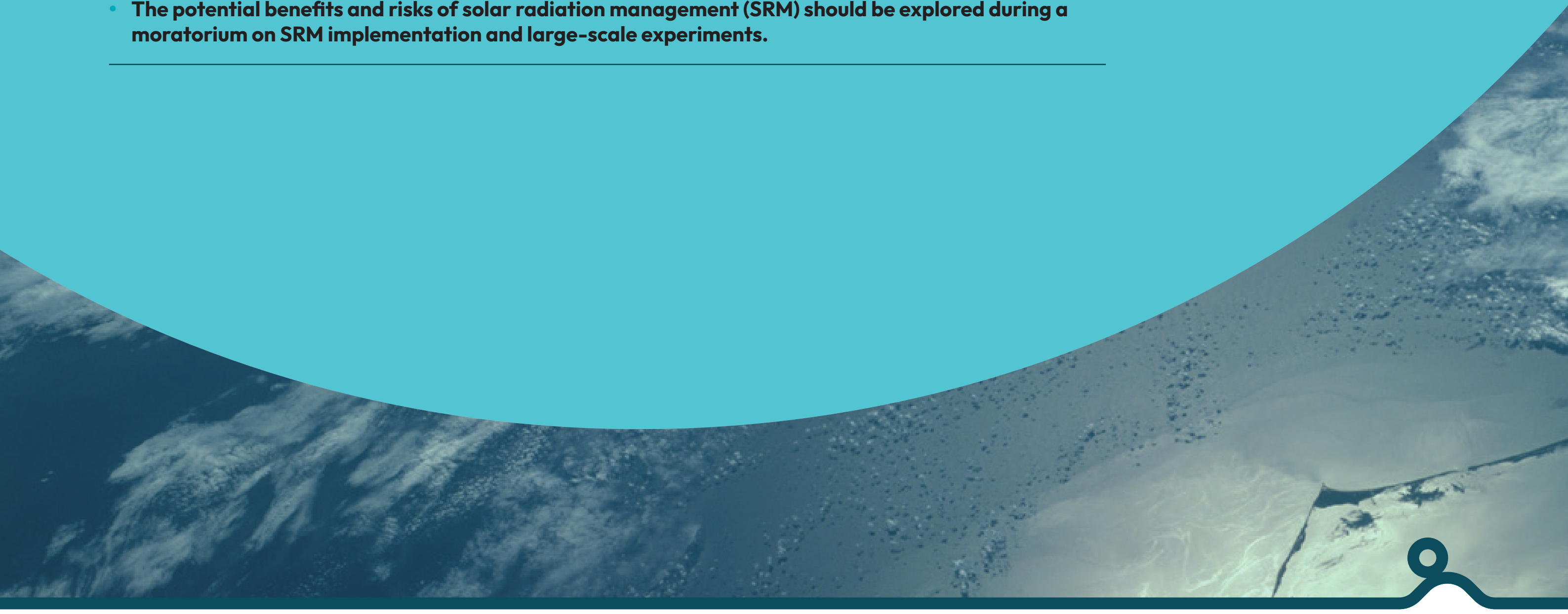
Risk assessment

- **The Atlantic Meridional Overturning Circulation (AMOC) and Subpolar Gyre (SPG) have different tipping points and timescales of transition but are strongly coupled via influencing stratification of the northern North Atlantic Ocean.**
- **Crossing either tipping point has numerous impacts, including much harsher northwestern European winters, disruption of the West African Monsoon, decreased agricultural yield and marine ecosystem shifts.**
- **The conditions under which SPG and AMOC can tip remain uncertain, due to a limited observational record and biases in climate models, but we cannot exclude that an AMOC tipping point may already have been passed.**
- **Deep winter mixing in the Labrador, Irminger and Nordic Seas is projected to collapse before 2050 in many CMIP6 models causing the AMOC to decline to a weak and shallow state beyond 2100.**
- **The likelihood of tipping for both SPG and AMOC systems increases with global temperature.**

Recommendations

- **Current observational arrays in the Atlantic Ocean should be maintained and Earth system model bias should be reduced as both are crucial for the science and future early warning systems of AMOC or SPG tipping.**
- **Continuous monitoring of SPG and AMOC risks, rapid communication of early warning signals and nation-specific complex risk-assessments of the impacts of AMOC or SPG tipping should be made for European countries to inform prevention and adaptation policies.**
- **Preventing the crossing of AMOC or SPG tipping points should be a primary governance target.**
- **The potential proximity of SPG collapse demands that European governments and the EU revisit and update national and European climate adaptation and preparedness plans, policies and institutions to account for the expected impacts of this tipping process.**
- **To minimize the risk of SPG or AMOC tipping, overshoot of 1.5°C global warming needs to be avoided.**
- **Net-zero timelines need to be shortened and immediate investment in the development and scaling of sustainable carbon removal technologies is required.**
- **The potential benefits and risks of solar radiation management (SRM) should be explored during a moratorium on SRM implementation and large-scale experiments.**



Executive Summary

The Atlantic Ocean Circulation is dominated by several large-scale currents, one prominent example being the Gulf Stream. The depth-dependent northward and southward volume transport of these currents is the Atlantic Meridional Overturning Circulation (AMOC). The AMOC is responsible for the northward heat transport which affects climate around the Atlantic basin (Rahmstorf, 2024). In the northern regions of the Atlantic, warm surface water from the upper branch of the AMOC is cooled and transformed into water of the deep AMOC branch. One of the regions where this water mass transformation occurs is the Subpolar Gyre (SPG) region (Straneo, 2006). Key components of the SPG region are currents in the Labrador and Irminger Seas, generating an overall counterclockwise flow (Figure 4.2.1) and the transformation of large volumes of lighter surface waters to denser deep waters in the interior of these seas.

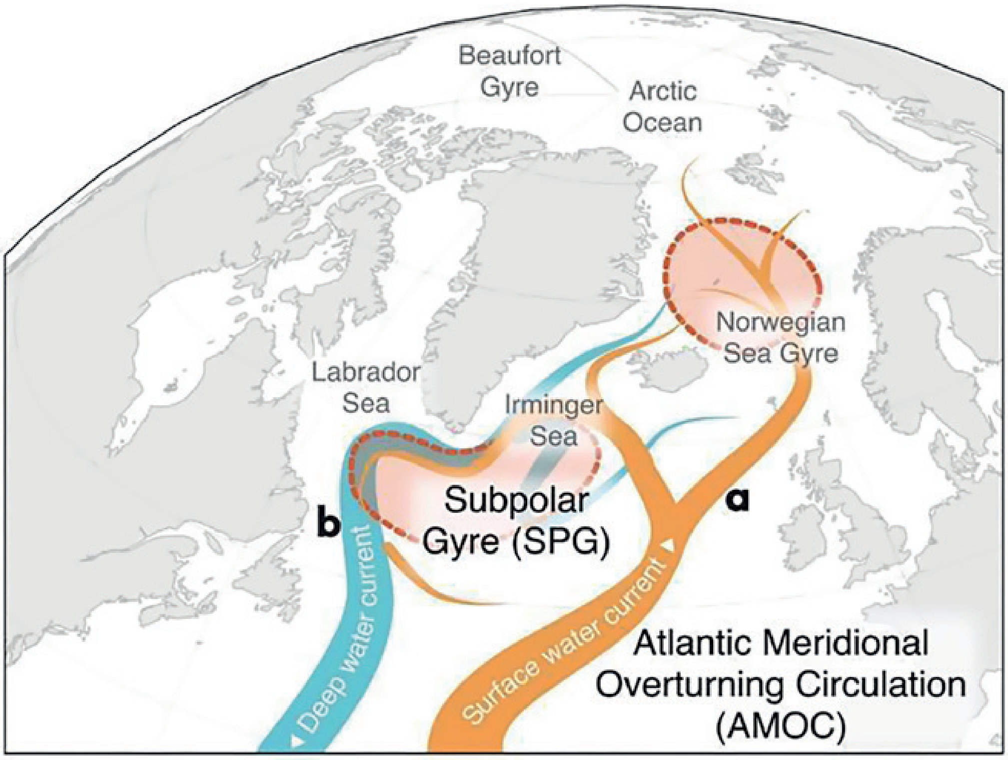


Figure 4.2.1: Sketch of the AMOC-SPG current systems in the North Atlantic, depicting (orange) lighter surface currents, (blue) dense deep currents and (shading) regions of pronounced water mass transformation. Source: Lenton et al. (2023), Figure 1.4.2; Credit: Sina Loriani.

Although the AMOC and the SPG are strongly coupled, it is useful to consider their behaviour separately regarding tipping (Loriani et al., 2025). First because different time scales are involved and second because the physical processes causing the tipping behaviour are different. Both SPG and AMOC are sensitive to freshwater input such as additional rainfall or inflow of meltwater from the Greenland Ice Sheet, and to changes in heat exchange between ocean and atmosphere. The AMOC can tip to a very weak state because critical conditions involving the salt advection feedback are crossed. The SPG can tip to a state with a strongly reduced formation of dense water when surface water becomes too buoyant, taking place on shorter time scales than the AMOC tipping.

We provide an overview of all aspects associated with the tipping of the Atlantic Meridional Overturning Circulation (AMOC) and Subpolar Gyre (SPG), including the physics of the tipping behaviour, the climate and ecosystem impacts and the possible role of governance in preventing and mitigating the effects.

4.2 1 Tipping of the AMOC and SPG

AMOC tipping

The AMOC has strongly varied in the past, notably during the last glacial period, where most paleodata are available. It has contributed to the large cooling and warming events that are recorded in Greenland ice cores, indicative of large instabilities in the ocean-cryosphere-atmosphere system in the North Atlantic (Sadatzki et al. 2023). In particular a large weakening of the AMOC might explain the cold Younger Dryas (~12,900–11,700 years ago) that interrupted the warming trend during last deglaciation (Velay-Vitow 2024).

Over the historical era, there is still a debate concerning the status of the AMOC trend. While some papers have proposed that the AMOC might have weakened over the historical period (Dima and Lohmann 2010, Drijfhout et al., 2012, Rahmstorf et al., 2015, Caesar et al. 2021, Zhu et al., 2023, Li and Liu 2025) with a potential amplitude of 15% (Caesar et al. 2018), other studies, using different proxies of the AMOC, question those conclusions (Fraser and Cummingham 2021, Worthington et al. 2021, Latif et al. 2022, Rossby et al. 2022, Terhaar et al. 2024). There remains an ongoing search for an optimal AMOC fingerprint which is sensitive to the forced anthropogenic signal, whilst minimizing noise resulting from multi-decadal variability. Given that the AMOC has only been directly observed since 2004, more observational evidence is required before any strong confidence will arise concerning the evolution of the AMOC over the historical era. Since 2004, the RAPID observations do show a downward linear trend (Volkov et al., 2024), consistent with model simulations that feature a collapse of the AMOC in the northern North Atlantic beyond 2100 (Drijfhout et al., 2025). However, this observed trend is only marginally significant (Volkov et al. 2024) and may not be only an ‘anthropogenically forced’ weakening signal, but also be ‘blurred’ by natural variability. A similar picture arises from an evaluation of deep convective mixing in the northern North Atlantic (Drijfhout et al., 2025). That observational trends are not (yet) being significant could possibly be explained by a ‘tug of war’ between natural and anthropogenic influence on AMOC (Bonnet et al. 2021). The latter may include remote teleconnections as well as local forcing (Liu et al., 2020).

The impact from anthropogenic forcing of the AMOC over the historical period in CMIP6 models is a weakening trend, but which is only starting in the late 1990s (Menary et al. 2021). Recent studies also evaluated the potential impact of Greenland melting which is usually poorly represented in those models. While Devilliers et al. (2024) found almost no impact of observed Greenland meltwater fluxes on the AMOC in the EC-Earth model, in line with results from IPSL-CM6A-LR (Devilliers et al. 2021), Pontes and Menviel (2024) did find a strong impact within the ACCESS-ESM1.5 model. However, the amount of freshwater is largely overestimated in the latter study as compared to Greenland meltwater reconstruction, casting doubt on the results of the latter study. Another study by Wei and Zhang (2024) reports the results of freshwater hosing restricted to the southern Greenland Sea and finds some impact (order a few Sv) on subpolar gyre overturning. However, the magnitude of the freshwater forcing perturbation is again rather large and the rationale behind the choice of the geographical region is unclear. Note that in CMIP6, already quite a few models do show a collapse or are en route to a collapse of the northern branch of the AMOC without including Greenland meltwater forcing. In line with the study of Bakker et al. (2016) who found that the effect of meltwater did enhance the weakening and probability of a collapse, but was of secondary importance compared with the effect of global warming. To conclude, based on recent results and projections available, the impact of anthropogenic forcing on the AMOC is a slight weakening trend of the AMOC since the 1990s, possibly due to internal variability (Latif et al. 2022).

In addition to changes in meltwater input, the oceanic freshwater transport from the Arctic to the Atlantic is expected to increase in the future due to the projected accumulation of freshwater in the Arctic caused by changing wind patterns and decreasing sea ice concentration (Lin et al,. 2023). The dynamical mechanisms, timing, magnitude and impacts of such a release are still very uncertain (Bellomo and Mehling, 2024), but in present-day climate models, it seems most likely to impact AMOC variability rather than to cause a collapse of the AMOC before the year 2100.

According to climate models, the AMOC will actually weaken

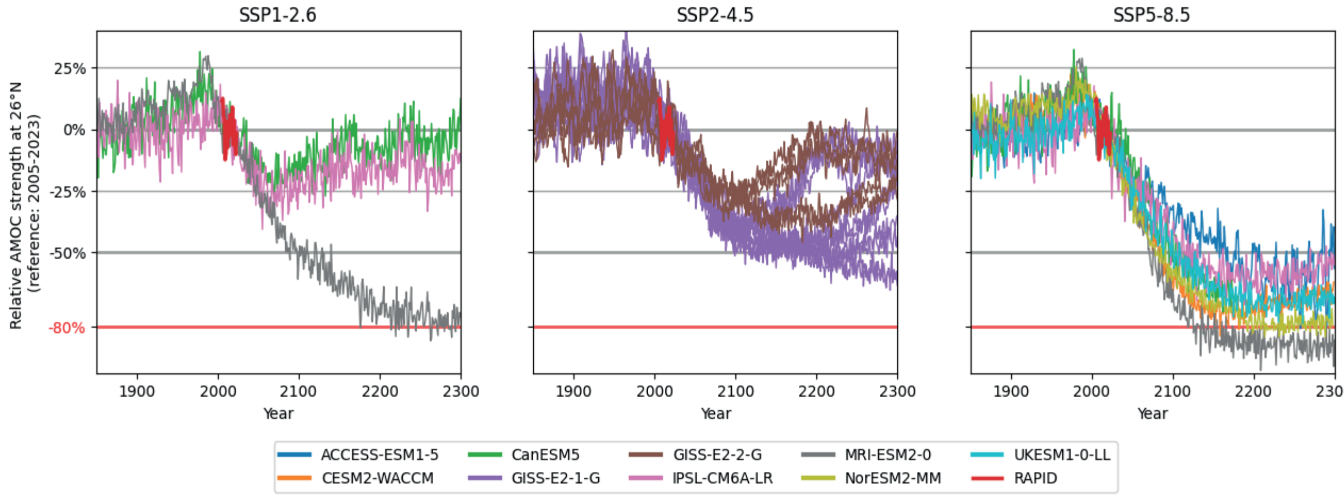


Figure 4.2.2: AMOC strength at 26°N (in Sv, 1 Sv = 10^6 m^3/s) for climate models that run projections beyond 2100. The historical simulations and various emission scenarios are shown, with SSP1-2.6 scenario on the left, SSP2-4.5 scenario in the middle and SSP5-8.5 scenario on the right. The different colors correspond to the different models presented in the legend. Some of them are providing different members. The RAPID observations are shown in red.

within this century (Weijer et al. 2020), which might not necessarily indicate a coming collapse. Thus, direct observations might inform us in the coming years to decades of a significant negative trend in the AMOC. However, a key question remains what the amplitude of such a weakening would be, also going beyond 2100. As shown in Fig. 2, the AMOC response is very dependent on the model analysed. For instance, at the end of this century, CMIP6 models project a weakening that goes from 3 to 72%. Beyond 2100, the few simulations that exist can show a strong AMOC reduction even for the low emission scenario SSP1-2.6 (Figure 4.2.2). The scenario SSP5-8.5 highlights a very strong weakening in all models, but while some seem to have almost collapsed, others do show early signs of recovery by 2300 (Fig. 2) which can be related to stabilising effects of the increased Southern Ocean upwelling (Baker et al. 2025) in such models, although it should be stressed that this might be an artifact of non-eddy-resolving models that do not show the effect of eddy-compensation and saturation seen in eddy-permitting and resolving models (Munday et al., 2013, Bishop et al., 2016). This spread among models illustrates the urgent need for knowledge concerning the proximity of the AMOC to a tipping point, which might strongly influence the AMOC response among the models (Van Westen and Dijkstra 2024). However, Fig. 2c is not implying necessarily that when the AMOC is collapsing it has crossed a tipping point since this is still a transient response to a very strong forcing in most cases. This, however, is not true for the SSP1-2.6 and SSP2-4.5 simulations where the forcing after 2100, or even earlier (SSP1-2.6), no longer increases and in SSP1-2.6 even weakens after 2050 (Riahi et al., 2017). As such, a number of studies highlights that the AMOC might recover after anthropogenic forcing in some models when greenhouse gas forcing is stabillised (Jackson et al. 2013, Bonan et al. 2022) although not true in all models (e.g. Romanou et al. 2024). Indeed, it should also be noted that the likely tendency of the current generation of models to be over stable with respect to the AMOC remains a concern. This too strong stability might be related to biases in South Atlantic salinity, which need concerted effort on the part of model developers to correct them (Van Westen and Dijkstra, 2024).

SPG tipping

The SPG is a crucial area, as the AMOC's upper branch and lower branches connect here. The SPG circulation is partly driven by the surface winds, and partly by temperature and salinity differences in the subpolar ocean. In the current climate, wintertime atmospheric cooling drives strong water mass transformation in the interiors of the Labrador Sea and Irminger Seas. The heat loss to the atmosphere makes the surface waters denser, causing them to mix vertically with the waters below. This process, known as deep ocean convection, may reach depths of more than 2.5 km (Marshall and Schott, 1999), thus creating vast volumes of dense waters. The anti-clockwise currents along the SPG boundaries (Fig. 1) are more buoyant, and their strength is partly governed by this cross-shore density gradient with the interior (Straneo 2006). On an annual timescale, the net buoyancy loss of the Labrador and Irminger Seas to the atmosphere is balanced by lateral advection of buoyancy. In particular, mesoscale eddies (vortices of ± 25-100 km) that are shed from the unstable SPG boundary currents transport lighter waters towards the interior, yielding a seasonal cycle of convection and restratification (Spall 2004, Gelderloos et al. 2011, Georgiou et al. 2019, Yashayaev 2024, Sterl and De Jong 2022).

SPG tipping refers to a longer-term (decadal or longer) shutdown of deep ocean convection and a drastic weakening of the part of the SPG circulation driven by the above-mentioned cross-shore density gradient (Born and Stocker 2014, Born et al. 2016). The tipping mechanism is linked to the properties of the waters transported to the interior by the eddies: compared to the basin interior, these are warmer and saltier. An increase in salinity in the SPG boundary current therefore results in a stronger lateral eddy salt transport and (as saltier waters are denser) facilitates and deepens convection. This densifies the water column at mid-depth, which strengthens the cross-shore density gradient and hence speeds up the boundary current. This in turn makes this current more unstable, enhances the shedding of eddies, and thus constitutes a positive feedback mechanism as more salt is transported towards the interior. Although such an increase in eddy shedding also yields a larger lateral heat transport (i.e., a negative feedback on convection), a heat anomaly can be efficiently removed by the atmosphere, in contrast to a salt anomaly. Reversely, a freshening of the boundary current suppresses convection. This poses a substantial tipping risk: as this fresh anomaly is not easily eroded by atmospheric interaction it can induce longer-lasting suppression of convection (Yashayaev (2024), Fedorov et al. (2023)) and even multiple years of shutdown (Born and Mignot 2012, Born et al. 2016, Swingedouw et al. 2021). In this respect, the tipping mechanism shares similarities with the salt advection feedback of the AMOC: the difference in persistence of temperature versus salinity anomalies is an essential ingredient.

Support for SPG tipping occurring in the past can be found in paleoclimate reconstructions and modeling. For example, two episodes of a shutdown of SPG convection prior to the Little Ice Age have been identified in high resolution bivalve data from the North Icelandic shelf (Arellano-Nava et al., 2022), corroborating earlier studies with similar findings (Lehner et al., 2013; Moffa-Sanchez et al., 2014, Moreno-Chamarro et al., 2015). Both episodes appear to be driven by freshening of the surface waters in the region, either by anomalously high amounts of Arctic sea ice or by anomalously strong melting of the Greenland Ice Sheet during the preceding Medieval climate optimum. SPG tipping events are also found in the warmer-than-present last interglacial period (Steinsland et al., 2023), and in a simulation of the mostly colder-than-present past 21,000 years (Mandal et al., 2024). However, the paleo records cannot answer if the SPG tipping is attributable to an expansion of the sea ice cover that creates freshwater anomalies that in turn trigger a response in the ocean circulation involving lateral exchange between boundary currents and interior as described above. An alternative explanation is that the sea ice expanded so far that it shielded the ocean from the atmosphere and thus shut down deep convection in the SPG region directly (Kleppin et al. 2015, Li and Born 2019).

For future climate conditions, the latter direct sea ice effect is not very plausible, and thus is freshwater transport into the interior of the SPG considered the key ingredient in the mechanism of SPG tipping (Born et al. 2016). This process thus needs to be represented properly in models to assess the tipping risk (Jackson et al. 2025). Model resolution is known to have a strong impact on the simulated susceptibility of the SPG to tipping, in line with the expected susceptibility to the representation of the freshwater transport. At the resolution typical for present-day climate models, the eddy field is too weak to generate sufficient lateral transport (Martin and Biastoch, 2023). Climate models typically produce ocean currents that are unrealistically sluggish and wide, and hence the boundary current and convection region are not sufficiently separated. As a result, freshwater anomalies in the boundary current may spread directly into the interior and shut down convection too fast and too drastically (Shan et al. 2024).

Falkena et al. (2025) investigated if the current generation of climate models comprises the feedback mechanisms that may lead to SPG tipping. They found that nearly all CMIP6 models display the expected response in mixed layer depth to changes in sea surface salinity. However, the feedback on the SPG strength via subsurface temperature and density changes could be identified only in a subset of the models, and appeared sometimes positive and sometimes negative. Consistent with the tipping mechanism described above, the models characterised by a negative feedback on SPG strength appeared prone to abrupt shifts in SPG circulation under climate warming.

In addition to a realistic representation of the freshwater transport in the SPG region, the properties of dense overflow waters from the Nordic Seas also need to be adequately simulated (Wei and Zhang 2024, Årthun et al. 2023). Since these overflow water properties affect the density properties at depth in the SPG region, they affect the ability of a model to correctly simulate convection depths and their response to freshwater input. The representation of overflows is another aspect in which climate models are known to have poor skills (Danabasoglu et al. 2014).

Early warning

Early detection of an impending tipping event is highly relevant for society. This information will guide current policies and long-term adaptation measures to climate change and a tipping event. On the specific topic of early-warning signals (Boers, 2021) and the proximity to an AMOC tipping point, a number of key publications have appeared since the last report. The study of Ditlevsen and Ditlevsen (2023) is warning of the risk of a collapse of the AMOC for this mid-century. Here, the time of the onset of the collapse was estimated using a proxy of the AMOC in the past based only on sea surface temperature. Ben Yami et al. (2024a) highlight the high sensitivity of this result to a number of factors, including the proxy of the AMOC used, so that the uncertainty concerning the date of the collapse is large. Note that it will take another 100 years from onset of the collapse to the realization of the associated very weak AMOC state.

Other studies based on climate models and analysis of the dynamics of the AMOC have also progressed our understanding of the risk of the AMOC to cross a critical threshold. Van Westen and Dijkstra (2023) showed that the overturning transport of fresh water at 34°S is a very useful indicator of AMOC multistability as illustrated in the CESM model. Van Westen et al. (2024a) also showed that the time evolution of this indicator might be an interesting early-warning signal of a potential collapse. However, the latter study was not analysing the potential change in surface forcing of the AMOC due to global warming, which is able to strongly modify the AMOC stability (van Westen et al. 2025c). Furthermore, it has also been shown that the AMOC might have a more complex behaviour than anticipated from the Stommel (1961) simple model, with many additional multiple equilibria (Lohman et al. 2024). Machine learning is an alternative approach to locating the proximity to tipping and its potential has begun to be explored (Zhai et al. 2024). These methods still rely on training data in the form of direct or proxy observations or model output. However, one can envision them using a much richer variety of data, potentially enhancing their effectiveness.

