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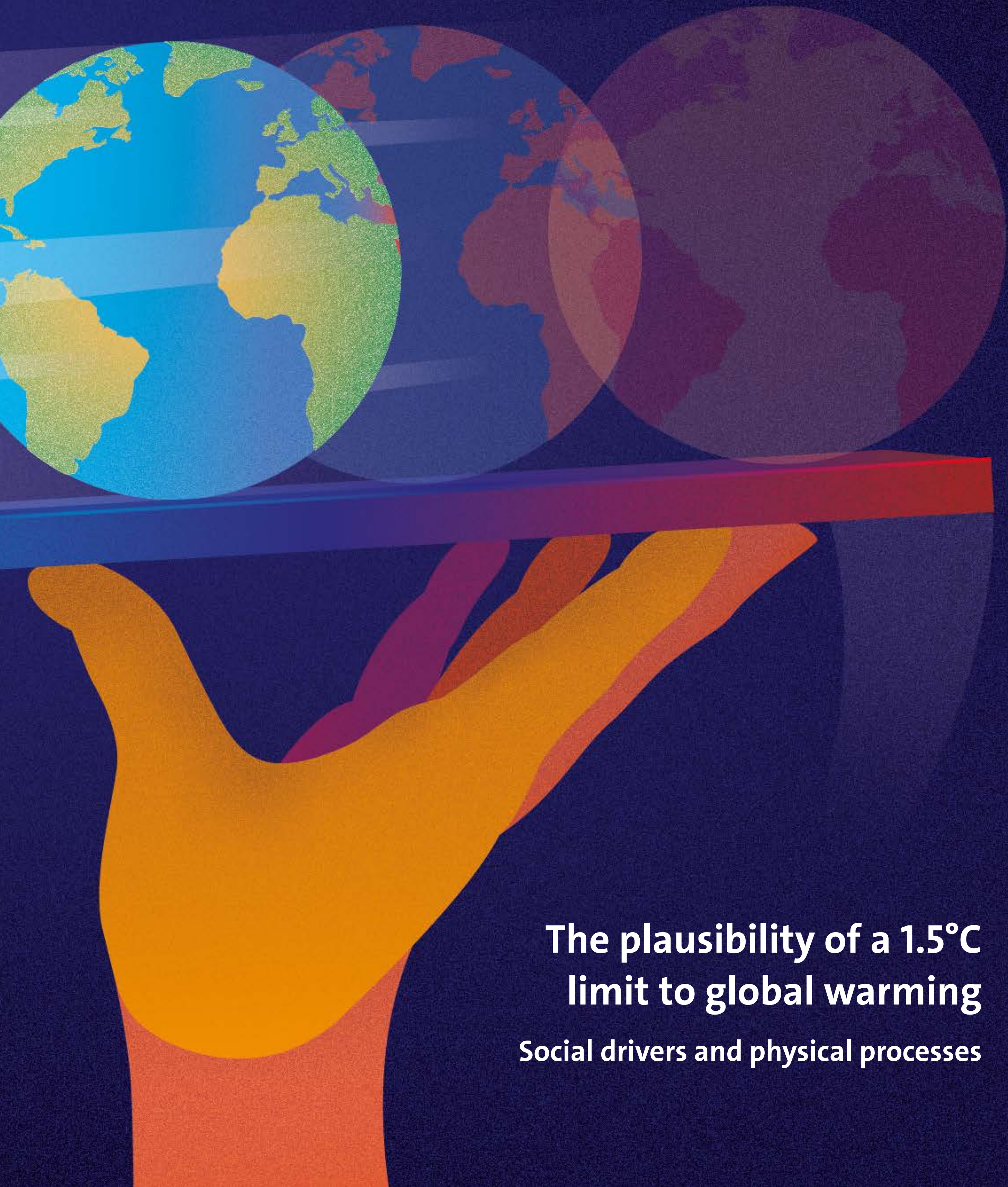
HAMBURG CLIMATE FUTURES OUTLOOK



The plausibility of a 1.5°C limit to global warming

Social drivers and physical processes

6.2.5

Amazon Forest dieback

Forest dieback is a phenomenon characterized by the loss of health and vitality of trees in a forest ecosystem. Forest dieback usually includes multiple interacting factors that can range from abiotic (e.g., drought) and biotic (e.g., insect pests, disease) to human interventions (e.g., deforestation) and can encompass reversible as well as irreversible damage. Here, we understand forest dieback as a large-scale phenomenon in which tree mortality exceeds usual mortality levels on a continental scale (hundreds of thousands of square kilometers).

