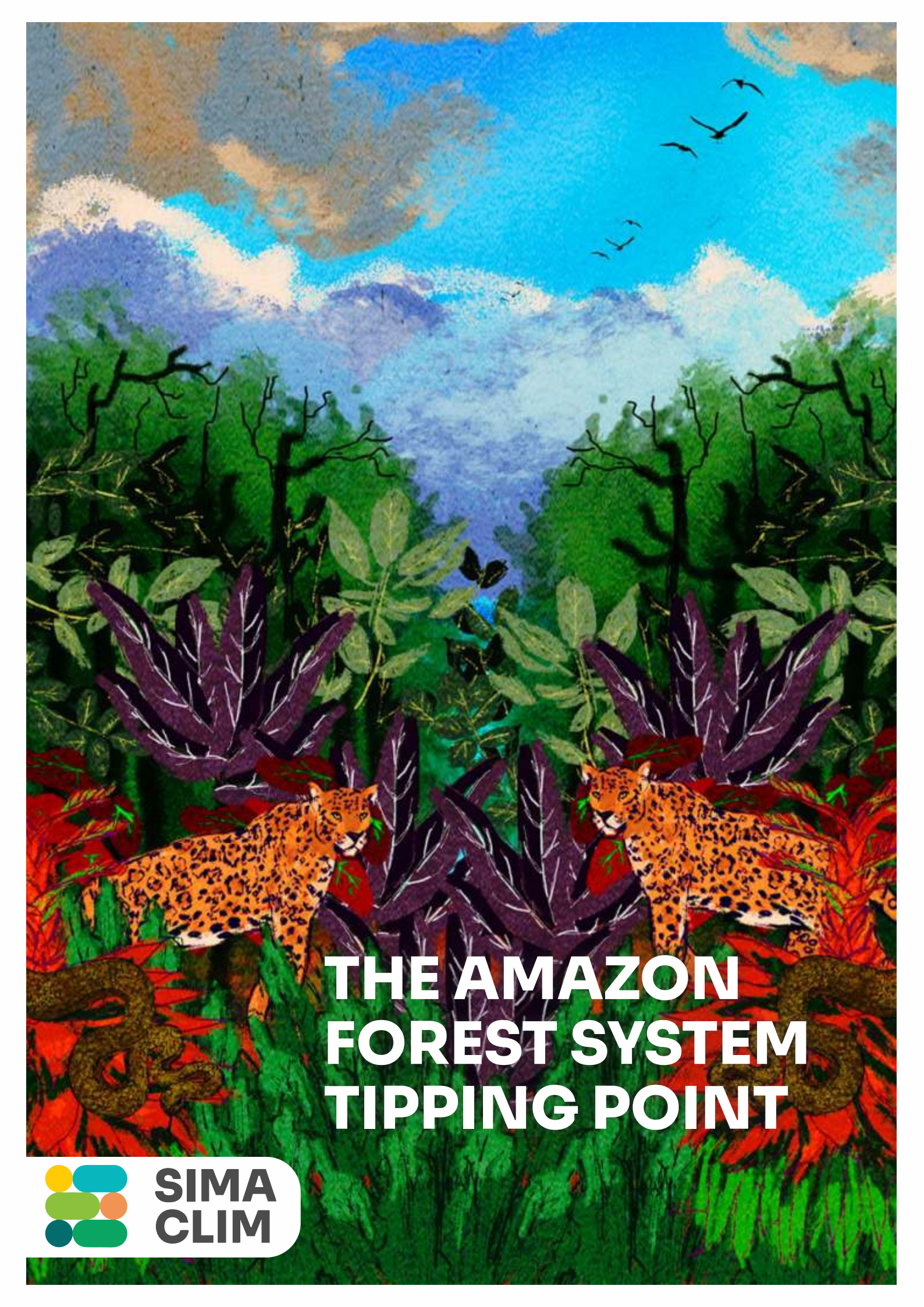




THE AMAZON FOREST SYSTEM TIPPING POINT



**SIMA
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The cover of this report was created by Auá Mendes

Auá Mendes, an indigenous member of the Mura people, is a graphic artist, illustrator, muralist, and art educator, born in Manaus (1999) and based in São Paulo since 2020. With a degree in Graphic Design, her career combines cultural identity with powerful visual creations developed for major brands such as Nike, Google, Natura, Banco do Brasil, Hershey's, and Nubank, as well as cultural institutions such as MAM, Instituto Tomie Ohtake, and the São Paulo and Amazon Biennials. Recognized for her imposing urban interventions — murals up to 60 meters long — and for her work in campaigns on female empowerment, diversity, and the Amazon, Auá stands out as a fundamental voice in Brazilian contemporary art, with works also presented internationally.



**SIMA
CLIM**

THE AMAZON FOREST SYSTEM TIPPING POINT

2025



Relatório de Síntese

The Amazon Forest System Tipping Point

Coordinating Lead Author:

Regina Rodrigues Rodrigues (UFSC)

Lead Authors:

Andrew Hartley (Met Office)

Carlos Afonso Nobre (IEA/USP)

Carlos Alberto Nobre Quesada (INPA)

Chris D. Jones (Met Office, Universidade de Bristol)

Edson Paulo Domingues (UFMG)

Francisco de Assis Costa (UFPA)

Gustavo Luedemann (IPEA)

Jean Pierre Henry Balbaud Ometto (INPE)

Jeffrey Chambers (Universidade da Califórnia)

Lincoln Muniz Alves (INPE)

Pedro Ivo Ferraz da Silva (MRE)

Sandra de Souza Hacon (FIOCRUZ)

Tomas Ferreira Domingues (USP)

Review Authors:

Bernardo Monteiro Flores (UFSC)

Moacyr Cunha de Araujo Filho (UFPE)



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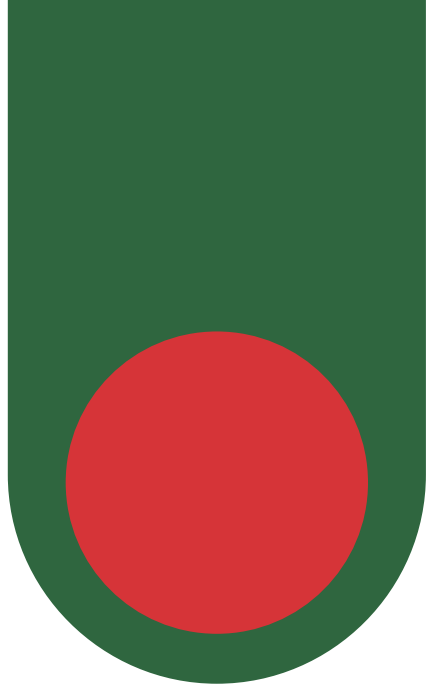
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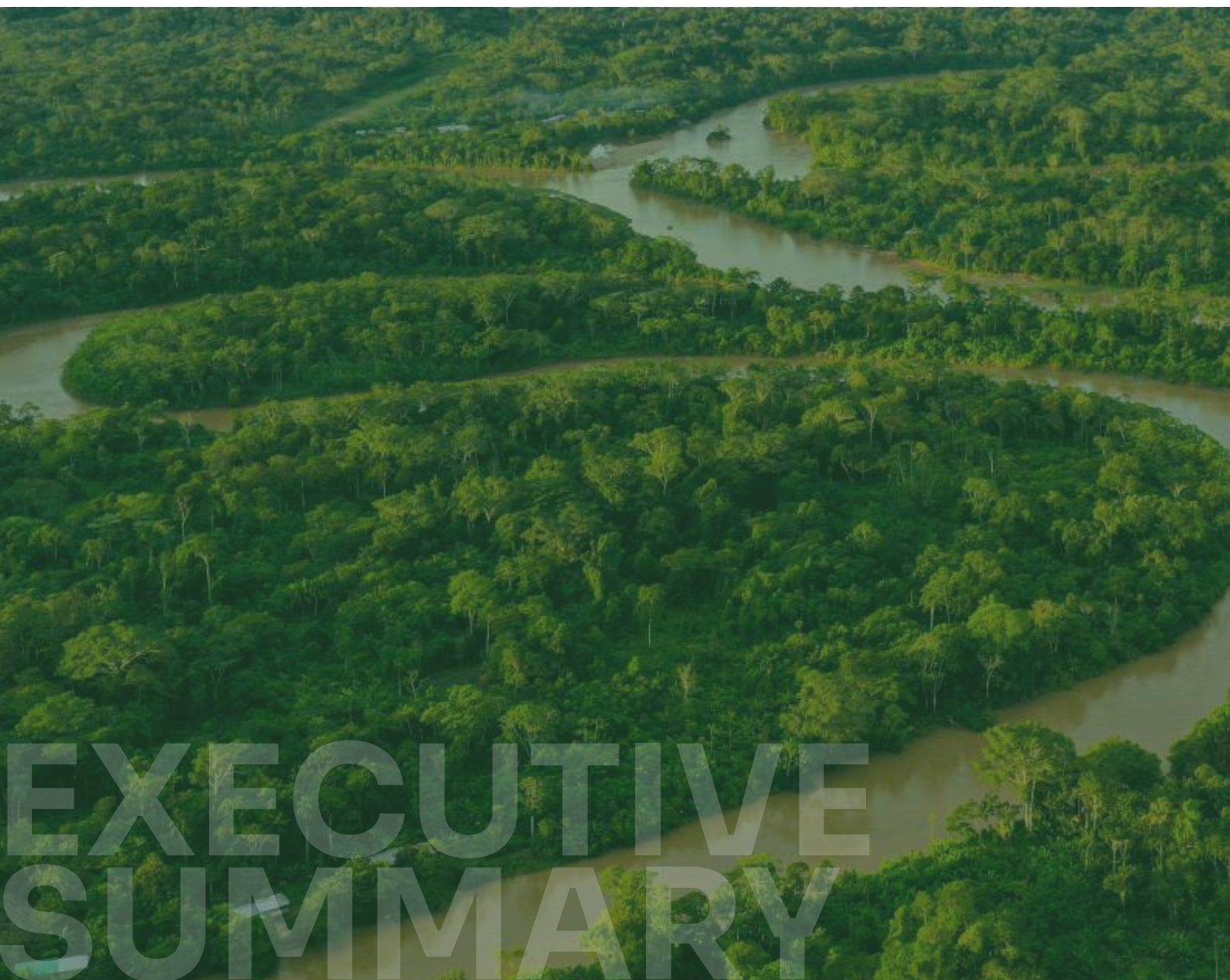
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EXECUTIVE SUMMARY





EXECUTIVE SUMMARY

Human activities are causing major transformations to Earth's climate system, resulting in dangerously higher temperatures, more intense droughts and heat waves, with substantial detrimental effects on nature and society. In addition to these direct impacts, as the planet continues to change under mounting pressures, other indirect effects can accelerate global change impacts through processes known as system feedbacks. These feedbacks can push conditions past tipping points, leading to abrupt and irreversible ecosystem change. In the Amazon forests, droughts under continuously hotter conditions, altered precipitation patterns caused by widespread deforestation, forest degradation and fire, all act to drive ecosystems past potential tipping points that can negatively impact on local, regional, and global climates.

Droughts cause stress to plants and result in elevated mortality rates for forest trees. As the climate system continues to warm, each successive drought occurs at yet higher temperatures, further aggravating ecosystem impacts. At the same time that intact forests are experiencing elevated stress, large areas of forest are being razed for conversion to agricultural activities, and forests adjacent to these anthropogenic landscapes are succumbing to degradation. These changes also accelerate the dynamics of fires that result in further forest loss, with additional influence on air quality from aerosols produced from biomass combustion.

Beyond the direct effects of heat and drought stress, changes to Amazon ecosystems under a warming climate also cause a reduction in the forest's capacity to recycle precipitation back to the atmosphere. This regional drying effect can shift forests to more open-canopy degraded states, while at the same time land-use results in the replacement of forest trees by agricultural crops that recycle less precipitation. Together, these climate and land-use changes act to reduce regional precipitation, and once forest loss tipping points are crossed, the Amazon can be pushed to permanently drier conditions and with lower biomass and more arid ecosystems. When these tipping points have been exceeded, altered conditions at local, regional and global scales can drive negative impacts to food and water security, human health, essential infrastructure, and key ecosystem services.



To avoid the severe consequences of permanently altered Amazon ecosystems, it is critical to keep levels of global warming and deforestation below those that are likely to drive conditions past tipping points. While it is now all but inevitable that the world will reach a dangerous 1.5°C of warming above pre-industrial levels in the coming decade. The extent to which this guardrail warming level will be exceeded, and how quickly we can reduce temperatures again, depends strongly on global collaborative actions taken now to limit emissions. Regarding deforestation, the Brazilian government has committed to reach zero deforestation (PPCDAm, NDC, 2024). Alternatives to deforestation must consider biological and sociocultural diversity in the Amazon, and adopt strategies and technologies that consider the interactions of local, regional and global solutions over longer relevant times scales, and that contribute to restructuring conservation actions in the Amazon. As approaches to avoid Amazon tipping points are envisioned and implemented, it is also critical to recognize that protecting Amazon forests alone is not a solution for climate change – black carbon emissions from fossil fuels cannot be neutralized with green carbon sinks from forest carbon sequestration alone.

Adaptation plans must also be in place if tipping points are not avoided to secure the ecological functions of ecosystems, water resources, food security, forest communities, and biodiversity. Unlike mitigation efforts, which aim to reduce the drivers of change, adaptations focus on adjusting to the changes that are already happening, and those that are inevitable. Integrated assessment models focused on projecting outcomes of varying climate change and socioeconomic pathways are part of the essential tools for charting reasonable paths forward. Early warning systems to detect forest dieback processes, the risk of catastrophic fire spread, and impacts to agricultural production systems are required to indicate when specific adaptation plans need to be put into effect. Preparing for adaptation across the Amazon, and increasing resilience to the extreme events, are crucial for ensuring social and ecological stability.

Tipping points that are exceeded are not just threats to the environment and biodiversity, but also to the millions of people who depend on the Amazon for their livelihoods, culture, and well-being. Yet according to the New Economy for the Brazilian Amazon study by the World Resources Institute, a deforestation-free scenario following a low-carbon pathway would result in substantial and equitable

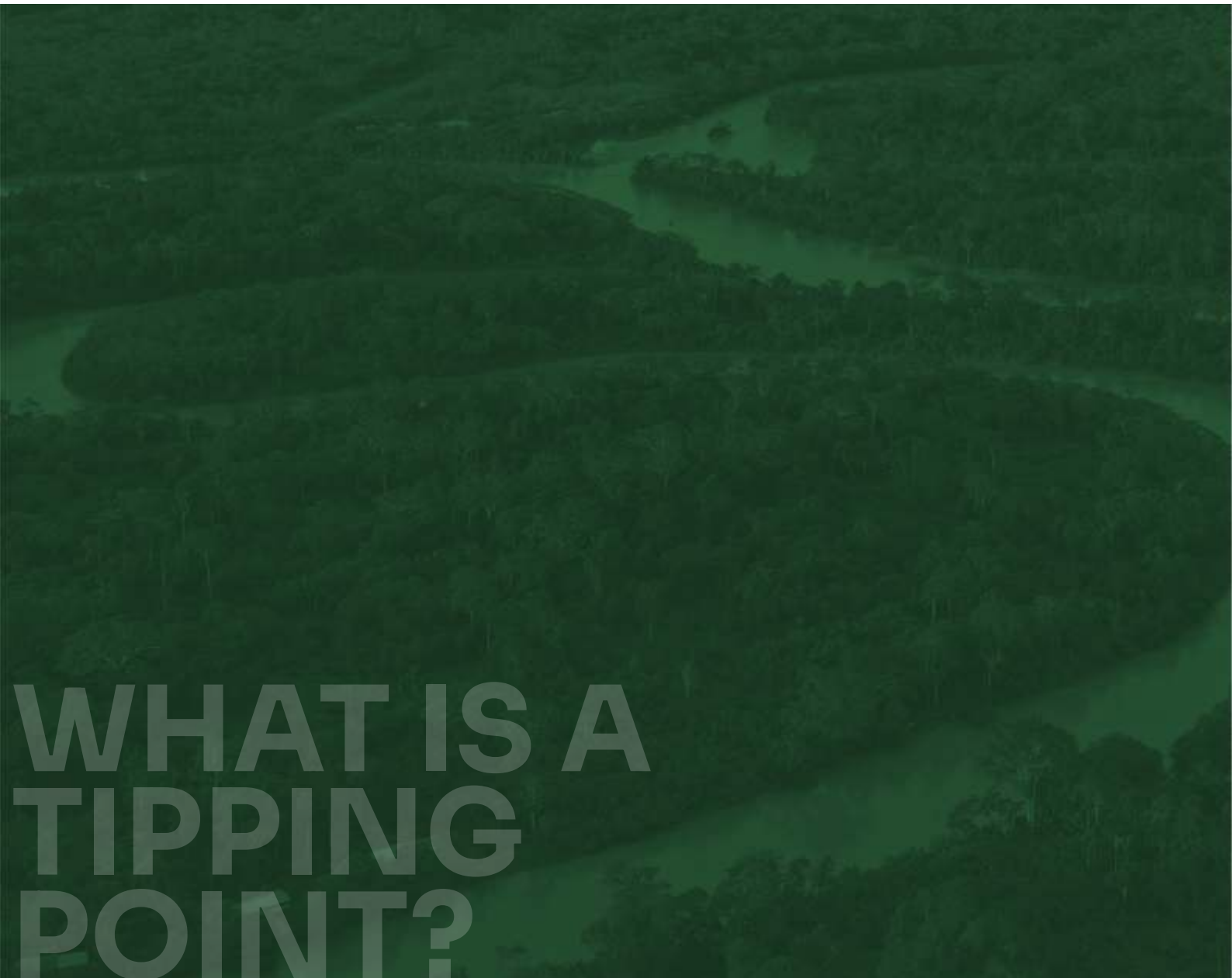


economic growth for the Amazon region and Brazil. Similarly, global-scale reductions in greenhouse gas emission to prevent dangerous alterations of the climate system also provide for widespread economic benefits. Paradigms must shift if Amazon tipping points are to be avoided, which will only be a consequence of effectively integrative societal and governmental actions catalyzing proactive change.



1

WHAT IS A TIPPING POINT?



WHAT IS A
TIPPING
POINT?

1. WHAT IS A TIPPING POINT?

Humanity is currently on a perilous trajectory, as highlighted by the IPCC's (2023) most comprehensive assessment of climate change. Every region of the world is already experiencing the impacts of climate change, and these effects will intensify with each increment of additional warming. The risk of reaching tipping points increases as the planet warms.

Tipping points are prevalent across Earth's interconnected systems, such as the cryosphere, biosphere, oceans, and atmosphere. While these systems often respond in a linear manner to human pressures like climate change, land use change, and pollution as well, surpassing certain thresholds can trigger abrupt, irreversible shifts due to self-sustaining feedback mechanisms. This critical threshold is known as a tipping point.