Meanwhile there has been further study of noise- and rate-induced tipping, underlining its possible role in causing tipping even before a bifurcation point is reached (Ritchie et al. 2023). Thus far, the studies have been largely for idealised systems (Alkhayuon et al. 2019, Castellana et al. 2019, Chapman et al. 2024) and the implications for the real world AMOC remains unclear. A promising new approach, applicable for more realistic models is that of Cini et al. (2024) where a rare event algorithm is used to find trajectories in an intermediate complexity climate model. Here the AMOC collapses due to internal noise without the need for changes to external forcing such as artificial oceanic freshwater input. Lohmann et al. (2025) explore a data-driven method for identifying optimal observables for early warning based on operator-theoretic arguments.

Another approach to determine proximity to tipping is by developing physics-based early-warning indicators. The freshwater transport at the southern boundary of the Atlantic Ocean is such an indicator which is currently being monitored (Arumí-Planas et al. 2024). Although this indicator suggests that the present-day AMOC is on route to tipping, the time series is too short to make a reliable tipping time estimate (van Westen et al. 2024). Another physics-based indicator which has been recently developed is the northern North Atlantic surface buoyancy flux (van Westen et al. 2025c) which also suggests a mid-century onset of an AMOC collapse (van Westen et al. 2025c, Drijfhout et al. 2025). For early warning, it is of great societal interest to maintain current observational arrays in the Atlantic Ocean, which are very useful for monitoring the AMOC strength. An important future challenge is to develop both statistical and physics-based early-warning signals for SPG tipping.

4.2.2 Potential impacts

Climate impacts

While the horizontal circulation in the SPG may possess bistability (Born and Stocker, 2014), this type of tipping has not been identified in climate models as occurring in isolation, and the more general and impactful tipping is the collapse of deep convection or mixing in the SPG, sometimes accompanied by an abrupt shift in circulation (Sgubin et al., 2017). Such an SPG collapse is a necessary but not sufficient precursor for an AMOC collapse, as an SPG collapse may be accompanied by an intensification of deep convection in the Nordic Seas. This leads to a dipole pattern in SST with a cold anomaly in the centre of the SPG, but intensified warming and sea-ice retreat in the Nordic and Barents Seas (Sgubin et al. 2017; Swingedouw et al. 2021). Due to the limited extent of the area of cooling over the North Atlantic and concurrent warming over the Nordic Seas and Arctic Ocean, temperature effects over Europe are much smaller than in case of an AMOC collapse.

They do have in common, however, a southward shift of a main precipitation region, the Intertropical Convergence Zone, and an enhancement and northward shift of the North Atlantic jet stream through a basic state shifting towards a more positive North Atlantic Oscillation (Jackson et al. 2015). There is, as in case of an AMOC collapse, drying in Boreal summer over the Sahel and in Austral summer over the Amazon region, associated with a weakened monsoon system (Dunstone et al. 2011). Furthermore, summers get dryer in North and Central Europe and winters a bit wetter. Apart from the wetter winters, all these precipitation changes are also present in case of an AMOC collapse, but there the amplitude is a few times larger (Swingedouw et al. 2021, Bellomo et al. 2023). The different impacts between an SPG collapse and an AMOC collapse result from the former evolving much faster and abruptly, within one or two decades due to local convective feedbacks (Rahmstorf, 2001) that interrupt the vertical heat transfer from the deep ocean to the surface (Brodeau and Koenigk, 2016), while an AMOC collapse evolves more gradual and evolves over typically over five to ten decades (Sgubin et al. 2015, Drijfhout et al. 2025) involving large scale advective feedbacks, freshening and cooling the SPG and the Nordic Seas and Arctic Ocean, and invoking a much stronger sea-ice response by increasing sea-ice cover over the North Atlantic.

An AMOC collapse would have widespread global impacts, with relatively large climate impacts over Europe (Jackson et al. 2015, Orihuela-Pinto et al. 2022, Bellomo et al. 2023, Ben-Yami et al. 2024b; Saini et al. 2025). The European impact is first and foremost dependent on the mean global temperature at the time of tipping (van Westen et al. 2025b). In general, the European impact is larger for a cooler climate than for a warmer climate (van Westen and Baatsen, 2025). The effects of changes in ocean heat transport between the Northern and Southern Hemispheres are much more pronounced in the Northern Hemisphere, which is the net receiver of heat. This is because heat loss in the north happens over a smaller area compared to heat spread in the south. When this heat transport diminishes, cooling occurs in regions that are already cold in the north, leading to significant growth in sea ice (van Westen et al. 2024). This sea-ice expansion plays a major role in amplifying the cooling effect, by capping off heat release to the atmosphere and returning otherwise absorbed solar radiation back to space. And the expansion of sea-ice is larger in a colder climate. Increased sea-ice cover also inhibits evaporation, drying and cooling the Northern Hemisphere by reducing water vapour in the atmosphere, a strong greenhouse gas (Vellinga and Wood, 2008, Drijfhout, 2015a, Jackson et al. 2015, Liu et al. 2020). This process can result in a noticeable drop in global mean temperatures, even though the root cause is a shift in how heat moves through the oceans.

These effects are ultimately determined by large-scale changes in the AMOC itself, determining the regional freshening and cooling in the North Atlantic. The evolution of the freshening and cooling patterns and sea-ice expansion is strongly time-dependent and much less instantaneous than the response to an SPG collapse (Drijfhout 2015b). Initially, the cooling is concentrated in a key region of the North Atlantic, but over time, it spreads and intensifies as sea ice expands southward during winter (Vellinga and Wood, 2008, Jackson et al. 2015). In today's climate, this cooling pattern would emerge in the northeast Atlantic, and as the climate warms or cools, the location of these effects would shift slightly. When the climate is warmer, the impacts are confined further north; when it is colder, they extend further south (Drijfhout 2015a, van Westen and Baatsen, 2025). The zone where the globe is maximally heated shifts southward, implying southward shifting tropical rain belts and drying in e.g., the Sahel and northeast Brazil (Ben-Yami et al. 2024b). With increased warming in the Southern Hemisphere subtropics, southern westerlies increase and the Benguela upwelling system strongly weakens.

The climate in Northwest European winter becomes harsher with stronger winds, more often snow and less often rain and especially stronger (and colder) extremes (Meccia et al. 2024), implying more and more often stormy weather (Woollings et al. 2012, Orbe et al. 2023, Jackson et al. 2015). Summer weather is getting sunnier and less cloudy often due to more frequent blocking high pressure systems east of the British Isles (Haarsma et al. 2015, Bellomo et al. 2021, Orihulea-Pinto et al. 2022). These blockings change the frequency of heatwaves across Europe, where Eastern Europe sees more heatwaves (Meccia et al. 2025). The warm extremes are not much affected under an AMOC collapse and are expected to increase in combination with climate change (van Westen and Baatsen 2025). While an AMOC collapse in general counteracts the effect of warming on the hydrological cycle, diminishing the "wet gets wetter" and "dry gets drier" pattern, it invigorates the drying (especially in summer) in Europe (van Westen et al. 2025c) leading to strong reductions in arable farming in the UK (Ritchie et al. 2021), water supply and agricultural output (Jackson et al. 2015; Bellomo et al. 2021). With increased temperature gradients in the Northern Hemisphere, zonal winds and the jet stream intensify with maximum winds moving to the north. Storm tracks do not show such poleward movement, but strongly increase and extend eastward, especially over the northern half of west and central Europe (Woollings et al. 2012, Orbe et al. 2023). Consequently, storm surges would become higher and more frequent, enhancing the risk of flooding (Volkov et al. 2023, Howard et al. 2024), in particular in combination with North Atlantic dynamic sea-level rise due to an AMOC collapse (Levermann et al. 2005, van Westen et al. 2024, van Westen et al. 2025a).

In the Pacific, warming south and cooling north of the Equator leads to a modification of the El Niño-Southern Oscillation (ENSO). While the upwelling off the coast of Peru decreases and the surface waters get warmer, also ENSO shifts eastward with the warming signal becoming more confined to the east (Williamson et al. 2018). The ENSO period was also found to increase and become more regular. An AMOC shutdown also influences the Australasian region, with overall drier conditions over the southeastern portion of this region (Saini et al. 2025). The West African, Indian Summer and East Asian Monsoons will be disrupted with shorter wet and longer dry seasons and less overall rainfall. The opposite seems to occur with the South American monsoon, with especially rainfall increasing over the southern Amazon (Ben Yami et al. 2024b). In general, the Southern Hemisphere becomes wetter and the Northern Hemisphere drier after an AMOC collapse.

Ecosystems impacts

An AMOC and SPG collapse would influence both marine and terrestrial ecosystems. An AMOC collapse can have global consequences, directly affecting the ocean's horizontal and vertical transport of heat and nutrients, and indirectly altering the climate system, such as through changes in temperature, precipitation, and wind patterns. In contrast, an SPG collapse would lead to more localised effects, including reduced nutrient concentrations in the euphotic zone and regional cooling. These ecosystem changes also influence the capacity of marine and terrestrial systems to sequester carbon, potentially contributing to elevated atmospheric CO_2 levels (Boot et al. 2023, Boot et al. 2024).

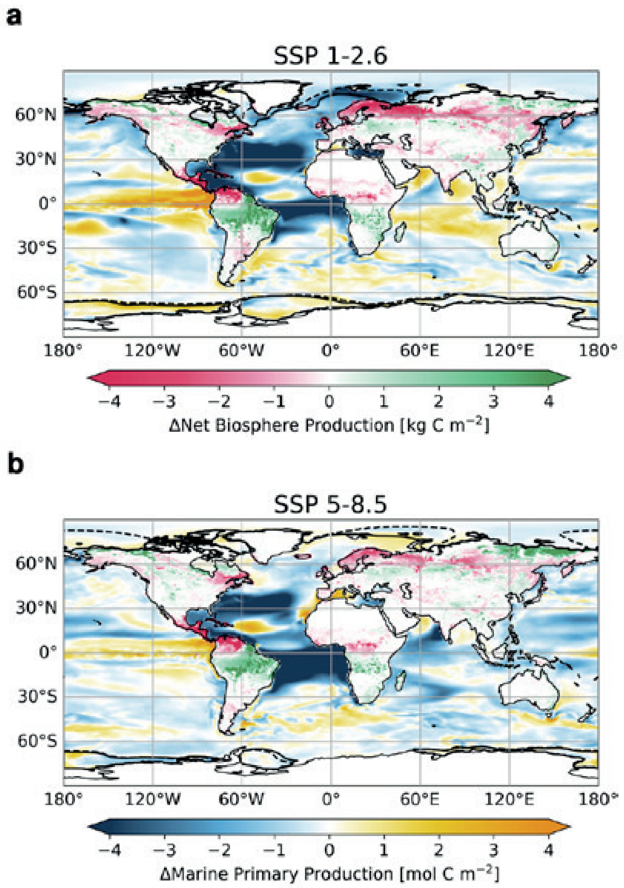


Figure 4.2.3: *The effect of an AMOC weakening on Net Biosphere Production on the land integrated over the period 2015 – 2100, and the change in Marine Primary Production over the period 2096 – 2100 compared to the period 2016-2020. The figures show the difference between a simulation with a strongly weakened AMOC, and a slightly weakened AMOC. Black dashed lines represent the average sea ice cover over the period 2081-2100 in the simulations with a slightly weakened AMOC, and solid lines represent the strongly weakened AMOC simulations. (a) For SSP1-2.6. (b) For SSP5-8.5. Source: Boot et al. (2024), with permission from Copernicus Publications.*

Marine ecosystems in the North Atlantic are particularly sensitive to changes in the AMOC and the SPG. Over the past 75 years, some regions in the North Atlantic have undergone shifts in ecosystems already which are tightly coupled to temperature (Beaugrand et al. 2008, Greene et al. 2013, Osman et al. 2019, Bode 2024). Whether this is due to variability in the AMOC or the SPG is not clear, however, it shows the clear potential of effects of an AMOC or SPG collapse on marine ecosystems through its effects on temperature. Changes in the AMOC and the SPG have the potential to affect the North Atlantic bloom. Reduced deep convection decreases nutrient entrainment which decreases (Figure 4.2.3) productivity of phytoplankton (Yool et al. 2015, Boot et al. 2023, Boot et al. 2024, Kelly et al. 2025) and temperature changes can result in biogeographical shifts (Barton et al. 2016). These changes have the potential to cascade through the food web with potentially amplifying effects on higher trophic levels (Boot et al. 2025). Also, the timing of the North Atlantic bloom can shift. If species higher up the food web cannot adapt to this shift, this might lead to a strong change in functioning of ecosystems (Asch et al. 2019, Cyr et al. 2024).

A recent study (Boot et al. 2025) analyses impacts on marine ecosystems in simulations with an SPG collapse and simulations with an AMOC weakening. An SPG collapse leads to a shift in dominant phytoplankton type from large phytoplankton to small phytoplankton. However, the net effect is a decrease of total phytoplankton biomass in the SPG region of around 50% in 2100 compared to the beginning of the 21st century. Higher trophic levels show a much smaller decrease in SSP5-8.5 (12%), whereas in SSP1-2.6 there is even an increase (13%). Whether this is a sustainable response is uncertain. When accompanied with a strong AMOC weakening, a similar net response is found in total phytoplankton biomass. However, higher trophic level biomass in the SPG region decreases by 20% in SSP1-2.6 and 43% in SSP5-8.5 over the 21st century as a response to the strong AMOC weakening. Species important for fisheries decrease up to 17%, meaning that both the functioning of the ecosystems and the services these ecosystems provide, will be negatively impacted by an AMOC weakening.

Terrestrial ecosystems are mostly impacted through changes in precipitation and temperature following an AMOC collapse. Strong cooling in the Northern Hemisphere can, for example, negatively impact the productivity of boreal forests but also prevent permafrost melt. Shifts in the ITCZ also shift the locations of prime productivity in the equatorial rainforests (Figure 4.2.3). Models using dynamic vegetation also suggest there is a significant relation between vegetation type and AMOC strength (Armstrong et al. 2019), and a collapse of the AMOC can show large changes in vegetation type locally (Woillez et al. 2013).

Besides vegetation also animals can be affected. An AMOC weakening can enhance the effects of warming globally and lead to a decline in amphibians (Velasco et al. 2021) and reduce the geographic range of both plants and animals, suggesting that an AMOC weakening can enhance the biodiversity crisis (Ureta et al. 2022).

More research is necessary that directly investigates the impact of AMOC and SPG tipping on marine ecosystems. Based on physical princples, and the few available studies, both the AMOC and the SPG tipping can strongly impact the functioning of ecosystems and consequently the services they provide.

Societal impacts

There are great uncertainties around societal impacts, whether direct or systemic/cascading and more research needs to happen to model and where possible quantify possible societal impacts. However, using the risk framework from Chapter 2.1 we can try to map out possible pathways of societal impacts while translating them into risk currencies for policy makers. The AMOC/SPG hazards were outlined above. It is important to emphasise that, while the collapse of SPG (one to two decades) and AMOC (one to five decades) unfolds over decade(s), some impacts of these unfolding collapses would materialise immediately and continuously intensify over time. For instance, the weakening of AMOC has already impacts such as the North Atlantic Warming Hole (Li and Liu, 2025). The change in temperature and precipitation patterns described above would first of all have direct impacts, such as decreasing agricultural yield or even recurring crop failure (medium confidence) particularly in European countries in the North-West, such as UK, Norway or Finland (OECD 2022, Merikanto et al. 2024), furthermore intensifying water shortage in the same region (medium confidence) (Haustein and Rayer 2023), which further complicate agricultural production. While a SPG collapse would affect mainly North-West Europe and North-East US, an AMOC collapse would have more global and more severe repercussions with possibly catastrophic implications for global food production (Ritchie et al. 2020, Ben-Yami et al. 2024b, see Figure 4.2.4). Furthermore, given that infrastructure in some of these areas have not been built for this drastically ecological regime shift and the intensifying, recurring storms, direct impacts would likely include frequent and at times severe infrastructure damage or even infrastructure loss (Shakou et al. 2019). The increased likelihood of storms and flooding would moreover likely result in the direct impacts of property loss or in the long-term even settlement loss (e.g. on US east coast) and more generally accumulating asset loss as well as life los (Lenton et al. 2023).

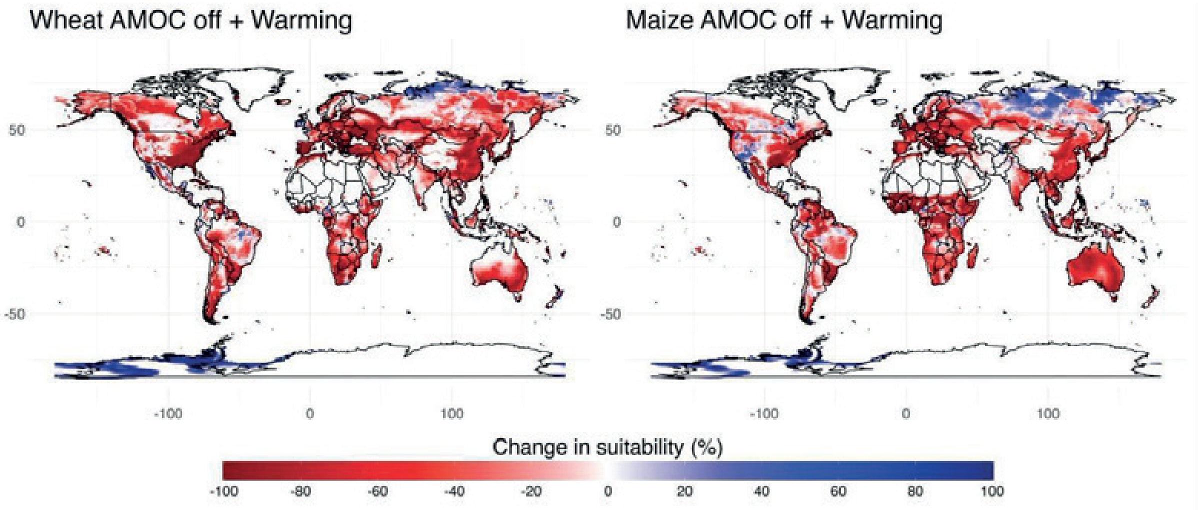


Figure 4.2.4: AMOC effects on food production (wheat and maize), Percentage difference in crop suitability between no AMOC collapse (present day) and the effects of AMOC collapse plus 2.5°C of global warming. Decreases in suitability are represented with red shading, increases with blue. Source: Laybourn et al. (2024), Figure 2.4, with permission from the IPPR. For discernment of the AMOC effects vs. warming effects, see OECD (2021).

These are the most likely direct impacts, however as outlined in the Chapter 2.1 risk framework, societal impacts tend to be systemic, with cascading effects, as direct impacts accumulate and interact, resulting in systemic risks that can reinforce each other (Simpson et al. 2021, Schweizer and Juhola, 2024) and even exhibit secondary tipping dynamics (Spaiser et al. 2024). It is more difficult to establish likelihoods for systemic and cascading risks as further factors (such as state capacity, economic resources, structural resilience, international cooperation, people's response to interventions etc.) play a huge role and our confidence here can only be low. Considering worst case scenarios (e.g., when adaptation largely fails due to insufficient state capacity or compounding crises), possible systemic risks from AMOC/SPG collapse include displacement from lost settlements (e.g. US East coast, West Africa), rising poverty linked to displacement (e.g. US East coast, West Africa) and loss of property and loss of assets (e.g. US East coast, North Europe). Furthermore, these may give increased food insecurity (incl. spiraling food prices, globally, e.g. see Jackson 2025) due to decreasing agricultural yield and/or crop failure, which further drives poverty, both also resulting in poor health (Lenton et al. 2023).

The disruptions from direct impact and the cascading impacts just described will strain social cohesion and social stability, likely leading to increased disorder and social fragmentation (Spaiser et al. 2024). Poor health as well as the more direct impacts, e.g. on infrastructure, will also cascade into economic productivity loss, which will in turn drive further impoverishment. The accumulating loss of assets could also trigger a financial crisis, which itself could display tipping dynamics (Gajewski et al. 2025) and result in further impoverishment as well as weakening of national states and their capacity to respond to multiplying crises. In this explosive situation, political destabilisation may escalate, resulting in social unrest (Jones et al. 2023), potentially aided by external intervention of some form.

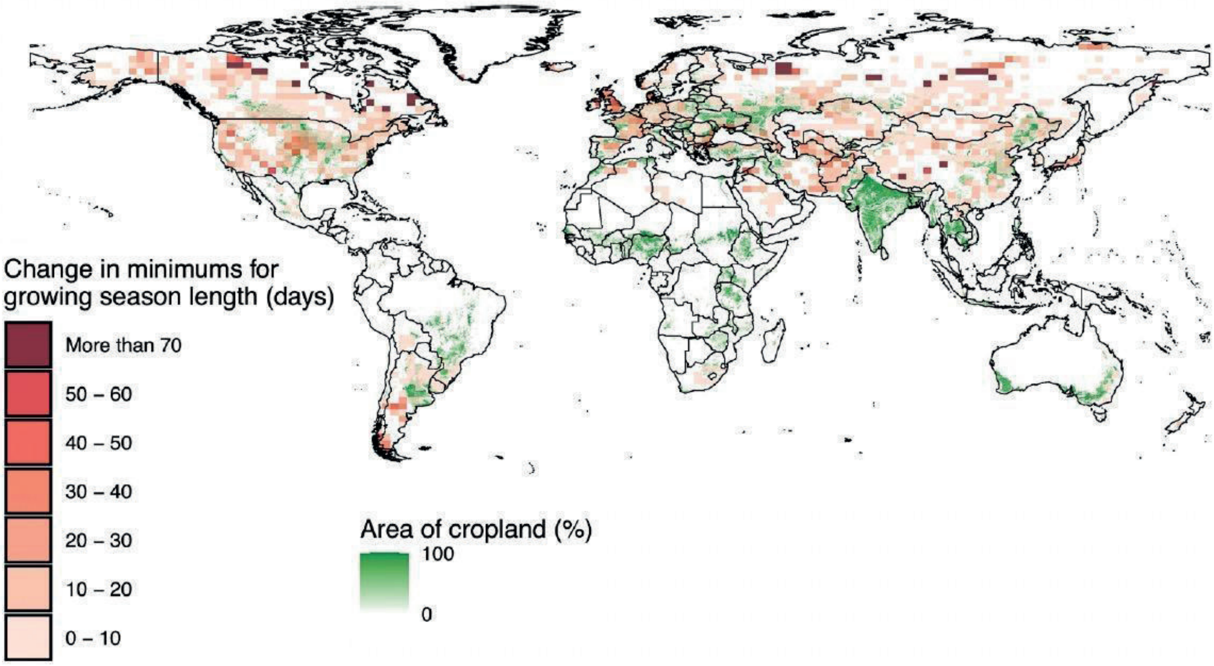


Figure 4.2.5: Modelling results comparing minimum growing season length (GSL) in pre- and post-collapse in an SPG collapse scenario, mapped over crop growing locations (in green), with darker shading representing larger reductions in GSL. Source: Laybourn et al. (2024), Figure 2.6, with permission from the IPPR.

Given the increasing geo-political destabilisation and fragmentation, some nation states may seek to exploit the weakening of certain countries (in particular North Europe, incl. UK) hit by the AMOC/SPG collapse hazards, contributing to political destabilisation for instance through hybrid forms of warfare, such as spreading misinformation to generate rage and social unrest, strengthening radical groups and undisclosed attacks on infrastructure (Lawrence et al. 2024, Bosch et al. 2025). There is a danger of the state increasingly failing to respond to multiple crises and helping its citizens with adaptation, and if state failure becomes increasingly endemic, social order may further break down and social unrest could turn into violence (e.g. gang violence) (White et al. 2025). For a detailed exemplary exploration of security implications for the UK from an AMOC/SPG collapse, see Laybourn et al. (2024) or for Finland, see Merikanto et al. (2024). Nation-specific complex risk-assessments are needed for many more countries and regions (e.g. EU) too, as every nation would be affected by an AMOC collapse in some way (e.g. at the very least through increasing food prices).