In this section, we focus on the Amazon Forest dieback and describe underlying physical processes, providing insights on the conditions that enable or constrain the plausibility of attaining the Paris Agreement temperature goals. Furthermore, we consider the potential consequences and future developments of the Amazon Forest dieback if the global temperature is not limited to the temperature goals. We also address links to social processes, such as settlement, agriculture, forestry, protected areas, and geopolitics. Finally, we assess the plausibility of drastic changes in the Amazon Forest dieback within the 21st century.

Description of the physical process and its past evolution

Amazonia covers an area of about 7 million km^2. It is characterized by floodplains, whitewater-flooded *Várzeas* and blackwater-flooded *Igapó*, which are seasonally inundated by the Rio Amazonas and its tributaries, and by uplands, called *Terra firme*, which lie above the flood levels. About 5.3 million km^2 of Amazonia are forested and comprise about 40% of the world's tropical forests area (Nobre et al., 2016; FAO, 2020; da Cruz et al., 2021).

Amazonia showed an average warming trend of about 1°C between 1979 and 2018 (Marengo et al., 2018; Gatti et al., 2021). However, not only higher temperatures but also changes in weather patterns and precipitation have had large repercussions for the Amazon Forest. In addition to climate change, changing land use is a particularly significant large-scale driver in ecosystems. Thus, in this section, we specifically address the role of deforestation and forest degradation.

Deforestation

Although the Amazon Forest's biome is of outstanding ecological importance and harbors 10% to 15% of global land biodiversity (Hubbell et al., 2008), forest cover directly competes with other forms of land use, especially agriculture. The loss of tropical forest cover is closely linked to diverse interests in socioeconomic and political realities such as higher benefits from land use, control over strategic resources, or poverty-driven efforts to survive. Changes in land use may be caused by demographic trends, technological advances, changes in consumer behavior, or the desire to increase economic output (Walker, 1993). Before the 1960s, deforestation in Amazonia was due mainly to subsistence farming. In the 1960s, Amazonian states mostly under military rule applied modernist development models integrating Amazonia as a resource-rich zone to be colonized and exploited into their national strategies. Subsequently, deforestation increased and proceeded in waves, influenced by the respective national development plans for raw material extraction, agrarian colonization, infrastructural expansion, or, since the 1990s, for sustainable development and nature conservation (Hall, 1997; Becker, 2016). Thus, since the 1970s, significant parts of the old-growth forests have been converted into agricultural land and pasture. In the tropics, fire is often used as a land-management tool, and deforestation usually results from the burning of tree vegetation. By 2020, an area of nearly 600,000 km^2 had been deforested. Between 1996 and 2005, average annual deforestation amounted to 19,625 km^2 and reached a peak of 27,772 km^2 in 2004. Thereafter, deforestation declined and reached a historic low of 4,571 km^2 in 2012 (Assis et al., 2019; Silva Junior et al., 2021). Due to a change in Brazilian land-use policies, the rate of deforestation has increased significantly again in recent years, reaching a decade high of 11,088 km^2 in 2020 (Marengo et al., 2018; FAO, 2020; Beuchle et al., 2021; Silva Junior et al., 2021).