Strong evidence suggests that the Amazon rainforest is nearing a tipping point, driven by unprecedented stress from rising temperatures, severe droughts, deforestation, degradation and fires (Hirota et al., 2011; Lovejoy & Nobre, 2018; Flores et al., 2024; Nobre et al., 2026). The Amazon plays a crucial role in the global climate system, yet projections indicate it could deteriorate to a less diverse and productive state if current trends continue. This would not only result in loss of biodiversity but also turn the forest into a source of carbon to the atmosphere, thereby exacerbating global climate change (Gatti et al., 2021; 2023). Early warning signals and monitoring data indicate that parts of the Amazon are already destabilizing and could transition due to compounding disturbances. It suggests that the system as a whole could cross a tipping point around 2050, beyond which a biome-wide transition may become self-sustained (Flores et al., 2024).

However, pinpointing the exact threshold at which the Amazon might tip remains uncertain, with estimates varying widely. Current climate models, despite effectively capturing past and present trends, often lack the resolution to accurately predict the dynamics of these tipping points. Nevertheless, evidence from conceptual models and paleo reconstructions supports the likelihood of past tipping events in similar systems (Lenton et al., 2023).

1.1. Definition



In everyday language, a tipping point is where a small change makes a big difference to a system (Gladwell, 2002) or “the point at which a series of small changes or incidents becomes significant enough to cause a larger, more important change” (Oxford English Dictionary). Here, a system is any group of interacting or interrelated components that act according to a shared set of rules to form a recognizable unified whole – for example, an ice sheet, or an economy. A tipping point is a threshold. The small change that causes a system to cross a tipping point can be described as a trigger, leading to a significant transformation in the system's structure or function to another stable state.

Passing a tipping point often involves qualities such as abruptness (rapid change relative to the drivers forcing it), self-perpetuation (the change continues even if the forcing is removed until a new state is reached), and irreversibility (the change is difficult or impossible to reverse) (Milkoreit et al., 2019).

A tipping point occurs when a small change sparks an often rapid and irreversible transformation. Tipping points are crossed when a system is pushed beyond the conditions that enable dynamic stable coexistence of its parts, forcing it to reorganize into a new stable state. Under gradual changes, like current rates of global warming, ecosystems may persist in an apparently similar state (despite the increasing loss of resilience) until conditions pass the tipping point and push them to a new dynamic equilibrium. Tropical forests, existing at the wet and warmest extent of Earth's biomes and with additional warming, will be pushed to no-analog conditions on Earth for potentially millions of years (Williams et al., 2007; Barlow et al., 2018; Westerhold et al., 2020). Hotter droughts under a warmer climate can drive ecosystem transitions in the Amazon forest system, with higher tree mortality rates and plant compositional shifts, pushing these systems toward novel conditions (Cox et al., 2004; Lapola et al., 2018; McDowell et al., 2018). Deforestation and forest degradation from land-use change can also push tropical forests past tipping points. A large portion of Amazonian resilience results from the recycling of rainfall, where moisture is returned to the atmosphere through the transpiration of forest trees and re-precipitates downwind, enhancing rainfall and climate stability in the west part of the biome. The loss of forest cover from land use can weaken this precipitation recycling effect and intensify drought conditions in the interior and western locations of the basin (Shukla et al., 1990; Nobre et al., 1991; Nobre et



al., 2016; Marengo et al. 2018). As precipitation rates decline toward the level required to support closed-canopy forests, forests lose resilience, and disturbances can push forests to more open canopy states. Therefore, large parts of the Amazon forest system could collapse, for instance, due to frequent extreme hot droughts.

In that sense, understanding and identifying tipping points within Earth's environmental systems is crucial for predicting and mitigating the impacts of climate change. The tipping point of the Amazon rainforest underscores the urgency for coordinated actions to reduce human pressures such as deforestation, forest degradation and wildfires, and to limit global warming. To effectively address and mitigate the risks associated with tipping points, it is essential to understand the primary drivers behind these changes. The following section explores the key factors contributing to tipping points, including climate change, land-use change, and other anthropogenic influences. By examining these drivers, we can better inform our strategies and actions to safeguard the Earth's interconnected systems

1.2. Drivers

i) Deforestation and degradation

The Amazon forest system provides multiple ecosystem services, yet for the purpose of understanding the risk of a tipping point in the Amazon and in the Earth system, two of these ecosystem services are of huge importance, moisture recycling and carbon storage and sequestration. Deforestation and forest degradation limit the ability of the forest to provide these services and could potentially destabilize the global climate. For instance, a smaller Amazon forest that stores less carbon and is more prone to droughts would have a reduced capacity to store carbon and sequester atmospheric CO₂ concentrations, therefore, amplifying global climate change.

Between 2000 and 2022, the Pan-Amazon basin lost 12.6% of its intact humid forest of 1999 (totaling 542.5 Mha), either by deforestation (8.0%) or by forest degradation (4.6%) (Vancutsem et al., 2021; Beuchle et al., 2023) (Figure 1). While this rate slowed in the period 2006-2013, recent monitoring shows a possible resurgence since 2018. Lapola et al. (2023) estimate that 5.5% of the Amazon is under some form of degradation driven by fire, edge effects or timber extraction, increasing to 38% when also considering disturbance from extreme

droughts. They estimate that this can reduce dry season evapotranspiration by up to 34%.

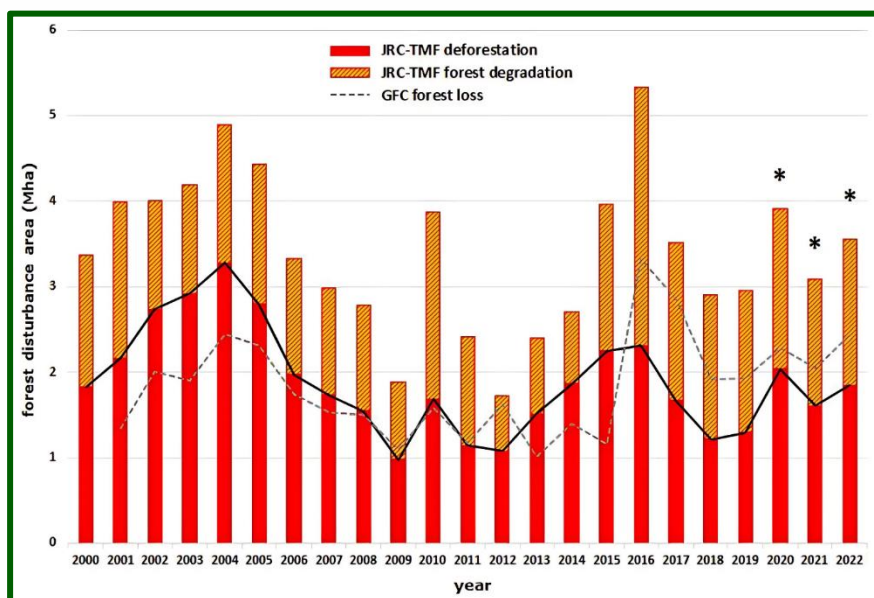


Figure 1. Annual tropical moist forest deforestation and disturbance rate from the JRC-Tropical Moist Forest long term record (Source: Beuchle et al., 2023). Grey dotted line denotes forest loss from the Global Forest Cover Change dataset (Hansen et al., 2013).

Earth System Models have been used to understand the amount of forest loss that might induce a systemic collapse of the Amazon forest into an alternative stable state. In these studies, an Amazon tipping is usually defined as a change to an open-canopy ecosystem state, although other types of transition have been identified (Flores et al., 2024). While there is considerable uncertainty regarding the level of deforestation may induce a change in the stable state of the Amazon, some studies suggests that a loss of forest above 40% (relative to the original extent of the Amazon) could lead to a reduction in precipitation in the region that would have an impact on the whole system, particularly in the South-western Amazon (Sampaio et al., 2007; Zemp et al., 2017; Staal et al., 2018).

ii) Precipitation and temperature changes

Tropical rainforests require consistently wet conditions to thrive. Seasonally, dry regions, which are more susceptible to regular disturbances such as fire, are typically dominated by savannah ecosystems. Consequently, changes in climate - specifically increasing surface temperature and reducing rainfall - can trigger a transition of

the forest to a qualitatively different state. The risk of climate-driven loss of Amazon forest has been known for many years (Cox et al., 2000; Salazar et al., 2007; Lapola et al., 2009; Malhi et al., 2009). Large scale climate changes, leading to substantial warming and drying of the region, may exacerbate regional drying due to reduced water-recycling (Betts et al., 2004). Changes in the forest itself also affect the local climate, as discussed in Section 3.

Studies investigating the potential dieback of the Amazon forest have examined both changes in temperature and rainfall as drivers. Good et al. (2011) define a threshold in climate space in terms of temperature and dry-season length. If a region crosses this threshold, the risk of forest loss increases significantly. The Amazon forest is closer to this threshold than other tropical forests (Good et al., 2011) (Figure 2). This figure from Good et al. (2011) illustrates the relationship between dry season length, temperature, and broadleaf forest fraction in tropical regions. The clear separation of high and low forest cover into distinct bioclimatic zones, based on dry season length and temperature, demonstrates the critical role these factors play in determining forest resilience. The degree of potential dieback depends on both how each location moves through the phase space (i.e., changes to a warmer and drier climate move the points towards the right and upwards respectively), but also how the direct effect of elevated CO₂ on water-use efficiency and forest resilience may move the threshold upwards and towards the right.

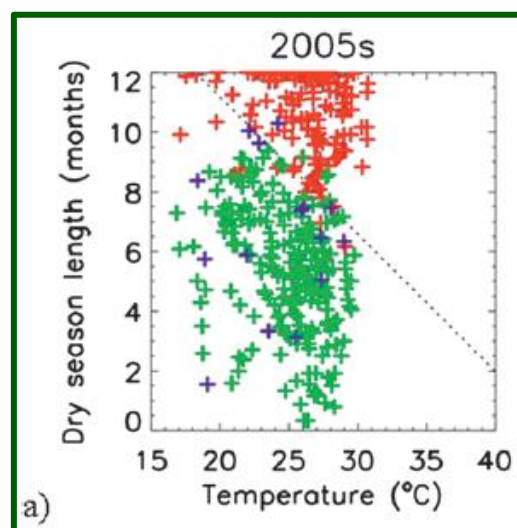


Figure 2. Simulated bioclimatic zones of the tropical broadleaf forest fraction. Data points represent grid cells of tropical land, with color indicating the fraction of broadleaf forest. The dotted line indicates the threshold of the dry season resilience (DSR) function, which predicts the sustainability of broadleaf forests under variable climatic conditions. Source: Good et al. (2011).

Malhi et al. (2009) show how reductions in precipitation would lead to the Amazon forest transitioning to seasonal and then savanna-type ecosystems (Figure 3). The Figure 3 from Malhi et al. (2009) plots the distribution of vegetation types against the rainfall regime, defined by annual precipitation (AP) and **maximum climatological water deficit** (MCWD). The shaded area indicates the suggested savanna zone (MCWD $\leq$ -300 mm, AP $\leq$ 1500 mm). The figure illustrates how vegetation types transition across different rainfall regimes. Evergreen forests predominate in areas with higher AP and higher MCWD (more negative means higher deficit), while savannas are more common in regions with lower AP and higher MCWD. This suggests that as climate conditions shift, areas currently supporting rainforests could transition to an open-canopy state (either savannas or degraded ecosystems) if they move into the shaded savanna zone.

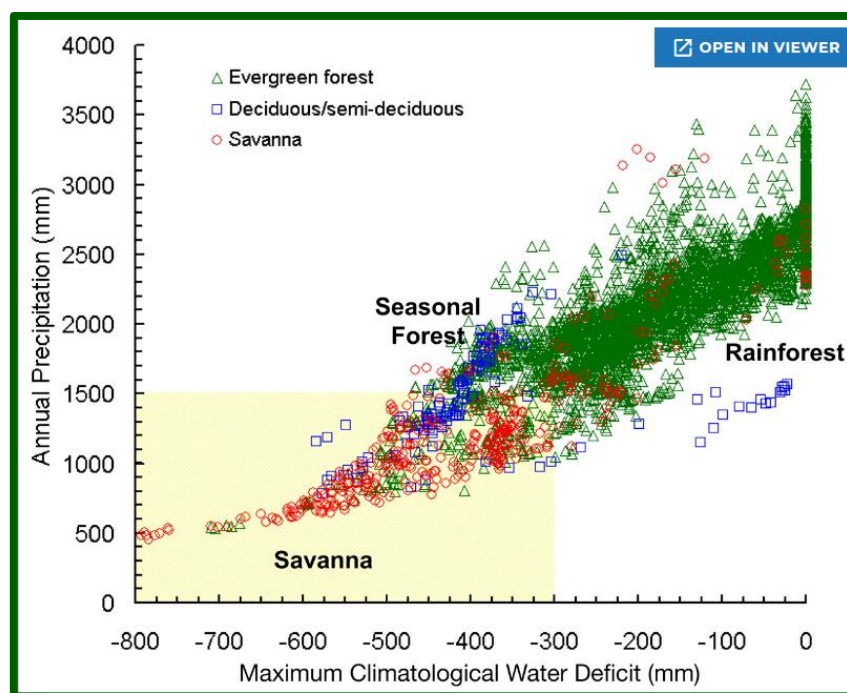


Figure 3. The relationship between vegetation type and rainfall regime. Rainfall regime is derived from TRMM for the period 1998–2006. Our suggested savanna zone is shaded (MCWD $<$ -300 mm, AP $<$ 1500 mm). Source: Malhi et al. (2009).

The IPCC's Sixth Assessment Report (AR6) assessed the loss of tropical forest as a potential abrupt change that could be irreversible for multi-decades (Canadell et al., 2021; Lee et al., 2021). The report states, with high confidence, that the Amazon forest – one of the world's largest biodiversity and carbon repositories – is highly vulnerable to drought (Castellanos et al., 2023).



Changes in precipitation and temperature create feedback loops that can accelerate forest loss. For instance, deforestation reduces evapotranspiration, which in turn decreases regional precipitation, creating a drying loop that further threatens forest stability (Shukla et al., 1990; Nobre et al., 1991; Nobre et al., 2016). The lengthening of the dry season is particularly critical. Studies indicate that the Amazon's rainfall patterns are becoming increasingly seasonal, with longer dry periods that stress the forest ecosystem and increase vulnerability to fire and other disturbances (Fu et al., 2013; Costa et al., 2022). Rising temperatures not only directly stress plant physiology but also exacerbate drought conditions by increasing evaporation rates and reducing soil moisture. These combined stresses can push the forest beyond critical thresholds more quickly than either factor alone (Cox et al., 2004; Duffy et al., 2015).

Harper et al. (2010) show how access to deep soil moisture buffers trees from seasonal dry spells, but longer-term droughts cause substantial mortality. This mortality is primarily due to hydraulic failure rather than reduced carbon uptake or productivity (Rowland et al., 2015; da Costa et al., 2018).

Several studies based on satellite observations in tropical South America identify a critical rainfall threshold between 1,000 and 1,250 mm annually for tree cover distribution (Staver et al., 2011; Staal et al., 2020; Flores et al., 2024). Below 1,000 mm of annual rainfall, forests become rare and unstable, whereas between 1,000 and 1,800 mm, the Amazon exhibits two stable states of high and low tree-cover ecosystems. Forests in this range are more vulnerable to collapse under severe disturbances compared to regions with over 1,800 mm of annual rainfall (Flores et al., 2024). Floodplain ecosystems, covering 14% of the forest biome, face a critical threshold at 1,500 mm of annual rainfall, suggesting they may be the first to collapse in a drier future.

However, other factors can cause disturbances and anticipate a possible tipping point for the Amazon. For instance, if the length of the dry season surpasses 8 months, the forest can collapse with a bistability range between 5 and 8 months. Nobre et al. (1991) have also shown in a modelling exercise that the savannization would be reached when the dry season reaches 6 months due to high deforestation all over the southern Amazon. In addition, if the maximum cumulative water deficit is below -350 mm, the forest can collapse, and it can be bistable between -350 and -450 mm. To prevent local-scale



ecosystem transitions from compounded disturbances, Flores et al. (2024) proposed safe boundaries in annual rainfall conditions of 1,800 mm, in the length of the dry season of 5 months and in the maximum cumulative water deficit of -350 mm.

Understanding the interplay between precipitation and temperature changes and their impact on the Amazon rainforest is critical for predicting future scenarios and developing strategies to mitigate these impacts. The complex feedback mechanisms, the critical role of dry season length, and the severe consequences of prolonged drought underscore the urgent need for comprehensive climate action.

i. Fire

Fire is a major disturbance in forest ecosystems which may contribute to the establishment and maintenance of seasonal, drier and lower-carbon density biomes (Hirota et al., 2011; Staver et al., 2011). Fire may therefore be a mechanism which triggers abrupt forest loss when a climate threshold is reached, for instance, in parts of the Amazon where the amount of annual rainfall is under 1,800 mm (Flores et al., 2024). Closed canopy forests in wet climatic zones reduce fire occurrence, but if the climate dries or direct human interference fragments or opens the canopy this can lead to drying and increased vulnerability to fires and transition to low biomass forests (Malhi et al., 2009). Increased fire activity prevents re-establishment of trees thus maintaining the more open canopy state (Druke et al., 2023).

Dutra et al. (2022) quantify how current climate change trends (including lengthening dry season) and human deforestation have led to increased fire occurrence on a forest/deforestation boundary in the Amazon. Burton et al. (2021) showed how the future changes in fire risk across South America increased markedly for higher levels of climate change.

Burnt area (Lizundia-Loiola et al., 2020) and the fire season length have increased strongly across South America (Jolly et al., 2015), although this has also been linked to ongoing land-use change and not just climate change (Kelley et al., 2021).

There remains substantial uncertainty regarding the processes determining the reversibility of forest cover loss. However, emerging evidence indicates that as more climate models incorporate fire activity into their simulations, the risks of Amazon forest dieback

increase (Parry et al., 2022). That is a difficult modelling task, once in severe drought years, there are less lightning strikes ignites fires, but most are human-made and criminal. For example, more than 95% of fires were man-made in 2023 and 2024.

ii. Ocean variability

The Amazon forest gets moisture from the tropical Atlantic Ocean. The Intertropical Convergence Zone (ITCZ) brings rain, particularly over the northern Amazon basin, mainly during austral summer when the ITCZ moves southward. This seasonal shift of the ITCZ is strongly controlled by the surface temperatures of the tropical Atlantic. Hence, interannual variability in sea surface temperatures of the Atlantic can have strong effects on the annual rainfall across the Amazon basin. In parallel, another crucial element of the Earth System, the Atlantic Meridional Overturning Circulation (AMOC), is another bistable system that can affect the stability of the Amazon. Evidence from paleoclimate proxies and from models suggests that there is likely a second, substantially weaker circulation mode in addition to the present strong mode. Shifts between these alternative modes could occur relatively abruptly (within decades) and affect the global climate, with potential impacts on the stability of the Amazon forest. The reduction of AMOC goes through a stage in which the temperature over the Tropical North Atlantic Ocean increases. That leads to droughts in the Amazon, as it is more and more happening (e.g., 2005, 2010, 2024).