We note that the described cascading impacts could unfold similarly over one or several decades, alongside the unfolding of AMOC/SPG collapse, depending on the speed with which impacts from the unfolding AMOC/SPG collapse materialise and interact with social, political and economic factors. And this is why governance strategies are vital. Furthermore, we note that direct impacts of an SPG collapse are likely to be less severe and more regionally contained, compared to an AMOC collapse (Figure 4.2.5). We thus expect also less severe systemic risks; still for counties such as the UK or Canada the risks are severe enough to lead to significant consequences, including increasing poverty due to increased food prices due to decreasing agricultural productivity and property loss due to severe weather events, economic productivity loss as well as the danger of some social unrest and political destabilisation as people are likely to turn against established political elites (Laybourn et al. 2024).

4.2.3 Governance

Current governance frameworks do not adequately address the potential risks of SPG and AMOC tipping, making it essential to prioritise these high-stakes climate threats on the global governance agenda. We address two complementary governance tasks: prevention of AMOC and SPG tipping and management of potential impacts. Both tasks require continuous monitoring, learning, systemic risk assessments, and early warning systems. Governance approaches should be polycentric, linking institutions across global, regional and national scales, and embedded within existing climate and ocean governance frameworks.

At present, responsibility for addressing AMOC and SPG tipping risks is diffuse, and relevant actors and institutions need to recognise and adopt clear roles. Given the high uncertainty regarding timing, magnitude, and affected regions, the precautionary principle is essential in guiding decision-making. Plurilateral and regional initiatives—particularly among states likely to experience the earliest or most severe impacts—could complement broader international cooperation by facilitating knowledge exchange, joint planning, and coordinated risk management.

Prevention strategies

Given the severity of potential impacts of an AMOC and SPG collapse on relevant timescales, preventing the crossing of these tipping points should be the primary governance objective. Both systems are primarily driven by global temperature change, and prevention strategies must focus on curbing global warming. This places a critical responsibility on the United Nations Framework Convention on Climate Change (UNFCCC), the success of the Paris Agreement in driving global mitigation ambition, and national policies, particularly from major emitters and fossil fuel producers. The objective of preventing these tipping points provides new impetus for the 1.5°C global temperature goal of the Paris Agreement.

There is significant uncertainty regarding the threshold temperature for AMOC collapse (1.5°C - 8°C) and a more narrow range for the SPG (1.0°C – 3.8°C). Both systems might be destabilised by increasing meltwater inflow from the Greenland Ice Sheet, creating potentially reinforcing risks between cryosphere and ocean circulation systems. However, the meltwater effect is likely to play out over long time horizons without a significant effect on AMOC stability this century (Klose et al. 2024). Given these uncertainties and the possibility of near-term tipping-point transgression for both systems, prevention strategies for AMOC and SPG collapse should prioritise as:

- Rapidly returning global average temperatures to below 1.5°C,
- Minimizing peak warming, and
- Minimizing the duration of any overshoot above 1.5°C.

This reframes the policy focus from solely end-of-century temperature targets to the shape and speed of near-term emissions pathways. Only pathways that achieve front-loaded emissions reductions and limit reliance on Carbon Dioxide Removal (CDR) meaningfully reduce SPG and AMOC tipping risks. Delivering these trajectories requires immediate acceleration of fossil fuel phase-out and scaling up of sustainable CDR technologies to enable net-negative emissions. At the same time, rapid drawdown of atmospheric CO_2 following any temperature overshoot could trigger AMOC oscillations on centennial timescales (Schwinger 2022), introducing additional risks and uncertainty, and therefore must be implemented cautiously and in conjunction with continuous monitoring and adaptive management.

Fostering international agreement on mitigation pathways that minimise tipping risks could occur within the Paris Agreement, e.g., in the Mitigation Ambition and Implementation Work Programme or in a new ad-hoc working group under the UNFCCC. The Global Stocktake should assess to what extent collective mitigation efforts minimise tipping risks and prepare for their potential impacts. Future NDCs should explicitly address to what extent a country is exposed to AMOC/SPG tipping risks, how national mitigation efforts contribute to reducing tipping risks based on explicit emission/temperature pathway assumptions.

Model-based assessments have examined a range of prevention strategies, from well-established to speculative:

- Rapid GHG emissions phase-out – the most reliable and safest approach, directly addressing the root cause.
- Negative emission/carbon removal technologies – essential to achieve future reductions in global temperature and return to 1.5° C, though scalability and permanence remain concerns.
- Solar Radiation Modification (SRM) – such as Stratospheric Aerosol Injection (SAI) and Marine Cloud Brightening (MCB), which may help slow or prevent AMOC weakening, but come with significant risks and uncertainties.
- Greenland Ice Sheet preservation through geoengineering approaches such as undersea membranes to limit warm water intrusion into fjords (Wolovick et al. 2020, Hunt et al. 2019, Keefer et al. 2023). While potentially reducing basal meltwater flows, these methods do not prevent surface runoff and have limited impact if marine glaciers retreat inland.

The effect of the prevention options has been studied in climate models but not exhaustively, especially for SRM. While SRM may reduce near-term AMOC weakening, it should only be considered as a temporary, emergency measure to buy time for emissions reductions and CDR to take effect. SAI must not be deployed on a permanent basis. Instead, its design and governance must include from the outset a clear, feasible exit strategy aligned with steep reductions in greenhouse gas emissions and the buildup of sustainable carbon removal capacity. Without this, SRM risks creating long-term dependency and exposure to termination shock, undermining rather than supporting climate stabilization efforts.

Some models suggest that mitigation alone may have limited short-term (next 30–50 years) influence on AMOC weakening (Weijer et al. 2020), though it substantially reduces post-2100 tipping risks (Drijfhout et al., 2025). SAI (Futerman et al. 2023) and MCB (Hirasawa et al. 2023) may exert stronger short-term effects. One study using a single climate model showed that SAI from 2080 onwards prevents further AMOC weakening but cannot restore it to earlier levels while earlier SAI deployment (from 2020) preserves more of the AMOC's strength (Pflüger et al. 2024). For SPG, results are mixed and uncertain: Kelly et al. (2025) show SPG collapse before 2100 regardless of mitigation, while Pflüger et al. (2024) show partial preservation of Irminger Sea deep convection with early SAI. Overall, SRM remains understudied, especially for SPG dynamics, and should not be considered a silver bullet.

Model uncertainty remains high, particularly in single-model studies, and results should be interpreted with caution. Nonetheless, available evidence tentatively supports the conclusion that if reducing AMOC and SPG tipping risks were the only goal, the most effective strategy would involve a combination of rapid and deep emission reductions, strategic use of carbon dioxide removal, and timely, temporary SRM deployment if ever deemed acceptable through robust governance. However, SRM introduces significant physical, ethical, and geopolitical risks. Its potential benefits for the ocean circulation must be weighed against potential harms elsewhere—such as triggering a tipping point in the Amazon or undermining global cooperation on mitigation. Any deployment must be evaluated through a comprehensive, risk-risk framework, which weighs different kinds of risk against each other, identifying trade-offs (Sovacool et al. 2023, McLaren 2023). However, even a risk-risk approach has shortcomings, and novel risk assessment approaches might be needed (McLaren 2025). Such an assessment would also have to consider that the deployment of SAI for the prevention of SPG or AMOC collapse could increase the risks of a tipping point in the Amazon Rainforest.

Impact governance

The potential impacts of SPG collapse and/or AMOC changes present significant threats to human security, especially in European countries, but also in tropical countries and in the Amazon region. Currently these impacts are understudied, poorly understood and to the extent they are known, they are not considered in adaptation planning and preparedness efforts of affected countries (Roman Cuesta et al. 2025). More broadly, there is an immediate need to assess and respond to the impacts of potential tipping dynamics in the North Atlantic Ocean. This is particularly important for the SPG, which has a tipping threshold close to 1.5°C, could be triggered within a few years, and would unfold in less than a decade, i.e., before 2040.

Here, we discuss two specific domains of impact governance, with two distinct action horizons: 3-5 years for adaptation and 5-10 years for food security. Other national and international policy domains would also be affected, including disaster preparedness, trade, infrastructure, and energy production.

Adaptation (3-5 years): SPG and AMOC tipping impacts present major challenges to current adaptation planning, especially in Northern Europe. Considering tipping impacts should not impede urgently needed and ongoing climate adaptation efforts, but adaptive planning needs to consider a larger range of possible futures, including the passing of tipping points (Biesbroek et al. 2025). AMOC and SPG tipping could have three types of effects: amplifying well-known climate change impacts (especially sea-level rise, coastal erosion, flooding, increased storm frequency), reversing the direction of currently expected climate change impacts (e.g., cooling rather than warming temperatures and wetting rather than drying), and changes to the timing and spatial distribution of these impacts (i.e., creating different vulnerabilities).

We recommend that all countries potentially affected by SPG tipping initiate a review of their national adaptation strategy or plans in light of this (and other) tipping risk within the next three years. This requires:

- Incorporating climate tipping elements into risks and adaptation scenarios.
- Preparing for a broader spectrum of possible futures with uncertain timing.
- Updating regional models and vulnerability assessments.
- Coordinating cross-border adaptation initiatives, especially in Europe and the North Atlantic basin.

Food Security (5-10 years): A weakening or collapse of the AMOC/SPG taking place over one (SPG) or multiple decades (AMOC) could significantly disrupt agricultural productivity, fisheries, and food trade across Europe, Africa and South America (see sections 2.2 and 2.3). Over the coming 5-10 years, governments should invest in early-warning systems for agricultural impacts, diversify trade relationships, increase food storage and distribution resilience, and support research into climate-resilient and regionally adaptive crop systems.

Other governance considerations

Preparing for and responding to AMOC and SPG tipping impacts requires novel science–policy engagement mechanisms that enable iterative, timely, action-oriented learning and capacity building related to AMOC and SPG in Europe and around the North Atlantic. This could include:

- Rapid response risk panels to conduct iterative, policy-relevant assessments under deep uncertainty. These could support regional political bodies (e.g., EU, Arctic Council, Nordic Council of Ministers) and connect/align with international scientific assessments in the IPCC and IPBES.
- A permanent North Atlantic tipping element monitoring facility, equipped to detect and communicate early-warning signals, and rapidly respond to observed change.

Policy priorities for AMOC and SPG risk governance

Immediate Actions (1–5 years)

Objective: Lay the foundation for tipping risk prevention through urgent mitigation and foster preparedness for possible emergency responses.

Prevention

- Accelerate fossil fuel phase-out: Legislate phase-out schedules, redirect subsidies.
- Strengthen global mitigation: Update NDCs with early reductions to avoid overshoot.
- Invest in CDR: Launch large-scale pilots with verified accounting.
- Initiate SRM governance frameworks: Start multilateral dialogues and research into impacts, design temporary-only frameworks.

Impact governance

- Foster research on impacts of SPG/AMOC tipping scenarios with a focus on social and economic impact categories.
- Integrate into national planning: Include SPG/AMOC in climate risk and contingency strategies.
- Adaptation Planning: Initiate national reviews of adaptation strategies in potentially affected regions, especially Europe and West Africa; include SPG/AMOC tipping scenarios in adaptation planning.
- Food Security and Infrastructure: Begin climate stress-testing of food supply chains, storage, and trade exposure.

Research, monitoring and early warning

- Enhance observation systems: Fund AMOC/SPG monitoring, including Greenland Ice Sheet meltwater tracking.
- Launch a North Atlantic tipping element monitoring initiative.
- Begin scenario planning and foresight exercises on tipping-related uncertainties, including rapid response expert panels for dynamic tipping risk assessment.

Near-term Actions (5-10 years)

Objective: operationalise risk minimisation pathways and revise climate adaptation and preparedness measures.

Prevention

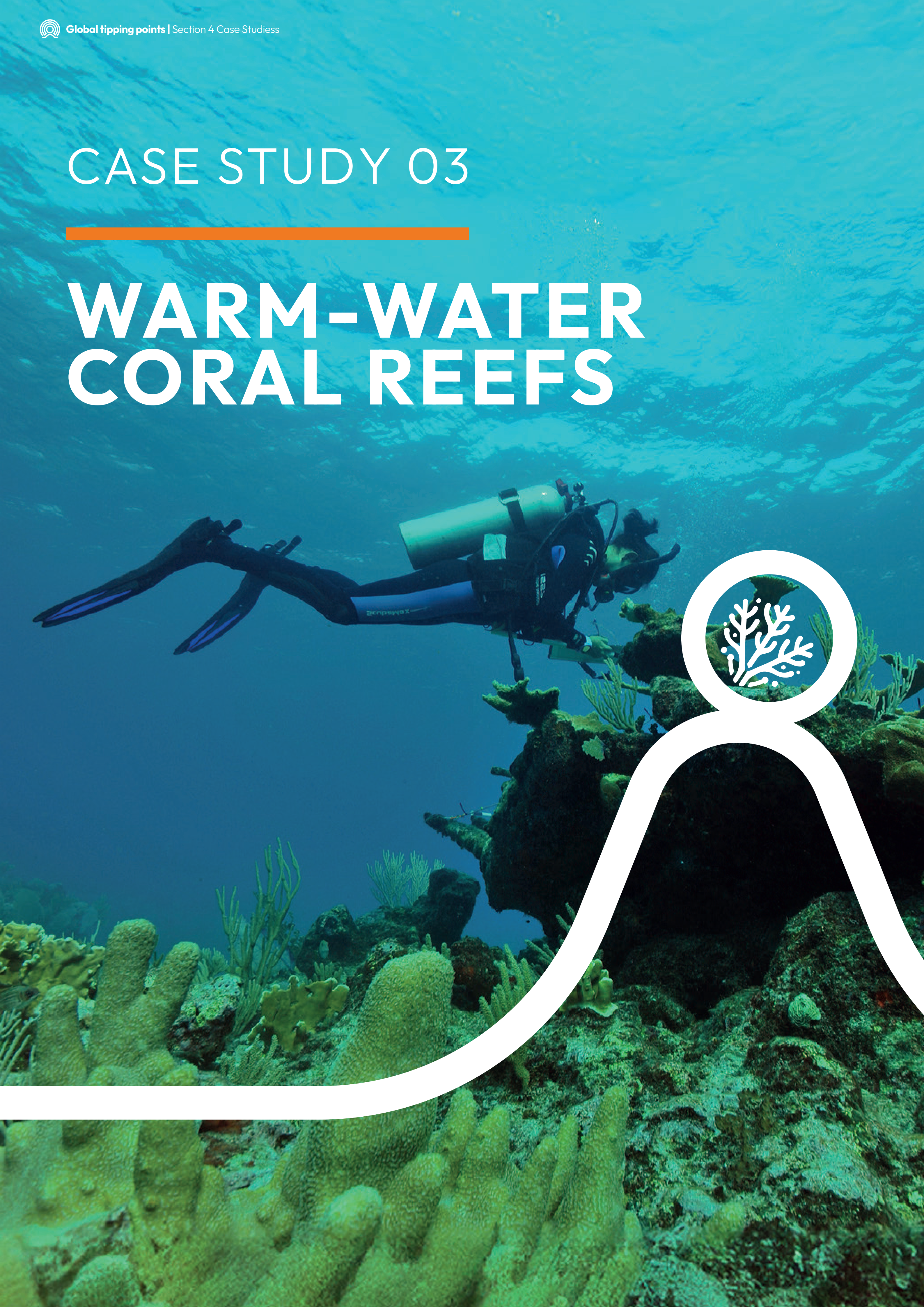
- Assess progress towards minimizing tipping risks in the Third Global Stocktake.
- Scale sustainable carbon removal to support net-negative emissions post-overshoot.
- Refine early-warning systems: Operationalise risk dashboards.
- Continue developing SRM governance aligned with precautionary and ethical frameworks: Define legal limits, triggers, and exit strategy.
- Mainstream into global policy: Make tipping prevention a criterion in finance and adaptation priorities.

Impact governance

- Food Security: Strengthen global and regional food reserves and diversify agricultural systems with region-specific adaptation R&D.
- Infrastructure: Prioritise resilient critical systems (e.g., power, communications) in high-risk zones.
- Integrate tipping-related scenarios into the Loss and Damage Fund and national adaptation planning.
- Expand access to climate finance for tipping-relevant monitoring, preparedness, and adaptation, especially for vulnerable countries.

Research, monitoring & early warning

- Fully operationalise a dedicated North Atlantic Tipping Observatory, integrating oceanic, cryospheric, and atmospheric data.
- Formalise transdisciplinary science–policy interfaces to enable policy-relevant, iterative risk updates and response capacity development.
- Build capacity in national and subnational institutions to interpret and respond to early warnings.



CASE STUDY 03

WARM-WATER CORAL REEFS

4.3 Warm-water coral reefs

Authors: Paul Pearce-Kelly, Chris Yesson, Melanie McField, Aarón Israel Muñiz-Castillo, Melina Soto, Jesus Ernesto Arias-Gonzalez, Kyle Morgan, Alina Bill-Weilandt, Björn Kjerfve, Christopher E. Cornwall, Lorenzo Alvarez-Filip, Manjana Milkoreit, Tim E. Lenton, Rosa M. Roman-Cuesta.

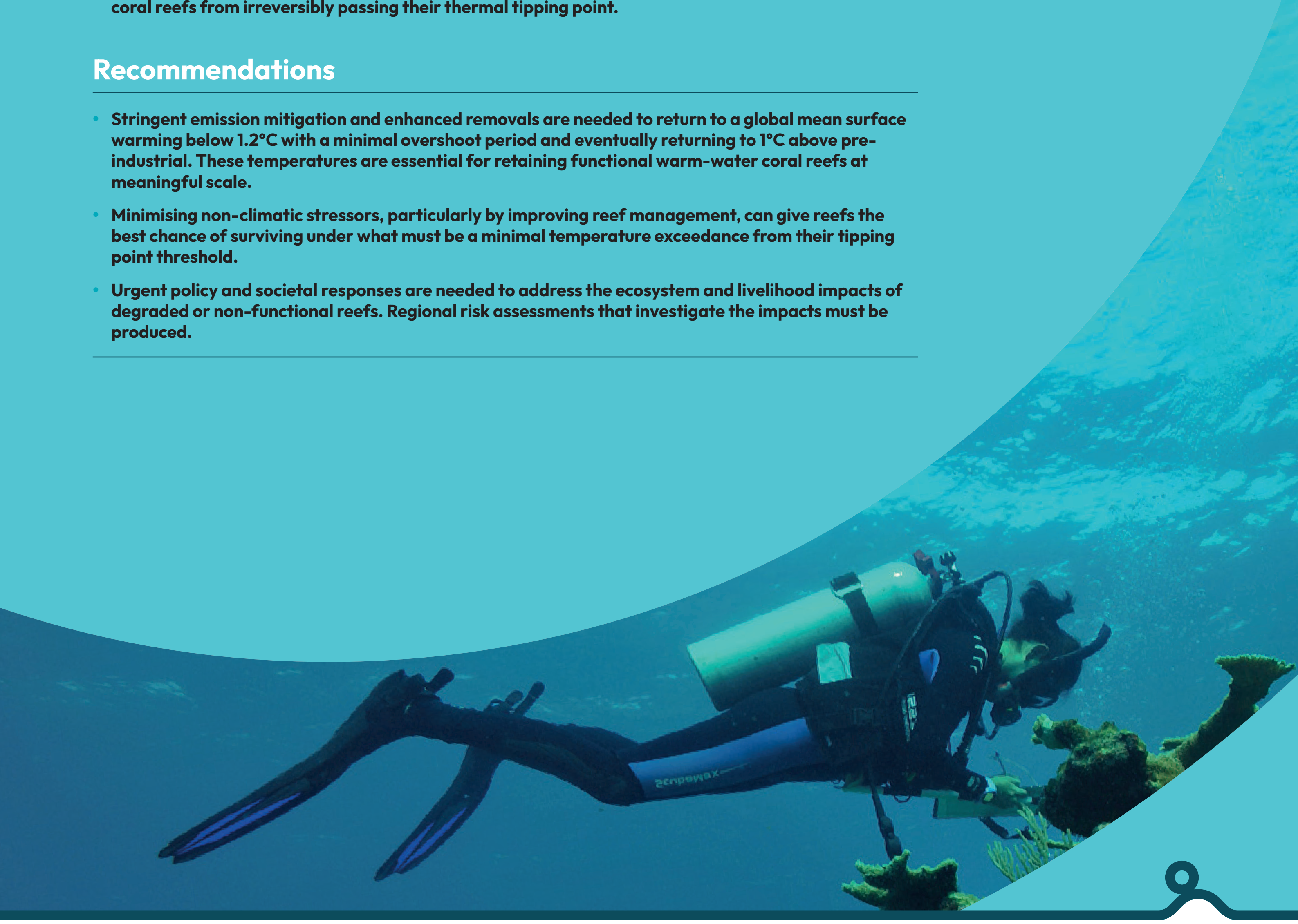
Reviewers: David O. Obura, Chris T. Perry

Risk assessment

- **Warm-water coral reefs are vital to the wellbeing of up to a billion people and almost a million species.**
- **Globally, coral reefs are experiencing unprecedented mortality under repeated mass bleaching events, highlighting the impact that global warming (interacting with other, predominantly human-driven environmental stressors) is already having.**
- **The central estimate of the thermal tipping point for warm-water coral reefs of 1.2°C global surface warming above pre-industrial is already exceeded and without stringent climate mitigation their upper thermal threshold of 1.5°C may be reached within the next 10 years, degrading reef functioning and provision of ecosystem services to millions of people.**
- **Even under the most optimistic current emission scenarios of stabilising warming at 1.5°C without any overshoot, it is considered that warm-water coral reefs are virtually certain (>99% probability) to tip, given the upper range of their thermal tipping point is 1.5°C.**
- **The goal of the Paris Agreement to limit global warming "well below 2°C" (ie. 1.5°C) will not prevent coral reefs from irreversibly passing their thermal tipping point.**

Recommendations

- **Stringent emission mitigation and enhanced removals are needed to return to a global mean surface warming below 1.2°C with a minimal overshoot period and eventually returning to 1°C above pre-industrial. These temperatures are essential for retaining functional warm-water coral reefs at meaningful scale.**
- **Minimising non-climatic stressors, particularly by improving reef management, can give reefs the best chance of surviving under what must be a minimal temperature exceedance from their tipping point threshold.**
- **Urgent policy and societal responses are needed to address the ecosystem and livelihood impacts of degraded or non-functional reefs. Regional risk assessments that investigate the impacts must be produced.**



Executive summary

Warm-water coral reefs are among the most biodiverse and valuable ecosystems on Earth, sustaining nearly a billion people and contributing trillions of dollars annually in goods and services. They provide food, coastal protection, cultural value, and livelihoods. Yet, these reefs are now facing an unprecedented crisis, as the first Earth System to cross its central estimated thermal tipping point of 1.2 °C of global warming above pre-industrial levels. This is triggering widespread reef degradation. Under current emission trends, the upper tipping point threshold of 1.5°C for coral reefs could be crossed within the next decade. Even under the most currently optimistic scenario of stabilising warming at 1.5 °C, all coral reefs are virtually certain to globally tip, making this one of the most pressing ecological losses humanity confronts.

The risks and impacts associated with crossing thermal tipping points are severe. Coral reefs are undergoing the 4th Global Coral Mass Bleaching Event which is the most extensive and intense ever recorded with over 80 percent of reefs worldwide being impacted . Marine heatwaves are increasing in frequency and intensity, which is increasingly pushing corals beyond their recovery limits. Heat stress is exacerbated by local to regional scale stressors such as overfishing, nutrient pollution, disease outbreaks, predator and competitor species imbalance, and destructive coastal development, reducing resilience, hindering recovery, and accelerating coral reef degradation and loss with major implications for the structural and ecological functions that sustain biodiversity, food security and protect shorelines, upon which millions of people are reliant.

The Caribbean illustrates the severity of these impacts, with reefs there already experiencing quasi-annual bleaching compounded by chronic, largely human-caused stressors, at multiple scales. The combination of climate-driven stress, low species diversity, and frequent disease outbreaks is pushing Caribbean reefs toward collapse. Their decline threatens fisheries, tourism, and coastal protection, heightening the vulnerability of small island states and coastal nations to storms and flooding. Globally, the effective loss of functional coral reefs will disrupt food systems, trade, and geopolitical stability, highlighting their significance as a systemic risk far beyond reef regions.

Societies and Governments remain unprepared for this reality, with no regional risk assessments investigating the consequences of these impacts on societies, economies and ecosystems. Urgent discussions on resilience and societal adaptation are needed. Addressing these risks requires coordinated action at multiple scales. At the global level, rapid and stringent greenhouse gas mitigation is fundamental to return coral reefs back from the brink. Unless we return to global mean surface temperatures of 1.2°C (and eventually to at least 1°C) as fast as possible, we will not retain warm-water reefs on our planet at any meaningful scale. To address non-climate drivers of reef tipping, coordinated efforts to eliminate local and regional human stressors on reefs are crucial to retaining these invaluable ecosystems. This includes “strategically” expanding marine protected areas, acting on overfishing, curbing agricultural runoff, and regulating coastal development. Restoration and innovation, such as coral nurseries, assisted evolution, and breeding of heat-tolerant genotypes, may support local resilience, though their effectiveness will remain limited without decisive climate action.