Degradation

Forest degradation plays a crucial role and the area affected by degradation exceeds the one of deforestation (Matricardi et al., 2020; Vancutsem et al., 2021). Degradation is much more difficult to detect in satellite remote sensing data than deforestation, because degradation activities open but do not completely remove the canopy (Baldauf and Galo, 2016). Degradation is a gradual process by which a forest's biomass or soil quality decline, or its species composition changes. Major causes of degradation are forest fires, edge effects, and timber harvesting (Silva Junior et al., 2020; Beuchle et al., 2021; Qin et al., 2021). In Amazonia, forest fires are almost exclusively due to human influences (Johnson and Miyanishi, 2001; Goldammer, 2016). Unlike forests in Siberia, California, or Australia, where ground fires are part of ecological processes, forests in Amazonia are not natural fire ecosystems. Here, fires are either deliberately set, or fires from slash and burn or burning agricultural fields which migrate uncontrollably into adjacent forests. Forest edges are exposed to higher temperatures, wind speed, and less humidity than the forest interior and therefore are more susceptible to fires and droughts. Timber harvesting in the Amazon Forest utilizes one to three commercially viable trees per hectare. Though this at first seems to have minor impact, in addition to utilized harvested timber, a substantial volume is removed from growing stock due to improper felling techniques and skid trails. Timber-harvesting losses can make up as much as seven times the timber volume extracted from the forest (Enters, 2001). Exploitation that removes too much wood at too-short intervals is common in Amazonia. Often, even when timber-harvesting measures are described as sustainable, the growth rates of the remaining forests and thus their ability to recover from harvest interventions are significantly overestimated (Butarbutar et al., 2019; Gräfe et al., 2020; Gräfe and Köhl, 2020).

In this section, we summarize the impact of climate change, deforestation, and forest degradation on three areas reflecting recent changes in the Amazon Forest: the hydrological cycle, forest resilience, and the carbon cycle. Indeed, changes in the hydrological cycle affect forest resilience, which in turn has repercussions for carbon fluxes.

Hydrological cycle

The Amazon basin is the largest watershed on Earth and plays a crucial role in the water and energy cycles at the atmosphere-biosphere-soil interface by actively driving atmospheric circulation and continental moisture recycling (Zemp et al., 2014; Espinoza et al., 2019). About one-third of the precipitation in the Amazon Forest originates within the Amazon basin, and two-thirds are the result of tree transpiration (Staal et al., 2018). Thus, evapotranspiration shapes regional and remote rainfall patterns. The average precipitation in Amazonia is 2200 mm yr^{-1} (Marengo et al., 2018).

Spatial and temporal precipitation patterns in Amazonia are also regulated by the sea surface temperature (SST) across the tropical and North Atlantic Ocean and by the rain belt associated with the Intertropical Convergence Zone, a region around the equator where southward and northward trade winds converge and create a vertical motion of air. Also, El Niño and La Niña events affect weather patterns in Amazonia. El Niño events show above-average SST in the central and east-central equatorial Pacific Ocean and are accompanied by low air pressure in the eastern and high air pressure in the western Pacific Ocean. El Niño events usually cause higher temperatures and water deficits in Amazonia and thus favor droughts. By contrast, La Niña conditions lead to intense rainfall over northern Amazonia with consequent flooding of the basin (Cox et al., 2008; Jiménez-Muñoz et al., 2016; Barichivich et al., 2018; Espinoza et al., 2022).

Over the last three to four decades, the Amazon Forest has experienced a decrease in rainfall during the dry season and an increase during the wet season (Fu et al., 2013; Debortoli et al., 2015; Almeida et al., 2017). It has been observed that eastern and southern Amazonia, which are more strongly affected by anthropogenic activities, are turning drier, while northern and central Amazonia are becoming wetter (Haghtalab et al., 2020). A shortening of the rainy season and a lengthening of the dry season in southern Amazonia have also been observed, mainly due to a delay in the onset of rainfall and premature demise (Fu et al., 2013; Debortoli et al., 2015; Arvor et al., 2017). An extended dry season is characterized by anomalously low river levels, and is often followed by a prolonged fire season (Fu et al., 2013; Marengo and Espinoza, 2016). Furthermore, Amazonia has experienced more frequent extreme hydrological events such as droughts and floods characterized as "once in a century." There were exceptional droughts in 2005, 2010, 2015–2016, and 2019–2020 (Marengo et al., 2022), while historical floods occurred in 2009, 2012, 2017, and 2021 (Espinoza et al., 2022).