Modelling analysis by Nian et al. (2023) also shows that a collapse of the AMOC could stabilize the Amazon forest by increasing rainfall and decreasing temperature in most parts. However, empirical paleoecological evidence from past events of slowdown and shutdown of the AMOC (Akabane et al., 2024) suggest that increased stability of the southern Amazon would likely have little effect in the 'Arc of deforestation' region, whereas the more preserved forests of the northern Amazon could destabilize due to reduced rainfall, thus increasing the risk of a biome-wide collapse. This is because a collapse of the AMOC would make the tropical South Atlantic warmer and shift the ITCZ southward. Thus, the collapse of the AMOC, coupled with deforestation in the southern Amazon, could in principle anticipate a dieback of the Amazon.

1.3. Potential Scenarios of Change

i) IPCC scenarios: Climate projections

At global scale, the climate is projected to continue to warm as the world continues to emit CO₂ and other greenhouse gases. Almost all scenarios project that warming will reach 1.5 degrees Celsius above pre-industrial levels within the next decade (IPCC/AR6 SYR). However, the extent to which warming will exceed 1.5 degrees and whether it can be brought back to 1.5 degrees will depend on human activity and societal choices.

The IPCC's Sixth Assessment Report AR6 (Lee et al., 2021) concludes that global warming will likely reach between 1.6 and 2.4 degrees Celsius by mid-century, depending on emissions scenario. Under very low emissions (SSP1-1.9) warming could be limited to 1.4°C (with a range of 1.0 - 1.8°C) by the end of century, whereas very high emissions (SSP5-8.5) could result in warming of 4.4°C (with a range of 3.3 - 5.7°C). It is important to stress that we have already reached 1.55°C in 2024, and that January 2025 reached 1.75°C.

Almost all land areas will continue to warm faster than the global average, although tropical regions may warm less quickly than mid- and high-latitude land areas. Rainfall patterns will vary regionally and seasonally, with some areas becoming wetter and others drier. Climate model projections show significant uncertainty in rainfall changes globally, but they continue to suggest reduced precipitation over large parts of Brazil during June-July-August under both low and high emissions scenarios (Lee et al., 2021 - Figure 4.13). Consequently,



climate-driven dieback of the Amazon forest remains therefore a plausible low-likelihood but high impact outcome, when considering only climate change as a result of global warming.

The IPCC AR6 Atlas (Gutiérrez et al. 2021) provides detailed regional climate projections, including a range of potential outcomes for the Amazon region. Specifically, the IPCC states that "It is very likely that annual mean temperature will increase over South America, with projected changes ranging from 1.0°C to 6.0°C by the end of the 21st century. The largest warming is expected in the Amazon basin and the central Andes, especially during the dry and dry-to-wet transition seasons (austral winter and spring) (high confidence)." (Blázquez and Nuñez, 2013a; Coppola et al., 2014; Pabón-Caicedo et al., 2020; Teichmann et al., 2021). These projections are being confirmed by observations from across the Amazon since 1980, showing that central and south-eastern parts of the biome have already warmed up by up to 2°C (Flores et al., 2024).

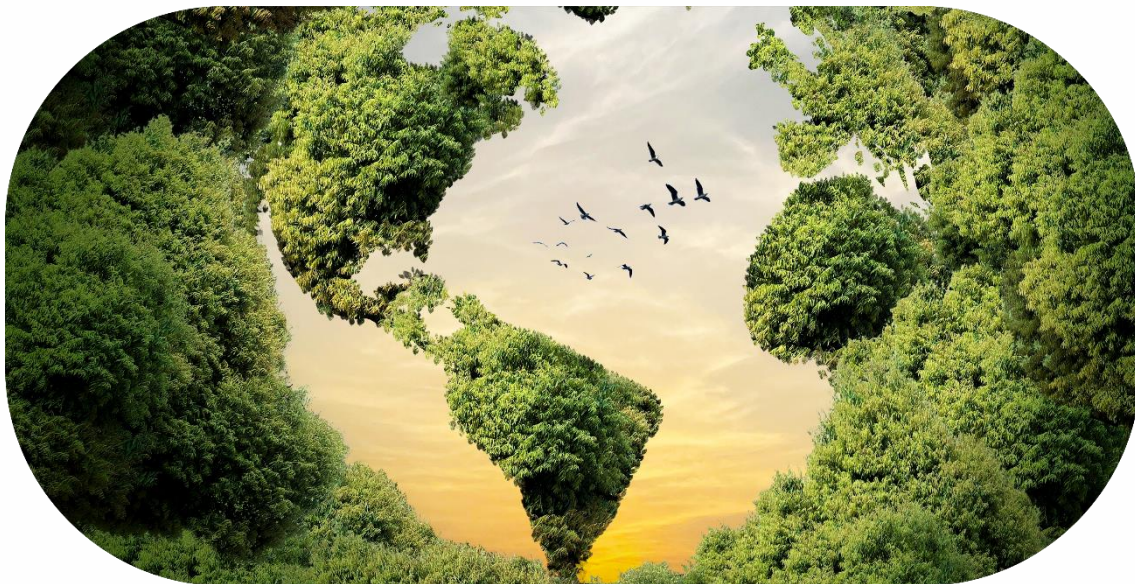
The CMIP6 multi-model ensemble projects that under a high-emissions scenario, precipitation may increase by more than 10% in parts of south-eastern South America and north-western South America, and a decrease by the same amount in northern South America across seasons (high confidence, robust evidence). Under high emissions scenario, all Brazilian regions will likely experience more rainfall variability in the future, with extreme dry and wet periods occurring more frequently from daily through seasonal time scales (medium confidence) (Alves et al., 2021).

Jones et al. (2009) analyzed Amazon forest changes in a single model and found that substantial loss of forest might be committed decades before it becomes observable, especially with global warming above 2°C. Pugh et al. (2018) found that many, but not all, models found a long-term committed loss of tree cover in the tropics for warming levels above 2°C, while Munday et al (in press) found a risk of long-term unavoidable Amazon dieback, beginning as early as 1.4°C global warming. This emphasizes the need for using analytical tools known as early warning signals to detect loss of rainforest resilience (Boulton et al., 2022). Moreover, Burton et al. (2021) show large increases in fire risk and burned area under all scenarios, with greater increases for higher levels of warming. Cano et al. (2022) found similar magnitudes of biomass losses under high emissions due to increased fires, projecting a 40% decline in biomass by 2100. Their model showed that grass

regrowth in burned areas facilitated repeat burning and hindered forest recovery.

ii) Paris Agreement overshoot

Given that most regional climatic changes are a result of global warming (e.g., Lee et al., 2021; Mathison et al., 2024), the best way to reduce the climate-induced threat to the Amazon Forest is undoubtedly to limit the magnitude of global warming. The Paris Agreement aims to limit warming to well below 2°C or even pursue efforts towards 1.5°C, in part due to the risk of so-called “dangerous climate change” if the world exceeds these levels. COP26 also indicated the need not to exceed 1.5°C associated with the Special Report of IPCC 2018, showing the risks of reaching 2°C.



IPCC AR6 (SYR) assessed that the world will reach 1.5°C warming above pre-industrial levels in the coming decade but also show that it is possible to halt global warming to, or below, this level if CO₂ can be removed from the atmosphere. The near-linear relationship between global warming and cumulative emissions of CO₂ means that the more CO₂ we emit, the warmer the planet gets. When net-zero emissions are reached, global temperature approximately stabilizes (MacDougall et al., 2020). We can go beyond this target, however, and there are numerous techniques which could be scaled up to allow large-scale removal of CO₂ from the atmosphere. Under scenarios of globally net-negative emissions, the world would eventually cool back again below the target levels of the Paris Agreement. IPCC assesses 220 GtCO₂ for every 0.1°C increment in temperature. This means that for every removal of 220 GtCO₂, the global temperature will be reduced by 0.1°C.



This “overshoot” scenario may provide a feasible way to maintain global warming around 1.5°C by 2100, but this strategy could expose the world to elevated risks and impacts during the period of overshoot (Reisinger et al., in press). The risk and magnitude of impacts due to temperature overshoot on key forest ecosystems, such as the Amazon forest, are not well quantified and were identified as a knowledge gap by the IPCC special report on 1.5 degrees (Hoegh-Guldberg et al., 2018). Munday et al (in press) found that risk of Amazon forest loss is greater at higher levels of global warming but can be mitigated in overshoot scenarios which lead to reducing global temperatures back below 1.5°C. Nonetheless, it is well accepted that both the magnitude of exceedance and the duration of overshoot contribute to elevated risks to key vulnerable ecosystems.

For instance, the impacts experienced during the overshoot may not be reversible. If we already reached 1.5°C, we may reach 2.5°C by 2050, potentially triggering many tipping points beyond the Amazon tipping point and release a gargantuan amount of CO₂ and making the temperature reach more than 3°C by 2100. Components of the Earth System which exhibit significant inertia – such as ocean heat uptake, ice sheets or forest ecosystems – may be committed to changes for many decades or centuries. If feedbacks with the local climate are strong enough, such changes may have tipped into alternative stable states and be truly irreversible. For components with longer timescale dynamics than the duration of the overshoot, a climate threshold may be temporarily exceeded without necessarily triggering the tipping point (Ritchie et al., 2021), although this also involves many uncertainties.

What is clear is that rapid reduction in emissions and subsequent focus on limiting warming levels as low as possible is the first key strategy to reduce the risk of irreversible loss of the Amazon forest.

1.4. Observations: Amazonia is already experiencing change

- i) Long-term changes in forest dynamics (productivity, mortality, general demography, changes in species composition)**

Since the end of the last century, Amazonia has been experiencing a process of intensification of its hydrological cycle. From 1990 to the present, a significant increase in the region's annual rainfall has been



observed in the region, along with a corresponding rise in the discharge of water from the Amazon River in Óbidos, a city in the state of Pará, Brazil, where the confluence of the basin's largest rivers is located (Gloor et al., 2013). Amazon Precipitation has increased in the western part of the Basin and decreased in its southern and northern parts (Marengo et al., 2022; Flores et al., 2024). Furthermore, the region has become warmer with longer dry seasons (Marengo et al., 2022; Flores et al., 2024) and has experienced frequent hydrological and climatic extremes. Severe floods and droughts, which previously occurred rarely, are now common and frequent (Costa et al., 2021). The Amazon suffered major floods in 2009, 2013, 2014, 2017 and 2021. These events were alternated by extreme drought events in 2005, 2010, 2015–16 and 2023. This intensification of the hydrological cycle also increased the amplitude between such extremes (Gloor et al., 2015).

Also, relatively more remote forest areas, far from deforestation frontiers are enduring change. Observations from forest inventory plots across the basin show that since the 1970's, tree turnover rates and forest productivity have been increasing (Baker et al., 2004; Phillips et al., 2004). While the Amazon was a significant global carbon sink of ca. 0.42 to 0.65 Pg C yr⁻¹ during the 1990–2007 period (Pan et al., 2011), recently, carbon sequestration is losing strength. In the last 30 years, the carbon balance of the Amazon has shown a long-term decreasing trend of biomass accumulation, in which rates of net increase in biomass accumulation decreased by 30%, therefore losing their ability to remove carbon from the atmosphere (Brienen et al., 2015). This results from a levelling-off of forest productivity in the last decades and a consistent trend of increasing tree mortality. This is at odds with modelling projections that predict that the Amazon would be a carbon sink in the 21st century due to the CO₂ fertilization effect (Huntingford et al., 2013). Tree species composition is also changing, with a slow trend towards more dry-affiliated tree species and increased mortality in wet-affiliated trees (Esquivel-Muelbert et al., 2019). The most probable reasons for this mismatch between models and observations are: (1) CO₂-fertilization is driving a shift in tree composition to fast-growing species with short life spans, (2) climate-related disturbances, such as windthrows and extreme droughts, or (3) human-driven forest degradation by activities, such as logging and fires (Flores et al., 2024).



Some regions, such as the southern and southeastern Amazon, in the deforestation arc region, may already be undergoing climate-induced degradation. Gatti et al. (2021; 2023) report that forests in this region are already acting as a source of carbon for the atmosphere and are already suffering from significant temperature increases and reduced rainfall. In addition to climate forces, the Amazon is undergoing strong human pressure, whether through deforestation or degradation processes of the remaining forests. Lapola et al. (2023) estimate that 38% of the remaining forest area in Amazonia is already degraded by processes such as logging, exposure to extreme drought, fire, and edge effect. The compound effects of degradation, deforestation, and land-use change, combined with changes in the hydrological cycle and rising temperatures associated with ongoing climate change, could lead to unprecedented degradation of the region's forests, increasing the risk of a large-scale tipping point (Flores et al., 2024).

ii) Carbon balance

Rising atmospheric CO₂ can enhance forest productivity and carbon sequestration, and Earth System Models (ESMs) project the highest CO₂-driven carbon sinks in tropical forests (Canadell et al., 2021; Friedlingstein et al., 2023). Observational evidence supports a large tropical forest carbon sink, although sink strength can be confounded by prior forest disturbance history (Chambers et al., 2013) and elevated forest mortality rates over the past two decades have driven declining Amazon forest carbon sinks (Brienen et al., 2015; Hubau et al., 2020). Hotter and more intense droughts can lead to elevated stress and higher tree mortality rates, and greater total ecosystem-scale carbon emissions, and these so-called carbon-climate feedbacks are

expected to strengthen as Earth's climate continues to warm. An increase in the total deforested area of the Amazon can also drive a reduction in precipitation recycling, and lower overall basin-scale rainfall, and this land-use driven shift in climate can also cause vegetation stress and higher mortality rates as regional climate become drier (Shukla et al., 1990; Nobre et al., 1991; Nobre et al., 2016; Marengo et al., 2018). Airborne and satellite-based measurements of atmospheric CO₂ find strengthened carbon-climate feedbacks in anomalously dry years, leading to large reductions in Amazon forest carbon sinks (Gatti et al., 2014; Liu et al., 2017). Crossing tipping point thresholds of drought intensity and total deforested area can push the balance of CO₂ fertilization sinks and carbon-climate feedback sources, with potential shifts of Amazon forests under extreme scenarios from global carbon sinks to carbon sources.

iii) River dynamics, droughts and floods

The Amazon basin, which hosts the largest river system in the world, is experiencing significant changes in river dynamics, droughts, and floods due to climate change and anthropogenic activities. These changes are having profound impacts on the region's hydrology, ecosystems, and human populations.

The Amazon River's flow regime is highly sensitive to variations in precipitation patterns and temperature. Studies have shown that the Amazon's discharge has been increasing over the past few decades, likely due to rising temperatures and changes in rainfall distribution (Gloor et al., 2013). This increased discharge can enhance sediment transport and alter river morphology, affecting the habitats of aquatic and riparian species (Dunne et al., 1998).





Changes in land use, particularly deforestation, have also influenced river dynamics. Deforestation reduces evapotranspiration, leading to higher runoff and increased river flows during the wet season (Coe et al., 2009). Conversely, the dry season may see reduced flows due to diminished groundwater recharge, potentially altering the timing and magnitude of river discharge.

Drought frequency and intensity in the Amazon have been increasing, with severe droughts recorded in 2005, 2010, and 2015–2016 (Marengo et al., 2018), as well as the most powerful one in 2023–2024. These droughts have been linked to anomalous sea surface temperatures in the Atlantic and Pacific Oceans, which disrupt normal weather patterns and reduce rainfall over the basin (Espinoza et al., 2011). However, the recent drought of 2023/2024 was mostly linked to climate change and not El Niño (Clarke et al., 2024). El Niño reduced precipitation by about the same amount as climate change. But the strong drying trend was almost entirely due to increased global temperatures, so the severity of the 2023–2024 drought being experienced is largely driven by climate change. Due to climate change, the likelihood of the meteorological drought occurring has increased by a factor of 10 and the agricultural drought by 30.

Droughts have significant ecological and socio-economic impacts. They can lead to reduced water levels in rivers and lakes, affecting water supply for local communities and industries. The lowered water levels also impact fish populations and other aquatic life, leading to decreased biodiversity (Castello et al., 2013). Furthermore, droughts increase the vulnerability of forests to fires as well, which can cause extensive damage to vegetation and release large amounts of carbon dioxide into the atmosphere (Aragão et al., 2018).

While droughts pose one set of challenges, the Amazon is also experiencing more frequent and severe flooding events. These floods are often driven by extreme rainfall events, which are becoming more common due to climate change (Gloor et al., 2015). Major floods were recorded in 2009, 2012, and 2014, causing widespread disruption to communities and ecosystems. In fact, the record floods were at 2021 due to the record-breaking and long La Niña during the years 2020, 2021 and 2022.

Floods in the Amazon can have both beneficial and detrimental effects. On the positive side, seasonal flooding is essential for nutrient



deposition and maintaining the productivity of floodplain forests and wetlands (Junk et al., 2011). However, extreme floods can destroy infrastructure, displace communities, and lead to loss of life. They can also disrupt agricultural activities, leading to food insecurity and economic losses (Marengo & Espinoza, 2016).

The interplay between droughts and floods creates a complex dynamic in the Amazon basin and contributes to shape ecosystem resilience (Mattos et al., 2023). For example, prolonged droughts can be followed by intense rainy seasons, leading to extreme flooding events. This variability poses significant challenges for water resource management and requires adaptive strategies to mitigate the impacts on human and ecological systems (Siqueira Júnior et al., 2015).

The observed changes in river dynamics, droughts, and floods in the Amazon basin highlight the region's vulnerability to climate change and anthropogenic pressures. Addressing these challenges requires integrated approaches that consider the interconnectedness of hydrological, ecological, and human systems. Continued research and monitoring are essential to improve our understanding of these processes and to develop effective adaptation and mitigation strategies.

iv) Temperature and precipitation

The Amazon basin has seen a noticeable increase in average temperatures over the past few decades. Studies indicate that the region has warmed up by approximately 0.6°C to 0.7°C since the mid-20th century (Marengo et al., 2011). This warming trend is expected to continue, with projections suggesting a rise of 1.5°C to 3.5°C by 2050 under moderate to high emission scenarios (IPCC, 2021).

Higher temperatures have several impacts on the Amazonian ecosystem. Increased heat can stress plant physiology, reduce photosynthesis rates, and alter species distributions. Warmer temperatures also enhance evaporation rates, leading to lower soil moisture and increased water stress for vegetation (Malhi et al., 2008). Additionally, higher temperatures contribute to the frequency and intensity of heatwaves, which can further stress both plant and animal species.

Precipitation in the Amazon basin is characterized by high variability, both spatially and temporally. The region receives an average of 2,300



mm of rainfall annually, but this can range from 1,500 mm in the east to over 3,000 mm in the west (Espinoza et al., 2009). However, recent observations and climate models indicate significant changes in these patterns.

Several studies have documented a decline in wet season rainfall and an increase in the length and intensity of dry seasons (Gloor et al., 2013; Marengo et al., 2018). The severe droughts of 2005, 2010, 2015–2016, and 2023–2024 are indicative of these shifts, with some regions experiencing up to a 30% reduction in rainfall during drought years (Aragão et al., 2018). These changes are linked to anomalous sea surface temperatures in the Atlantic and Pacific oceans, which disrupt the normal weather patterns that bring moisture to the Amazon (Marengo et al., 2018).