4.3.1 Introduction

Warm-water coral reefs (tropical and subtropical) occur in over 100 countries and territories and cover up to 900,000 km2 (Carlson et al 2021). They are the world's most biodiverse ecosystem, supporting up to a third of all known marine biodiversity (Plaisance et al., 2011), including over 25% of marine fish species (Laffoley and Baxter, 2016), and provide essential habitat for over 800,000 species (Fisher et al 2022). These reefs contribute up to USD 9.9 trillion annually in goods and services, including $109 billion in GDP worldwide, from which up to a billion people benefit (Costanza et al 2014). The degradation of reefs and reef-dependent species threatens the livelihoods of these people, most of whom are living in lesser developed countries and face severe consequences of reef demise (Wilson et al., 2006; Cinner et al., 2016; Pendleton et al., 2016).

In addition to the ongoing increase in average ocean temperatures, coral reefs face an urgent threat from marine heatwaves. These are distinct, prolonged periods during which ocean waters become significantly hotter than normal (i.e. 5 or more days above the 90th percentile for the last 30 years) (Smith et al., 2023; Capotondi et al. 2024; Marcos et al., 2025;). Since 1940, comparisons between real ocean temperatures and a world without global warming reveal that human activity is driving nearly half of all marine heatwaves. This influence has already tripled the number of days each year that the oceans experience extreme heat conditions with an increase of 1°C higher in the maximum intensity of these events.(Marcos et al. 2025). Unlike the gradual increase in average temperatures, marine heatwaves hit abruptly and intensely, pushing corals beyond their limits and causing mass bleaching, subsequent mortality, and major disruptions in reef ecosystem states (Smith et al 2023).

The central thermal tipping point for warm-water coral reefs has been estimated to be of 1.2°C global warming (range 1–1.5°C) (Lenton et al 2023, Pearce-Kelly et al 2025). With 2025 reaching global mean surface temperatures ~1.3-1.4°C above the pre-industrial level (Copernicus 2025), this central thermal tipping point has already been passed. This situation is causing severe global mass bleaching events (NOAA 2025), and in combination with other stressors, is leading to unacceptably high risk of widespread reduction of coral cover, mortality of major reef-building taxa, loss of critical geo-ecological functions including reef growth potential, and thus degradation of the ecosystem services reefs sustain (IPCC 2022, Lenton et al. 2023, Henley et al. 2024; Byrne et al. 2025; Pearce-Kelly et al. 2025).

Unprecedented ocean heating over the latest global mass bleaching period 2023–2025, highlights the severe functional degradation risk warm-water coral reefs are facing at a global scale. Societal and policy responses are urgently needed to minimize the magnitude and duration of this tipping point temperature exceedance, to avoid the functional loss of reefs at any meaningful scale (Lenton et al. 2023, Pearce-Kelly et al. 2025). Accelerated climate change mitigation and large-scale ocean conservation actions are needed to attempt to rescue coral reefs. The precautionary principle must be followed when considering uncertainty regarding thermal tipping points and the feasibility of the duration of their temperature exceedance for such critically important systems (Wunderling et al 2022; Meyer et al 2022; Schleussner et al 2024).

In the following sections, we provide an update on the global status of warm-water coral reefs in 2025 and consider the escalating threats they face in the near future. We consider their resilience and adaptation potential and conclude with a deeper dive into Caribbean coral reefs, as witnesses of the risk of irreversibly crossing ecological tipping points. We consider policy and societal conservation and sustainable ocean management responses to minimise human-driven stressors impacting reefs and maximise reef resilience under what must be a minimal period of temperature exceedance of their tipping threshold.

4.3.2 Global status of reefs in 2025

Coral reefs are one of the most sensitive ecosystems to direct and indirect human activities, with an estimated 50% of global live coral cover lost over the last 50 years (Eddy et al. 2021, Souter et al. 2021) and accelerated decline over the last 30 years (IPBES, 2019, Eakin et al 2019; Heron et al. 2016). Over 80% of the world's coral reefs are severely overfished or have degraded habitats (IPBES, 2019). Local, regional and even larger scale stressors such as unsustainable fishing, water pollution, disease, nutrient enrichment, and predator imbalance remain major issues. However, climate change, especially ocean heating, has now become the dominant global-scale threat to the functional viability of these ecosystems (IPBES, 2019; IPCC, 2022).

Since the 2023 Global Tipping Points Report (Lenton et al. 2023), warm-water coral reefs have experienced a 4th global bleaching event (GBE4), declared on 15 April 2024 by the National Oceanic and Atmospheric Administration (NOAA) and the International Coral Reef Initiative (ICRI). Beginning in January 2023, bleaching-level heat stress has impacted 83.8% of the world's coral reefs as of 20 May 2025, with mass coral bleaching documented in at least 83 countries and territories. (NOAA update 21 May 2025). This 2023-2025 Global Bleaching Event is the second global bleaching event in less than a decade and is both the warmest and most widespread bleaching event ever recorded (Figure 4.3.1).

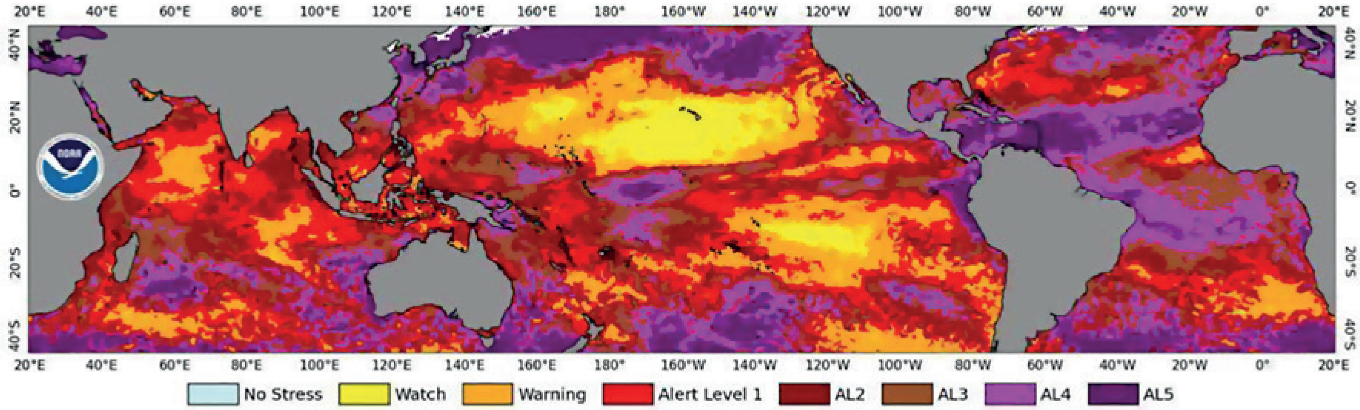


Figure 4.3.1 NOAA Coral Reef Watch 5km Bleaching Alert Area Maximum (V3.1) 1 January 2023-20 May 2025 (NOAA 2025). Three new highest alert levels had to be added in December 2023.

In the Caribbean and wider regions, global ocean circulation changes are heightening and prolonging heat stress episodes including GBE4 (2023-2025) (Goreau and Hayes, 2024). Several authors highlight that background ocean warming is now so severe in this region that bleaching events are occurring quasi-annually and becoming desynchronized from El Niño events. Bleaching in normal and even La Niña years is now common (Muñiz-Castillo et al. 2019, Reimer et al. 2024). This region is considered in more detail in Section 6, below.

In the Great Barrier Reef (GBR) region, the ocean reached unprecedented warming levels, duration and depth in GBE4 (AIMS 2025), leading to rapid bleaching, disease onset, and mortality in diverse corals and depths, including genera that were formerly considered resilient. Catastrophic bleaching has occurred in protected reefs of the Southern GBR (Byrne et al., 2025) and Coral Sea (Henley et al 2024, AIMS 2025). A reef to rubble phenomenon (Image 4.3.1) is occurring, whereby colonies fragment and transition to rubble (Hoegh-Guldberg et al 2023; Kenyon et al 2022; Kopecky et al 2023) as part of a transformation towards lower complexity ecosystems that are difficult to recover from (Byrne et al., 2025). Drone imagery at Lizard Island confirmed one of the highest rates of bleaching mortality ever recorded, despite cumulative heat stress exposure being lower than many other parts of the GBR (Raoult et al 2025).

Image 4.3.1: reef to rubble trajectory in the Caribbean. @Kieth Ellenbogen/iLCP (left) Healthy Reefs for Healthy People (right)

As in the Caribbean, bleaching on the GBR, is now becoming a biennial event. Researchers conclude that the GBR ecosystem is under existential threat from climate change (Byrne et al. 2025) and, globally here are increasing risks of regime shifts from coral dominated systems towards non-coral dominated systems (IPCC 2022).

4.3.3 Reefs have crossed a dangerous tipping point

> **"Catastrophic conditions and dire reef ecosystem changes are no longer a threat on a distant horizon: It's happening now." Michael Kingsford. Marine Biologist. James Cook University (2025).**

The central estimate of the thermal tipping point for warm-water coral reefs of 1.2°C global warming above pre-industrial (Lenton et al 2023, Pearce-Kelly et al 2025) is already exceeded and without stringent climate mitigation their upper thermal threshold of 1.5C may be exceeded within the next 10 years (Bevacqua et al 2025). The resultant severe impacts on reef functioning and provision of ecosystem services to millions of people will be compounded by a range of co-occurring and interacting coral reef stressors, including ocean acidification, pollution, unsustainable fishing, invasive species, and disease outbreaks.

Even under the most optimistic current emission scenarios of stabilising warming at 1.5C without any overshoot, it is considered that warm-water coral reefs are virtually certain (>99% probability) to tip, given the upper range of their thermal tipping point is 1.5°C, Richie et al (2025) Chapter 2.3., High peak warming levels and prolonged exposure due to temperature exceedance of their tipping thresholds (Reisinger et al 2025) imply irreversible damage to coral reefs (Tachiiri et al 2019; IPCC 2022; Santana-Falcón et al 2023). Therefore, except for relatively few isolated refuge areas, functional warm-water coral reef ecosystems are expected to be severely degraded unless global mean atmospheric temperature returns below their central thermal tipping point threshold of 1.2°C with a minimal exceedance period and eventually returns to their lower thermal threshold of 1.0°C (Lenton et al. 2023). There is thus an urgent need for rapid greenhouse gas emissions phase out and atmospheric CO2 draw down at the speed and scale necessary to realise these temperature reduction imperatives.

The oceans are warming at unprecedented rates, particularly in the upper mixed layer (Cheng et al. 2024; von Schuckmann et al. 2024; Cheng et al. 2025). Surface warming has quadrupled since the late 1980s (Merchant et al. 2025), with marine heatwave persistence and intensity also rising (Marcos et al. 2025). Depending on emission scenario, by 2100, projected ocean temperature in the top 2000m is 2-6 times that observed so far (Cheng et al. 2022) and currently, ocean temperature is rising at 0.27 °C per decade (Merchant et al 2025). These increases are already driving severe global bleaching (NOAA 2025; Smith et al. 2025) and, if not reduced, will overwhelm coral resilience and adaptation potential, especially in combination with other human-driven stressors (Lenton et al. 2023; Pearce-Kelly et al. 2025). Ocean circulation changes are exacerbating the problem, warming currents are slowing vertical mixing with cold deep water, increasing ocean stratification (Goreau and Hayes 2024). This amplifies surface warming and reduces CO_2 mixing with the deep ocean compounding coral stress.

Delayed warming of the ocean in response to the Earth's energy imbalance takes approximately 25–50 years, for the majority of committed warming to be realised with upper layers responding fastest (Hansen et al. 2005; Abraham et al. 2023). This lag factor masks the full impact that any given global mean surface temperature and atmospheric CO2 concentration will have on reefs. Increasing Earth's energy imbalance (Allan and Merchant 2025, Forster et al 2025, Mauritsen et al. 2025) has the potential to increase onset, magnitude and duration of heat stress events and severity of exceedance of the thermal tipping point for coral reefs. The possibility that equilibrium climate sensitivity (the warming expected for a doubling of CO2) is greater than 3°C (Witkowski et al. 2024, Hansen et al. 2025; Kaufhold et al 2025; Myhre et al. 2025) could also increase rate and magnitude of thermal stress (and other temperature driven stressors such as extreme weather events) that coral reefs are exposed to, whilst reducing the time available for corals to adapt to and recover from mass bleaching events and their compounding stressors.

Other interacting Earth system dynamics have the potential to further compromise coral reef futures, predominately by increasing the rate and magnitude of global warming. These include the weakening of land and possibly ocean carbon sinks (Ke et al. 2024; Oziel et al 2025; Virkkala et al. 2025) and the possibility that major cryosphere and ocean circulation systems are more sensitive to global warming than previously thought (Möller et al. 2024, Stokes et al. 2025). Such cascading impact risks, combined with inadequate greenhouse gas emissions reductions (World Metrological Organisation 2025, Forster et al 2025) may significantly increase coral reef threat severity, challenge adaptation and restoration potential and the scale of global warming mitigation required. Therefore these factors need to be considered when evaluating coral reef tipping point sensitivity and mitigation response requirements.

4.3.4 Reef resilience, adaptation and restoration potential

Mass bleaching events, due to climate change driven marine heat wave severity, and other mortality drivers such as disease and predation, more than twice per decade are generally considered to give insufficient time for the recovery of impacted populations and their ecological functions, due to compromised reproduction, dispersal, recruitment, and growth of corals (Hughes et al.,2018; Sheppard et al. 2020; Lenton et al. 2023; Venegas et al.2023). Other local and regional scale stressors reduce the ability of corals to resist thermal stress, further lowering their thermal tipping thresholds (Setter at al 2022, Lenton et al 2023; Pearce-Kelly et al 2025). In addition to population and species level impacts, key geo-ecological functionality characteristics of healthy coral reefs, such as the production of complex calcium carbonate structures, that sustain reef growth and habitat complexity, are increasingly being impaired as thermal and other stressor impacts increase (Hoegh-Guldberg et al 2018; Perry and Alvarez-Filip 2019, IPBES, 2019; Souter et al 2021).

There is a large and often conflicting literature regarding the potential for coral reefs to resist, and adapt to increasingly challenging environmental conditions, especially marine heatwaves and compounding stressors. The largest consensus projections foresee 70 –90 % coral loss at 1.5°C (Hoegh-Guldberg et al. 2018; IPBES, 2019; Souter et al 2021), whereas finer-scale modelling projects a 95 –98 % loss (Kalmus et al 2022) and a 99 % loss (Dixon et al 2022). Existing evidence (mainly from the Indo-Pacific) shows that coral communities can come back after severe periods of thermal stress, but these novel coral communities do not necessarily have the same life-story traits and physical functionality as the previous communities. Furthermore, the existing evidence does not ensure that coral and reef communities will be able to resist the probable future levels of stress occurring at more frequent time periods (Lorenzo Alvarez-Filip pers com 12 August 2025).

There is some evidence of the persistence of heat-adapted genotypes in some species (eg. Lachs et al 2023, Lachs et al 2024) but also that heat stress is increasingly overwhelming this resilience (Logan et al.2021; Venegas et al., 2023; Cornwall et al 2022, Byrne et al. 2025). Some laboratory-based analyses have shown better than expected results for a broad range of Indo-Pacific coral species, suggesting these species have sufficient heritability to allow for adaptation to both warming and acidification levels (Jury and Toonen, 2024). However, these analyses do not explicitly account for wider climatic and non-climatic stressors, nor for out-of-the lab survival conditions.

The potential for significant thermal refugia for corals under future scenarios is looking increasingly doubtful (Dixon et al., 2022; Setter et al.,2022; Lenton et al. 2023). Bleaching is reaching ever greater depths, and very few reef areas are predicted to remain below tipping thresholds for temperature and other stressors. The existence of putative refuges at greater depths or higher latitudes is increasingly questioned (Hoegh-Guldberg et al., 2017, Rocha et al 2018; Setter et al. 2022; Fuchs et al 2024; Muñiz-Castillo et al 2024; Vogt-Vincent et al 2025). Hence, although we may see some resilience of coral to future ocean heating through acclimatization, and adaptation, this potential is likely to be overwhelmed by increasing rate and magnitude of thermal stress and compounding stressors (Dixon et al. 2022; Setter et al. 2022; IPCC 2022; Lenton et al. 2023; Hoegh-Guldberg et al 2023; Henley et al., 2024; Muñiz-Castillo et al 2024; Byrne et al. 2025; Vogt-Vincent et al 2025; Raoult et al 2025; Wang et al 2025).

If reefs manage to persist in the future, they are likely to be very different to those we benefit from today (Figure 4.3.2), with much less diversity in coral species (Hughes et al 2018, Henley et al. 2024), and lower structural complexity (Perry and Alvarez-Flip 2019). Mass bleaching events have differential impact on different coral species, with fast-growing branching and tabulate corals being more affected than slower-growing massive species (Hughes et al 2018), although latest mass bleaching observations suggest increasing vulnerability of all types. Ocean acidification is also expected to increasingly negatively impact coral communities around the world, selecting species that have an inherent resistance to elevated pCO2 (Agostini et al 2021), which are not necessarily the same taxa most resistant to thermal stress (Cornwall et al 2024, Pearce-Kelly et al 2025).

The changing geo-ecological functions of reefs (Perry and Alvarez-Flip 2019) will have increasingly severe impacts on the thousands of species that rely on the complex three-dimensional structure of reefs and also on the ecosystem services reefs provide, including coastal protection, food security and livelihoods (Laffoley and Baxter, 2016; Perry et al 2018; Resource Watch 2022, Henley et al. 2024; Smith et al 2024).

Restoration efforts are ongoing and have been shown to be effective at small scales in the absence of thermal stress and with intensive maintenance effort (Boström-Einarsson et al 2020; Lange et al. 2024). Multiple scientific initiatives are looking for coral genotypes that can stand increasing thermal stress. Coral restoration is likely to continue to be compromised unless climate change and other anthropogenic drivers are urgently reduced (Hughes et al.,2023). Scale remains the biggest hurdle (Mulà et al 2025) with fewer than 4% of restoration initiatives being more than a hectare in extent. Large scale restoration is greatly limited by funding constraints and increasing stress severity (Boström-Einarsson et al 2020; Hughes et al.,2023; Mulà et al 2025).

While innovations like assisted evolution or heat-tolerant corals can offer coral reefs a temporary lifeline, they cannot replace decisive and immediate climate action—without it, such efforts will be powerless to prevent the degradation and effective loss of these reefs through long-term tipping point thermal exceedance. This underscores the urgent need for phase out of greenhouse gas emissions and carbon drawdown mitigation.

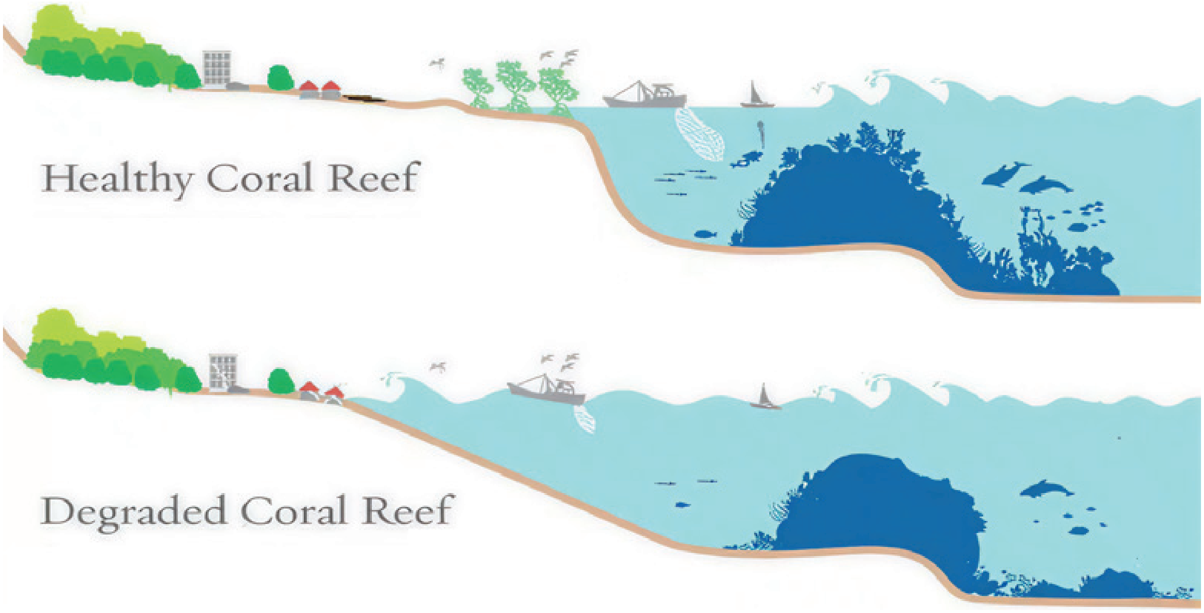


Figure 4.3.2: Severely degraded reefs lose much of their ecosystem services, such as coastal protection and food provision (Adapted from: Germanwatch 2023)

4.3.5 Caribbean reefs: a miners' canary of the tipping and degradation of warm-water coral reefs

The 2023–2025 mass bleaching event has left a stark and widespread imprint on global coral reef ecosystems, which were already weakened by a diversity of co-stressors. This global crisis underscores the urgent need for targeted conservation strategies, and the Caribbean offers a compelling case study. While reefs across the globe suffered, the Caribbean's unique ecological, economic, and cultural reliance on coral reefs makes it particularly significant.

The Caribbean is home to the largest concentration of Small Island Developing States and overseas territories and comprises five coral reef subregions, representing 10% of the global coral reef extent.

The region ranks among the most vulnerable globally for coral reef degradation due to several factors: first, unlike other regions, the Caribbean is a semi-enclosed oceanic basin (Miloslavich et al. 2010). This geography influences water circulation, thermal stress, pollution retention, hurricane landing, and larvae dispersal. Second, the Caribbean hosts far fewer coral species (65-75) than more diverse regions like the Indo-Pacific (McWilliam et al. 2018). This lower functional redundancy means less backup species to perform similar ecological roles, making these reefs more vulnerable to disturbances. Third, as a highly inhabited region, the Caribbean has long suffered from chronic human stresses including overfishing, poor wastewater management, coastal development, and pollution from nutrient runoff and sedimentation. Fourth, the Caribbean has experienced region-wide coral disease outbreaks rare or absent elsewhere, with white-band diseases decimating Acropora species since the 1980s and Stony Coral Tissue Loss Diseases (SCTLD) rapidly spreading since 2014 (Aronson and Precht 2006; Precht et al. 2016; Precht et al. 2020; Cramer et al. 2021; Alvarez-Filip et al. 2022).

These conditions are now adding to a warmer Caribbean Sea, with the ocean being 0.7-1 °C warmer than in pre-industrial times. Past heat stress events (e.g., 1998, 2005, 2010, 2015–2017) produced widespread bleaching but variable mortality across the Caribbean (Eakin et al. 2010; 2022; Muñiz-Castillo et al. 2019, 2024). By contrast, the 2023–2024 marine heatwave was unprecedented, with mass bleaching and mortality documented at multiple sites (Neely et al. 2024; (Bon et al. 2025; Doherty et al. 2025; Goreau & Hayes 2024). Climatic and human compounding impacts have been pushing Caribbean reefs towards their ecological collapse, with already reported regime shifts that are adversely affecting ecosystem functions and services (Goreau & Hayes 2024; Rodrigues et al., 2025a). Aligned with the recent passing of the central estimate for the thermal tipping point of warm-water coral reefs (1.2 °C) (Lenton et al. 2023, IPCC 2022), researchers fear that Caribbean corals may already be trapped in an extinction vortex, being vulnerable to the interplay of climate change, habitat degradation, small coral population size, low genetic diversity and reduced coral dispersal (Goreau & Hayes 2024; Richards Z.T. 2024).