Reducing the forest cover has feedback effects on rainfall patterns and the hydrological cycle. While the impact of business-as-usual deforestation on the annual mean rainfall is expected to exceed natural variability, avoiding new deforestation may positively affect the hydrological cycle in Amazonia (Spracklen and Garcia-Carreras, 2015).

Forest resilience

Forests are dynamic ecosystems subject to environmental change or disturbance. According to IPCC, resilience is "the capacity of interconnected social, economic, and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning, and/or transformation" (IPCC, 2021a). Decisive for the assessment of the resilience of an ecosystem is whether the system follows a single equilibrium, thus a single stable state, or whether there are several stable states, implying that an ecosystem can shift to another stable state after disturbances (Gunderson, 2000).

While temperate forests and high-latitude regions have shown a greening trend associated with land management, climate change, and CO_2 fertilization over the last two decades, the Amazon Forest reveals a browning trend (e.g., Winkler et al., 2021). The drying trend comes on top of ongoing deforestation and forest fragmentation and degradation, raising the issue of Amazon Forest resilience with respect to future climate and CO_2 scenarios. Analysis of early-warning signals in remote-sensing time series indicates that three-quarters of the

Amazon Forest are already experiencing a loss in resilience due to deforestation and climate change (Boulton et al., 2022). Additionally, droughts amplify the trees' physiological stress (Fontes et al., 2018) and affect tree biomass production. Droughts and fires can lead to enhanced tree mortality (Brando et al., 2014). It was observed that regions with deficient rainfall and vicinity to anthropogenic activities lose their resilience faster than wetter and more pristine regions of Amazonia (Boulton et al., 2022). In contrast to these findings on reduced resilience, Huntingford et al. (2013) found evidence for forest resilience in tropical rainforests based on a simulation study using 22 climate models and a land-surface model, with the largest uncertainties related to plant-physiological behavior.

The seasonally flooded forests, Várzea and Igapó, and the upland Terra firme forests differ in structure and composition (e.g., Bredin et al., 2020). In floodplain forests, the increase in biomass is mainly determined by the length of the flood-free period. As mentioned above, El Niño causes anomalously low precipitation in the Amazon basin, which in turn reduces the intensity of flooding. Since trees stop growing when flooded, El Niño prolongs the plant-growing season and a larger sequestration of atmospheric CO_2 was observed for floodplain forests during El Niño events (Schöngart et al., 2004). However, these results apply to floodplain forests only and are not generally applicable to the entire Amazonia. Indeed, tree species are affected in varying degrees by changing environmental conditions, especially soil-water deficits. Tall trees and trees with low wood density, as well as smaller trees, which tend to have shallower roots, suffer from soil-water deficits (Enquist and Enquist, 2011; Fauset et al., 2012; Rowland et al., 2015). Esquivel-Muelbert et al. (2019) report that in Amazonia the mortality of wet-affiliated trees has increased in dry seasons, leading to a shift to taxa which are more drought-tolerant.

In addition to drought, other causes of increased tree mortality in Amazonia are increased temperatures and associated vapor pressure deficits (Trenberth et al., 2014) and increased CO_2 levels. Rising temperatures initially lead to an increase in photosynthetic rates, but when an optimal temperature is exceeded, the photosynthetic rate decreases. This depends, on the one hand, on the temperature-dependent intensity of photosynthetic enzymes, and, on the other hand, on the decreasing stomatal conductance at higher temperatures (Matyssek et al., 2010). Furthermore, model-based results suggest a benefit for survival under increasing CO_2 levels (Liu et al., 2017). However, these benefits are not supported by observational studies on drought-CO_2 relationships (Allen et al., 2015). This is attributed to the fact, among others, that rising CO_2 leads to stronger tree growth and thus to increased competition between trees and corresponding mortality (McDowell et al., 2008; McDowell et al., 2018). Changes in temperature and precipitation will also increase the occurrence and impact of other biotic (e.g., insects, fungi, lianas) and abiotic (e.g., wind, fire) agents (Anderegg, 2015; Anderegg et al., 2015; Aragão et al., 2018; McDowell et al., 2018), and thus reduce tree growth and increase tree mortality.