Changes in temperature and precipitation are profoundly affecting the Amazon's hydrological cycle. Reduced rainfall during the dry season leads to lower river levels and diminished groundwater recharge. This can impact water availability for both ecosystems and human populations, affecting agriculture, hydroelectric power generation, and drinking water supplies (Coe et al., 2009).

Conversely, increased intensity of wet season rainfall can lead to more frequent and severe flooding, which can disrupt ecosystems, damage infrastructure, and displace communities. Flooding can also cause soil erosion and nutrient leaching, impacting agricultural productivity and forest health (Junk et al., 2011; Flores et al. 2020).

The shifts in temperature and precipitation have cascading effects on the Amazon's biodiversity. Extended dry seasons and higher temperatures increase the risk of forest fires, which can cause large-scale deforestation and carbon emissions. These fires can also destroy habitats, leading to loss of biodiversity (Aragão et al., 2018). Moreover, changes in precipitation patterns can alter the distribution of plant and animal species, as some may not be able to adapt to the new conditions.

The Amazon rainforest plays a critical role in regulating the global climate through carbon sequestration and the water cycle. Changes in temperature and precipitation can reduce the forest's ability to sequester carbon, turning it from a carbon sink to a carbon source (Gatti et al., 2021; 2023). This has significant implications for global

climate change, as the release of stored carbon into the atmosphere can accelerate warming.

Additionally, the alteration of the water cycle can affect atmospheric circulation patterns, potentially impacting weather systems far beyond the Amazon basin (Marengo et al., 2011). The reduced moisture recycling due to deforestation and climate change can lead to further drying, creating a feedback loop that exacerbates the impacts of climate change.



2

WHY IS IT IMPORTANT?

WHY IS IT
IMPORTANT?

2. WHY IS IT IMPORTANT?

2.1. Amazon Feedback to Global Climate Change: Local, Regional and Global Perspectives

The Amazon can feed back onto climate change through local, regional and global-scale processes including CO₂, heat balance, moisture supply and aerosols.

Exchanges of carbon dioxide with the atmosphere can affect the forest and are affected by the forest. The Amazon forest is a large store of terrestrial carbon in both living biomass and soil organic matter (approximately 120 PgC and 160 PgC, respectively, Gloor et al., 2012). Any reduction in the forest carbon sink, therefore, feeds back onto amplifying global climate change (e.g. Cox et al., 2000). Similarly, stomatal closure due to elevated CO₂ reduces evaporation and, therefore, moisture is available for rainfall. This regional climate drying response to elevated CO₂ via stomatal closure is different from other tropical forests and leads to greater vulnerability of the Amazon forest (Skinner et al., 2017; Sampaio et al., 2020). This physiological effect also drives changes in soil moisture, river flow (Gedney et al., 2006; Betts et al., 2007) and surface temperature (Kimm et al., 2024).

At regional scales, the forest-rainfall feedback provides a strong stabilizing process by helping maintain annual rainfall levels and reducing its seasonal and interannual variability (Stall et al., 2020). This feedback also means, though, that reductions in forest can amplify forest loss through positive feedbacks – i.e. loss of tree cover due to deforestation can cause reduced rainfall (Costa & Pires, 2009). Shukla et al. (1990) and Nobre et al. (1991) first demonstrated the risk of deforestation induced reductions in Amazon basin scale precipitation through transpiration-precipitation feedback and the recycling of precipitation. Land surface changes from land clearing and logging impact moisture cycling and shifts from small-scale to large-scale deforestation can also modify the mechanisms and patterns of regional precipitation (Khanna et al., 2017). Vegetation can affect rainfall amounts through changes to moisture and energy exchange at the surface (Spracklen et al. 2012). Reduced forest cover can lead to diminished evapotranspiration and hence reduced atmospheric humidity and precipitation (Aragão, 2012). Large-scale deforestation can, therefore, cause reduced regional rainfall.

Forests can affect local atmospheric composition in numerous ways. Direct emissions of aerosols and trace gases, such as methane, result from burning. Biomass burning emissions are a large source of aerosols over the Amazon and can impact regional precipitation when they act as cloud condensation nuclei. Forests also produce aerosol precursors such as isoprene and other BVOCs, which affect local air quality and lead to secondary organic aerosol formation, which, in turn, can affect rainfall and surface energy balance (Figure 4).

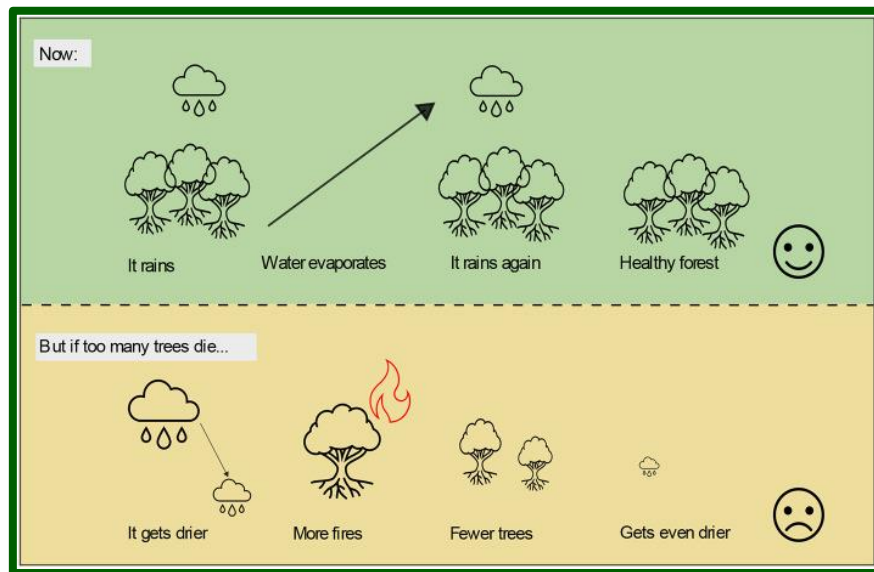


Figure 4. Positive (self-reinforced) feedbacks with the forest are key for maintaining Amazonian resilience. Now, through evapotranspiration, healthy forests pump moisture and aerosols into the atmosphere, contributing to form clouds that are transported downwind (westward from the Atlantic Ocean to the Andes). As these clouds precipitate, increasing rainfall amount and stability in central and western parts of the Amazon biome, the system remains resilient to climate change. But if too many trees die, for instance because of extreme drought events or deforestation, less moisture is transported across the Amazon, causing more tree mortality and increasing ecosystem flammability. This positive feedback of forest degradation can accelerate a large-scale tipping point of the Amazonian system. Figure reproduced from Palazzo Corner & Jones (2021).

2.2. Ecosystem Functioning and Biodiversity

Primary productivity in the Amazon basin is high, with small seasonal variations (Aragão et al., 2009). This constitutes a striking difference from all other biome-types, that show a strong decline in productivity during either winter or dry seasons. In the tropics, warm and wet climate favors the back-and-forth exchange of large quantities of



water and carbon between the biosphere and the atmosphere. Still, the magnitude of these fluxes is sensitive to interannual variations in climate and, more importantly, to extreme events. This variability means that environmental conditions have a strong influence on the biogeochemical processes involved. As global warming gradually takes place, and associated with increasing atmospheric CO₂ concentrations, the Amazon rainforest is being pushed out of its previous state of dynamic equilibrium (Malhi et al., 2014; Lapola et al., 2023). While higher atmospheric CO₂ concentrations facilitate carbon uptake by plants, linked to a lower water cost in terms of transpiration, higher ambient temperatures translate into stronger demand for water vapor by the atmosphere. The resulting balance between these two contrasting drivers of primary productivity and its consequences to Amazon is still under investigation.

Furthermore, the high rates of primary productivity observed in rainforests around the tropics is, in part, responsible for maintaining the high species diversity in those regions. In a positive feedback loop, higher availability of resources favors the accumulation of species through evolutionary timescales, which are able to more fully explore the resources due to their greater diversity of ecological strategies. Such diversity of strategies developed by plants to compete for resources (light, carbon, nutrients and water) enables the coexistence of species in these hyperdiverse communities.

Currently, habitat loss via land-use changes, mainly in the form of deforestation, is the greatest threat to Amazonian biodiversity (Vieira et al., 2008). Nonetheless, increasing ambient temperature, more frequent heat waves, decreasing precipitation, increasing dry season length and increased frequency of extreme droughts are becoming more threatening to biodiversity than habitat loss. The thermotolerance of species (not just plants) determines their performance (Cheng et al., 2013) in a warmer environment. Beyond the optimum temperature, any given process (e.g., photosynthesis) will show a decline in rates. Considering the plant component of the Amazon, this scales up to the ecosystem level as reduced primary productivity. In the other hand, changes in water availability also led to declining primary productivity, but also important, causes increased mortality rates of trees. Considering that trees have a long lifespan and may take decades to reach reproductive stages, increased mortality can cause fast changes in the composition of species in forest communities. The accelerated turnover of trees often favor fast-



growing species such as pioneers and lianas, which are less effective as carbon stocks.

Therefore, the interplay between biodiversity and primary productivity in the Amazon is subjected to climatic changes, with loss of species and reduced primary productivity in scenarios of warmer and dryer environment.

1.3. Ecosystem Impacts and Transition Trajectories (from Local to Global)

i) Water and food security and energy production

The Amazon rainforest is crucial for sustaining ecological balance, providing a wide range of ecosystem services that can be categorized into four main types: provisioning, regulating, cultural, and supporting services (TEEB, 2010). Provisioning services include the diverse array of resources the rainforest supplies, such as timber, food, and medicinal plants. Regulating services refer to the rainforest's ability to stabilize the climate by storing carbon, thus contributing to mitigating the effects of climate change.

The Amazon forest plays a critical role in water regulation, influencing the local and regional rainfall pattern, which is essential for both terrestrial and aquatic ecosystems. Moreover, the agricultural production in Brazil and South America is highly dependent on the rainfall derived from the dynamic and ecological functioning of the Amazon. Considering the current trend of direct anthropogenic impacts (fire, deforestation, selective logging) and climate change (extreme droughts), leading to the degradation of important patches of forest, the Amazon's hydrological services tend to degrade, risking the local communities, the biodiversity and ecosystem services, but also the agriculture production (Leite-Filho et al., 2021). Reduced rainfall in critical agricultural production areas in Brazil, could lead to significant yield losses driving up global food prices, impacting the food security (Brando et al., 2020).



In recent work, Mattos et al. (2024) have argued that the economic income of the agricultural sector in the states that benefit most from this rainfall totaled R\$ 338 billion in 2021 – around 57% of the national agricultural income. Authors stressed that the Amazon Indigenous Lands influence the rainfall that supplies 80% of the area of agricultural activities in the country.

Deforestation and degradation of forests in Indigenous Lands cause a reduction in this rainfall and, therefore, pose serious risks to the country's water, food, energy and economic security. Furthermore, smallholder farmers, who in general, lack access to advanced technology (water resistant plants varieties, irrigation systems, etc.) are particularly vulnerable to changes in rainfall patterns, leading to decreased agricultural output threatening both their food supply and income (Assad et al., 2013; Lapola et al., 2018).

Thus, the conservation of these forests is crucial not only to guarantee the country's water and food security, but also to the agribusiness production chain and, therefore, the economic production of a significant portion of the national economy (Mattos et al., 2024). Changes in the rainfall, influenced by the Amazon degradation, may lead to impacts beyond Brazil boundaries, affecting neighboring countries such as Bolivia, Paraguay, and Argentina.

The hydroelectric power generation relies heavily on stable precipitation patterns and river water flows. According to a recently published study by the Climate Policy Initiative/PUC-RIO and Amazon 2030 (<https://www.climatepolicyinitiative.org/publication/cutting-down-the-hydropower-plants-how-the-amazon-deforestation-is-jeopardizing-electricity-generation-in-brazil/>), “Deforestation in the Amazon rainforest could reduce Brazil’s power generation capacity and the profitability of the electricity sector by up to 10%, affecting even hydroelectric power plants (HPPs) located thousands of kilometers away from the Amazon biome.” The study highlights that



85% of the biggest hydropower plants in Brazil are under the influence of the water vapors coming from the Amazon basin.

ii) Health impacts

Environmental changes due to deforestation, such as increased wildfire frequency and heat waves, pose significant health risks to people and communities living in the region, but also remotely due to the transport of particles and aerosols to the southern region of Brazil and other countries in South America. These risks include respiratory issues from air pollution and higher vulnerability to vector-borne diseases, e.g, malaria (www.adaptabrasil.mcti.gov.br). The temperature increase resulting from forest loss also elevates heat-related illness risks, particularly for vulnerable populations.

The severe drought and flood events experienced in recent decades, disproportionately affect Indigenous, riverine communities and urban population (Hacon et al., 2024). These events increase the risk of water, food, and vector-borne diseases, malnutrition, traumatic injuries, chemical exposures, cardiovascular and respiratory illnesses, mental health disorders, and the increment of mortality (Papastefanou et al., 2022; Salvador et al., 2023). Floods lead to dermatological illnesses due to physical trauma, stagnant water, exposure to pollutants, wastewater toxins, infection diseases and inadequate sanitation. The highest risk of wound infection and disease transmission occurs during the post-impact phase (Parker & Goodman, 2022). Children, pregnant women and the elderly are the most vulnerable groups impacted by floods and droughts (Langil & Abizaid, 2020).

The climate crisis threatens human health not only in the Brazilian territory, but also in the Pan Amazon, affecting all countries and their borders. Health impacts vary due to population size, density, location, time, frequency of exposure, socioeconomic conditions, local vulnerabilities, such as, access to health services and individuals' vulnerabilities such as comorbidity. The region endures a triple burden of climate change, biodiversity loss, and ecosystem pollution marked by socioeconomic inequalities; lack of access to basic amenities; violence; and difficulties in implementing public policies (Simpson, 2024). Urban communities suffer from socioeconomic insecurity, climate crisis, and poor sanitary conditions, while rural and remote populations face inadequate health services, lack of logistics and infrastructure.



Indigenous communities are particularly vulnerable due to their reliance on forest resources and exposure to these environmental changes; immune issues, high exposure to extreme weather events, income poverty, and low education levels (Parry et al., 2018, Ellwanger et al., 2020; Hacon et al., 2024). The Amazon is a significant arbovirus reserve, with potential global health impacts. Climate change, biodiversity loss, and land-use changes have increased social and environmental vulnerability, disrupted ecosystems, and heightened pathogen transmission risks (Ellwanger et al., 2020; Vale et al., 2021; Winck et al., 2022). Predicting future epidemics in the Amazon is challenging due to the complex interplay of ecological and socioeconomic drivers. Human activities have created fragmented landscapes where high-density animal populations in degraded ecosystems are prone to epidemics (Wegner et al., 2022). Deforestation, extractive industries, loss of biodiversity, road construction, habitat destruction, trade, hunting, and wildfires, combined with climate change, have all contributed to this increased risk, suggesting that spillover events may become more frequent. The Amazon's high biodiversity increases the likelihood of pathogen presence and mutations, especially with the growing presence of livestock in the region. Examples of Emerging Infectious Disease (EID) include Severe Acute Respiratory Syndrome (SARS), Hantavirus Pulmonary Syndrome (HPS), highly pathogenic avian influenza H5N1, influenza virus H1N1, and HIV (Faria et al., 2014; Worobey et al., 2016; Gryseels et al., 2021).

Environmental degradation poses significant health risks in the Amazon, such as increased wildfires releasing pollutants causing respiratory and cardiovascular diseases (Requia et al., 2021; Romero et al., 2023), changing precipitation patterns affecting water availability and quality; and increasing vector-borne diseases, such as: yellow fever, dengue, malaria, Mayaro and Oropouche fever (Uhart et al., 2012). The impacts of climate change are strongly influenced by social vulnerabilities and adaptive capacity, requiring timely and adequate responses to both rapid and slow-onset climate risks (Lowe et al., 2020; Winck et al., 2022). Weak governance, limited disaster risk management policies, and inadequate and limited climate adaptation, combined with social inequalities, high poverty levels, informal employment, and health systems gaps, contribute to the devastating health impacts of climate change (CEPAL, 2022).



These impacts disrupt daily life, affecting health, well-being, social development, and human capital. In the Brazilian Amazon, primary care is the most present type of healthcare facility and the main point of access for the Unified Health System in the region, making it a key strategy for addressing regional inequities and overcoming these obstacles (Hacon et al., 2024). However, it is well known that the health sector is not capable of combating the driving forces and their pressures on health on its own. Therefore, what we need to work better is, actually, how to work together, and in connectivity. It is essential to establish intersectoral synergies between institutional agendas, enabling government, research institutions, and monitoring agencies to collaborate in an effective network.

Furthermore, food security in the Amazon is threatened by a tipping point and exacerbated by the synergy of monocrop farming, concentrated land ownership, intense pesticide use, deforestation, biodiversity loss, extreme climate events, unhealthy diets, and loss of traditional food practices, especially those practiced by traditional communities. The most vulnerable groups that face disproportionate impacts (IPCC, 2022; Hacon et al., 2024). Indigenous people face significant nutritional challenges, such as high rates of malnutrition, anemia, and stunting among children and maternal populations (Segoviano-Lorenzo et al., 2022; Santos da Silva et al., 2023).

iii) Ecosystem impacts

Decades of field research have revealed many ways in which ecosystems across the Amazon can respond to disturbances. Despite heterogeneity related to biogeographic and environmental factors, as well as disturbance histories (Jakovac et al., 2022; Lapola et al., 2023), three most plausible ecosystem trajectories have been identified for the forests exposed to compounding disturbances (Flores et al., 2024). The first is a trajectory toward ‘degraded forest’, with canopies still closed as in forest ecosystems, yet with a lower species diversity and high dominance of species that arrest forest succession and maintain through competition, such as lianas, bamboos and the *Vismia* sp. trees. This trajectory is most likely in parts of the Amazon that remain with annual rainfall above 1,800 mm.

For parts of the Amazon where rainfall is below this critical threshold, a second trajectory to ‘degraded open-canopy ecosystems’ becomes more likely. What happens below this threshold is that less rainfall

increases the risk of recurrent fires that limit tree recruitment, hence keeping the ecosystem permanently flammable (Cochrane et al., 1999). Also, proximity to pasturelands in deforestation frontiers allows exotic grasses to invade disturbed sites, which also reduces tree recruitment and increases flammability (Silvério et al., 2013).

A third trajectory to ‘white-sand savanna’ has been shown in seasonally flooded parts of the Amazon (Flores et al., 2021), where burnt forests shift into this alternative stable state within a few decades, altering drastically the ecological networks and ecosystem services.

Expansion of these three alternative ecosystem states in the coming decades will likely reduce the capacity of the Amazonian system to maintain the atmospheric moisture flows that are vital for its resilience to climate change. Yet, further studies are needed to better understand these impacts within Amazon and on other biomes. For instance, the Pantanal wetlands are in a region downwind and receive moisture from the Amazon. These wetlands are already diminishing in extent, and wildfires are becoming increasingly catastrophic.