Degrading reefs are not merely an environmental issue, they are a socioeconomic and geopolitical concern. Coral reefs are foundational to the livelihoods, nutrition, and safety of millions across the Caribbean. They provide critical habitat for over 25% of all marine species and support regional fisheries that supply both subsistence and commercial markets (Pearce-Kelly et al., 2025; IPBES, 2019). In many Caribbean nations, where alternative food sources and economic opportunities are limited, the collapse of reef ecosystems would seriously impact food security and increase economic instability. In hurricane-prone regions, reefs act as natural breakwaters, though their protective role depends on reef structure. In the Caribbean, for example, reefs in Mexico reduced hurricane damage by 43% during Hurricane Dean and now prevent an estimated 42 million USD in building losses and 20.8 million USD in hotel damage annually (Reguero et al. 2019). Reefs therefore significantly mitigate the impacts of storm surges and hurricanes on coastal communities (Pearce-Kelly et al., 2025; Guannel et al., 2016). The Caribbean is one of the most hurricane-exposed regions globally, and reef degradation is increasing flood and storm-related damages in a region with intensifying hurricane seasons (e.g. loss of coral reefs in Florida and Puerto Rico could raise flood risk to over 7,300 people, with $824 million/year in additional damage) (Storlazzi et al. 2021). Losses and displacement are growing in the Caribbean due to the impacts of a diversity of extreme weather events (Mycoo et al. 2022; Henley et al., 2024).

Economically, coral reefs generate approximately USD 8–10 billion annually through fisheries, tourism, and shoreline protection in the Caribbean alone (Pearce-Kelly et al., 2025). The tourism sector contributes over 11% to the regional GDP (year 2023) (World Bank 2025), and between 25-90% GDP in ten island nations (Statista 2022). Tourism is tied to the health and visual appeal of its sea, beaches and coral reefs, for snorkeling, diving, and recreational fishing. Their degradation threatens, therefore, vital pillars of regional economic stability (Pearce-Kelly et al., 2025; IPCC, 2022; Mycoo et al. 2022), which currently suffer from the high levels of exposure and vulnerability associated with small island economies.

Evidence for coral reef degradation in the Caribbean and its multiple drivers

Over the past six decades, the percent of living coral coverage has declined by c. 71.7% (relative percent change) in the Caribbean, from c. 60 to 17 percent from 1970 to 2023 (GCRMN - Caribbean, 2025) (43% absolute percent change) (Figure 4.3.3). These values are aligned with other authors' regional declines in living coral coverage of up to 83% (relative percent change), from c. 60 to 10 percent in an earlier time period (70s-2001) (Gardner et al. 2003, Precht et al. 2020; Jackson et al. 2014) (50% absolute percent change).

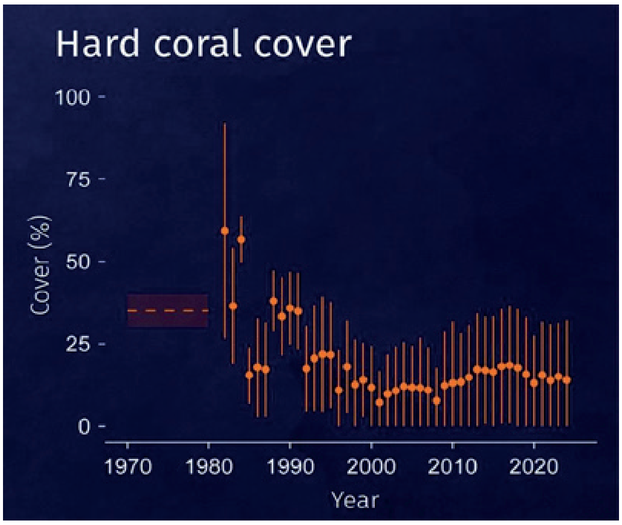


Figure 4.3.3: taken from the Global Coral Reef Monitoring Network (GCRMN-Caribbean (2025), this graph shows the estimated regional decline of living coral cover on Caribbean reefs for the period 1980-2024, expressed as annual percent of coral cover. Points and error-bars represent yearly average and standard deviation calculated on raw data from 12,000 sites across the region, respectively.

The decline of Caribbean coral reefs has been driven primarily by human pressures over decades, with recent ocean warming and climate disturbances further weakening reef resilience. Among these drivers, coral diseases stand out as a particularly important cause of mortality. Since the 1980s, white band disease has decimated populations of Acropora palmata and A. cervicornis, leading to subregional losses of 50–90% of reef-building corals (Cramer et al. 2020, Precht et al. 2020). More recently, the emergence of Stony Coral Tissue Loss Disease (SCTLD) since 2014 has caused unprecedented mortality across multiple coral species, accelerating reef decline throughout the region (Alvarez-Filip et al. 2022; Dobbelaere et al. 2024). These disease outbreaks, though influenced and exacerbated by human-induced stressors such as poor water quality and habitat degradation, represent ecological crises of their own rather than simply consequences of local human activity.

Nutrient pollution and coastal development have also been central drivers of reef degradation. Sewage, urban runoff, and agricultural inputs increase nitrogen and phosphorus loads, promoting phytoplankton and macroalgal growth (Fabricius 2005). Research by the World Resources Institute (Burke & Sugg 2006) highlighted the contribution of large watersheds in the Mesoamerican Reef region, where fertilizer use, soil erosion, and poor land management elevate nutrient and sediment loads reaching coastal reefs. These bottom-up processes fuel algal proliferation, with regional and local analyses documenting widespread increases in macroalgae that in many cases surpass the declines in live coral cover (e.g., Jackson et al. 2014; Suchley et al. 2016; Arias-González et al. 2017).

The expansion of macroalgae is one of the clearest ecological shifts on Caribbean reefs. Macroalgae outcompete corals for space and resources, inhibit coral recruitment, and reduce the potential for reef recovery. Their increase is driven both by nutrient enrichment and by the depletion of herbivores. Overfishing of parrotfish and surgeonfish reduces grazing pressure, allowing algae to proliferate unchecked (Martinez-Rendis et al. 2015; Suchley et al. 2016; Arias-González et al. 2017; Randazzo-Eisemann et al. 2021). However, while herbivory is critical for maintaining coral–algal balance, nutrient enrichment often plays the more pervasive role in promoting rapid algal growth across the region (Lapointe et al. 2004; Szmant 2002; Jackson et al. 2014). Both processes interact, reinforcing a trajectory of phase shifts from coral-dominated to algal-dominated systems.

Additionally, increased frequency and intensity of hurricanes, which are projected to rise with climate change, physically damage reef structures through wave action and sediment displacement, reducing coral cover and disrupting reef ecosystems, complicating recovery efforts (Mumby & Harborne, 2020).

Building on these chronic stressors, marine heatwaves have become the most acute and rapidly increasing threat in recent years (Muñiz-Castillo et al. 2019, Goreau & Hayes 2024), stressing already damaged reefs (Cramer et al. 2020). The record-breaking ocean heat stress during the El Niño 2023–2024 (highest ever recorded ocean temperatures in the region) (Goreau & Hayes, 2024), has led to unprecedented levels of coral bleaching and mortality across the Caribbean (Birkart & Alvarez-Filip 2025; Neely et al. 2025; Thompson et al. 2025). Unprecedented values of > 19 DHW for 2023 and 2024, suggest this latest ocean heat wave is ~ three times stronger than the prior heat waves, entering a new climate dynamic. As examples, during the 2023 bleaching event, Caribbean reefs reported SST anomalies of 1.5–2.5°C above the climatological mean, generalized DHW values exceeding 16°C-weeks, and widespread coral bleaching (>80% of the reefs) (Goreau & Hayes 2024). In Florida Keys, monitoring of over 4,200 coral colonies revealed near-100 % bleaching, with site-level mortality peaking at 43 % and 24 %, while other sites experienced minimal losses (Neely et al. 2024). Reports from Little Cayman and Martinique also confirmed widespread bleaching and mass mortality (Bon et al. 2025; Doherty et al. 2025). These events underscore spatial heterogeneity in outcomes.Extreme thermal events and associated bleaching responses are now occurring in a rapid succession regionally (1998, 2015-2017, 2023-2025) and quasi-annually subregionally (2003, 2005, 2010-2011) (Muñiz-Castillo et al. 2019). Such short return intervals alter local environmental conditions and leave not enough time for reef recovery, damaging reef recruitment, and pushing many reefs beyond their resilience thresholds (Pratchett et al. 2018; Stuart-Smith et al. 2018; Hughes et al. 2019). Combined, these drivers have created a cumulative impact resulting in long-term declines in coral cover, loss of reef diversity and complexity, and diminished ecosystem services (Rodrigues et al. 2025b, Smith et al. 2025). Under current heat trends, Caribbean reefs are under imminent risk of long-term regime shifts to algal-dominated or degraded states.

Figure 4.3.4: shows the evolution of human-driven stressors since the 70s and later combination with heat driven impacts (year 1998) on reef physical functionality trajectories in the Caribbean (Alvarez-Filip et al. 2022).

Human-stressors such as water-vector diseases have long diminished the region's reef health, before heat stress overtook these ecosystems (Cramer et al. 2020, 2021, Precht et al. 2020, Alvarez-Filip et al. 2022).

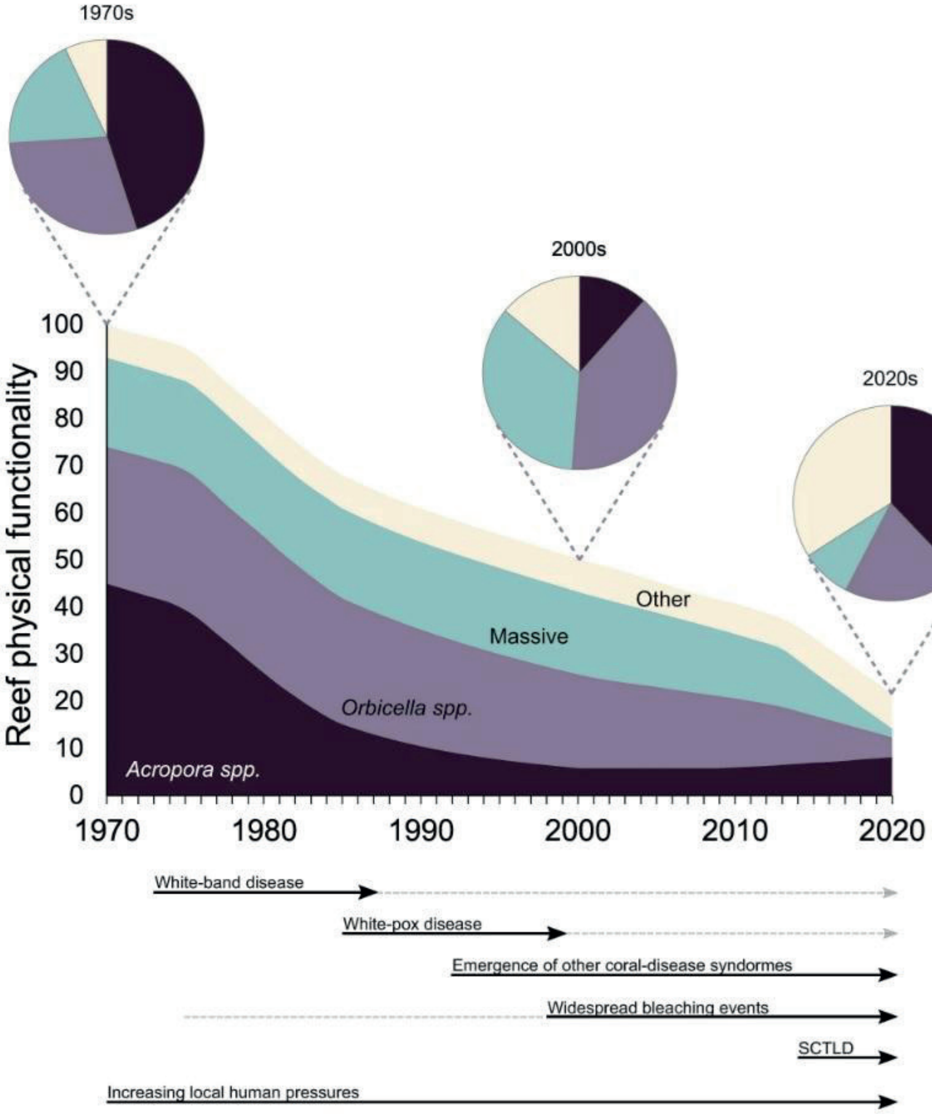


Figure 4.3.4: Taken from (Alvarez-Filip et al. 2022) this is a conceptual diagram of the long-term trajectory of the physical functionality of Caribbean reefs from 1970-2020 showing the occurrence of human-driven stressors, particularly white-band disease, white-pox disease and Stony Coral Tissue Loss Diease. The physical functionality of reefs depends on the abundance (or cover), capacity to accumulate CaCO3, and structural complexity of each species present in the system. The stacked plot represents the functional contributions of four coral groups. The pie charts illustrate the proportional contributions of each coral group during three different periods. Acropora spp. and Orbicella spp. contain all the species for each of these genera and are illustrated as a single group, as they are the main reef-building corals in the Caribbean. The group of massive corals includes reef framework builders from the Diploria, Pseudodiploria, Colpophyllia, Montastraea, and Dendrogyra genera (many of which were severely affected by SCTLD). The other group includes all other coral species, which are largely classified as weedy, submassive, or foliose-digitate corals for which little evidence of declines exists. The black arrows indicate major sources of coral decline widely recognized in the literature. White-band disease resulted in severe population declines of acroporids. The white-pox epidemic has infected many of the remaining colonies of this genus since the 1990s. Other coral-disease syndromes (e.g., white plague and Caribbean yellow band) that mainly affect Orbicella and other massive species have increased in frequency and virulence over the last three decades. Coral mortality has also continued to increase in the Caribbean and is associated with warm-water bleaching events and other local-scale anthropogenic impacts. The grey-dashed arrows indicate that the source of stress remains, although the effects on widespread coral mortality are unclear.

Monitoring systems and indicators in the Caribbean

Effective monitoring of coral reef health in the Caribbean relies on both in situ observations and remote sensing. While not regionally nor temporally complete (Cramer et al. 2021), the region counts on one of the largest and longest in-situ datasets of reef health in the world, collected under diverse initiatives and methodologies (e.g. CARICOM, CoRIS, AGRRA), including fossil records (Reverter et al. 2022). We here focus on data from the Healthy Reefs for Healthy People, which runs biennial regional data collection with the standardized AGRRA (Atlantic and Gulf Rapid Reef Assessment) methodology (Kramer et al. 2003). Their Healthy Reefs Initiative provides reef health indicators to reef managers and policy-makers in the Mesoamerican Reef region, aiming for policy responses. We also rely here on NOAA's Coral Reef Watch program, which provides real time Degree Heating Weeks (DHW) data and bleaching alerts. DHW is a metric used to quantify cumulative thermal stress, and the principal remote sensing tool to measure heat stress relevant for coral bleaching employed worldwide. Caribbean reefs now frequently experience Degrees Heating Weeks (DHW) values exceeding 8°C-weeks, a threshold associated with high mortality risk (Skirving et al., 2019; Goreau & Hayes, 2024). Onsite data collection both in the Mesoamerican Reef (MAR) (Healthy Reefs database) and in the wider Caribbean (AGRRA database) have long supported NOAA's early warning system, largely validating their model. The region counts on a unique regional long-term database (since 2006) that covers classical indicators of reef health: coral cover, fish biomass (herbivores and commercial carnivores), macroalgae cover, and macrobenthos presence (urchins, seastars, etc), among others. This allows general tracking of the reef health that supports policy responses.

A widely recognized ecological threshold for coral reef degradation occurs when live coral cover drops below ~10% (Vercelloni et al. 2020).While reefs may have already seen their functionality collapse above this threshold, below 10% of living coral cover, fish community structure deteriorates significantly (with noticeable declines in fish diversity and abundance), and eventually ecosystem functions and services collapse as reefs lose structural complexity, habitat provision, and resilience (Darling et al. 2019; Sheppard et al. 2020; Vercelloni et al. 2020). An analysis of 12,000 reef sites across 44 countries and territories and 22,000 surveys reported a regional mean live coral cover of c. 17% in 2023 for the Caribbean (GCRMN-Caribbean 2025) (Figure 3). These values differ subregionally and the latest statistics for the MAR countries (Mexico, Belize, Guatemala, Honduras) show coral cover percent that range from national averages of 13% (Mexico) to 26% (Guatemala) in 2022-2023 (Report Card, 2024). However, these recent studies do not include the regional mortality of the 2023-2024 bleaching event. Local post-bleaching mortality statistics are already showing a gloom view of the Caribbean reefs' health status in 2025 (Birkart & Alvarez-Filip 2025; Neely et al. 2025; Thompson et al. 2025).

Live coral cover is a commonly used indicator of reef health but it hides relevant information on reef diversity and structure, offering an overoptimistic view of their status. Because data on diversity and structure are not typically included in standardized monitoring programs (they require taxonomic training), a frequently used indicator to complement the evolution of reef health beyond live coral cover is the evolution of live coral cover vs algae cover. These indicators show clear declines for the Caribbean, as presented in Figure 5a below, where Precht et al. (2020) display the absolute difference between coral cover and algae cover for 1983-2001. In a similar line, but for a longer period, 1980s-2023, data from the Global Coral Reef Monitoring Network- GCRMN-Caribbean (2025) (https:/gcrmn.net/) captures regional mean increases of up to 60% for algae cover since the 90s and the already mentioned decreases in coral cover from c. 60% to c. 17% (Figure 5b).

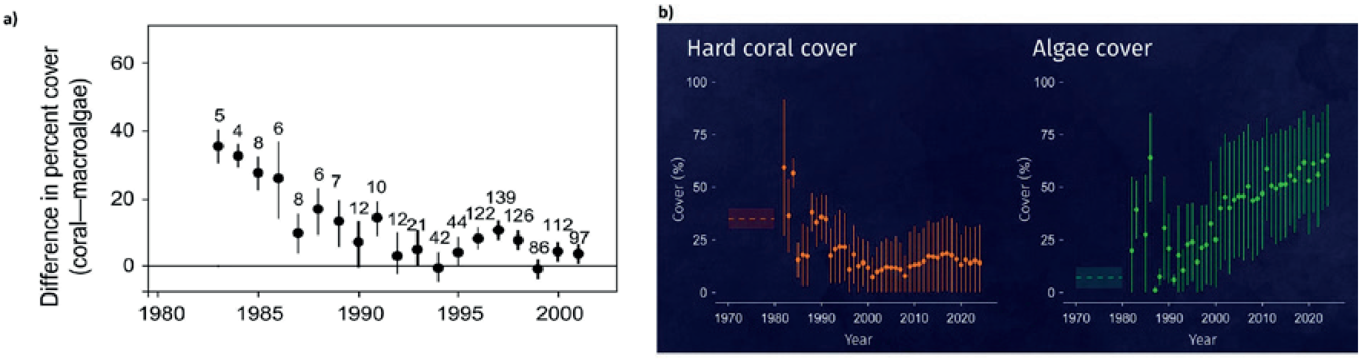


Figure 4.3.5: Reef degradation observed as declining trends of live hard coral cover and increasing trends of macroalgae on Caribbean reefs in different time periods, from different datasets. a) figure modified from Precht et al. (2020), this series represents regional annual differences between live coral cover and macroalgae on Caribbean reefs between 1977 and 2001 (black dots). Positive values indicate that the cover of coral was higher than that of macroalgae. Numbers above the error bars show the sites contributing to each mean, with higher uncertainties in earlier data. And b) annual trends of living hard coral and algae cover in reefs of the Caribbean from 1970 to 2024. Points and error-bars represent yearly average and standard deviation calculated on raw data from 12,000 sites across the region, respectively. Dashed lines from 1970 to 1980 indicate the likely benthic cover in this decade, and taken from Jackson et al. (2014). This figure has been obtained from GCRMN-Caribbean (2025) with permission for use.

Call for action: strategic responses for the Caribbean region

The Caribbean is affected by unprecedented climate hazards (e.g. hurricanes, sea level rise, extreme ocean heat, drought), where urgent societal and policy responses are needed. While global GHG mitigation and carbon removal remain key to reducing the impacts of those climate hazards, in the meantime, improved reef governance is a matter of survival for coastal ecosystems and the livelihoods of coastal communities in the Caribbean. Climate combines with human-driven stresses such as overfishing, water pollution, sedimentation or coastal development. Given the multi-faceted nature of reef degradation, an integrated approach that combines local conservation with global climate action is essential. Actions will need to be site-specific but will cover activities that reduce human impacts, such as:

Control Overfishing and Establish and Enforce Marine Protected Areas (MPAs) to prevent habitat destruction.

- Expand no-take (fishing prohibition) zones and enforce patrols to reduce fishing pressure and protect reef biodiversity.
- Enforce bans on herbivorous fish capture (e.g., parrotfish and surgeonfish).
- Shift toward rights-based fisheries and co-management with local communities.
- Integrate ecological connectivity and reef health indicators into MPA zoning plans.
- Support alternative livelihoods (e.g., ecotourism, aquaculture) for small-scale fishers.

Regulate Coastal Development and Reduce Sediment Runoff to limit land-based pollution and habitat destruction.

- Implement coastal zone management laws that regulate hotel, marina, and port construction.
- Strengthen mangrove protection and watershed reforestation programs to reduce erosion and sedimentation.
- Introduce setback policies and sustainable land-use zoning near sensitive reef areas.

Regulate Agricultural Pollution and Watershed Inputs to limit nutrient-run off, algae blooming and turbidity through soil erosion

- Ban and regulate agrochemical (e.g. phosphorous, nitrogen) runoff through watershed-based agreements and farming best practices (e.g., buffer zones, cover crops).
- Support cleaner practices in upstream agriculture, including fertilizer reduction and wetland restoration.
- Regulate perverse subsidies in agriculture that result in reef degradation.

Respond to Coral Disease and Heat Stress

- Establish rapid coral disease surveillance and treatment protocols (e.g., antibiotic application, coral rescue nurseries).
- Expand bleaching early warning systems and coral restoration for resilient genotypes.
- Limit anthropogenic stressors (e.g., all the above) to improve coral immune response.

Support Regional Monitoring and Science-Policy Integration to target data gaps and lack of enforcement.

- Fund and extend regional reef monitoring efforts under standardized protocols (e.g., AGRRA, GCRMN-Caribbean, HRI).
- Operationalize surveillance and law enforcement in MPA.
- Use citizen science and national reef report cards to inform policymakers and the public.
- Embed reef data into marine spatial planning (MSP), coastal development review, and tourism regulations.

Scale Up Reef Restoration Through Coral Nurseries and Outplanting in selected areas where reefs have the capacity to deliver the most significant functional gains, and in areas where the other stressors are already attended.

- Establish in situ and ex situ coral nurseries focusing on thermally tolerant and disease-resistant genotypes.
- Promote large-scale outplanting of nursery-grown corals to degraded reefs using micro-fragmentation or larval seeding.
- Integrate coral gardening into national restoration plans and tourism partnerships.

Implement Blue Bonds and Debt-for-Nature Swaps to tackle underfunded conservation, economic dependence on reef-degrading industries

- Launch Blue Bonds to refinance national debt in exchange for marine conservation commitments (e.g., protected areas, enforcement, tourism taxes).
- Use debt-for-nature swaps to direct debt relief toward reef management and monitoring.
- Develop sustainable tourism fees or coral conservation trust funds to finance long-term.reef protection.

Use Reef Insurance and Risk-Based Financial Instruments to protect reefs and communities against storm damage, bleaching, and loss of tourism value.

- Adopt parametric reef insurance policies, triggered by storm or heat events, to fund rapid coral restoration and post-disaster response.
- Establish reef protection as critical infrastructure, eligible for climate resilience and disaster recovery funding.

Active participation in regional Policy and International Advocacy to elevate coral reef conservation as a priority global issue.

- Actively participate in UNFCCC negotiations to advocate for ambitious global climate mitigation, particularly to limit warming below 1.5°C —a threshold critical to reef survival (IPCC, 2022).
- Integrate coral reef protection into the SIDS Accelerated Modalities of Action (SAMOA Pathway) and the Blue Economy agendas, ensuring reef health supports economic resilience.
- Leverage participation in regional agreements like the Cartagena Convention and its Protocol on Specially Protected Areas and Wildlife (SPAW) to harmonize reef governance.

4.3.6 From prevention to adaptation: Governing coral reef tipping points

Governance of warm-water coral reefs requires returning global mean warming below 1.2°C with a minimal overshoot period, and eventually returning to 1°C above preindustrial, as essential targets for retaining functional warm-water coral reefs at meaningful scale, beyond a relatively few isolated refuge areas.

Policy makers and societies remain fully unprepared for the imminence of reefs' functional collapse. While urgent global and local action can still reduce drivers of decline, the irreversible loss (in the absence of effective mitigation outcomes) of many reef functions requires governance systems that also prepare societies for profound ecological, social, and economic transitions.