Carbon cycle

The Amazon Forest plays a crucial role in the global carbon cycle, as it stores roughly 50% of tropical-forest carbon as vegetation biomass and soil carbon (Pan et al., 2011; Castanho et al., 2013). In the form of vegetation biomass, it holds about one-tenth of the total carbon stored in land ecosystems (Tian et al., 2000). As soil carbon, it is estimated to store 123 to 200 PgC (Malhi et al., 2006; Saatchi et al., 2011). Besides exchanging CO_2 with the atmosphere, the Amazon Forest is also cycling methane. Living and dead trees can emit methane produced by microorganisms or by abiotic photochemical processes (Covey and Megonigal, 2019; Welch et al., 2019). Carbon fluxes in Amazonia show interannual differences depending on the vegetation response to dry or wet conditions, turning Amazonia from a net carbon sink to carbon-neutral during dry years (Gatti et al., 2014). Indeed, it has been observed that during dry periods the carbon sequestration in the woody biomass of stems, branches, and roots decreases (Doughty et al., 2014; Feldpausch et al., 2016; Rifai et al., 2018; Janssen et al., 2021). Thus, changes in climatic conditions impact the Amazon Forest's carbon emission and sequestration.

Forest clearing processes such as fragmentation and deforestation (Silva Junior et al., 2018) also lead to a decline in the carbon sink (Brienen et al., 2015; Hubau et al., 2020; Gatti et al., 2021). Carbon emissions are more pronounced in the eastern Amazonia than in the western, mainly due to human-induced carbon-monoxide-derived emissions. In particular, the south-eastern Amazonia became a net carbon source due to fire emissions (Gatti et al., 2021). Mainly at the end of the dry season, human-induced forest fires intensify because large quantities of easily combustible dead wood accumulate. Carbon emissions due to fires are estimated to account for half of the emissions from deforestation (Aragão et al., 2018). Avoided deforestation would reduce the spread of fires, cutting the total net fire emissions in half (Brando et al., 2020). Additionally, greenhouse gas emissions from harvesting can reach 10% to 50% of the emissions caused by deforestation (Pearson et al., 2017). In contrast to sustainably managed forests, carbon substitution and storage effects of wood use cannot compensate for carbon loss associated with timber harvesting (Butarbutar et al., 2016). Qin et al. (2021) estimated that the Brazilian Amazonia lost annually 0.67 PgC from 2010 to 2019 in the form of aboveground biomass, 73% due to degradation and 27% due to deforestation. Old-growth trees in tropical forests generally remove more carbon than young trees (Köhl et al., 2017). However, with respect to CO_2 removals by forests, the capacity of the area, rather than that of individual trees, is decisive.

Heinrich et al. (2021) report that secondary forests in Amazonia sequester carbon up to 20 times faster than old-growth forests and thus represent a significant carbon sink.

About one-tenth of global CO_2 emissions are due to deforestation and forest degradation (Canadell et al., 2021, WGI AR6 Chapter 5), which counteract international efforts to reduce emissions. According to FAO (2022b), "halting deforestation could cost-efficiently avoid emitting 3.6±2 $GtCO_2$ per year between 2020 and 2050, equivalent to 14% of the additional mitigation needed by 2030 to keep planetary warming below 1.5°C." In summary, in the recent past, the Amazon Forest has experienced changes in precipitation and more frequent extreme weather events due to global warming. Prolonged and more intense dry seasons put the vegetation under water stress, leading to higher rates of tree mortality and extensive fire outbreaks, which in turn could lead to a loss in resilience. These trends accelerate and intensify in areas close to human activities, such as the southern and eastern Amazon Forest. Consequently, the Amazon carbon sink is declining, which might have implications for the global climate.

What would a continuation of recent dynamics under increased global warming mean for the prospect of attaining the Paris Agreement temperature goals?