3

**WHAT CAN
WE DO
ABOUT IT?**



**WHAT CAN
WE DO
ABOUT IT?**

3. WHAT CAN WE DO ABOUT IT?

3.1. Deforestation: How much do we need to limit it by?

As exposed in the previous sections, tipping points threatening the Amazon Forest can be reached through land use changes such as deforestation and forest degradation, climate change or as a combined effect of both environmental changes. The Brazilian government, as stated in its National Determined Contribution to the UNFCCC (NDC, 2024), has chosen to go beyond existing laws and policies and commit to reach zero deforestation, according to the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm). The Permanent Interministerial Commission for the Prevention and Control of Deforestation, established by the Decree 11,367/2023 will define and coordinate interministerial actions to reduce deforestation rates in the national territory.

Action Plans for each of the Brazilian biomes will be defined, having as reference PPCDAm, which is in its 5th phase of implementation and has shown that under political will, the combination of command and control, economic alternatives to the deforestation cycle, and other policies are capable of halting high deforestation rates (CEPAL, IPEA, GIZ, 2011). However, its potential to address the logic of land concentration that started during the military dictatorship (Costa, 2022) and that depends on continued deforestation, degradation, and rural poverty to maintain low the costs of land and labor in its production function is limited.

The socioeconomic model that still prevails in the Amazon territory is one that starts with illegal land appropriation of public forest areas and is transformed to low productivity cattle grazing to force recognition of land ownership. This is done on a large scale by land grabbers against the interests of forest inhabitants. This “production of land” happens in the absence of state governance and distant of any public policy decision center, in an environment classified by Costa et al. (2023) as an “ecosystem of illegalities”, where illegal logging finances the forest removal and many other illegal activities like illegal mining coexist or are related to the main activity of land appropriation. Some of the areas prosper as agricultural hotspots, like Paragominas, in the state of Pará, but at a high socio-ecological cost, not compatible with Brazil’s ambition to foster a just and green economy, as stated in its NDC.



Part of the process described above reflects an erosion of the state structure towards environment protection (Abessa et al., 2019; Vale et al., 2021; Nunes et al., 2024). The uncertainties of the political cycle and the lobby behind predatory ways of exploiting natural resources are still threats to the continuation of policies aiming to halt deforestation (Vilani et al., 2023). Proposed solutions for the regional development of the region must consider strengthening local communities and law enforcement at the Federal level to avoid unconstitutional action of economic power over the ecosystem and its inhabitants.

Nonetheless, none of the development plans drawn by a federal government for the region is ecologically viable and the space left as potential “legal deforestation” e.g. the percentage of the rural properties where the forest is still preserved that is above the binding “legal reserve” rule is already threatening the existence of the ecosystem. This forces society to urge for alternatives considering the development of the region.

Alternatives for regional development policies must consider the diversity of the Amazon in terms of biological diversity, sociocultural diversity and in terms of the diverse dynamics of behavior, strategies and technological solutions through time used by inhabitants that for generations lived in the forest without having to deforest large areas. Just to illustrate, Bertha Becker (2010) cites an example of Nova Califórnia, in Rondônia, where family-based agriculture uses a consortium of chestnuts, cupuaçu and peach palm to maintaining the forest structure and the ecosystem services, managing natural resources in a community based system of values and cooperation.

Many other ventures like this Nova California example are constituting technology trajectories that coexist to the forest preserving indigenous and to the forest destructive mainstream development trajectories. Val et al. (2024), explains how the Indigenous People’ and local communities’ knowledge on the sustainable use of Amazon’s resources is vital for the future regional nutritional security and that fostering scientific and technological development in that direction must be the base for an Amazonian bioeconomy. Costa (2024), analyses the technological trajectories of Amazonian peasantries and conclude that Agroforestry Systems paths tending to follow a kind of agricultural solution, in successions or combinations seeking to imitate the qualities of the biome, in a kind of diverse, complex “holistic



agriculture” is more economically efficient than the ones managing resources originating in the Amazon biome, in a kind of “dynamic extraction”.

Indeed, much archeological evidence shows that even large populations, concentrating in cities, were sustained by such a kind of “holistic agriculture”, using the expression by Francisco Costa (Lombardo et al., 2022). It is largely ignored that the more than 10,000 years history of indigenous cultural and technological evolution and cycles of arising and declining cultures drew the botanical composition of the Amazon forests (Magalhães, 2023), with a majority of the public believing that the biogeography of the species exists by processes that do not link to human activities. Furthermore, even though a great deal of people still belongs to cultural lineages that helped constitute the forests as we know them, people who carry an ancient knowledge and depend on this knowledge for their survival are not invited to participate in the decision-making process.

The development planning will shape the Amazon ecosystem soon or cause it to collapse leaving an unknown floristic composition of a savanna like landscape as seen in previous sessions. The recent creation of a Ministry of Indigenous Peoples is much more related to the necessity of protecting indigenous people’s existence. Its public policies aim to protect their health and enforce territorial rights, more than it really helps the cultural exchange between different cultures and knowledge, which could lead to a broader creation of solutions aiming the ecosystem function preservation while fostering human development based on equity and climate justice.

Analyzing this situation, Vilani et al. (2023) suggest seven elements that could contribute to restructuring conservation actions in the Amazon. These elements are:

- 1) complete the restoration of the Amazon Fund;
- 2) encourage all Amazonian states to create special secretariats for Indigenous Peoples;
- 3) reconsider large investment projects in mining and agribusiness;
- 4) revoke the former government’s anti-environmental measures;
- 5) establish a new institutionality with Indigenous Peoples and traditional communities as protagonists;
- 6) rebuild citizenship of the Amazonian peoples in favor of forest conservation; and

- 
- 7) improve funding for the environmental and Indigenous Peoples ministries and associated policies.

These elements could also contribute to address a list of nine ways to avoid the Amazon tipping point, proposed the Science Panel for the Amazon (Flores et al., 2023):

1. Drastically reducing global greenhouse-gas emissions;
2. Ending large-scale deforestation, degradation, and forest fires;
3. Restoring abandoned and degraded forests at large scales;
4. Creating and maintaining protected areas and Indigenous territories;
5. Investing in science, technology and innovation;
6. Strengthening the participation of civil society organizations;
7. Developing a sustainable sociobioeconomy of standing forests and flowing rivers;
8. Maintaining forest connectivity across the Andes-Amazonian frontier;
9. Including the fundamental 'Rights of the Amazon' in constitutions of Amazonian countries.

Alternatives to mainstream reductionist development practices are often viewed as unrealistic, not compatible with the mainstream view based on neoliberalism and colonial thinking. However, as the previous sections have shown, the present trajectory is not viable and new solutions have to be presented.

A great scenario design and innovative economic modelling effort trying to foresee barriers and advantages of a 'bioeconomical' alternative for the development strategy for the Amazon and also the Brazilian economy, called New Economy for the Brazilian Amazon (Nobre et al., 2023), brought some important insights. This kind of understanding of economics at local, national and global levels is important to avoid misunderstandings of the drivers of deforestation. Haddad et al. (2024) show that a major part of deforestation in the Legal Amazon derives from local and national demands. This does not mean that importers shouldn't care about the origin of their imported goods but shows that moratoriums may be essential but are insufficient as measures for halting deforestation. The authors of the New Economy for the Brazilian Amazon recommend:

1. The public sector must assert its allocative and distributive roles to signal the directions to be taken by the economy going forward;
2. The private sector needs to increase its capacity for innovation and become a driver of the new economy;
3. Employ instruments and methods that enable adequate assessment of the Amazon's social and economic development;
4. Establish clear milestones in the conceptualization of bioeconomy plans and programs that are compatible with products, processes and productive structures that protect the standing forest, biodiversity and knowledge of indigenous peoples and traditional populations;
5. Eliminating subsidies or promoting cross-subsidies from fossil fuels to energy from renewable sources with an emphasis on solar generation and second-generation biofuels is essential to the decarbonization of the economy¹;
6. Redirect the availability of rural credit, gradually transforming the Plano Safra into a Low Carbon Emission Agricultural Plan (ABC);
7. Re-establish the role of the public sector in territorial management and governance;
8. Restore governance and guarantee the investments of the Amazon Fund. The Amazon Fund, in addition to providing support for command and-control actions, indigenous communities and the implementation and analysis of the Rural Environmental Registry (CAR);
9. Create a methodological framework and taxonomies for the financial and capital markets on the requirements for green investments in the Amazon that promote the reduction of emissions and the preservation of biodiversity.

All local measures to halt deforestation are essential to avoid an Amazonian tipping point but are altogether not sufficient. As exposed in the previous pages and discussed in more detail below, global climate change can trigger an Amazonian tipping point by itself. This exposes the commonsense idea that protecting the Amazon forest is a solution for climate change as a myth “You cannot, and should not

¹ For the reasons explained in the topic about climate mitigation below, this must be a global effort, being a recommendation for the Brazilian government the specificities of the study by Nobre et al. 2023 but bearing in mind that this is a global problem with a global tendency to enhance despite all involved countries being parties of the UNFCCC. Without a global effort on reducing emissions, the countries which encompasses the Amazon Region won't be able to avoid the Amazon's tipping point. For more detail on fossil fuel subsidies, read <https://www.imf.org/en/Topics/climate-change/energy-subsidies>.



purport to, equate ‘black’ carbon emissions (coal, oil or gas) with ‘green’ carbon sinks such as forests” (CCAG, 2024). It is not possible to neutralize CO₂ emissions from fossil fuels (“black carbon”) with “green carbon” sinks from photosynthesis. The black carbon is taken from a stable carbon stock that is many times older than human existence and would continue to stay stable if not assessed by humans and cannot be offset against the biological green carbon cycle, which gets C enriched by fossil fuel burning. So, it is correct to understand that the Amazon is not a solution for, but rather endangered by, human induced climate change as long as fossil C is dumped to the atmosphere, the oceans and the biological system.

3.2. Climate mitigation: How much does the risk of Amazon tipping point increase with warming?

IPCC AR6 Synthesis Report concluded that “Every increment of global warming will intensify multiple and concurrent hazards (high confidence)” and that “Deep, rapid, and sustained reductions in greenhouse gas emissions” would slow global warming and, therefore, reduce impacts.

While it is now all but inevitable that the world will reach 1.5°C of warming above pre-industrial in the coming decade, the extent to which we exceed this guardrail warming level and how quickly we may be able to reduce temperatures again depend strongly on global activity taken now to limit emissions. IPCC Special Report on 1.5°C assessed risks of warming and overshooting temperature targets and concluded, “Risks to unique and threatened terrestrial ecosystems are generally higher under warming of 2°C as compared to 1.5°C, while at the global scale, severe and widespread risks are projected to occur by 2°C of warming”.

AR6 WG2 report (O’Neill et al., 2021 – IPCC AR6 WG2 ch.16) updated the reasons for concern and included dieback of the Amazon forest under RFC5 “Large scale singular events” and are assessed to transition from moderate to high risk above 2 degrees of global warming. If the Amazon forest did reach a tipping point and lose substantial coverage, then this both impacts global climate through the release of large amounts of carbon into the atmosphere and may be irreversible, at least on timescales of decades (Lee et al., 2021 – IPCC AR6 WG1 ch. 4). Loss of forests may also be committed to before substantial changes



are observed (Jones et al., 2009), increasing the importance of early action to limit global climate change.

Therefore, it is imperative for the long-term stability of the Amazon Forest that global-scale mitigation efforts increase the urgency of stopping CO₂ emissions and limiting the extent of global warming.

3.3. Adaptation: Could we adapt to the large-scale changes that happen?

The Amazon is facing unprecedented challenges due to climate change (SPA, 2021). As global temperatures rise, the Amazon is experiencing more frequent and intense weather events, including extreme droughts and flooding. These changes are not just threats to the environment and biodiversity, but also to the millions of people who depend on the Amazon for their livelihoods, culture, and well-being. In this context, adaptation in the Amazon region, increasing resilience to the extreme events, is not just important – it is crucial.

The Amazon forest is a complex and interdependent ecosystem, where slight changes in temperature and precipitation can have cascading effects on the entire region (Ometto et al., 2022). Climate models predict that the Amazon will become increasingly vulnerable to extreme weather events, leading to a higher risk of forest dieback – a situation where large portions of the forest degrade or collapse due to prolonged droughts and rising temperatures (Lapola et al., 2023). This process threatens to transform the Amazon from a carbon sink into a carbon source (Gatti et al., 2021), releasing carbon dioxide into the atmosphere and exacerbating global warming.

Thus, the adaptation strategies are needed to preserve the ecological functions of the natural ecosystems, protect biodiversity, and support the communities that rely on the forest. Unlike mitigation efforts, which aim to reduce the drivers of climate change, adaptation focuses on adjusting to the changes that are already happening and those that are inevitable.

The Amazon is home to a myriad of animal, plant and microorganism species, many of which are endemic, not found anywhere else on the planet. As climate change alters habitats, many species will need to adapt by migrating to new areas, changing their behavior, or evolving over time. However, the rapid pace of climate change may outstrip the



ability of species to adapt naturally, leading to significant losses in biodiversity. Adaptation efforts must include the creation of ecological corridors, connecting conservation areas, that allow species to move to more suitable habitats as climate conditions change. Protecting large, contiguous areas of forest is also essential to maintaining the ecosystem services that the Amazon provides (Aragão et al., 2018).

Water is a critical resource in the Amazon. Extreme droughts can lead to water shortages, while extreme flooding can damage infrastructure and disrupt local economies, by changing the geography of flooded areas and connectivity among river channels (Espinoza et al., 2024). Effective water management and flood forecasting are therefore vital components of adaptation in the Amazon. Restoring and protecting wetlands and floodplains, which act as natural buffers against flooding is a critical action.

These areas can absorb excess water during heavy rain, reducing the impact on downstream communities. In addition, improving water management infrastructure, such as reservoirs and irrigation systems, can help to ensure a stable water supply during periods of drought. Planning supporting infrastructure to act on extreme events, e.g, supply of water and food to remote regions during long drought spells or planning distributed structure and fire brigade to act to avoid large fires, are essential.

The indigenous peoples and traditional communities of the Amazon have a deep connection to the forest and possess valuable knowledge about its management (SPA, 2021). However, they are also among the most vulnerable to the impacts of climate change. Adaptation in the Amazon region must prioritize the needs and rights of these communities, ensuring that they have the resources and support needed to cope with changing conditions. Concerns on vulnerable populations in urban systems is the region is also critical. These communities are the first to be affected by climate extremes and increasing resilience and creating opportunities to adapt need to be central to urban planning and governance.

Adaptation action in urban systems include, among others, nature-based solutions, strengthening communication and information networks, support for better and climate friendly architecture in houses and communal buildings; waste treatment, exposure reduction



to pollution. Also, community-based adaptation strategies can include promoting sustainable agriculture practices, enhancing food security, and improving access to clean water. By integrating traditional knowledge with scientific research, these strategies can be tailored to the specific needs of each community, helping to build resilience against climate-related threats.

Adaptation in the Amazon requires strong policy frameworks and effective governance at local, national, and international levels. Governments must implement and enforce policies that protect the Amazon from further deforestation and degradation. This includes regulating land use, promoting sustainable development, and ensuring that adaptation measures are integrated into broader climate change strategies. Adaptation must also rely on sound, scientific based and accessible information, which shall reach the manager at local level and provide clear mapping of climate impact risks and the possible solutions.

International cooperation is also essential. Multilateral agreements and organizations, such as the Amazon Cooperation Treaty Organization (ACTO), play a critical role in coordinating efforts to adapt to climate change and protect the Amazon.

3.4. Research: Observations, early warning, modelling, AI, etc.

The main priorities for research around the Amazon Tipping point are:

1. Forest response to change. Understanding the ongoing and potential responses of the forest to regional drought, heat waves and wildfires and elevated CO₂ through in-situ experiments, field and remote sensing observations and modelling studies;
2. Evidence for global climate change mitigation. How much more likely the crossing of an Amazon tipping point is with incremental warming. Is there a level of global warming that might make an Amazon tipping much more likely, and therefore that we need to avoid?
3. Early warning system. How will we know if we are approaching an Amazon tipping point? Improving ESMs and using these models to understand the elements of the earth system that we can consider giving an early warning of an Amazon tipping, and how can we use earth observation to monitor these signals of ‘critical slowing down’;
4. Cascades of tipping within the Earth system. Would other Earth system elements induce an Amazon tipping? Alternatively, which

tipping elements of the Earth system would become more unstable in a scenario of Amazon forest collapse?

5. Understanding local, regional and global impacts of an Amazon tipping point. What will the societal and ecosystem consequences of an Amazon tipping point be, and what would it mean in practical terms for food and water security, human health, critical infrastructure and other sustainable development goals?

6. Decision support and co-production of policy responses. How can this new science-based information be used to inform and interact with existing local, national, regional and global Governance?

Table 1. List of research priorities and corresponding projects related to the Amazon Forest System's Tipping Point.

Research Priority	Project	Brief description of project's contribution
Forest response to change	AmazonFACE	UK and Brazil funded project to build towers that pump CO ₂ into the air around trees, to study their response to elevated atmospheric CO ₂ .
Forest response to change	CSSP Brazil Forest Plots (RAINFOR)	Support to Caixana throughfall experiment, and development of the UK Earth System Model to represent vegetation response to drought, CO ₂ , temperature and land use change. Monitoring of tree dynamics across Amazonian forest regions.
Evidence for mitigation	OptimESM & TipESM & ClimTip	Earth system model (ESM) simulations to identify tipping points at a range of global warming levels. Additional simulations will look at the potential to reverse tipping points by ramping down CO ₂ emissions
Early warning system	TipESM	Using ESMs to identify pre-cursors to tipping points that can be used for monitoring, and understanding reversibility once an early warning is identified
Early warning system	European Space Agency	ESA CLIMATE SPACE Tipping Elements activity, aims to strengthen the levels of confidence in our understanding of the risk of tipping elements and abrupt changes by harnessing climate data records

Cascades of tipping	TipESM	ESM simulations will induce tipping points, and continuity simulations in the new stable state may reveal new dependencies in the earth system
Local to global impacts	TipESM	Multi-sector impacts assessed using a range of impacts models including human heat stress, fire weather, drought, flooding, infectious disease
Decision support	TipESM	Out-reach activities with associated institutions such as European national governments the European Commission

Links:

DicaESM: <https://www.tipesm.eu/>

ClimTip: <https://www.climate-tipping-points.eu/>

AmazonFACE: <https://amazonface.unicamp.br/en/>

CSSP Brasil:

<https://www.metoffice.gov.uk/research/approach/collaboration/wcssp/cssp-brazil/inde>



4

FUNDING OPPORTUNITIES



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Financing the necessary transformation from the business as usual to the new economy in the Amazon Region is probably the most significant hurdle besides convincing society that another model is possible.

At the international level, the Climate Change Convention established that developed countries should finance actions to combat climate change in developing countries, such as Brazil and other Amazon countries, through loans and donations, establishing a financing mechanism in Article 11¹. The four most significant multilateral climate funds, the Adaptation Fund², Climate Investment Funds (CIFs)³, the Global Environment Facility (the GEF)⁴, and Green Climate Fund (GCF)⁵ – have programs and projects dedicated to adaptation and/or mitigation efforts related to the forestry sector.