Effective governance of coral reef tipping points requires action at multiple, interconnected scales, because the drivers of reef decline are simultaneously global, regional, and local. At the global level, the persistence of functional reefs depends overwhelmingly on rapid decarbonization, carbon dioxide removal, and speedy return to a global temperature well below 1.5°C. This means coral reef governance cannot be siloed into marine or biodiversity policy alone, but must be integrated into climate governance under the UNFCCC and linked financial, trade, and energy regimes. Equally, prevention requires coordinated action at national and local scales to reduce non-climatic drivers of tipping dynamics, including pollution from agriculture and industry, overfishing, unsustainable tourism, and coastal development. Marine protected area networks, improved fisheries management, and stricter land-use and water-quality regulation can help alleviate these stressors, buying reefs precious time during what is expected to be a protracted period of global temperature overshoot above coral reefs upper tipping point threshold of 1.5°C.

At the same time, recognition that the central thermal tipping point for warm-water coral reefs has already been exceeded and with near-term exceedance of the upper 1.5°C tipping point threshold, implies that even the most ambitious, current mitigation pathways will not prevent large-scale, irreversible loss of reef functions. This presents an urgent challenge to improve mitigation pathways to their fullest potential to align with temperature reduction needs for functional coral reef persistence. Failure to sufficiently mitigate will require governance frameworks to shift emphasis from "saving" reefs to managing the consequences of their decline, including supporting transitions in livelihoods, securing food security, and ensuring just adaptation for the most affected communities. Globally, impact governance for coral reef tipping includes the Paris Agreement goals and mechanisms. Adaptation governance will need to be anticipatory and transformative, with dedicated governance bodies (e.g., a strengthened International Coral Reef Initiative [ICRI]) or regional platforms (e.g., in the Caribbean or Southeast Asia) facilitating exchange of experiences, coordination of responses, and integration of science with policy. Such polycentric arrangements can help societies prepare for futures in which current reef-based subsistence and economic activities may no longer be viable. Inclusive governance processes that integrate Indigenous and local knowledge alongside global trade and development policy are essential for designing equitable adaptation pathways. Importantly, the decline of coral reef-based fisheries will reverberate well beyond reef regions, affecting international food trade, nutrition, and global security.

The governance of coral reef tipping points must be elevated onto global governance agendas, as no existing international framework directly addresses the risk of widespread and irreversible reef collapse. Strongly affected states, together with intergovernmental organizations such as UNEP, will be essential in championing this issue, mobilizing political attention, and creating the institutional space for both preventive and adaptive responses.

CASE STUDY 04

MOUNTAIN GLACIERS: ÁAK’W T’ÁAK SÍT’ (MENDENHALL GLACIER)

4.4 Mountain glaciers: Áak’w T’áak Sít’ (Mendenhall Glacier)

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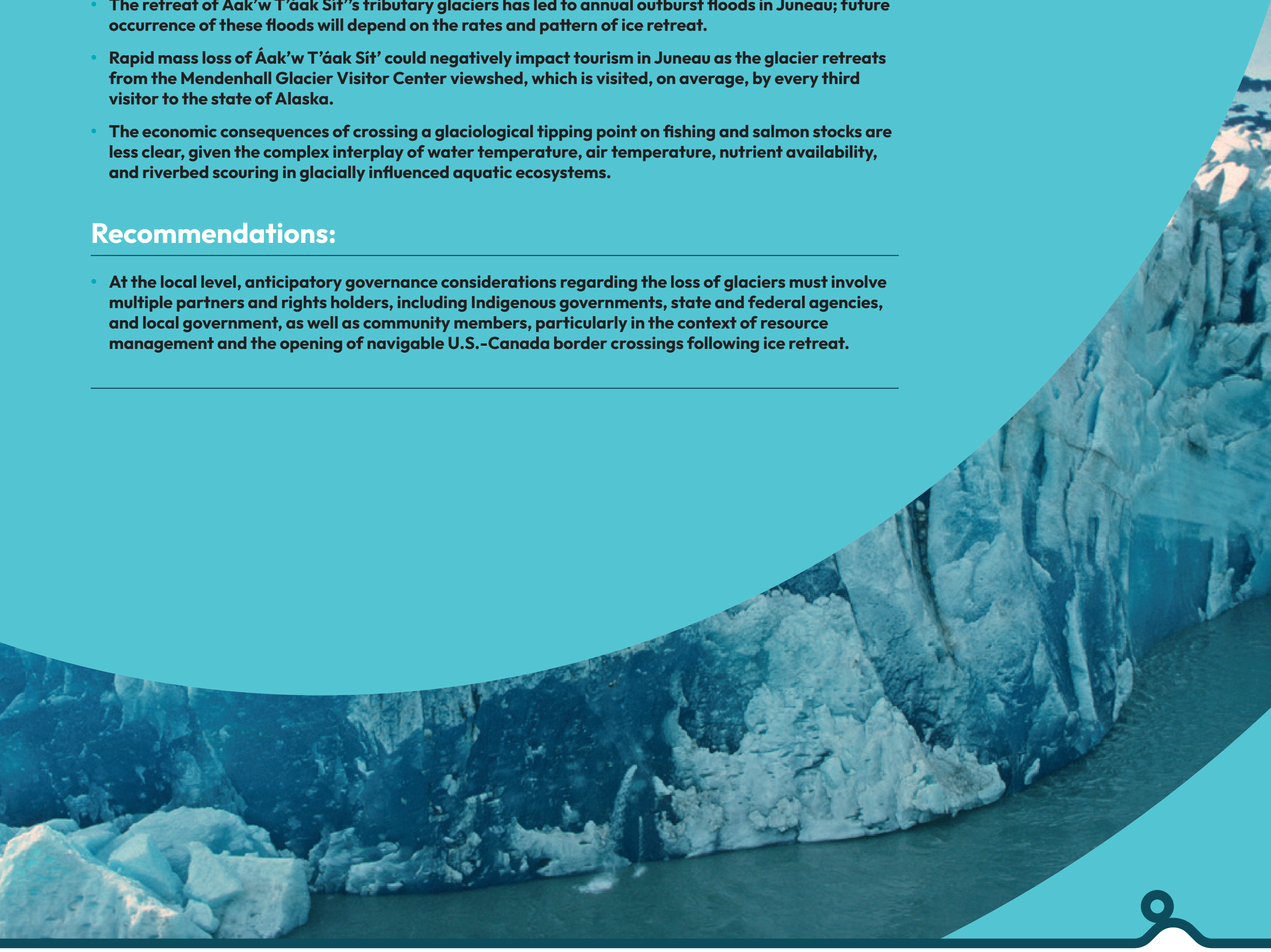
Reviewed by: Jason Fellman, Eran Hood, Sonia A. Nagorski, Allen Pope, and Helen Werner

Risk Assement:

- **Mountain glacier tipping behaviour depends on a complex interplay between topography and climate, with mountain glaciers that experience similar external forcing having the potential to respond differently depending on local conditions.**
- **Áak’w T’áak Sít’ as well as the broader Juneau Icefield and its outlet glaciers have been suggested as a potential mountain glacier tipping system, with the segmentation of the glacier into multiple components (“glacier disconnection”) and the bedrock hypsometry leading to nonlinear mass loss and glacial retreat.**
- **Rapid deglaciation of Áak’w T’áak Sít’ and other glaciers disrupts the relationship between Indigenous communities, glaciers, and glacial landscapes, depriving future generations of this component of their identity and history, which are inseparable from the land.**
- **The retreat of Áak’w T’áak Sít’’s tributary glaciers has led to annual outburst floods in Juneau; future occurrence of these floods will depend on the rates and pattern of ice retreat.**
- **Rapid mass loss of Áak’w T’áak Sít’ could negatively impact tourism in Juneau as the glacier retreats from the Mendenhall Glacier Visitor Center viewshed, which is visited, on average, by every third visitor to the state of Alaska.**
- **The economic consequences of crossing a glaciological tipping point on fishing and salmon stocks are less clear, given the complex interplay of water temperature, air temperature, nutrient availability, and riverbed scouring in glacially influenced aquatic ecosystems.**

Recommendations:

- **At the local level, anticipatory governance considerations regarding the loss of glaciers must involve multiple partners and rights holders, including Indigenous governments, state and federal agencies, and local government, as well as community members, particularly in the context of resource management and the opening of navigable U.S.-Canada border crossings following ice retreat.**



Executive Summary

Mountain glaciers are undergoing rapid retreat in response to global warming, yet their potential for non-linear responses (i.e. "tipping") remains poorly understood. While most studies suggest glaciers outside Greenland and Antarctica will, as a collective, respond linearly to temperature increases this century, under higher emissions pathways and over longer timescales, regional and local tipping points have already been identified at the individual glacier-, ice cap-, and icefield-scale. These variations are driven by local topography, microclimates and other site-specific factors, complicating predictions of glacier stability and reversibility.

Despite the limited research, the stakes are high. Mountain glaciers contribute disproportionately to global sea-level rise, accounting for 21% between 2005 and 2019, with Alaska alone responsible for nearly a quarter of this loss. Nearly one billion people live in glacially-influenced watersheds globally, where they play an important role in freshwater availability, influence hazard susceptibility, shape cultural identity, and contribute to local economies. Focused investigations of key glaciers are therefore critical for anticipating the consequences of climate change in these settings.

The Juneau Icefield (JIF), the fifth-largest body of ice in North America, is experiencing accelerated retreat under present-day warming, with its temperate, low-elevation glaciers particularly vulnerable to small temperature increases. Áak'w T'áak Sít' (Mendenhall Glacier) illustrates these changes: since its Little Ice Age maximum around 1760, it has retreated over 4 km, now losing appx. 48 m annually. Recent work suggests that, under continued warming, the unique characteristics of the icefield's physical setting may lead Áak'w T'áak Sít' and other JIF glaciers to "tip" into a state of rapid, irreversible, and self-sustained ice loss. Already, the retreat of Áak'w T'áak Sít' has created a proglacial lake and altered downstream hydrology, affecting salmon habitats, water quality, and the residents of Juneau's most populated valley.

The continued retreat of Áak'w T'áak Sít' is already driving profound ecological and cultural change. For indigenous Tlingit communities, glaciers are more than components of the landscape: they are sentient beings woven into oral histories, spiritual practices and cultural identity. Their retreat and disappearance represent not only ecological disruption but also cultural trauma, severing deep intergenerational ties and depriving future generations of relationships central to place, memory and identity.

At the same time, glacier retreat creates escalating physical hazards. Most pressing are glacial lake outburst floods (GLOFs) from Suicide Basin, a tributary to Áak'w T'áak Sít'. Since 2011, annual floods have released tens of millions of cubic meters of water, with recent events destroying homes, prompting disaster declarations, and forcing multi-million-dollar investments in levees and flood barriers. Despite these interventions, flooding events have affected hundreds of properties, underscoring the growing risks as glacier retreat reshapes valley hydrology. The likelihood of future GLOFs is high, with additional unstable basins potentially forming as ice thins and disconnects. On long timescales, the continued loss of glacier ice will lead to the opening of navigable borders between the United States and Canada, and expose previously inaccessible georesources for potential extraction.

Together, these dynamics reveal a poly-crisis which includes material risks to downstream communities and cultural and environmental losses of immeasurable value. Effective governance will require integrating Indigenous voices, recognizing cultural heritage as central to adaptation, and addressing both the physical hazards and intangible dimensions of glacier decline. Preserving cultural continuity and community resilience demands that governance strategies extend beyond technical fixes to honour the full meaning of glaciers in Tlingit homelands.

Introduction and Motivation

In comparison to other Earth system components, relatively limited research has investigated the capacity for mountain glaciers to respond non-linearly to climate change–i.e., to "tip". This is despite their important role in many communities and ecosystems, as well as indications that critical thresholds likely exist for many mountain glacial systems (Kääb et al., 2023). That they are already changing rapidly in response to a warming climate is well-documented (IPCC, 2019). More specific investigations into potential nonlinear responses to warming, i.e. mountain glaciers' "tipping behaviour", have found that, considered in the aggregate, glaciers outside the Greenland and Antarctic ice sheets are expected to respond linearly to temperature change within this century (Rounce et al., 2023). However, at more rapid warming rates induced by high emissions pathways in the 21st century (Bolibar et al., 2022) and on longer timescales beyond the year 2100 (Marzeion et al., 2018), they may exhibit nonlinear responses. Additionally, nonlinear behavior has been identified at the individual glacier, ice cap, and icefield scales (Åkesson et al., 2017; Criscitiello et al., 2010; Davies et al., 2022; 2024; McNeil et al., 2020; Zekollari et al., 2017), indicating that there may be important regional tipping points for specific glaciers.

Though influenced by the same regional atmospheric forcings (i.e., temperature and precipitation), the response of individual, and even neighbouring, mountain glaciers can differ according to local topography and microclimate(s) (Oerlemans, 2001). Because of these and other complexities, mountain glacier tipping potential, timing, dynamics, and potential reversibility are poorly-understood, and likely driven by combinations of locally-specific factors (Kääb et al., 2023). The limited body of research on mountain glacier tipping dynamics stands in stark contrast to their disproportionate contribution to global sea level rise (Hugonnet et al., 2021); their centrality for mountain ecosystems; and their role in sustaining human societies (IPCC, 2019). Globally, mountain glaciers lost more than 250 billion tons of ice during the 2005-2019 period and are responsible for 21% of the contemporaneous global sea-level rise (Hugonnet et al., 2021). Of that, glaciers from Alaska account for nearly one quarter of total ice loss (appx. 67 billion tons; Hugonnet et al., 2021).

While careful investigation of the dynamics of the hundreds of thousands of individual mountain glaciers worldwide is prohibitive, investigations of key glaciers are nevertheless necessary, particularly for the nearly 1 billion people living in glacier-influenced regions (Viviroli et al., 2020) who may be impacted by their potential loss and/or tipping. In these settings, glaciers exert important controls on the local environment as sources of freshwater (Hamish, 2019; Ultee et al., 2022; Immerzeel et al., 2020); the cause of glaciogenic natural hazards (Zhang et al., 2022); as important cultural touchstones (Cruikshank, 2001); or as economic drivers for local communities (Salim et al., 2021). This case study summarises the possible causes and implications of tipping in a localised mountain glacier system, serving as an analogue for furhter local-scale tipping system evaluations. In the setting of interest here (Áak'w T'áak Sít' and the Juneau Icefield), the even more rapid loss of glacier ice due to the crossing of critical local warming thresholds would impact, among other systems, regional glacial hazards, salmon habitats, and water quality, all of which may be particularly responsive to the crossing of tipping points.

4.4.1 Áak'w T'áak Sít' and the Juneau Icefield

The Juneau Icefield (JIF) is a large (~3,700 km^2) temperate icefield straddling the Alaska-Canada border, situated roughly between Skagway and Juneau, the capital of the U.S. state of Alaska, and Atlin, British Columbia (Canada). It is the fifth-largest contiguous body of ice in North America and consists of hundreds of constituent glaciers which flow from a north-south orientated central plateau at ~1900 m a.s.l (Davies et al., 2022; Sprenke et al., 1999). Excepting the Taku glacier (which terminates in the ocean as a tidewater glacier, thus exhibiting more complex flow dynamics than other mountain glaciers; see McNeil et al., 2020), the major outlet glaciers of the JIF have been in retreat since the mid- to late-18th century (Clague et al., 2010; Miller, 1964; Motyka, 2003), with ice retreat rates increasing rapidly into the 21st century (Davies et al., 2024). As a temperate icefield with many low-elevation outlet glaciers, the JIF is sensitive to relatively small changes in regional temperature and therefore particularly susceptible to present-day warming (Davies et al., 2022; 2024; Larsen et al., 2007).

Áak'w T'áak Sít' (Mendenhall Glacier; place name cited by Central Council Tlingit & Haida) is a large JIF outlet glacier approximately 20 km in length and 120 km^2 in area, with ice thicknesses reaching over 500 m (Motyka et al., 2002; Ziemen et al., 2016). It flows south and west from an ice divide at 1700 m a.s.l., and drains, along with the Taku Glacier, the southwestern quadrant of the icefield (Boyce et al., 2007; Figure 1).

The glacier reached its Little Ice Age maximum extent around 1760 (Miller, 1964; Molnia, 2007), since which it has retreated nearly 4.3 km, with present-day retreat rates of approximately 48 m per year (Davies et al., 2024). This corresponds to an annual area change of appx. 0.52 per cent, compared to an average of 1.52 per cent per year across all JIF outlet glaciers (Davies et al., 2024). The present-day glacier terminates in a proglacial lake (Sit'.áa; Mendenhall Lake; place name cited by Central Council Tlingit & Haida), formed by glacial meltwater runoff collecting in the basin eroded by Áak'w T'áak Sít' in its previously extended states (Figure 4.4.1). A river (Wooch Eel'óox-'u Héen; Mendenhall River; place name cited by Central Council Tlingit & Haida) carries glacier meltwater down-valley from the lake, flowing through the city of Juneau before eventually connecting to the ocean (Kienholz et al., 2020). Downstream of the glacier, the Mendenhall Valley supports the highest density and proportion of homes in Juneau. Due to its ease of access and the popular Mendenhall Glacier Visitor Center, Áak'w T'áak Sít' is a significant driver of regional tourism. Nearly 700,000 tourists, one in every three tourists visiting Alaska, stop at Áak'w T'áak Sít' or the Mendenhall Glacier Visitor Center each year (USFS, 2019). Likewise, tributaries of the Wooch Eel'óox-'u Héen watershed provide salmon spawning and rearing habitat, fishing opportunities, and food resources since settlement by Indigenous peoples nearly 10,000 years ago (Cruikshank, 2005).

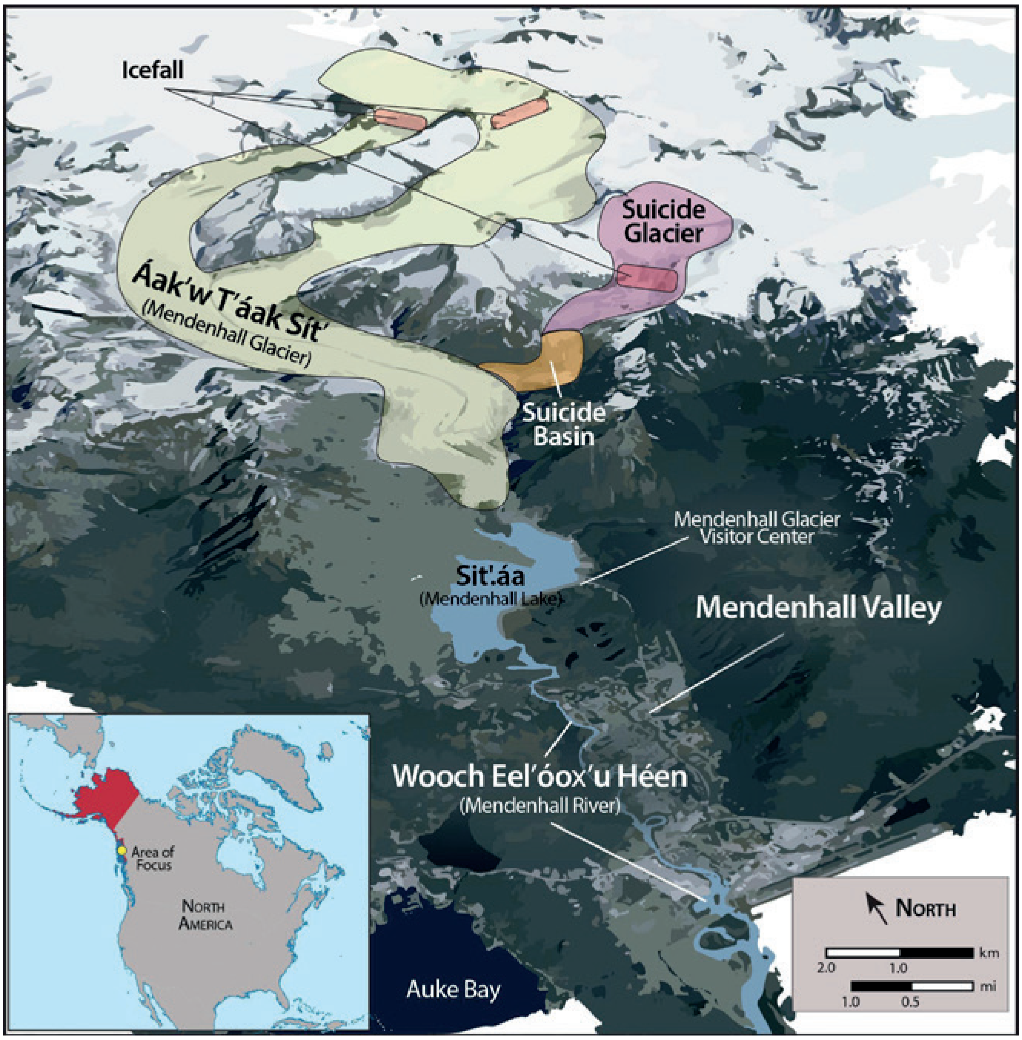


Figure 4.4.1: Overview of Áak'w T'áak Sít's glaciological and topographic setting.

4.4.2 Ecological and environmental feedback loops in Áak’w T’áak Sít’ tipping dynamics

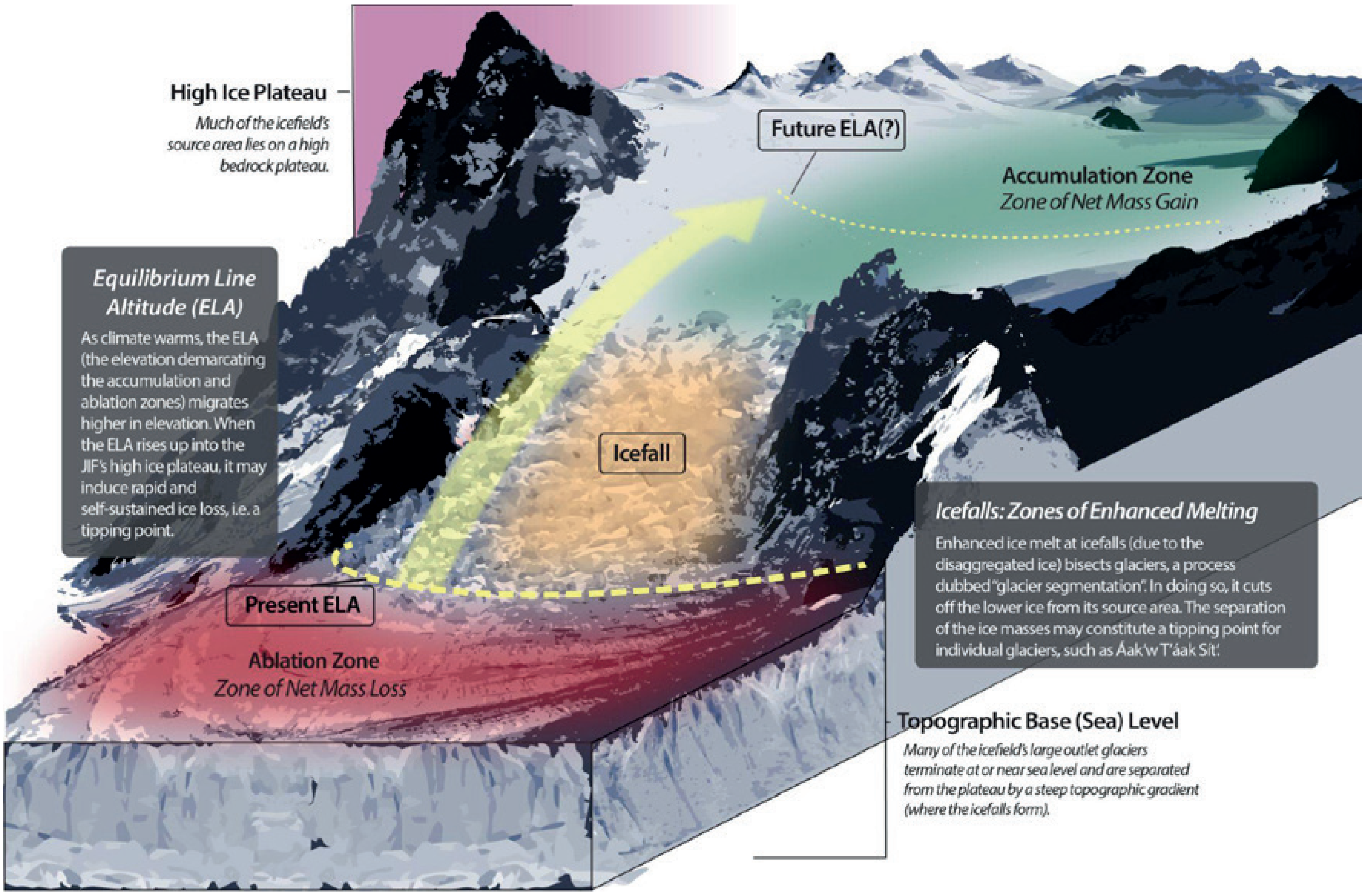
A glacier’s mass balance is the difference between the annual influx of new ice in the form of high elevation snow accumulation and the mass lost due to low elevation melting and discharge. The elevation band separating the accumulation and melting zones is referred to as the equilibrium line altitude (ELA). A glacier’s mass balance is sensitive to the distribution of its surface area at varying elevations (i.e., its “hypsometry”; Jiskoot et al., 2007; McGrath et al., 2017). Glaciers fed from high, plateau icefields such as the JIF have a ‘top-heavy’ hypsometry that is particularly susceptible to non-linear responses to climatic changes, because a relatively small rise in the ELA leads to a large area of the glacier switching from gaining mass to losing mass (Figure 2). This instigates disproportionately large, nonlinear changes in mass loss in response to a small climate forcing (Åkesson et al., 2017; Davies et al., 2022; Jiskoot et al., 2007; McGrath et al., 2017; Zekollari et al., 2017). This nonlinear feedback is compounded when enhanced thinning along the glacier profile causes glacier segmentation (“disconnection”), where ice from the plateau no longer connects with the low lying outlet glacier tongues, causing rapid deterioration of the lower glacier segment (Åkesson et al., 2017; Davies et al., 2024; Jiskoot et al., 2009; Figure 4.4.2).