To assess whether the changes in the Amazon Forest enable or constrain the plausibility of staying well below 2°C warming above pre-industrial levels, we need to consider recent dynamics in carbon fluxes in Amazonia. As mentioned above, carbon fluxes in Amazonia depend on the vegetation response to dry and wet conditions (Gatti et al., 2014), as well as on human activities in the region (Brienen et al., 2015; Hubau et al., 2020; Gatti et al., 2021). Although a decline in the carbon sink has been observed, models still show uncertainties about tropical carbon pool sensitivity to climate change, and the related feedbacks and impact on temperature.

Extrapolating from the current trend in Amazonian deforestation (11,000 km^2 per year, see above) until 2050, we predict less than additional 7 GtC of accumulated emissions until 2050. Since these emissions have to be subtracted from the remaining global carbon budget, there is a small plausibility that the deforestation of the Amazon Forest can constrain the Paris Agreement temperature goal. However, 7 GtC accumulated over 28 years, compared to the annual anthropogenic carbon emissions of 10 GtC in 2021, shows that deforestation of the Amazon Forest will not significantly increase the transient climate response to cumulative emissions of CO_2 (TCRE) and will thus not substantially reduce the plausibility of staying below the Paris Agreement temperature goals.

Only abrupt changes in climate or policy not reflected in current trends, such as nature conservation efforts at regional, national, and global levels, could prevent the decline in the carbon sink. Indeed, whether changes in temperature, droughts, deforestation, and forest degradation, and therefore carbon sequestration, can be mitigated or even stopped depends on the one hand on future land management and the protection of natural forests, and on the other hand on the resilience of forests to climate change.

What are the consequences of failing to reach the goals of the Paris Agreement, and what would be the consequences for the Amazon Forest dieback of exceeding given global warming levels?

If the temperature goals of the Paris Agreement are not met, Amazonia is likely to experience not only an increase in temperature but also changes in precipitation patterns and changes in the intensity and length of dry seasons in the 21^{st} century (Debortoli et al., 2015; Cook et al., 2020; Parsons, 2020; Ukkola et al., 2020; Douville et al., 2021, WGI AR6 Chapter 8).

In all emission scenarios that breach the Paris Agreement temperature goals, the likelihood of extreme events increases (Section 6.2.6). For example, extreme droughts in Amazonia are expected to increase by 100% and 200%–300% under low- and middle-high-emissions scenarios respectively (Cook et al., 2020). A decrease in precipitation in the region will increase the mortality rate, and at the same time, loss of forests may contribute to reduced precipitation. This creates the risk of self-reinforcing vegetation-atmosphere feedback loops. Furthermore, the fire activity in Amazonia is projected to intensify under both mild and severe climate change, even doubling the burned area by 2050 (Brando et al., 2020).

The unprecedented severe drought event experienced by the Amazon Forest in 2015–2016 can serve as an indication of possible climate change impact. Extremely high temperatures and low soil moisture steered 46% of the Brazilian Amazon biome into severe to extreme drought (Anderson et al., 2018), greatly amplifying the degree of trees' physiological stress, and enhancing tree mortality (Fontes et al., 2018). The incidence of fires also increased by 36% in 2015 compared to the single years of the previous decade (Aragão et al., 2018).

Observations and the literature suggest two plausible outcomes. On the one hand, the above-mentioned changes can drive the Amazon Forest toward a shift in the (regional) ecosystem. Patches of the Amazon Forest are projected to transit from a high-biomass moist forest to a drier savanna-like ecosystem (Malhi et al., 2009; Levine et al., 2016). Shifts toward a new stable savanna state mostly expected in the southeastern Amazon Forest are difficult to recover from because of stabilizing feedbacks (Staal et al., 2015). On the other hand, the abovementioned changes can destabilize at least large parts of the Amazon Forests (Zemp et al., 2017). Since ecosystem resilience is highly dependent on local conditions, we are less likely to see a uniform, large-scale dieback of forests. Rather, a pattern of local declines will emerge that can also be attributed to different local drivers and cause-effect relationships.

In summary, by failing to meet the Paris Agreement temperature goals, extreme events, as well as high-fire regimes will become the new norm in Amazonia by the end of the 21st century. Less moisture recycling in combination with deforestation and degradation could shift the Amazon ecosystem toward savanna-like vegetation. The new environmental conditions will have devastating impact on Amazonian ecosystems, with plausible regional dieback. Not only climate change, but also human activities are pushing the Amazon Forest toward tipping points.