The Climate Investment Funds, created before the UNFCCC designed the climate finance architecture, having the Green Climate Fund as the main financial instrument, serves as a kind of laboratory for financing climate action in innovative ways, having invested more than US\$ 7 billion since 2008. CIF supports transformational change toward low-carbon, climate-resilient development. It has a grant for supporting Indigenous Peoples and Local Communities (IPLC) and a forest investment program meant to “reverse the impact of human actions and climate change on forest ecosystems, through empowering governments and local communities to sustainably address the drivers of deforestation and forest degradation”⁶. The grants are still far too small to drive the necessary shift from the tendency of economic unsustainable exploitation of the natural resources of the Amazon Region or elsewhere. Their existence, nevertheless, is the recognition of the international community of the way forward and lessons learned from the already invested grants are valuable in continuing prospecting for solutions.

¹ <https://unfccc.int/resource/docs/convkp/conveng.pdf>

² <https://www.adaptation-fund.org/>

³ <https://www.cif.org/>

⁴ <https://www.thegef.org/>

⁵ <https://www.greenclimate.fund/>

⁶ <https://www.cif.org/>

The Amazon Fund⁷ has established a higher level of investment, with donors financing sustainable economic alternatives of natural resources' use, land use planning, monitoring & control mechanisms and science, technology & innovation. More than US\$ 1 billion has already been invested and many lessons are to be learned from its monitoring. In that sense, the Arc of Restoration Project headed by the Brazilian Development Bank (BNDES) aims to restore 240,000 km² from now to 2050 in the Brazilian Amazon. The Amazon Fund is starting to support donations to IPLCs to do forest restoration. The needed impact evaluation of the Amazon Fund has to focus on the macro transformational change, as discussed by Van den Berg and Magro (2019), more than in micro results of individual project investments. This is because system changes need lower risk aversion of investment, considering the higher risk of inaction and unprecedented costs of reaching the tipping point.

Another important fund is the Brazilian Climate Fund⁸ that also maintains a Native Forest program, which is focused on projects associated with sustainable forest management; to the forest planting with native species, including the production chain; to the processing; and consumption of forest products of sustainable origin; as well as to the technological development of these activities. The Fund is receiving US\$ 1.9 billion for loans and the interest rates charged for the Native Forest program will be 1%⁹.

Paradigms can shift either in a scenario where it is not proactively caused, but rather a consequence of different factors catalyzing the change or proactively, as this document urges to happen, as a result of entrepreneurs' actions towards a change (Uitto et al. 2019). To foster behavioral change in entrepreneurs, there is a need for social signaling and effective policy design. Despite all the international funding initiatives and collaboration, the Brazilian Government has the highest burden in financing all the monitoring, law enforcement and science & education needed to protect the Amazon. Nevertheless, it fails in giving the correct incentives to private investment to flow into sustainable activities. One example is the lack of enforcement of its forest code (Azevedo-Ramos et al., 2017; Brock et al., 2021; Kuschinig et al., 2023), which frustrates the few landowners who have invested in

⁷ <https://www.amazonfund.gov.br/en/home/>

⁸ <https://www.gov.br/mma/pt-br/assuntos/mudanca-do-clima/fundo>

⁹ <https://www.gov.br/planalto/en/latest-news/2024/04/federal-government-signs-contract-for-brl-10-4-billion-from-the-climate-fund>



restoring or maintaining protected forests over the legally obligatory limit inside their properties expecting financial compensation on a compliance market. Nobre et al., (2023) estimate the requested investments for the transition to the new economy for the Brazilian Amazon to be in the order of half a trillion US\$, financial resources that can only be achieved if private investment is considered. Carvalho et al (2017) estimated the costs of controlling legal deforestation in the Amazon, which could be achieved at low costs. Souza et al. (2024) analyzed the economic costs of zero deforestation policies in the Cerrado and the Amazon. According to the authors, one way to offset these costs would be to increase investments in the agricultural sectors to increase their productivity. An annual investment of 2.3% of the GDP in these regions would be necessary to finance this zero-deforestation scenario: the total amount invested would be R\$ 225 billion in the Amazon and Cerrado biomes from 2021 to 2040, equivalent to an average of R\$ 11.6 billion annually.

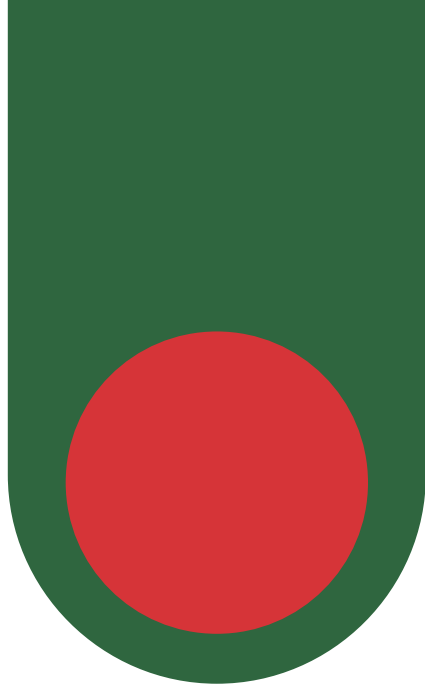
According to the New Economy for the Brazilian Amazon study by the World Resources Institute (WRI; Nobre et al., 2023), a deforestation-free scenario following a low-carbon pathway would result in substantial and equitable economic growth for the Amazon region and Brazil. This scenario would yield significant economic benefits, create jobs, and contribute positively to Brazil's climate goals. The necessary investments to facilitate this transition would be 1.8% of Brazil's national GDP annually, representing a slight increase of 0.8% compared to the reference scenario. Specifically, this translates to an additional BRL 2.56 trillion (equivalent to \$513 billion) by the year 2050.

This level of investment flow can only be achieved if regulation is designed, and enforced, in a manner that all potential private investment in activities that counteract the new economy for the Brazilian Amazon is avoided i.e., design a market framework where private loans and public subsidies and loans are only available for activities that promote or are neutral to the preservation of the ecosystem services of the Amazon, like nature-based solutions business models (Kreibiehl et al., 2022).

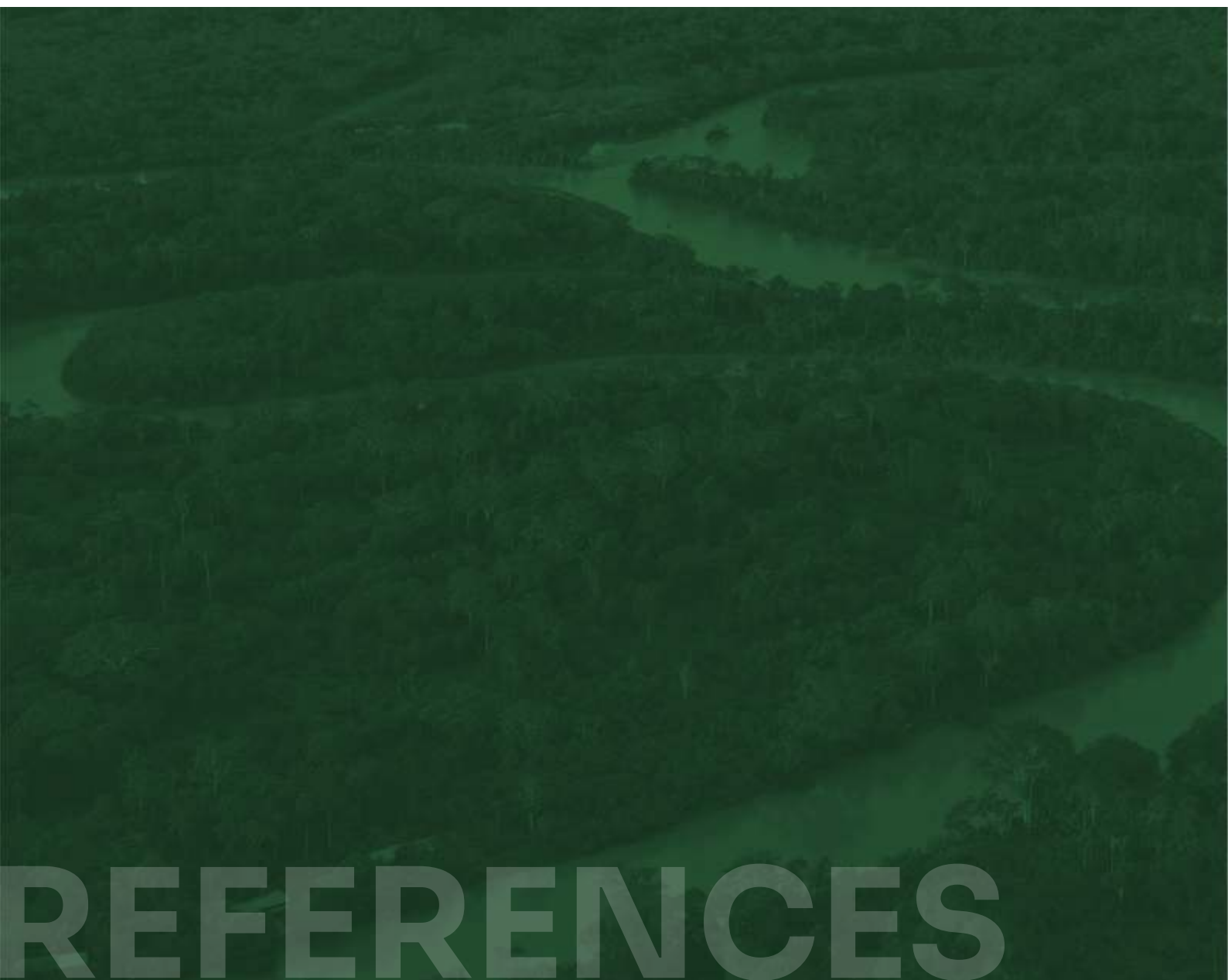
The Tropical Forests Forever Facility (TFFF) is another of Brazil's strategies for addressing climate change and financing. It was introduced during COP28 in Dubai, United Arab Emirates. It aims to compensate developing countries that conserve their tropical forests by channeling the invested capital into green assets and applying the



returns to keep the forests standing. In the proposed strategy, the initiative will make payments for each hectare of standing forests, with penalties for each hectare that is deforested or degraded. It would also ensure additional resources for the protection of biodiversity, traditional territories, and the maintenance of environmental services. It would create an international vehicle to compensate countries for the preservation of their tropical forests. The plan seems to implement this policy in a simplified manner by comparing satellite photos and making payments per hectare of maintained green área.



REFERENCES



REFERENCES

REFERENCES CITED

- ABESSA, D.; FAMÁ, A.; BURUAEM, L. The systematic dismantling of Brazilian environmental laws risks losses on all fronts. *Nature Ecology & Evolution*, v. 3, p. 510-511, 2019. Disponível em: <https://doi.org/10.1038/s41559-019-0855-9>. Acesso em: 17 ago. 2025.
- AKABANE, et al., 2024. Weaker Atlantic overturning circulation increases the vulnerability of northern Amazon forests. *Nature Geoscience*, v. 17, p. 1284-1290, 2024. Disponível em: <https://www.nature.com/articles/s41561-024-01578-z>. Acesso em: 17 ago. 2025.
- ARAGÃO, L. E. O.; et al. Above and below-ground net primary productivity across ten Amazonian forests on contrasting soils. *Biogeosciences*, v. 6, p. 2759-2778, 2009. Disponível em: <https://doi.org/10.5194/bg-6-2759-2009>. Acesso em: 17 ago. 2025.
- ARAGÃO, L. E. O. C. The rainforest's water pump. *Nature*, v. 489, n. 7415, p. 217-218, 2012. Disponível em: <https://doi.org/10.1038/nature11485>. Acesso em: 17 ago. 2025.
- ARAGÃO, L. E. O.; et al. 21st century drought-related fires counteract the decline of Amazon deforestation carbon emissions. *Nature Communications*, v. 9, p. 536, 2018.
- AZEVEDO-RAMOS, C.; et al. Limits of Brazil's Forest Code as a means to end illegal deforestation. *Proceedings of the National Academy of Sciences of the USA*, v. 114, p. 7653-7658, 2017.
- BAKER, T. R.; PHILLIPS, O. L.; MALHI, Y.; ALMEIDA, S.; ARROYO, L.; DI FIORE, A.; ERWIN, T.; HIGUCHI, N.; KILLEEN, T. J.; LAURANCE, S. G.; LAURANCE, W. F.; LEWIS, S. L.; MONTEAGUDO, A.; NEILL, D. A.; NUÑEZ VARGAS, P.; PITMAN, N. C. A.; SILVA, J. N. M. VÁSQUEZ MARTÍNEZ, R. Increasing biomass in Amazonian forest plots. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, v. 359, n. 1443, p. 353-365, 2004. Disponível em: <https://doi.org/10.1098/RSTB.2003.1422>. Acesso em: 17 ago. 2025.
- BARLOW, J.; et al. The future of hyperdiverse tropical ecosystems. *Nature*, v. 559, p. 517-526, 2018.
- BECKER, B. K. Novas territorialidades na Amazônia: desafio às políticas públicas. *Boletim do Museu Paraense Emílio Goeldi. Ciências Humanas*, v. 5, n. 1, p. 17-23, 2010. Disponível em: <https://doi.org/10.1590/S1981-81222010000100003>. Acesso em: 17 ago. 2025.
- BETTS, R. A.; COX, P. M.; COLLINS, M.; HARRIS, P. P.; HUNTINGFORD, C.; JONES, C. D. The role of ecosystem-atmosphere interactions in simulated Amazonian precipitation decrease and forest dieback under global climate warming. *Theoretical and Applied Climatology*, v. 78, n. 1-3, p. 157-175, 2004. Disponível em: <https://doi.org/10.1007/s00704-004-0050-y>. Acesso em: 17 ago. 2025.
- BETTS, R. A.; BOUCHER, O.; COLLINS, M.; COX, P. M.; FALLOON, P. D.; GEDNEY, N.; HEMMING, D. L.; HUNTINGFORD, C.; JONES, C. D.; SEXTON, D. M. H.; WEBB, M. J. Projected increase in continental runoff due to plant responses to increasing carbon dioxide. *Nature*, v. 448, n. 7157, p. 1037-1045, 2007. Disponível em: <https://doi.org/10.1038/nature06045>. Acesso em: 17 ago. 2025.
- BOULTON, et al., 2022. Pronounced loss of Amazon rainforest resilience since the early 2000s. *Nature*, v. 12, p. 271-279, 2022. Disponível em: <https://www.nature.com/articles/s41558-022-01287-8>. Acesso em: 17 ago. 2025.
- BRIENEN, R. J. W.; PHILLIPS, O. L.; FELDPAUSCH, T. R.; GLOOR, E.; BAKER, T. R.; LLOYD, J.; LOPEZ-GONZALEZ, G.; MONTEAGUDO-MENDOZA, A.; MALHI, Y.; LEWIS, S. L.; VÁSQUEZ MARTINEZ, R.; ALEXIADES, M.; ÁLVAREZ DÁVILA, E.; ALVAREZ-LOAYZA, P.; ANDRADE, A.; ARAGÃO, L. E. O. C.; ARAUJO-MURAKAMI, A.; ARETS, E. J. M. M.; ARROYO, L.; ... ZAGT, R. J. Long-term decline of the Amazon carbon sink. *Nature*, v. 519, n. 7543, p. 344-348, 2015. Disponível em: <https://doi.org/10.1038/nature14283>. Acesso em: 17 ago. 2025.
- BROCK, et al. Implementing Brazil's Forest Code: a vital contribution to securing forests and conserving biodiversity. *Biodiversity and Conservation*, v. 30, p. 1621-1635, 2021. Disponível em: <https://doi.org/10.1007/s10531-021-02159-x>. Acesso em: 17 ago. 2025.
- BURTON, et al., 2021. South American fires and their impacts on ecosystems increase with continued emissions. *Climate Resilience and Sustainability*, v. 1, n. 1, p. 1-15, 2020. Disponível em: <https://rmets.onlinelibrary.wiley.com/doi/10.1002/cli2.8>. Acesso em: 17 ago. 2025.
- CANO, et al., 2022. Abrupt loss and uncertain recovery from fires of Amazon forests under low climate mitigation scenarios. *Proc. Natl. Acad. Sci. U.S.A.*, v. 119, n. 52, p. e2203200119, 2022. Disponível em: <https://www.pnas.org/doi/10.1073/pnas.2203200119>. Acesso em: 17 ago. 2025.
- CANADELL, J. G. et al. Chapter 12: Climate change and regional impacts. In:

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC). *Climate Change 2021: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, 2021.

CARVALHO, L. M.; et al. Controlling deforestation in the Brazilian Amazon: Regional economic impacts and land-use change. *Land Use Policy*, v. 64, p. 327–341, 2017. Disponível em: <https://doi.org/10.1016/j.landusepol.2017.03.001>. Acesso em: 17 ago. 2025.

CASTELLANOS, E. J.; LEMOS, M. F.; ASTIGARRAGA, L.; CHACÓN, N.; CUVI, N.; HUGGEL, C.; MIRANDA, L.; VALE, M. M.; OMETTO, J. P.; PERI, P. L.; POSTIGO, J. C.; RAMAJO, L.; ROCO, L.; RUSTICUCCI, M.; MENEZES, J. A.; BORGES, P.; BUENO, J.; CUESTA, F.; DRENKHAN, F.; VALLADARES, Central and South America. *Climate Change 2022: Impacts, Adaptation and Vulnerability – Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, 2025.

CASTELLO, L.; et al. Vulnerability of Amazon freshwater ecosystems. *Conservation Letters*, v. 6, n. 4, p. 217–229, 2013.

CCAG – Climate Crisis Advisory Group. Voluntary carbon markets: potential, pitfalls, and the path forward. Reino Unido, 2024. Disponível em: <https://www.ccag.earth/reports/voluntary-carbon-markets-pitfalls-potential-and-the-path-forward>. Acesso em: 17 ago. 2025.

CEPAL – Comissão Econômica para a América Latina e o Caribe. Panorama Social da América Latina e do Caribe 2022: A transformação da educação como base para o desenvolvimento sustentável. Resumo executivo, 2022.

CHENG, H.; SINHA, A.; CRUZ, F. W.; WANG, X.; EDWARDS, R. L.; M., F.; RIBAS, C. C.; VUILLE, M.; STOTT, L. D.; AULER, A. S. Climate change patterns in Amazonia and biodiversity. *Nature Communications*, v. 4, n. 1, p. 1–6, 2013. Disponível em: <https://doi.org/10.1038/ncomms2415>. Acesso em: 17 ago. 2025.

CLARKE, B.; BARNES, C.; RODRIGUES, R. R.; et al. Mudanças climáticas, e não o El Niño, são o principal fator de seca excepcional na altamente vulnerável Bacia do Rio Amazonas. *World Weather Attribution Report*, 2024.

COCHRANE, M. A.; et al., 1999. Positive Feedbacks in the Fire Dynamic of Closed Canopy Tropical Forests. Disponível em: <https://www.science.org/doi/abs/10.1126/science.284.5421.1832>. Acesso em: 17 ago. 2025.

COE, M. T.; et al. Deforestation and climate feedbacks threaten the ecological integrity of south-southeastern Amazonia. *Philosophical Transactions of the Royal Society B: Biological Sciences*, v. 363, n. 1498, p. 1903–1908, 2009.