In the case of the JIF, enhanced thinning and segmentation occurs at icefalls, features created by ice flowing off the high elevation plateau over steep topographic gradients and into lower elevation valleys (analogous to a waterfall resulting from a river flowing over a cliff). Icefalls have characteristic rough surfaces and extensive fracturing which increases the ice surface area exposed to ambient atmospheric temperature fluctuations (Figures 4.4.1 and 4.4.2). They are thus more susceptible to melting than the rest of the glacier (Davies et al., 2022; Davies et al., 2024). Icefalls occur at relatively uniform elevations on the JIF with the majority falling between 1400 and 1700 m a.s.l.. Currently, the ELA sits between 800-1600 m a.s.l. for many glaciers draining the JIF (McNeil et al., 2020; Pelto et al., 2013; Ziemen et al., 2016). However, as air temperatures rise, the ELA will shift up-glacier, sitting at higher elevation bands (Figure 2). This has already been observed for some key glaciers in the region, e.g., Taku Glacier (McNeil et al., 2020). If the ELA migrates above an icefall, the icefall will be within the new ablation zone, where it will regularly be exposed to above freezing air temperatures (Ramage and Isacks, 2017) and where precipitation is more likely to fall as rain than as snow (Ing et al., 2025).

The intersection of the ELA with the icefall-line-altitude and subsequent segmentation of the icefield’s outlet glaciers may constitute a second tipping point not only for individual glaciers, but icefield-wide (Davies et al., 2022), leading to rapid mass loss and a near total collapse of the JIF-glacier system. These local and glacier-specific dynamics will likely compound with other consequences of warming known to induce non-linear responses (e.g., decreased englacial freezing/increased runoff, the melt-elevation feedback, etc.; Schuster et al., 2025).

On Áak’w T’áak Sít’, icefalls occur at approximately 1450 m a.s.l. on both of the glacier’s main tributary trunks, where the ice intersects with the western extent of the underlying bedrock (Figure 1). Modeling studies anticipate considerable mass loss for Áak’w T’áak Sít’ and other JIF outlet glaciers given present warming trends, particularly in the second half of the 21st century (Ing et al., 2023; Ziemen et al., 2016). Ziemen et al. (2016) investigated the future evolution of the JIF under the RCP 6.0 scenario (van Vuuren et al., 2011), and found widespread glacier loss, particularly at lower elevations peripheral to the ice plateau. This and other ice dynamics modeling studies do not, however, account for the enhanced melting at Áak’w T’áak Sít’s icefalls in their simulations and thus cannot mechanistically represent the hypothesised tipping behaviour, in part due to the difficulty in capturing (brittle and fractured) icefall flow dynamics in continuum glacier models (e.g., Colgan et al., 2012; Riikilä et al., 2015).

While these projections of Áak’w T’áak Sít’ and the JIF do find rapid glacier wastage at low elevation, their ice loss rates may underestimate true future rates expected given the melt-enhancing feedbacks (e.g., lower bedrock albedo adjacent the ice, reduced total snow cover, lower ice surface albedo due to dust deposition) which result from glacier segmentation (Davies et al., 2022). Necessary future work on JIF tipping as well as the broader mountain cryosphere should include implementing and developing ice dynamical models that are able to capture or represent the expected tipping mechanisms at appropriate spatial scales, given the highly-localised nature of mountain glacier tipping, and thus be able to resolve the hysteresis behaviour of segmented glaciers proposed by Davies et al. (2024).



Much of the icefield's source area lies on a high bedrock plateau.

As climate warms, the ELA (the elevation demarcating the accumulation and ablation zones) migrates higher in elevation. When the ELA rises up into the JIF's high ice plateau, it may induce rapid and self-sustained ice loss, i.e. a tipping point.

Enhanced ice melt at icefalls (due to the disaggregated ice) bisects glaciers, a process dubbed "glacier segmentation". In doing so, it cuts off the lower ice from its source area. The separation of the ice masses may constitute a tipping point for individual glaciers, such as Áak'w T'áak Sít'.

Many of the icefield's large outlet glaciers terminate at or near sea level and are separated from the plateau by a steep topographic gradient (where the icefalls form).

Figure 2. Theoretical overview of proposed tipping mechanisms for Juneau Icefield outlet glaciers.

4.4.3 Socio-biophysical connections and impacts

Glaciers are deeply interwoven into southeast Alaska's physical and human geographies, often linking or lying at the interface between terrestrial, marine, and human ecosystems (Bidlack et al., 2021; O'Neel et al., 2015; Ord, 2024; Figure 4). With the exception of a more rapid rate of ice volume loss, the impacts specific to the tipping of mountain glaciers might be difficult to differentiate from that of broader and longer-term deglaciation and glacier loss. Where possible below, the consequences and impacts specific to tipping and (rapid) rates of ice loss are highlighted.

The human-earth system

Tlingit communities have lived in and stewarded the coastal rainforests and waters of southeast Alaska and southwest Canada for at least the last 10,000 years (Cruikshank, 2005; Lindo et al. 2017); Dauenhauer and Dauenhauer, 1987). Tlingit knowledge of the lands, waters, and animals have been passed down over millennia, shaping culture, sense of place and identity, and sustainable management practices. As landscapes change, Tlingit communities have expressed a deep sense of grief and loss, describing their culture and identity as being inseparable from the land (Cruikshank, 2005; Thornton, 2008; Ord, 2024).

Tlingit knowledge portrays glaciers, like Áak'w T'áak Sít,' as gendered, sentient beings, "willful and sometimes capricious." Tlingit teachings taught respect and gratitude towards glacier spirits (Figure 4.4.3), which helped to secure safe travel and passage. In response to acts of disrespect, glaciers were known to respond with devastating consequences, such as by overrunning villages (Crowell, 2024; Cruikshank, 2005; Dauenhauer and Dauenhauer, 1987; Nyman & Leer, 1993; Hebda et al. 2017). This is illustrated in oral histories of Glacier Bay, northwest of Juneau, in which a young woman violates social taboos by communicating with a glacier during her seclusion, calling it to advance which eventually leads to the destruction of her village:

Figure 4.4.3: Tlingit formline drawing by Maka Monture depicting the spirit of Sít' Tlein / Hubbard Glacier, a living guardian of Yakutat. In Tlingit cultures, glaciers are not only ice, but ancient beings whose breath shapes the land and whose presence protects the Tlingit people. Through this piece, Monture seeks to share their strength, memory, and enduring spirit.

Gathéeni,
the bay where the glacier was.
It was where people lived.
Salmon of all kinds ran there.
That's why the people lived there;
        they made it a village.
Many kinds of salmon are there.
Good salmon ran there."
[…]
Through the mountains there
        you could see the glacier waaaaaay up the bay;
        it was only a tiny piece.
It was hanging there up the bay.
It couldn't be seen much from the river;
        it could only
be seen from way out.
But she knew the glacier was there.
That is why she called the glacier
like a dog,
"Glacier,
here,
here." **(James, 1987)**

This and the many other oral histories from the southeast Alaska region demonstrate the dynamic relationships and exchanges that occurred (and continue to occur) between Tlingit communities and glaciers. Glaciers served as pathways for travel and trade, embodied sentience, and engaged in dialogue with Tlingit people, acting as a driver of change in social, marine and terrestrial landscapes (Cruikshank, 2005; Dauenhauer and Dauenhauer, 1987; Nyman & Leer, 1993; Gray, 2022). To understand how the loss of glaciers will impact downstream human and non-human communities, it is essential to recognize the dynamic and multifaceted relationships that continue to this day.

Describing the relationship between her Tlingit community and Hubbard Glacier on the Alaska-Yukon border, Tlingit anthropologist Judith Dax̱ootsú Ramos has described the loss of glaciers in her homeland as "very traumatic", as they are deep relationships that stretch back for generations, shaping cultural identity and harvest practices (Ord, 2024). Rapid deglaciation further disrupts the relationship between Indigenous communities and their connection to glaciers and glacial landscapes, depriving future generations of this component of their identity and history. With respect to Áak'w T'áak Sít', members of the Juneau community (including non-Indigenous persons) maintain a strong connection to the experiences and memories attached to the glacier, valuing its proximity to the city, the educational and recreational opportunities its presence affords, as well as the intangible connections across generations of Juneauites (Bruns and Andersen, 2023; Ord, 2024).

Local hydrology and water security

Freshwater discharge and hydrology

Rapid deglaciation of Áak'w T'áak Sít' stands to dramatically alter the hydrography and microclimates of the Wooch Eel'óox̱'u Héen (Mendenhall River) and downstream environments. Áak'w T'áak Sít' contributes up to half of Wooch Eel'óox̱'u Héen's discharge and, like other mountain glaciers, acts to stabilise discharge throughout the melt season by buffering the low-flow, late summer period when contributions from snowmelt decrease (Motyka et al., 2002; Neal et al., 2002). Glacier melt furthermore buffers interannual variability in regional precipitation, with runoff in warmer, dryer years augmented by enhanced glacial melt (Motyka et al., 2002). Increased melting in the short term will increase annual discharge until around 2080 (Shanley and Albert, 2009), followed by a decrease in annual discharge as the glacier's volume decreases, though these projections do not include rapid ice loss due to potential tipping.

As temperatures rise and glaciers surpass peak discharge, reduced snowpack volume will lead to reduced summer discharge. Reductions in total glacier cover will increase the available landscape for evapotranspiration and plant cover, further reducing total runoff (O'Neel et al., 2015). Greater variability in the timing and volume of freshwater delivered to coastal waters, especially during the winter, will likely affect the dominant circulation pattern in nearshore waters, influencing the transport and delivering of materials and nutrients to offshore ecosystems potentially impacting local food webs (Hood and Scott, 2008; O'Neel et al., 2015; Spencer et al., 2014).

Water quality stressors

Water quality and supply in glacially-dominated and influenced watersheds are intimately linked. More rapid deglaciation following the transgression of a tipping point may impact not only the supply of water, but also it's suitability for consumption by communities and ecosystems.

Investigations of the Wooch Eel'óox̱'u Héen and a nearby watershed (Lemon Creek) have revealed that both glacial rivers carry high annual watershed yields (total exports) of particulate-bound mercury, believed to be sourced primarily from the erosion of local bedrock (Vermilyea et al., 2017; Nagorski et al., 2021). The high volume of entrained sediment leads to high mercury fluxes compared with clearwater streams, although filtered water concentrations are exceedingly low. Deglaciation will likely lead to less erosion of the Hg-bearing bedrock as well as continued sediment trapping in Sit'.áa (Mendenhall Lake) and other lakes that may form in place of the glacier (Nagorski et al., 2021). Peatlands are conducive to mercury methylation (i.e., the process by which relatively harmless inorganic mercury is converted into more a toxic form) in soils, but the Mendenhall area does not include these types of land covers, and so this is of low concern (Nagorski et al., 2014).

Other sources of toxic or potentially hazardous material have not been reported from Áak'w T'áak Sít', though studies from similar glaciers worldwide have shown that sediment ("cryoconite") on the glacier surface can concentrate heavy metals (Łokas et al., 2016), antibiotic resistant genes (Makowska et al., 2020), microplastics (Ambrosini et al., 2019; Zhang et al., 2021), and (occasionally extreme levels of) fallout radionuclides (Baccolo et al., 2020; Łokas et al., 2016; 2022; Owens et al., 2019). While these contaminants generally pose low threats due to dilution by high rates of runoff discharge, their concentration in proglacial sediments following mobilisation can nevertheless pose hazards to human, plant, and animal health (Owens et al., 2019). High sediment loads in glacial rivers can likewise degrade overall water quality and pose management challenges. Deglaciation can elevate sediment supply to rivers as previously sub- and en-glacial sediments become exposed to subaerial remobilisation processes (Moore et al., 2009). The presence of proglacial lakes such as Sit'.áa modulates the impacts of increased sediment load (Hood and Berner, 2009; Milner et al. 2000), and may continue to do so for the Áak'w T'áak Sít', assuming the lake continues to serve as a sediment trap and does not fill with sediment.

Biological systems

Glacier ecosystems in southeast Alaska are vibrant ecological environments closely linked to downstream systems (e.g., O'Neel et al., 2015; Bidlack et al., 2021), and serve as an important source of bioavailable carbon for microorganisms in rivers and highly productive nearshore ecosystems that receive their runoff (Hood et al. 2009; Fellman et al. 2010). Reductions in total glacier inputs to downstream ecosystems including Áak'w T'áak Sít's are likely to result in predictable changes to dissolved organic matter (DOM) delivery, including a shift from ancient, highly bioavailable, aliphatic dominated DOM toward terrestrial-derived, modern DOM, though the extent to which this organic matter subsidizes downstream microbial food webs is unclear (Holt et al., 2023).

Salmon

Pacific salmon are a critical local resource, are culturally significant and are a key part of coastal food webs. Pacific salmon are affected by hydroclimatic factors at every stage of their lifecycle, beginning with egg incubation in freshwater habitats, during which water temperatures have the greatest effect on development rates (Quinn, 2005; Shanley and Albert, 2009).

As glaciers retreat, it is expected that new proglacial streams and rivers will be exposed that may be suitable for salmon spawning and rearing, while continued inputs of glacial melt will keep river and lake temperatures cool. In the medium- to long-term, however, the response of salmon to deglaciation and streamwater warming will impact species differently (Pitman et al., 2020). Temperature increases are likely to affect growth and survival of sockeye fry that rear in lakes such as Sit'.áa, with increasing temperatures leading to an increase in growth rates (and consequent metabolic requirements; Bryant, 2009). Nevertheless, McDonald et al. (1996) found that food resources (zooplankton) did not increase in Sit'.áa, and therefore they predict decreases in salmon populations. While on medium- to long-timescales, the reduction of (cold) glacier water may improve the conditions for salmon, as the cold Wooch Eel'óox̱'u Héen temperatures are below the ideal lower threshold for salmon (Fellman et al., 2013), the reduction in aquatic habitat heterogeneity (i.e., glacial versus non-glacial watersheds) may have negative consequences for salmon as different hydrological forcings produce variable food resource pulses and timings (Bellmore et al. 2022; Dunkle et al., 2024; Hood & Berner, 2009; Hood and Scott, 2008; Fellman et al., 2023). In short, continued glacial retreat could create environmental conditions more suitable for fish growth, but greater stochasticity in environmental conditions could increase year-to-year variability in fish populations.

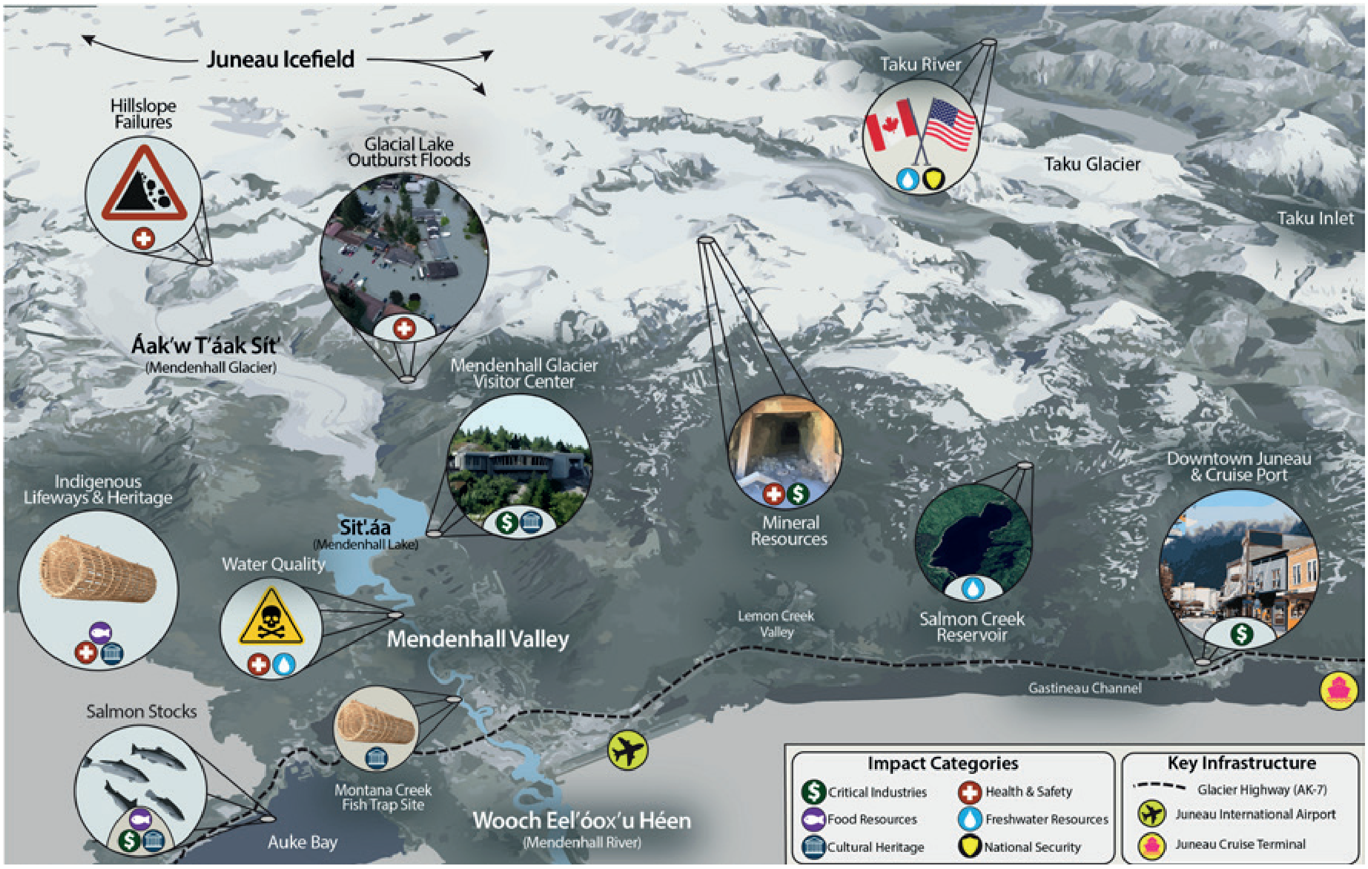


Figure 4.4.4: Overview of impacts from glacier loss in the Juneau region of southeast Alaska.

Regional Hazards, Security, and Economies

Glacial lake outburst floods (GLOFs)

The climate change-driven retreat and disconnection of Suicide Glacier, a tributary of Áak'w T'áak Sít', and the subsequent damming of its meltwater by Áak'w T'áak Sít' have led to the annual release of lake outburst flood water since 2011. Already-large floods in 2018 and 2019 released ~3.0 × 107 m^3 of water from Suicide Basin, adjoining to Áak'w T'áak Sít' (Figure 4.4.4), with the lake level falling more than 50 m over the course of a few days (Kienholz et al., 2020). Floods in 2023, 2024, and 2025 set subsequent records for the volume of water released, with the August 2024 flood approaching 5.53 × 107 m^3 of water discharge (Thiem, 2024; Rosen, 2025). The then-record-breaking flood in August 2024 destroyed several and damaged nearly 300 homes, prompting state and federal disaster emergency declarations. Costs for mitigation efforts proposed by local and U.S. federal agencies have approached $8 million, with immediate costs for the installation of military-grade flood barriers expected to amount to $4 million, including a direct cost to homeowners estimated between $6000 and $8000 per property (Canny, 2024). These barriers, installed following the 2024 event, protected hundreds of homes during the record-breaking 2025 GLOF, though levee failures and constraints in installation areas led to the flooding of several dozen homes. In addition to the economic costs of intervention, the installation of these and other flood barriers will have additional consequences for riverbank stability (Pinto et al., 2018) as well as downstream ecosystems. Juneau-specific studies on the impact of barrier installation are underway (City and Borough of Juneau, 2024b).

Both the floods and the consequent installation of barriers may threaten already sensitive historical and cultural sites, such as the Montana Creek Fish Trap Site (Carrlee, 2006), connected to Tlingit communities. High 2025 floodwaters have prompted the need for additional bank stabilisation strategies and levee construction in forthcoming years (Solimon, 2025a) prior to a planned long-term solution (Solimon, 2025b). Local, state, and federal officials have begun property appraisals as part of an optional buyout program for those homes not protected by the levee–a project estimated to cost up to $20 million (Solimon 2025b).

GLOFs sourced from Áak'w T'áak Sít's adjoining Suicide Basin are very likely to continue into the next decades (Kienholz et al., 2020). The risk of future glacier lake outburst floods sourced from different basins and tributary glaciers adjacent Áak'w T'áak Sít' will depend on the deglaciation pattern and shape of the underlying glacier bed (Kienholz et al., 2020). A disconnection formed at the two icefall(s), however, could yield morphologic conditions suitable for outburst floods if the disconnected, downvalley ice is sufficiently thick to dam precipitation and melt from the upstream glacier. Furthermore, the retreat and separation of several tributary glaciers up-valley of Suicide Basin or the separation of Áak'w T'áak Sít''s two tributary trunks could lead to additional basins wherein the formation of ice-marginal lakes and possible consequent outburst flooding can occur. Over the long term, more rapid (tipping-induced) retreat or thinning of the main trunk of Áak'w T'áak Sít' could attenuate the risk of ice-dammed outburst floods earlier than incremental deglaciation, as retreat above Suicide Basin would prevent water from being damned in the first place.

Hillslope hazards

In populated regions, landslides, rockfalls, and glacier collapses pose major threats to human life, livelihoods, and infrastructure. In cold, glacial regions, rockfalls and landslides commonly occur as a result of both deglaciation and permafrost thaw. Disentangling the compound effects of deglaciation and mountain permafrost thaw for rockfall hazards is difficult, as both occur simultaneously and in response to the same external driving conditions (warming) (Dennis, 2025; Draebing et al., 2021; Ravanel et al., 2017). Landsliding due to deglaciation, where oversteepened valley sidewalls fail due to the loss of ice buttressing following retreat, will continue and expand as more bedrock is exposed. Landslides linked to permafrost thaw (wherein the loss of cohesion due to permafrost thaw leads to hillslope destabilisation) are more likely to occur at higher elevation regions of the icefield's interior, though they may still impact downstream communities if they intersect with glaciers or expanding proglacial lakes and/or rivers (e.g., Cook et al., 2018; Petley, 2025; Wells et al., 2025). Landslides on glaciers are common elsewhere in Alaska (e.g., Dunning et al., 2016; Smith et al., 2023), though a high-resolution hazard evaluation of the JIF region does not yet exist. Permafrost around Juneau is likely limited to high-elevation peaks such as those in the interior of the icefield (Jorgenson et al., 2008). Evaluating potential rockfall hazards will take on greater importance as Áak'w T'áak Sít' continues to deglaciate alongside the rest of the icefield. Hazard assessments should, and can only, occur as part of a long-term evaluation of the future evolution of the Mendenhall Valley and the broader JIF region.