In which way is this physical process connected to other physical and social processes?

Precipitation in Amazonia is regulated by the SST across the tropical and North Atlantic Ocean and by the rain belt associated with the Intertropical Convergence Zone. These are both linked to the Atlantic Meridional Overturning Circulation (AMOC). Changes in the AMOC (Section 6.2.4), extreme weather events (Section 6.2.6), and a warmer North Atlantic could lead to a drier Amazonia (Hua et al., 2019).

In addition to the physical processes that influence the future vitality of the Amazon Forest, there are relevant feedback processes due to land-use changes and associated deforestation and forest degradation. These processes are human-initiated and have societal causes. Land-use change in Amazonia goes back to colonization and exploitation policies. It has accelerated significantly since the 1960s and is due primarily to economic opportunities. The social actors driving deforestation are heterogeneous and include traditional and Indigenous populations, ranchers, smallholders, and capital-intensive and mechanized agriculture. Thus, the change in deforestation rates and area can be attributed to a variety of factors, including the expansion of cattle ranching and soybean farming (Margulis, 2004), intensification of agricultural use (Garcia et al., 2019), expansion of infrastructure and road construction (Soares-Filho et al., 2006), as well as macroeconomic developments in the Brazilian economy and international exchange rates (Ewers et al., 2008), structure of the economic base for production and market connectivity (Aguiar et al., 2007), and land tenure and policy failures (Geist and Lambin, 2002). These factors, together with environmental conditions, explain 83% of deforestation rates in Amazonia (Ometto et al., 2011). Nevertheless, the economic return from the converted land is relatively low (Nobre et al., 2016).

In the following we provide two examples of national and international political processes.

Part of the Brazilian government's agricultural policy since the 1960s has been to control important geostrategic natural resources and to create a perspective for landless families. This was displaced by conservative agrarian modernization policies in the central regions of the country by implementing privately and publicly managed agrarian colonization projects in Amazonia. Between 2003 and 2014, approximately 218,000 families were settled in the planning region Legal Amazon (consisting of the states of the Brazilian North Region and the major northern part of Mato Grosso) by the National Institute for Agrarian Reform INCRA (INCRA, 2018), while an uncounted number of people settled informally as posseiros (Schminck and Wood, 1992). In addition, legal regulations (Brazil, 1964; Brazil, 1981) guarantee that new settlers can claim formal land title by utilizing a plot for five years (usocapião), which directly affects deforestation (Pacheco, 2009). In the Legal Amazon region, especially along large highways that link the agribusiness areas in Mato Grosso with the Rio Amazonas and Rio Paraguai waterways to facilitate the commercialization of products to global agrarian markets, the logging industry, large-scale cattle ranching, and monocultures for commodities such as soy and corn have expanded since the 1980s. This increased inequality in land tenure (Pacheo, 2009). These interlinked dynamics of subsistence- and profit-oriented land use are responsible for deforestation (Sauer, 2018).

In 2008, the UNFCCC initiated REDD+, a market-based approach to reducing emissions from deforestation and forest degradation (UNFCCC, 2008). REDD+ involves result-based payments for compliance with carbon markets, as well as from voluntary markets and public sources (Angelsen et al., 2018). To ensure financial benefits, countries need to implement a measurement, reporting, and verification (MRV) system (UNFCCC, 2014). However, high transaction costs associated with REDD+ payments lead to financial benefits only in limited situations, namely in countries with historically high deforestation rates (Nantongo and Vatn, 2019; Köhl et al., 2020). REDD+'s effectiveness in making a significant contribution to reducing deforestation has drawn criticism, but it has also drawn attention to forest conservation (Hall, 2008; Bayrak and Marafa, 2016; Hein, 2017).