COSTA, M. H.; PIRES, G. F. Effects of Amazon and Central Brazil deforestation scenarios on the duration of the dry season in the arc of deforestation. *International Journal of Climatology*, v. 30, n. 13, p. 1970–1979, 2010. Disponível em: <https://doi.org/10.1002/JOC.2048>. Acesso em: 17 ago. 2025.

COSTA, F. DE A. Da estrutura fundiária à dinâmica do desmatamento: a formação de um mercado de terras na Amazônia (1970–2017). *Nota de Política Econômica – MADE/USP*, n. 19, 2022.

COSTA, F. DE A.; LARREA, C.; ARAÚJO, R.; BENATTI, J. H.; GIRALDO, V.; HECHT, S.; MURMIS, M. R.; PETERS, S.; SCHMINK, M.; TERÁN, E.; TRECCANI, J. Land Market and Illegalities: the deep roots of deforestation in the Amazon. *Policy Brief – Science Panel for the Amazon*, 2023. Disponível em: <https://doi.org/10.55161/SLBQ1069>. Acesso em: 17 ago. 2025.

COSTA, F. DE A. A economia dos sistemas agroflorestais na Amazônia: uma trajetória crítica para o desenvolvimento sustentável (1995–2017). *Economia e Sociedade*, v. 33, n. 2, p. e260717, 2024.

COX, P. M.; BETTS, R. A.; JONES, C. D.; SPALL, S. A.; TOTTERDELL, I. J. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature*, v. 408, n. 6809, p. 184–187, 2000. Disponível em: <https://doi.org/10.1038/35041539>. Acesso em: 17 ago. 2025.

COX, P. M.; et al. Amazonian forest dieback under climate-carbon cycle projections for the 21st century. *Theoretical and Applied Climatology*, v. 78, p. 137–156, 2004.

DA COSTA, et al., 2018. Stand dynamics modulate water cycling and mortality risk in droughted tropical forest. *Global Change Biology*, v. 24, n. 1, pp. 249–258, 2018. Disponível em: <https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.13851>. Acesso em: 17 ago. 2025.

DUFFY, P. B.; BRANDO, P.; ASNER, G. P.; FIELD, C. B. Proceedings of the National Academy of Sciences of the United States of America, v. 112, n. 43, p. 13172–13177, 2015. Disponível em: https://doi.org/10.1073/PNAS.1421010112/SUPPL_FILE/PNAS.201421010SI.PDF. Acesso em: 17 ago. 2025.

- DUNNE, T.; et al. O comportamento de um rio de leito rochoso em um trecho de leito de areia: o rio Amazonas, Brasil. *Earth Surface Processes and Landforms*, v. 23, n. 12, p. 1061-1076, 1998.
- DRUKE, et al., 2023. Fire may prevent future Amazon forest recovery after large-scale deforestation. *Nature*, v. 4, 2023. Disponível em: <https://www.nature.com/articles/s43247-023-00911-5>. Acesso em: 17 ago. 2025.
- DUTRA, et al., 2022. Fire Dynamics in an Emerging Deforestation Frontier in Southwestern Amazonia, Brazil. *Fire*, v. 6, n. 1, 2023. Disponível em: <https://www.mdpi.com/2571-6255/6/1/2>. Acesso em: 17 ago. 2025.
- ELLWANGER, J. H.; et al. Além da perda de diversidade e das mudanças climáticas: impactos do desmatamento da Amazônia sobre doenças infecciosas e saúde pública. *Anais da Academia Brasileira de Ciências*, v. 92, 2020.
- ESPINOZA, J. C.; et al. Hotspots de precipitação no sul da bacia amazônica, distribuição temporal e espacial e controles atmosféricos associados. *Climatic Change*, v. 96, p. 187-197, 2009.
- ESPINOZA, J. C.; et al. The influence of the tropical Atlantic and Pacific Oceans on the Amazon basin's rainfall variability and climate extremes. *Hydrological Processes*, v. 25, n. 26, p. 342-358, 2011.
- ESQUIVEL-MUELBERG, A.; BAKER, T. R.; DEXTER, K. G.; LEWIS, S. L.; BRIENEN, R. J. W.; FELDPAUSCH, T. R.; LLOYD, J.; MONTEAGUDO-MENDOZA, A.; ARROYO, L.; ÁLVAREZ-DÁVILA, E.; HIGUCHI, N.; MARIMON, B. S.; MARIMON-JUNIOR, B. H.; SILVEIRA, M.; VILANOVA, E.; GLOOR, E.; MALHI, Y.; CHAVE, J.; BARLOW, J.; ... PHILLIPS, O. L. Compositional response of Amazon forests to climate change. *Global Change Biology*, v. 25, n. 1, p. 39-56, 2019. Disponível em: <https://doi.org/10.1111/GCB.14413>. Acesso em: 17 ago. 2025.
- FARIA, et al. HIV epidemiology. The early spread and epidemic ignition of HIV-1 in human populations. *Science*, v. 346, p. 56-61, 2014.
- FRIEDLINGSTEIN, P.; O'SULLIVAN, M.; JONES, M. W.; ANDREW, R. M.; BAKKER, D. C. E.; HAUCK, J. LANDSCHÜTZER, P.; LE QUÉRE, C.; LUIJKX, I. T.; PETERS, G. P.; PETERS, W.; PONGRATZ, J.; SCHWINGSHACKL, C.; SITCH, S.; CANADELL, J. G.; CIAIS, P.; JACKSON, R. B.; ALIN, S. R.; ANTHONI, P.; ... ZHENG, B. Global Carbon Budget 2023. *Earth System Science Data*, v. 15, n. 12, p. 5301-5369, 2023. Disponível em: <https://doi.org/10.5194/ESSD-15-5301-2023>. Acesso em: 17 ago. 2025.
- FU, R.; YIN, L.; LI, W.; ARIAS, P. A.; DICKINSON, R. E.; HUANG, L.; CHAKRABORTY, S.; FERNANDES, K.; LIEBMANN, B.; FISHER, R.; MYNENI, R. B. Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection. *Proceedings of the National Academy of Sciences of the United States of America*, v. 110, n. 45, p. 18110-18115, 2013.
- FLORES, et al., 2020. Soil erosion as a resilience drain in disturbed tropical forests. Disponível em: <https://link.springer.com/article/10.1007/s11104-019-04097-8>. Acesso em: 17 ago. 2025.
- FLORES, et al., 2021. White-Sand Savannas Expand at the Core of the Amazon After Forest Wildfires. Disponível em: <https://link.springer.com/article/10.1007/s10021-021-00607-x>. Acesso em: 17 ago. 2025.
- FLORES, B. M.; ESQUIVEL-MUELBERG, A.; EHRLICH, M.; VILANOVA, E.; CHAVES, R.; HIROTA, M.; KALAMANDÉEN, M. Nove maneiras de evitar o ponto de inflexão da Amazônia. *Policy Brief - Science Panel for the Amazon*, 2023.
- FLORES, B. M.; et al. Critical transitions in the Amazon forest system. *Nature*, v. 626, p. 555-564, 2024. Disponível em: <https://doi.org/10.1038/s41586-023-06970-0>. Acesso em: 17 ago. 2025.
- GATTI, L. V.; GLOOR, M.; MILLER, J. B.; DOUGHTY, C. E.; MALHI, Y.; DOMINGUES, L. G.; BASSO, L. S.; MARTINEWSKI, A.; CORREIA, C. S. C.; BORGES, V. F.; FREITAS, S.; BRAZ, R.; ANDERSON, L. O.; ROCHA, H.; GRACE, J.; PHILLIPS, O. L.; LLOYD, J. Drought sensitivity of Amazonian carbon balance revealed by atmospheric measurements. *Nature*, v. 506, n. 7486, p. 76-80, 2014. Disponível em: <https://doi.org/10.1038/nature12957>. Acesso em: 17 ago. 2025.
- GATTI, L. V.; et al. Amazonia as a carbon source linked to deforestation and climate change. *Nature*, v. 595, p. 388-393, 2021.
- GEDNEY, N.; COX, P. M.; BETTS, R. A.; BOUCHER, O.; HUNTINGFORD, C.; STOTT, P. A. Detection of a direct carbon dioxide effect in continental river runoff records. *Nature*, v. 439, n. 7078, p. 835-838, 2006. Disponível em: <https://doi.org/10.1038/nature04504>. Acesso em: 17 ago. 2025.
- GLADWELL, M. *The tipping point: how small things can make a big difference*. Back Bay: 2002.
- GLOOR, M.; GATTI, L.; BRIENEN, R.; FELDPAUSCH, T. R.; PHILLIPS, O. L.; MILLER, J.; OMETTO, J. P.; ROCHA, H.; BAKER, T.; DE JONG, B.; HOUGHTON, R. A.; MALHI, Y.; C. ARAGÃO, L.

- E. O.; GUYOT, J. L.; ZHAO, K.; JACKSON, R.; PEYLIN, P.; SITCH, S.; POULTER, B.; ... LLOYD, J. A review of the status, decadal trends and main determinants. *Biogeosciences*, v. 9, n. 12, p. 5407-5430, 2012. Disponível em: <https://doi.org/10.5194/BG-9-5407-2012>. Acesso em: 17 ago. 2025.
- GLOOR, M.; et al. Intensificação do ciclo hidrológico amazônico nas últimas duas décadas. *Geophysical Research Letters*, v. 40, n. 9, p. 1729-1733, 2013.
- GLOOR, M.; et al. Recent Amazon climate as background for possible ongoing and future changes of Amazon humid forests. *Global Biogeochemical Cycles*, v. 29, n. 9, p. 1384-1399, 2015.
- GOOD, P.; JONES, C.; LOWE, J.; BETTS, R.; BOOTH, B.; HUNTINGFORD, C. Quantifying Environmental Drivers of Future Tropical Forest Extent. *Journal of Climate*, v. 24, n. 5, p. 1337-1349, 2011. Disponível em: <https://doi.org/10.1175/2010JCLI3865.1>. Acesso em: 17 ago. 2025.
- GRYSEELS, S.; et al. Risk of human-to-wildlife transmission of SARS-CoV-2. *Mammal Review*, v. 51, p. 272-292, 2021.
- GOOD, P.; et al. 2011. Quantifying Environmental Drivers of Future Tropical Forest Extent. *Journal of Climate*, v. 24, n. 5, p. 1337-1349, 2011. Disponível em: <https://journals.ametsoc.org/view/journals/clim/24/5/2010jcli3865.1.xml>. Acesso em: 17 ago. 2025.
- HADDAD, E.; et al. Fatores econômicos do desmatamento na Amazônia Legal brasileira. *Nature Sustainability*, v. 7, p. 1141-1148, 2024. Disponível em: <https://doi.org/10.1038/s41893-024-01387-7>. Acesso em: 17 ago. 2025.
- HARPER, et al. 2010. Role of deep soil moisture in modulating climate in the Amazon rainforest. *Atmospheric Science*, v. 37, n. 5, 2010. Disponível em: <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2009GL042302>. Acesso em: 17 ago. 2025.
- HIROTA, M.; HOLMGREN, M.; VAN NES, E. H.; SCHEFFER, M. Global resilience of tropical forest and savanna to critical transitions. *Science*, v. 334, p. 232-235, 2011.
- HOEGH-GULDBERG, O.; JACOB, D.; TAYLOR, M.; BINDI, M.; BROWN, S.; CAMILLONI, I.; DIEDHIU, A.; DOYLE, R.; EBI, K.; ENGELBRECHT, F.; GUIOT, J.; HIJIOKA, Y.; MEHROTRA, S.; PAYNE, A.; SENEVIRATNE, S. I.; THOMAS, A.; WARREN, R.; ZHOU, G. Chapter 3: Impacts of 1.5°C of Global Warming on Natural and Human Systems. In: MASSON-DELMOTTE, V. et al. (eds.). *Global warming of 1.5°C: an IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Geneva: Intergovernmental Panel on Climate Change, 2018.
- HUBAU, W.; LEWIS, S. L.; PHILLIPS, O. L.; AFFUM-BAFFOE, K.; BEECKMAN, H.; CUNÍ-SANCHEZ, A.; DANIELS, A. K.; EWANGO, C. E. N.; FAUSET, S.; MUKINZI, J. M.; SHEIL, D.; SONKÉ, B.; SULLIVAN, M. J. P.; SUNDERLAND, T. C. H.; TAEDOUUM, H.; THOMAS, S. C.; WHITE, L. J. T.; ABERNETHY, K. A.; ADU-BREDU, S.; ZEMAGHO, L. Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature*, v. 579, n. 7797, p. 80-87, 2020. Disponível em: <https://doi.org/10.1038/s41586-020-2035-0>. Acesso em: 17 ago. 2025.
- HUNTINGFORD, C.; ZELAZOWSKI, P.; GALBRAITH, D.; MERCADO, L. M.; SITCH, S.; FISHER, R.; LOMAS, M.; WALKER, A. P.; JONES, C. D.; BOOTH, B. B. B.; MALHI, Y.; HEMMING, D.; KAY, G.; GOOD, P.; LEWIS, S. L.; PHILLIPS, O. L.; ATKIN, O. K.; LLOYD, J.; GLOOR, E.; COX, P. M. Simulated resilience of tropical rainforests to CO₂-induced climate change. *Nature Geoscience*, v. 6, n. 4, p. 268-273, 2013. Disponível em: <https://doi.org/10.1038/NNGEO1741>. Acesso em: 17 ago. 2025.
- IPCC – Intergovernmental Panel on Climate Change. *Climate Change and Land: IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. Cambridge: Cambridge University Press, 2022.
- IPCC – Intergovernmental Panel on Climate Change. *Resumo para formuladores de políticas*. In: H. Lee; J. Romero (eds.): *Climate Change 2023: Synthesis Report. Contribuição dos Grupos de Trabalho I, II e III para o Sexto Relatório de Avaliação do Painel Intergovernamental sobre Mudanças Climáticas*. Genebra, Suíça: IPCC, 2023.
- JAKOVAC, C. C.; et al., 2022. Strong floristic distinctiveness across Neotropical successional forests. *Science*, v. 8, n. 26, 2022. Disponível em: <https://www.science.org/doi/full/10.1126/sciadv.abn1767>. Acesso em: 17 ago. 2025.
- JOLLY, W. M.; COCHRANE, M. A.; FREEBORN, P. H.; HOLDEN, Z. A.; BROWN, T. J.; WILLIAMSON, G. J.; BOWMAN, D. M. J. S. Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications*, v. 6, n. 1, p. 1-11, 2015. Disponível em: <https://doi.org/10.1038/ncomms8537>. Acesso em: 17 ago. 2025.

- JONES, et al., 2009. Committed terrestrial ecosystem changes due to climate change. *Nature*, v. 2, p. 484-487, 2009. Disponível em: <https://www.nature.com/articles/ngeo555>. Acesso em: 17 ago. 2025.
- JUNK, W. J.; et al. A classification of major natural habitats of Amazonian white-water river floodplains (várzeas). *Wetlands Ecology and Management*, v. 19, n. 6, p. 609-621, 2011.
- KELLEY, D. I.; BURTON, C.; HUNTINGFORD, C.; BROWN, M. A. J.; WHITLEY, R.; DONG, N. Technical note: Low meteorological influence found in 2019 Amazonia fires. *Biogeosciences*, v. 18, n. 3, p. 787-804, 2021. Disponível em: <https://doi.org/10.5194/bg-18-787-2021>. Acesso em: 17 ago. 2025.
- KHANNA, J.; MEDVIGY, D.; FUEGLISTALER, S.; WALKO, R. Regional dry-season climate changes due to three decades of Amazonian deforestation. *Nature Climate Change*, v. 7, n. 3, p. 200-204, 2017. Disponível em: <https://doi.org/10.1038/nclimate3226>. Acesso em: 17 ago. 2025.
- KIMM, H.; PARK, S. W.; JUN, S. Y.; KUG, J. S. How Does Plant CO₂ Physiological Forcing Amplify Amazon Warming in CMIP6 Earth System Models?. *Earth's Future*, v. 12, n. 6, p. e2023EF004223, 2024. Disponível em: <https://doi.org/10.1029/2023EF004223>. Acesso em: 17 ago. 2025.
- KREIBIEHL, K.; et al. Investment and finance. In: IPCC, 2022: *Climate Change 2022: Mitigation of Climate Change*. [P. R. Shukla; J. Skea; R. Slade; A. Al Khourdajie; R. van Diemen; D. McCollum; M. Pathak; S. Some; P. Vyas; R. Fradera; M. Belkacemi; A. Hasija; G. Lisboa; S. Luz; J. Malley (eds.)]. Cambridge: Cambridge University Press, 2022.
- KUSCHNIG, M.; et al. Eroding resilience of deforestation interventions – evidence from Brazil's lost decade. *Environmental Research Letters*, v. 18, 074039, 2023.
- LANGILL, J. C.; ABIZAID, C. O que é uma inundação ruim? Perspectivas locais de inundações extremas na Amazônia peruana. *Ambio*, v. 49, p. 1423-1436, 2020.
- LAPOLA, D. M.; OYAMA, M. D.; NOBRE, C. A. Exploring the range of climate biome projections for tropical South America: The role of CO₂ fertilization and seasonality. *Global Biogeochemical Cycles*, v. 23, n. 3, 2009. Disponível em: <https://doi.org/10.1029/2008GB003357>. Acesso em: 17 ago. 2025.
- LAPOLA, D. M.; et al. Limiting the high impacts of Amazon forest dieback with no-regrets science and policy action. *Proceedings of the National Academy of Sciences*, v. 115, n. 46, p. 11671-11679, 2018.
- LAPOLA, D. M.; PINHO, P.; BARLOW, J.; C. ARAGÃO, E. O.; BERENGUER, E.; CARMENTA, R.; LIDDY, H. M.; SEIXAS, H.; J. SILVA, C. V.; L. SILVA-JUNIOR, C. H.; C. ALENCAR, A. A.; ANDERSON, L. O.; ARMENTERAS, D.; BROVKIN, V.; CALDERS, K.; CHAMBERS, J.; CHINI, L.; COSTA, M. H.; FARIA, B. L.; WALKER, W. S. The drivers and impacts of Amazon forest degradation. *Science*, v. 379, 2023.
- LEE, J.-Y.; MAROTZKE, J.; BALA, G.; CAO, L.; CORTI, S.; DUNNE, J. P.; ENGELBRECHT, F.; FISCHER, E.; FYFE, J. C.; JONES, C.; MAYCOCK, A.; MUTEMI, J.; NDIAYE, O.; PANICKAL, S.; ZHOU, T. Future Global Climate: Scenario-Based Projections and Near-Term Information. In: MASSON-DELMOTTE, V.; ZHAI, P.; PIRANI, A.; CONNORS, S. L.; PÉAN, C.; BERGER, S.; CAUD, N.; CHEN, Y.; GOLDFARB, L.; GOMIS, M. I.; HUANG, M.; LEITZELL, K.; LONNOY, E.; MATTHEWS, J. B. R.; MAYCOCK, T. K.; WATERFIELD, T.; YELEKÇI, O.; YU, R.; ZHOU, B., eds. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, New York: Cambridge University Press, 2021.
- LENTON, T. M.; ARMSTRONG MCKAY, D. I.; LORIANI, S.; ABRAMS, J. F.; LADE, S. J.; DONGES, J. F.; MILKOREIT, M.; POWELL, T.; SMITH, S. R.; ZIMM, C.; BUXTON, J. E.; BAILEY, E.; LAYBOURN, L.; GHADIALI, A.; DYKE, J. G. The Global Tipping Points Report 2023. Exeter: University of Exeter, 2023.
- LIZUNDIA-LOIOLA, J.; OTÓN, G.; RAMO, R.; CHUVIECO, E. A spatio-temporal active-fire clustering approach for global burned area mapping at 250 m from MODIS data. *Remote Sensing of Environment*, v. 236, 111493, 2020. Disponível em: <https://doi.org/10.1016/j.rse.2019.111493>. Acesso em: 17 ago. 2025.
- LOMBARDO, et al. Evidence confirms an anthropic origin of Amazonian Dark Earths. *Nature Communications*, v. 13, 3444, 2022. Disponível em: <https://doi.org/10.1038/s41467-022-31064-2>. Acesso em: 17 ago. 2025.
- LOWE, R.; et al. Emerging arboviruses in the urbanized Amazon rainforest. *BMJ*, v. 371, 2020.
- MACDOUGALL, A. H.; FRÖLICHER, T. L.; JONES, C. D.; ROGELJ, J.; DAMON-MATTHEWS, H.; ZICKFELD, K.; ARORA, V. K.; BARRETT, N. J.; BROVKIN, V.; BURGER, F. A.; EBY, M.; ELISEEV, A. V.; HAJIMA, T.; HOLDEN, P. B.; JELTSCH-THÖMMES, A.; KOVEN, C.; MENGIS, N.; MENVIEL, L.; MICHOU, M.; ZIEHN, T. A multi-model analysis of the Zero Emissions Commitment from CO₂. *Biogeosciences*, v. 17, n. 11, p. 2987-3016, 2020.