Local and regional tourism

Juneau is a hotspot for Alaska's tourism industry. In 2023 alone, Juneau hosted over 1.65 million tourists (McKinley Research Group, 2023b), which represents approximately $375 million in spending (McKinley Research Group, 2023a). Twenty percent of Juneau households (total population is approximately 32,000) reported a member having been employed in the tourism industry in 2022. Nearly 700,000 tourists, one in three visitors to the state of Alaska, visit the easily-accessible Mendenhall Glacier Visitor Center each year (U.S. Forest Service, 2019), a site built to accommodate less than 500,000 visitors. Current estimates expect the glacier to recede from the view of the current visitor center (Figure 1) by 2050, prompting the U.S. Forest Service to explore new locations for glacier viewsheds in its latest masterplan (U.S. Forest Service, 2019). Managing the Áak'w T'áak Sít' and other glacier viewsheds is a key management issue for southeast Alaska, highlighted by the case of Begich, Boggs Visitor Center near Portage Glacier in southcentral Alaska, which consistently lost visitors following the loss of its glacier viewshed due to retreat around 1994 (O'Neel et al., 2015). Rapid retreat of Áak'w T'áak Sít' into increasingly difficult to access terrain could diminish the appeal of Juneau and the Mendenhall Glacier Visitor Center as a tourism destination. The USFS currently plans expansion of the Mendenhall Glacier Recreation Area to account for glacier retreat (U.S. Forest Service, 2019), though this has been met with mixed response by residents who frequently object to the impact on the local environment (Bruns and Anderson, 2023).

Commercial, sport, and subsistence fishing

The productive salmon streams of the Tongass National Forest in southeast Alaska make the Tongass the United States' top salmon-producing forest, yielding more wild salmon than all other U.S. National Forests combined (U.S.F.S. Alaska Region, 2015). In 2023, 3,604 persons were employed in the commercial fishing industry regionally, earning almost $225 million in labor income and $261 million in catch value, making up 8% of earnings and jobs in the region (Southeast Conference, 2023). In 2023, sport fishing harvests of salmon, a substantial portion of the food people put away in their freezers every year, were estimated at 43,625 salmon for the Juneau survey area (Alaska Department of Fish and Game, 2025), determined through voluntary participation in a statewide mail survey. Additional, reported, non-commercial personal use and subsistence harvests of salmon totaled 10,831 salmon in 2020 within the Juneau sub-region, for which 628 permits were fished (Brown et al., 2023). While these estimates provide an order of magnitude estimate of salmon catches, they likely do not represent the true values relied upon by local residents, and are instead rather a minimum estimate.

The region's glaciers, including the Juneau Icefield and Áak'w T'áak are an important component of these commercially productive southeast Alaskan coastal ecosystems (O'Neel et al., 2015). Assessments of the impacts of tipping-induced glacier loss, as well as that of glacier loss more broadly, on the commercial fishing industry at the catchment-scale are not available. The outlooks for salmon stocks in the region highlight that the complex response of individual salmon species will depend on numerous anthropogenic (e.g., hatchery release) and natural factors, some of which link to the retreat of glaciers, but many of which that do not (e.g., changing ocean conditions such as marine heat waves, ocean acidification, shifting food webs).

4.4.4 Governance considerations at the regional and local scale

Given the severity of potential and current impacts and potential irreversibility of Áak'w T'áak Sít' and JIF glacier loss on applicable (decadal to century) timescales (Ziemen et al., 2016; Ing et al., 2024), preventing the crossing of any potential tipping points should remain a high priority. Nearly all Áak'w T'áak Sít' mass loss is driven by changes in climate, with the timescales of glacier response ranging from decades to millennia (Roe and O'Neal, 2009), meaning immediate reductions in temperature may not lead to an immediate decrease in ice volume loss. Prevention governance efforts should therefore center on preventing global temperature rise by reducing carbon emission as quickly as possible to limit the consequent loss of glaciers, along with related essential habitats, species, and lifeways. As current tipping temperature thresholds for the JIF are not yet identified or constrained, decision-making with respect to mitigation and impacts governance must be undertaken under conditions of deep uncertainty. Modeling studies focused on mountain glaciers do indicate, however, that a global mean temperature exceeding 2.0 C of warming will likely result in significant and large-scale retreat, if not the total loss, of most mountain glaciers. Successfully limiting warming to within 1.5 C, however, could mean that many of these glaciers would likely survive (ICCI, 2024; Rounce et al., 2016; Ziemen et al., 2016; Zekollari et al., 2025).

Here, we discuss governance considerations regarding prevention and impacts at the regional and local scale, highlighting the critical need to integrate Indigenous voices in governance considerations at every level. For a thorough discussion of global-scale governance efforts towards reducing total global atmospheric CO_2 concentrations, we direct the reader to 4.1 Atlantic Ocean circulation case study.

Preventing rapid glacier loss due to tipping

Limiting global warming to prevent glacial melt

Present-day glacier mass loss is driven primarily by global warming, itself a consequence of increasing atmospheric carbon dioxide concentration. The Paris Climate Agreement commits signatories to reducing emissions in line with global warming well below 2.0 C, with the intention of remaining at 1.5 C. While the United States initially joined as signatory of the agreement in 2016, it withdrew less than two years later, in 2017. In 2021 the United States rejoined, only to announce in 2025 its intention to withdraw again. Preserving glaciers requires consistent, sustained, and enforced international policy which commits signatories to reducing global greenhouse gas emissions (Huss, 2024; IPCC, 2022). In the absence of extensive modeling, it is difficult to estimate the absolute increase in temperature necessary forÁak’w T’áak Sít to reach a tipping point. Additional research is necessary to reduce uncertainty regarding when rapid ice loss, tipping behaviour, and irreversible ice loss may be triggered for the JIF (e.g., Davies et al., 2024; Ziemen et al., 2016), but these are understood to be likely long-term outcomes of the current warming path. Nevertheless, as every unit of warming corresponds to enhanced or additional melting irrespective of tipping, every effort should be made to limit increases in global atmospheric carbon dioxide concentrations (Hock et al., 2019; Rounce et al., 2023).

Local and regional stakeholders in Juneau are limited in their capacity to induce meaningful governance that prevents or slows global warming. Nearly all electrical power in Juneau is generated via zero-emissions hydropower. In response to climate change, the City and Borough of Juneau plan to expand the city’s hydropower generation anticipating an expanded demand for commercial heat pump heating systems (Powell et al., 2022). Nevertheless, legal frameworks to protect glaciers and, importantly, to provide recourse for those affected by the failure to preserve them have been proposed for various local, sub-national, and national jurisdictions (Bütler, 2007; Cox, 2016). In Taijikistan, for example, the Law on the Protection of Glaciers defines their protection in light of the impacts of their loss on regional freshwater availability (Republic of Tajikistan, 2024). Similar laws could be introduced at the state or national level in Alaska and the United States. Glacier protection laws implemented for southeast Alaska and elsewhere should take care not to impede hazards mitigation and climate adaptation activities (e.g., Anacona et al., 2018). Governance strategies must include and learn from Indigenous knowledges (or ways of knowing), by expanding definitions of loss and damage to include non-biogeophysical evaluations, such as the loss of cultural heritage (e.g., La Rose vs. Her Majesty The Queen, 2020) and constructing legal frameworks that both reflect the depth and severity of the risk for these communities. This means providing commensurate recourse in the absence of glacier loss prevention.

Interventions to minimise ice loss in the absence of reduced atmospheric greenhouse gas concentrations

Human-engineered (“geoengineering”) interventions have, with respect to mountain glaciers, so far focused primarily on highly-localised efforts to increase glacier mass balance and prevent surface melt. Strategies primarily focus on surface albedo (surface reflectivity) modification and artificial precipitation. In the European Alps, ski resort operators and other stakeholders have locally deployed geotextiles on glaciers to increase surface albedo and reduce surface melt since the 1940s. These methods have proven effective across the area of deployment (typically at the 10s to 100s of meters scale; Huss et al., 2021; Fischer et al., 2016; Olefs and Fischer, 2008). This is in contrast to artificial precipitation, which yielded little mass balance gain in Alpine settings (Huss et al., 2021) and moderate gain in limited applications in the Altai (Wang et al., 2020). While effective locally, rigorous investigation of the effectiveness of geotextile emplacement in Switzerland has demonstrated management costs of up to 8 CHF (~10 USD) per cubic meter of ice preserved and up to 3 EUR per cubic meter in Italy and Austria (Huss et al., 2021). Annual ice loss from 2010 to present-day for the entire JIF has been estimated at 5.91 ± 0.80 × 109 m^3 (Davies et al., 2024). To preserve the total volume of present-day JIF ice loss using geotextiles, it would cost between roughly 23-58 billion USD (20-50 billion EUR) based on these price estimates.

Artificial albedo management and implementation are thus not viewed as long-term solutions to reducing glacier loss at the scales necessary to prevent widespread JIF or Áak’w T’áak Sít’ tipping and/or deglaciation, and as the Juneau region is not presently water-stressed, interventions to preserve critical water resources are not immediately necessary. Recent investigations into the environmental impacts of geotextile emplacement have furthermore highlighted the environmental toll of geotextile-derived microplastics, which have been found at heightened levels in textile-bearing glaciers and can have negative consequences for aquatic ecosystems, including fish (Picece, 2021). Given the insurmountably high cost, limited feasibility and utility, and the likely negative environmental impacts for Juneau’s aquatic ecosystems and resources, we do not find either geotextile or artificial precipitation to be feasible, responsible, or ethical means of interrupting widespread ice loss. The only known safe and effective solution to prevent extensive ice loss and preserve glaciers into the future is to limit future warming by reducing carbon emissions (Siegert et al., 2025; Huss, 2024). Money that might be spent on geo-engineering to preserve glaciers could accomplish more if applied to decarbonization efforts without sacrificing standards with regards to safety and justice. Nevertheless, should geoengineering interventions move forward in any capacity, robust governance mechanisms are needed to evaluate their feasibility and to monitor and regulate their testing and deployment. As Áak’w T’áak Sít’ falls within the Tongass National Forest, governance around potential physical interventions would presumably fall under the U.S. Forest Service jurisdictional purview.

Impact governance

Indigenous cultural practices and community priorities

The impacts of both Áak’w T’áak Sít’ and JIF deglaciation will be felt far beyond the confines of the icefield. Among those most affected are the Indigenous communities who have stewarded the land and ecosystems for millennia. To respond to climate change, Tribes in southeast Alaska have developed widespread adaptation plans for implementation at the federated tribal and sub-tribal scale. In southeast Alaska, including the Juneau Icefield region, the Council of Tlingit and Haida Indian Tribes of Alaska developed a Climate Change Action Plan to anticipate the socioeconomic impacts of climate change (Central Council of the Tlingit & Haida Indian Tribes of Alaska, 2021). The report authors highlight the threat posed to Indigenous cultures and practices, including traditional subsistence practices, rising temperatures and threats to aquatic ecosystems, and threats from extreme weather events. While deglaciation is not specifically addressed, the threats to salmon resources due to environmental change are highlighted as having an irreplaceable social cost as well as priceless economic cost. Adaptation strategies for a range of community priorities, including subsistence activities, traditional practices, sacred sites and practices, water supply, water quality, and health are outlined (Central Council of the Tlingit & Haida Indian Tribes of Alaska, 2021).

The Central Council of the Tlingit and Haida Indian Tribes of Alaska have furthermore entered into a formal arrangement with the U.S. Department of Agriculture and the U.S. Forest Service (USFS) to serve as co-stewards of the Mendenhall Glacier Recreation Area, over which the USFS has historically claimed jurisdiction. The aim of this arrangement is to formalise efforts to preserve and protect historic and cultural resources in the region, and to support Indigenous governance of their traditional territory (Central Council of the Tlingit & Haida Indian Tribes of Alaska, 2023). Following U.S. Federal funding cuts in 2025, budget allocations from the Juneau Assembly will provide funding for additional staff within the cultural ambassadors program, underscoring the resilience of local means of governance in the absence of state- or national-level support for responding to climate change’s impacts (Krumrey, 2025).

Glacial lake outburst floods

Effective governance in Juneau with respect to glacial lake outburst floods (GLOFS) requires both long-term capacity building as well as shorter-term mitigation and adaptation. Current efforts are the result of a multi-layered, co-managed approach involving a range of actors, from the local city-borough government to U.S. Federal agencies, highlighting the centrality of national (federal) agency resources in local capacity building. The contributions of the various governance actors for GLOFs and other impacts of glacial retreat are summarised in Table 4.4.1.

Engagement from the national (U.S. Federal) government and agencies

The U.S. Army Corps of Engineers, in cooperation with the U.S. Geological Survey have funded studies to develop long-term GLOF mitigation strategies to be implemented in collaboration with the U.S. Forest Service who manage the Tongass National Forest and Mendenhall Glacier Recreation Area (City and Borough of Juneau, 2025b). The U.S. Geological Survey and the affiliated Alaska Climate Adaptation Science Center, in collaboration with partners at the University of Alaska Southeast and the National Weather Service, monitor flood risk through a network of stream gauges and time-lapse cameras (U.S. Geological Survey, 2021; Garrett, 2024). The Juneau Glacial Flood Dashboard (see: juneauflood.com, 2025) provides an important hub for this information, serving as a platform for the public to engage with real-time monitoring efforts, interactive flood maps, active warnings and alerts from the National Weather Service, resources for flood preparedness and response, and historic data. The tool is the product of extensive collaboration between local scientists, agencies, and community partners and aims to increase education and flood preparedness (Garrett, 2025). All efforts have been advocated for by the Central Council of the Tlingit and Haida Indian Tribes of Alaska, whose backing helped secure federal emergency declaration status and funding (City and Borough of Juneau, 2024a). The U.S. Department of Agriculture's Natural Resources Conservation Service (NRCS) administers the Emergency Watershed Protection Program (EWP) to assist project sponsors in protecting lives and property from flooding or soil erosion after a natural disaster and is exploring property buyouts for qualifying homes, with costs supported by local government partners (Soliman, 2025b).

State of Alaska and local government response to GLOFs

In the event of a GLOF, the burden of the response falls to local governments with the support of state and federal coordinating agencies. The City and Borough of Juneau issue emergency notifications, deploy flood barriers and coordinate response strategies, including post-flood debris and hazardous waste collection (Garret, J., 2024; KTOO News Department, 2024). The Council of the Tlingit and Haida Indian Tribes of Alaska provide emergency shelter to tribal members displaced by the flooding, as well as conduct door-to-door wellness checks (Larson, 2024; Central Council of the Tlingit & Haida Indian Tribes of Alaska, 2025). Private non-profit organisations like the American Red Cross of Alaska and Juneau Community Foundation provide immediate emergency assistance for those affected by the flooding (KTOO News Department, 2024). The State of Alaska coordinates state and federal emergency funding including the distribution of Federal Emergency Management Agency (FEMA) and U.S. Department of Housing and Urban Development (HUD) grants (State of Alaska, 2025). For the 2024 flood, U.S. HUD relief expenditures amounted to $6.05 million. At least 30 FEMA support grants of $605,000 or more were issued to community members (Sabbatini, 2024).

Mineral, hydrological, and ecological resources

The Juneau region has a long history of industrial mineral resource extraction, beginning with the establishment of gold mining camps in the late 19th century. The city sits within the "Juneau gold belt," stretching from Juneau to Tracy Arm, within which copper, lead, zinc and gold have historically been mined (Stowell, 2006). Several mineral mines are currently active in the region, and the recent allocation of $7.5 million will allow for further investigation of Alaska's critical mineral potential, including around Juneau (Herbert, 2025).

Deglaciation will continue to expose new mineral resources well into the future. Tensions between actors promoting mineral resource development in the region and the emergence of new glacially-cooled salmon habitat in the region have already emerged (Moore et al., 2023). Governance around resource use will, necessarily, require coordination between partner groups and local communities, including the City and Borough of Juneau and Tribes, such as the Central Council of the Tlingit & Haida Indian Tribes of Alaska, who have a vested interest both in economic development and sustainable ecosystem stewardship. State and national actors may not always act in consideration of local priorities and instead, respond to economic pressures and national concerns, for example, around the procurement of critical mineral resources (e.g., Dame et al., 2023). Balancing activities which have historically resulted in degraded ecosystems, such as mining and commercial forestry, with more sustainable stewardship practices will require adaptive, flexible, and anticipatory governance and coordination across local, state, tribal, U.S. federal, and international governments and agencies, including native corporations. Recent efforts such as Sustainable Southeast's Community Forest Partnerships for salmon stream restoration highlight the early success of such anticipatory efforts (House, 2023).

It is important to highlight that, as glacier retreat is expected to proceed even (a) absent tipping behavior and (b) in the event of global warming mitigation (e.g., Ziemen et al., 2016), anticipatory governance demands early consideration of these concerns, particularly with respect to industries reliant on healthy ecosystems, like commercial fishing (Moore et al., 2023).

Transnational access and national security concerns

While Áak'w T'áak Sít' falls entirely within the confines of the State of Alaska, the broader Juneau Icefield straddles the U.S.-Canada border. Continued deglaciation thus stands to alter the accessibility of the border and border regions, as well as the distribution and access to freshwater and mineral resources in the region. Though the location of the U.S.-Canada border was subject to arbitration in 1903 (Great Britain–United States Alaska Boundary Tribunal, 1903), because it has been defined using a system of boundary peaks and fjords rather than watersheds (as in other glaciated regions), the location of national boundaries is unlikely to change despite the consequences of deglaciation. Managing and mitigating the consequences of resource development from mining in transboundary river systems is an ongoing concern in the region, including in the Taku River watershed which is fed by the Juneau Icefield and flows from BC into Southeast Alaska and has a number of proposed and historic mining sites, including acid leaching from the abandoned Tulsequah Chief Mine (Moore et al., 2023).

Geo-engineering ice preservation strategies for the JIF would likewise require international negotiation and cooperation between the United States and Canada, as it is not possible to intentionally manipulate the icefield in such a way as to only impact the portion of the icefield that falls within one country's borders. Any effort to manipulate one side of the icefield in isolation could have dramatic consequences for ice dynamics across the full icefield-glacier system, with likely non-local impacts to surface mass balance and runoff potentially leading to disruption or redistribution of the meltwater-fed river systems. An intervention in one country could therefore lead to a change in GLOF behavior or negatively impact ecosystem functioning in the other, as examples. If the geo-engineering intervention were to involve the introduction of potentially hazardous materials into the ecosystem, the environmental impacts of that hazard are very unlikely to be contained within existing geopolitical borders, further heightening the risk of these strategies. Anticipating and governing eventualities, and drawing on existing resources, frameworks, and agreements such as the Convention on the Law of the Non-Navigational Uses of International Watercourses (within which glaciers may be included, e.g., Quilleré-Majzou & Majzoub 2010) and the International Joint Commission established by the Boundary Waters Treaty of 1909 between US and Canada (Sergeant et al., 2022), will become increasingly necessary as deglaciation proceeds irrespective of tipping.

Table 4.4.1: Summary of agency and stakeholder roles regarding glacial lake outburst floods; mineral, hydrological, and ecosystem resources; and national security in the Juneau Icefield region of southeast Alaska (USA).

Stakeholder / Agency	Agency Type	GLOF Response and Management Role	Mineral Resources Management Role	Hydrological and Ecological Resources Management Role	Border and Transnational Access Management Role	Key Interests
City and Borough of Juneau (CBJ)	Local Government	Emergency response, zoning regulations, and infrastructure repair	Local permitting/ zoning reviews	Local watershed and infrastructure management		Protect residents and infrastructure; promote tourism and local economic activities, including commercial fishing and other natural resources
Central Council of the Tlingit & Haida Indian Tribes of Alaska	Tribal Government	Engages in long-term planning, tribal consultation to assess and mitigate impacts on indigenous communities	Consulting on mine permitting and land use	Provides and consults on ecosystem stewardship	Advocates for cross-border Indigenous mobility and consultation	Protect tribal lands, natural and ecological resources and habitats; ensure tribal sovereignty; preserve indigenous cultures, knowledge and traditions; protect cross-border mobility
Alaska Division of Homeland Security and Emergency Management (DHSEM)	State Agency	Coordinates disaster declarations and FEMA aid		Works with DEC and FEMA on hazard mitigation	Coordinates with DHS for disaster-related security concerns	Minimize hazard exposure and ensure interagency response readiness
Alaska Department of Natural Resources (DNR)	State Agency		Primary regulator of mining claims and leases	Coordinates with DEC/ADF&G on land and water use		Economic development, efficient permitting, resource revenue
Alaska Department of Environmental Conservation (DEC)	State Agency	Monitors water quality during floods	Regulates pollution/ discharges from mining	Oversees water quality and hydrologic permitting		Maintain clean water, enforce state/federal environmental standards
Alaska Department of Fish and Game (ADF&G)	State Agency		Provides ecological input for mine permits	Manages salmon and aquatic ecosystems as well as state-owned hatcheries		Ensure biodiversity, regulate and maintain salmon fisheries; protect ecosystem health
Alaska Department of Transportation & Public Facilities (DOT&PF)	State Agency	Repairs roads and bridges after floods	Approves mining-related infrastructure	Manages flood-prone transport corridors		Maintain infrastructure integrity and access
Federal Emergency Management Agency (FEMA)	Federal Agency	Provides federal disaster aid and flood mapping		Supports floodplain management and resilience with USACE	Coordinates with border security if floods alter access routes	Disaster response, risk reduction, cost containment
U.S. Forest Service (USFS)	Federal Agency	Studies and implements flood mitigation with CBJ in Mendenhall Glacier Recreation Area	Manages mining access on National Forest lands	Oversees watershed and forest health		Balance public land use, conservation, recreation, and resources
U.S. Fish and Wildlife (FWS)	Federal Agency		Consults on permitting for activities which may impact wetlands and streams in accordance with the Clean Water Act	Collaborates with USFS on wildlife and aquatic habitat conservation within and around Tongass National Forest	Partners with DHS to prevent invasive species from entering the U.S.	Habitat conservation and management and the protection of endangered or threatened species; management of subsistence harvests; monitor ecological systems in collaboration with local, state, Tribal, and federal agencies
U.S. Bureau of Land Management (BLM)	Federal Agency		Manages federal mineral leases and exploration	Balances mining and ecological values under FLPMA		Balance land use with respect to resource exploitation, conservation, and public use and recreation
U.S. Army Corps of Engineers (USACE)	Federal Agency	Co-leads engineering studies for GLOF resilience	Permits wetland/ dredge impacts under Clean Water Act	Hydrological and slope stability modeling		Mitigate flood risk and damage; ensure navigable waters; protect infrastructure resilience

Stakeholder / Agency	**Agency Type**	**GLOF Response and Management Role**	**Mineral Resources Management Role**	**Hydrological and Ecological Resources Management Role**	**Border and Transnational Access Management Role**	**Key Interests**
U.S. Geological Survey (USGS)	Federal Science Agency	Monitors glacial change and watershed conditions as well as flood hazard tracking	Maps mineral potential and geological deposits;	Climate-hydrology monitoring and terrain stability analysis;	Supplies mapping to inform border infrastructure planning	Scientific accuracy; data collection to inform policy decisions
National Weather Service (NWS)	Federal Science Agency	Real-time weather forecasts prior to and during GLOF events				Facilitate public safety through accurate weather and hazard forecasting
National Oceanic and Atmospheric Administration (NOAA)	Federal Science Agency	Supports climate and hydrologic data collection as well as climate, glacial, and atmospheric modeling		Supports watershed and habitat analysis with monitoring data		Advance climate resilience and coastal resource protection
U.S. Customs and Border Protection (CBP)	Federal Agency				Responsible for monitoring new access routes across Canada-U.S. boundary due to glacier retreat; patrols remote terrain	Manage border access and control and monitor new transboundary threats
U.S. Department of Homeland Security (DHS)	Federal Cabinet Department	Supports FEMA in disaster coordination		National coordination on flood-related security	Oversees CBP and FEMA; monitors transnational risks from newly accessible terrain	National security, disaster resilience, international coordination
Environmental NGOs (e.g., Southeast Alaska Watershed Coalitionl)	NGO	Advocate for GLOF mitigation and impacts management	Oppose high-risk mining near glacial watersheds	Promote ecosystem protection and climate resilience		Promote and enhance environmental integrity, public participation, climate justice
Mining Companies	Private Sector		Stake claims, explore and develop mineral deposits	Subject to hydrological and ecological regulations	May seek access to cross-border geological resources as glaciers retreat	Access to critical minerals, investor returns
Local Tourism Operators & Commercial Fishers	Public Stakeholders	Depend on salmon runs and ecotourism, including access to key tourist sites like Mendenhall Glacier Recration Area		Depend on salmon runs and ecotourism		Ensure high water quality standards, sustainable ecosystem management, and promote long-term economic stability
University of Alaska - Southeast (UAS) / University of Alaska - Fairbanks (UAF) / Alaska Climate Adaptation Science Center (AK CASC)	Public Universities and Affiliated Institutes	Flood risk modeling; geoscientific and glaciological research	Assess mineral and terrain potential, as well as associated risks	Study watershed, permafrost, and glacial changes due to climate change	Provide spatial data for cross-border hazard and resource assessments; Investigate geopolitical and economic consequences of increased border access	Provide independent investigations for informed decision making and to support evidence-based policy

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