Similar developments in Amazonia, as well as historical development in the countries involved, show that reducing or even preventing deforestation is primarily determined by national policies, legislation, and law enforcement. However, international environmental and climate protection programs remain highly relevant in promoting national policies toward nature conservation activities in Amazonia. Since the end of the 19th century, several Amazonian states have been protecting forest and Indigenous areas, and by the 1980s, with the support of international environmental programs, most of them had developed efforts for identifying and implementing nature conservation areas at the local, regional, and national level (Hall, 1997; Sagayo et al., 2004; Neuburger, 2008). In 2002, 43% of the area of the Brazilian planning region Legal Amazon were under environmental protection, including all types of conservation categories and Indigenous areas (Walker et al., 2009). However, there has been criticism of the effect of protected areas on preservation or promotion of biodiversity (e.g., Pack et al., 2016), since ecosystem protection is not ensured and implementing protected areas depends on local, social, and land conflicts (Schleicher, 2018). Ethnobotanical studies highlight that Indigenous Peoples modify biodiversity using specific management systems (Piperno et al., 2015; Levis et al., 2017) that also suggest ways to improve ecosystem services.

The causes of deforestation and forest degradation are not only local or national. The EU alone is responsible for up to 16% of deforestation associated with crops and livestock products (WWF, 2022; European Commission, 2019). A legislative initiative to enforce deforestation-free supply chains is expected to address EU-driven global deforestation (European Commission, 2021). Furthermore, not only are consumption patterns highly relevant, but dependency structures and power relations in consumer-driven global value chains must also be considered. These include ranching for beef or soybean production for fodder in European cattle ranching. (Brand et al., 2021).

In summary, it is not a single factor but the interaction of various economic, institutional, technological, cultural, and environmental factors that is responsible for deforestation (Geist and Lambin, 2002). Since the end of the 19th century, several Amazonian states have been protecting forest and Indigenous areas. However, there is some criticism on the effectiveness of these efforts. If forests, as natural sinks, help achieve carbon neutrality, preserving existing natural forests by avoiding deforestation is a highly cost-effective, nature-based solution to mitigating global emissions and can make a much greater contribution than afforestation (Stern, 2007).

Is it plausible that drastic or abrupt changes in the Amazon Forest dynamics are triggered within the 21st century?

Predicting Amazonia's response to future warming is challenging because some important factors still need to be understood. For example, terrestrial biosphere models often only incompletely reflect the response of the Amazon Forest to climatic changes. There are, for example, uncertainties about rainfall predictions (e.g., Parsons, 2020), the representation of forests' structure (e.g., Levine et al., 2016), functional diversity (e.g., Sakschewski et al., 2016), resiliency (e.g., Boulton et al., 2022), and response to droughts (e.g., Powell et al., 2013), as well as subregional changes that need higher-resolution models (Staal et al., 2018). Nonetheless, modeling studies and observational evidence suggest that the Amazon Forest composition and carbon stocks are affected by changing temperature and precipitation patterns, as well as by increasing droughts.

It is widely accepted that the Amazon Forest is a potential tipping element in the global climate system (Lenton et al., 2008; Lovejoy and Nobre, 2018; 2019; Boulton et al., 2022). Recently, the IPCC assessed a dieback of Amazon Forest during the 21st century as a low-probability event (Canadell et al., 2021, WGI AR6 Chapter 5), and there is medium confidence in insignificant net changes in vegetation carbon storage in tropical regions (Table 4.10 in Lee et al., 2021, WGI AR6 Chapter 4). Thus, drastic changes in ecosystem processes, such as large-scale dieback of the Amazon Forest, solely driven by climate change during the 21st century are not plausible.

Nonetheless, it is unlikely that tipping points follow a single ecological gradient. They result from the interaction of a multitude of factors (Berdugo et al., 2020; Dudney and Suding, 2020). Besides climate change, the greatest risks for the Amazon Forest are, for example, deforestation and forest degradation (Nobre et al., 2016). Climate warming, social drivers, and political decisions may lead to serious but unknown implications for the development of the Amazon Forest, and the thresholds in precipitation change and forest degradation leading to Amazon Forest collapse are still uncertain. However, by assessing past developments we conclude that forest dieback as a result of deforestation and climate change is plausible in the 21st century, unless policies, regulation, and financial incentives are strengthened.