Disponível em: <https://doi.org/10.5194/bg-17-2987-2020>. Acesso em: 17 ago. 2025.

MAGALHÃES, M. P. O prístino e o devenir na história indígena de longa duração na Amazônia. *Boletim do Museu Paraense Emílio Goeldi. Ciências Humanas*, v. 18, n. 3, p. e20220079, 2023. Disponível em: <https://doi.org/10.1590/2178-2547-BGOELDI-2022-0079>. Acesso em: 17 ago. 2025.

MAIA, H. C.; HARGRAVE, J. C.; GÓMEZ, J. J. C.; RÖPER, M. C. Avaliação do Plano de Ação para a Prevenção e Controle do Desmatamento da Amazônia Legal – PPCDAm 2007-2010. Brasília, DF: CEPAL; IPEA; GIZ, 2011.

MALHI, Y.; et al. Climate change, deforestation, and the fate of the Amazon. *Science*, v. 319, n. 5860, p. 169-172, 2008.

MALHI, Y.; et al. 2009. Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proc. Natl. Acad. Sci. U.S.A.*, v. 106, n. 49, p. 20610-20615, 2009. Disponível em: <https://www.pnas.org/doi/10.1073/pnas.0804619106>. Acesso em: 17 ago. 2025.

MALHI, Y.; GARDNER, T. A.; GOLDSMITH, G. R.; SILMAN, M. Tropical Forests in the Anthropocene. *Annual Review of Environment and Resources*, v. 39, n. 1, p. 125-159, 2014. DOI: 10.1146/annurev-environ-030713-155141.

MATTOS, et al., 2023. Double stress of waterlogging and drought drives forest-savanna coexistence. *Proc. Natl. Acad. Sci. U.S.A.*, v. 120, n. 33, p. e2301255120, 2023. Disponível em: <https://www.pnas.org/doi/abs/10.1073/pnas.2301255120>. Acesso em: 17 ago. 2025.

MATTOS, et al. Manutenção das Terras Indígenas é fundamental para a segurança hídrica e alimentar em grande parte do Brasil. Nota Técnica Instituto Serrapilheira, 2024.

MARENGO, J. A.; et al. Climate change in the Amazon Basin: Tipping points, changes in extremes, and impacts on natural and human systems *Climate Change*, v. 2, n. 3, p. 253-271, 2011.

MARENGO, J. A.; ESPINOZA, J. C. Extreme seasonal droughts and floods in Amazonia. *International Journal of Climatology*, v. 36, n. 3, p. 1033-1050, 2016.

MARENGO, J. A.; et al. Changes in Climate and Land Use Over the Amazon Region. *Frontiers in Earth Science*, v. 6, 228, 2018.

MCDOWELL, N.; et al. Drivers and mechanisms of tree mortality in moist tropical forests. *New Phytologist*, v. 219, n. 3, p. 851-869, 2018.

MILKOREIT, M. Cognitive capacities for global governance in the face of complexity: the case of climate tipping points In: *Global Challenges, Governance, and Complexity*. Edward Elgar Publishing, 2019.

NDC – Nationally Determined Contribution, Brasil, 2023. Disponível em: <https://unfccc.int/sites/default/files/NDC/2023-11/Brazil%20First%20NDC%202023%20adjustment.pdf>. Acesso em: 17 ago. 2025.

NIAN, D.; BATHIANY, S.; BEN-YAMI, M.; BLASCHKE, L. L.; HIROTA, M.; RODRIGUES, R. R.; BOERS, N. A potential collapse of the Atlantic Meridional Overturning Circulation may stabilise eastern Amazonian rainforests. *Communications Earth & Environment*, v. 4, n. 1, p. 1-11, 2023. Disponível em: <https://doi.org/10.1038/s43247-023-01123-7>. Acesso em: 17 ago. 2025.

NOBRE, C. A.; et al. Riscos de uso da terra e mudanças climáticas na Amazônia e a necessidade de um novo paradigma de desenvolvimento sustentável. *Anais da Academia Nacional de Ciências*, v. 113, n. 39, p. 10759-10768, 2016.

NOBRE, C. A.; et al. Nova economia para a Amazônia brasileira. São Paulo: WRI Brasil, 2023. Relatório. Disponível em: <http://www.wribrasil.org.br/nova-economia-da-amazonia>. Acesso em: 17 ago. 2025.

NUNES, et al. Lessons from the historical dynamics of environmental law enforcement in the Brazilian Amazon. *Scientific Reports*, v. 14, 1828, 2024. Disponível em: <https://doi.org/10.1038/s41598-024-52180-7>. Acesso em: 17 ago. 2025.

O'NEILL, et al. IPCC AR6 WG2, capítulo 16, 2021.

PALAZZO CORNER, S.; JONES, C. D. Tipping Points: Climate Surprises. *Frontiers for Young Minds*, v. 9, 2021. Disponível em: <https://doi.org/10.3389/frym.2021.703610>. Acesso em: 17 ago. 2025.

PAPASTEFANOU, P.; et al. Recent extreme drought events in the Amazon rainforest: assessment of different precipitation and evapotranspiration datasets and drought indicators. *Biogeosciences*, v. 19, p. 3843-3861, 2022.

PARKER, E. R.; MO, J.; GOODMAN, R. S. The dermatological manifestations of extreme weather events: A comprehensive review of skin disease and vulnerability. *J. Climate Change Health*, v. 8, p. 100-162, 2022.

PARRY, L.; et al. Social Vulnerability to Climatic Shocks Is Shaped by Urban Accessibility. *Annals of the American Association of Geographers*, v. 108, p. 125-143, 2018.

- PARRY, I.; RITCHIE, P.; COX, P. Evidence of Amazon rainforest dieback in CMIP6 models. *EGUsphere* [preprint], 2022. Disponível em: <https://doi.org/10.5194/egusphere-2022-82>. Acesso em: 17 ago. 2025.
- PHILLIPS, O. L.; BAKER, T. R.; ARROYO, L.; HIGUCHI, N.; KILLEEN, T. J.; LAURANCE, W. F.; LEWIS, S. L.; LLOYD, J.; MALHI, Y.; MONTEAGUDO, A.; NEILL, D. A.; NÚÑEZ VARGAS, P.; SILVA, J. N. M.; TERBORGH, J.; VÁSQUEZ MARTÍNEZ, R.; ALEXIADES, M.; ALMEIDA, S.; BROWN, S.; CHAVE, J.; VINCETI, B. Pattern and process in Amazon tree turnover, 1976–2001. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, v. 359, n. 1443, p. 381–407, 2004. Disponível em: <https://doi.org/10.1098/RSTB.2003.1438>. Acesso em: 17 ago. 2025.
- PUGH, T. A. M.; JONES, C. D.; HUNTINGFORD, C.; BURTON, C.; ARNETH, A.; BROVKIN, V.; CIAIS, P.; LOMAS, M.; ROBERTSON, E.; PIAO, S. L.; SITCH, S. A Large Committed Long-Term Sink of Carbon due to Vegetation Dynamics. *Earth's Future*, v. 6, n. 10, p. 1413–1463, 2018. Disponível em: <https://doi.org/10.1029/2018EF000935>. Acesso em: 17 ago. 2025.
- REQUÍA, W. J.; AMINI, H.; MUKHERJEE, R.; GOLD, D. R.; SCHWARTZ, J. D. Health impacts of wildfire-related air pollution in Brazil: a nationwide study of more than 2 million hospital admissions between 2008 and 2018. *Nature Communications*, v. 12, p. 6555, 2021.
- RITCHIE, P. D. L.; CLARKE, J. J.; COX, P. M.; HUNTINGFORD, C. Overshooting tipping point thresholds in a changing climate. *Nature*, v. 592, n. 7855, p. 517–523, 2021. Disponível em: <https://doi.org/10.1038/s41586-021-03263-2>. Acesso em: 17 ago. 2025.
- ROMERO, L. S.; JACOBSON, L. da S. V.; HACON, S. de S. Mortalidade cerebrovascular: tendência e sazonalidade nas capitais brasileiras, 2000–2019. *Revista de Saúde Pública*, v. 57, n. 1, 53, 2023. Disponível em: <https://doi.org/10.11606/s1518-8787.2023057004813>. Acesso em: 17 ago. 2025.
- ROWLAND, et al., 2015. Death from drought in tropical forests is triggered by hydraulics not carbon starvation. *Nature*, v. 528, p. 119–122, 2015. Disponível em: <https://www.nature.com/articles/nature15539>. Acesso em: 17 ago. 2025.
- SALAZAR, L. F.; NOBRE, C. A.; OYAMA, M. D. Climate change consequences on the biome distribution in tropical South America. *Geophysical Research Letters*, v. 34, n. 9, p. 9708, 2007. Disponível em: <https://doi.org/10.1029/2007GL029695>. Acesso em: 17 ago. 2025.
- SALVADOR, C.; et al. Public Health Implications of Drought in a Climate Change Context: A Critical Review. *Annual Review of Public Health*, v. 44, p. 213–232, 2023.
- SAMPAIO, G.; SHIMIZU, M. H.; GUIMARÃES-JÚNIOR, C. A.; ALEXANDRE, F.; GUATURA, M.; CARDOSO, M.; DOMINGUES, T. F.; RAMMIG, A.; VON RANDOW, C.; REZENDE, L. F. C.; LAPOLA, D. M. CO2 physiological effects can cause rainfall decrease as strong as large-scale deforestation in the Amazon. *Biogeosciences*, v. 18, n. 8, p. 2511–2525, 2021. Disponível em: <https://doi.org/10.5194/BG-18-2511-2021>. Acesso em: 17 ago. 2025.
- SANTOS DA SILVA, L. L.; et al. Maternal pre-pregnancy body mass index, gestational weight gain and child weight during the first 2 years of life in an Amazonian birth cohort. *J. Hum. Nutr. Diet. Off. J. Br. Diet. Assoc.*, v. 36, p. 1327–1338, 2023.
- SEGOVIANO-LORENZO, M. del C.; et al. Prevalência de desnutrição, anemia e helmintíase transmitida pelo solo em crianças em idade pré-escolar que vivem em populações periurbanas na Amazônia peruana. *Cadernos de Saúde Pública*, v. 38, n. 11, p. e00248221, 2022.
- SCHAEFER, B. M.; KRAUSE, S. Financiamento eleitoral e representação política no Brasil durante o governo Bolsonaro (2019–2022): entre velhos e novos problemas. *Revista Uruguaya de Ciencia Política*, v. 33, n. 1, p. 1–24, 2024. Disponível em: <https://doi.org/10.26851/rucp.33.2>. Acesso em: 17 ago. 2025.
- SHUKLA, J.; NOBRE, C.; SELLERS, P. Amazon deforestation and climate change. *Science*, v. 247, n. 4948, p. 1322–1325, 1990.
- SILVÉRIO, D.; et al. Testing the Amazon savannization hypothesis: fire effects on invasion of a neotropical forest by native cerrado and exotic pasture grasses. *Phil. Trans. R. Soc. B*, v. 368, n. 1619, p. 20120427, 2013. Disponível em: <https://royalsocietypublishing.org/doi/full/10.1098/rstb.2012.0427>. Acesso em: 17 ago. 2025.
- SIQUEIRA JÚNIOR, J. L.; et al. Hydrological Changes Driven by Climate Change and Deforestation in the Amazon. *Science Advances*, v. 1, n. 6, e1500321, 2015.
- SIMPSON, S. Challenges in the Amazon Basin: Environment, Security, and Governance. Instituto Republicano Internacional, 2024. Disponível em: <https://www.iri.org/news/challenges-in-the-amazon-basin-environment-security-and-governance/>. Acesso em: 17 ago. 2025.
- SKINNER, C. B.; POULSEN, C. J.; CHADWICK, R.; DIFFENBAUGH, N. S.; FIORELLA, R. P. The Role of

Plant CO₂ Physiological Forcing in Shaping Future Daily-Scale Precipitation. *Journal of Climate*, v. 30, n. 7, p. 2319–2340, 2017. Disponível em: <https://doi.org/10.1175/JCLI-D-16-0603.1>. Acesso em: 17 ago. 2025.

SOUZA, G.; DOMINGUES, E.; MAGALHÃES, A. Impactos do Crescimento Econômico com Preservação Florestal nos Biomas Amazônia e Cerrado no Brasil. *Economia da Mudança Climática*, 2024.

SPRACKLEN, et al. Observations of increased tropical rainfall preceded by air passage over forests. *Nature*, v. 489, p. 282–285, 2012. Disponível em: <https://www.nature.com/articles/nature11390>. Acesso em: 17 ago. 2025.

STAAL, A.; et al. Forest-rainfall cascades buffer against drought across the Amazon. *Nature Climate Change*, v. 8, n. 6, p. 539–543, 2018.

STAAL, A.; FLORES, B. M.; AGUIAR, A. P. D.; BOSMANS, J. H. C.; FETZER, I.; TUINENBURG, O. A. Feedback between drought and deforestation in the Amazon. *Environmental Research Letters*, v. 15, n. 4, p. 044024, 2020. Disponível em: <https://doi.org/10.1088/1748-9326/AB738E>. Acesso em: 17 ago. 2025.

STAYER, C.; et al. The Global Extent and Determinants of Savanna and Forest as Alternative Biome States. *Science*, v. 334, n. 6053, p. 230–232, 2011. Disponível em: <https://www.science.org/doi/10.1126/science.1210465>. Acesso em: 17 ago. 2025.

LOVEJOY, T. E.; NOBRE, C. Amazon Tipping Point. *Science Advances*, v. 4, eaat2340, 2018. Disponível em: <https://doi.org/10.1126/sciadv.aat2340>. Acesso em: 17 ago. 2025.

UHART, M.; et al. A 'One Health' Approach to Predict Emerging Zoonoses in the Amazon, 2012. Disponível em: <https://doi.org/10.13140/RG.2.1.3549.1609>. Acesso em: 17 ago. 2025.

UITTO, J.; et al. Evaluating Transformational Change – Lessons from International Environmental Funds. In: VAN DEN BERG, R. D.; MAGRO, C.; MULDER, S. S. Evaluation for Transformational Change. Exeter, Reino Unido, p. 105–130, 2019.

VAL, A. L.; et al. Como a Bioeconomia na Amazônia Pode Contribuir para a Segurança Alimentar dos Povos Originários e Consumidores Tradicionais. In: HUNGRIA, M. (org.). *Segurança Alimentar e Nutricional: O Papel da Ciência Brasileira no Combate à Fome*. Rio de Janeiro: Academia Brasileira de Ciências, v. 1, p. 105–115, 2024.

VALE, et al. Could a future pandemic come from the Amazon?. *Zenodo*, v. 1, 2021. Disponível em: <https://doi.org/10.5281/ZENODO.4606591>. Acesso em: 17 ago. 2025.

VALE, et al. The COVID-19 pandemic as an opportunity to weaken environmental protection in Brazil. *Biological Conservation*, v. 255, 2021. Disponível em: <https://doi.org/10.1016/j.biocon.2021.108994>. Acesso em: 17 ago. 2025.

VAN DEN BERG, R. D.; MAGRO, C. Systems Assessments for Transformational Change: Challenges and Opportunities. In: VAN DEN BERG, R. D.; MAGRO, C.; MULDER, S. S. Evaluation for Transformational Change. Exeter, Reino Unido, p. 131–155, 2019.

VIEIRA, I.; TOLEDO, P.; SILVA, J.; HIGUCHI, H. Desmatamento e ameaças à biodiversidade da Amazônia. *Revista Brasileira de Biologia*, v. 68, n. 4, p. 949–956, 2008. Disponível em: <https://doi.org/10.1590/S1519-69842008000500004>. Acesso em: 17 ago. 2025.

VILANI, et al. The first acts of Brazil's new president: Lula's new Amazon institutionalism. *Environmental Conservation*, v. 50, n. 3, p. 148–151, 2023. Disponível em: <https://doi.org/10.1017/S0376892923000139>. Acesso em: 17 ago. 2025.

WEGNER, G. I.; MURRAY, K. A.; SPRINGMANN, M.; MULLER, A.; SOKOLOV, S. H.; SAYLORS, K.; MORENS, D. M. Averting wildlife-borne infectious disease epidemics requires a focus on socio-ecological drivers and a redesign of the global food system. *EClinicalMedicine*, v. 47, p. 101386, 2022. Disponível em: <https://doi.org/10.1016/j.eclinm.2022.101386>. Acesso em: 17 ago. 2025.

WESTERHOLD, T.; et al. An astronomically dated record of Earth's climate and its predictability over the last 66 million years. *Science*, v. 369, p. 1383–1387, 2020.

WILLIAMS, J. W.; JACKSON, S. T.; KUTZBACH, J. E. Projected distributions of novel and disappearing climates by 2100 AD. *Proceedings of the National Academy of Sciences*, v. 104, p. 5738–5742, 2007.

WINCK, G. R.; et al. Socioecological vulnerability and the risk of zoonotic disease emergence in Brazil. *Science Advances*, v. 8, 2022.

WOROBAY, M.; et al. 1970's and 'Patient 0' HIV-1 genomes illuminate early HIV/AIDS history in North America. *Nature*, v. 539, p. 98–101, 2016.

ZEMP, D. C.; et al. Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks. *Nature Communications*, v. 8, n. 1, p. 14681, 2017.





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

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