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Managing ecosystem services in the Brazilian Amazon: the influence of deforestation and forest degradation in the world's largest rain forest

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Abstract

The Amazon rain forest covers an area of ~ 6.7 million km^2 of South America; nearly 60% of it is in Brazil, while the rest is shared among eight other countries. This vast extent of rain forest is a globally significant ecosystem that provides numerous ecosystem services that benefit humanity including essential climate regulation, biodiversity conservation, and hydrological stability. However, deforestation and forest degradation have led to the loss of approximately 15% of the Amazon rainforest since the 1970s, primarily driven by agricultural expansion, illegal mining, logging, and wildfires. These pressures have triggered a cascade of consequences, including biodiversity loss, disruption of cultural and ecosystem services, depletion of carbon sinks, and severe alterations to the hydrological cycle. While initially manifesting at local and regional scales, these effects increasingly pose risks to global climate stability. We simulated deforestation scenarios (15%, 50%, and 100% forest loss) using the Community Atmosphere Model (CAM 3.1) to evaluate precipitation changes and atmospheric responses. Results indicate substantial reductions in regional precipitation, hydrological disruptions affecting agricultural productivity, and an increasing risk of the Amazon transitioning from a carbon sink to a carbon source. This underscores the urgency of policy interventions, including stricter environmental regulations, trade restrictions on commodities produced illegally or in deforested areas, enhanced Indigenous land protection, and international cooperation to mitigate deforestation and promote sustainable land use. Immediate action is necessary to prevent irreversible ecological and climatic tipping points.

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Ecosystem services of the Amazon rain forest: essential benefits to nature and society

The Amazon rain forest is the largest contiguous tract of tropical forest on Earth. It is an incredibly important biome playing a key role in global biogeochemical cycles as well as being one of the most biodiverse places on the planet with a large number of species still undiscovered, but with some already extinct or being threatened with extinction (Grelle 2005; Feeley and Silman 2009; Gomes et al. 2019; WWF 2022). It furthermore homes over 200 Indigenous groups many of whom are isolated in protected Indigenous lands (Leal Filho et al. 2020). A very large proportion of the trees found in the Amazon have human uses (Coelho et al. 2021). It is therefore considered a critical ecosystem because it provides numerous ecosystem services, which are classified into the following categories (Millennium Ecosystem Assessment 2005):

i. Regulating services are ecological processes that are essential for life support systems, providing stability to ecosystem dynamics, such as global climate and water flow regulation.
ii. Supporting services offer suitable conditions for water cycling and primary production etc.
iii. Provisioning services are the products people obtain from ecosystems including resources such as timber, fresh water, food, fibres, and medicinal plants.
iv. Cultural services are spiritual, symbolic and other interactions with the abiotic components of the natural environment; these include traditions, beliefs, and knowledge of Indigenous, traditional, and local peoples.

The Amazon rain forest offers various ecosystem services (Fig. 1). One example among them is water cycling, whereby 20% of the global freshwater discharge is from the Amazon basin (Fassoni-Andrade et al. 2021). In addition, this vast moist forest plays an important role in regulating the mass balance across the globe due to the trees' transpiration mechanism, which returns water vapour to the atmosphere, thereby regulating the precipitation regime of the whole planet (Coe et al. 2016). Particular mention can be made regarding the moisture from the forest's evapotranspiration processes, which is transported to the southeast and midwest regions of Brazil, where most of the country's population, agricultural production, and reservoirs for energy generation are located. Arraut et al. (2012) predicted that

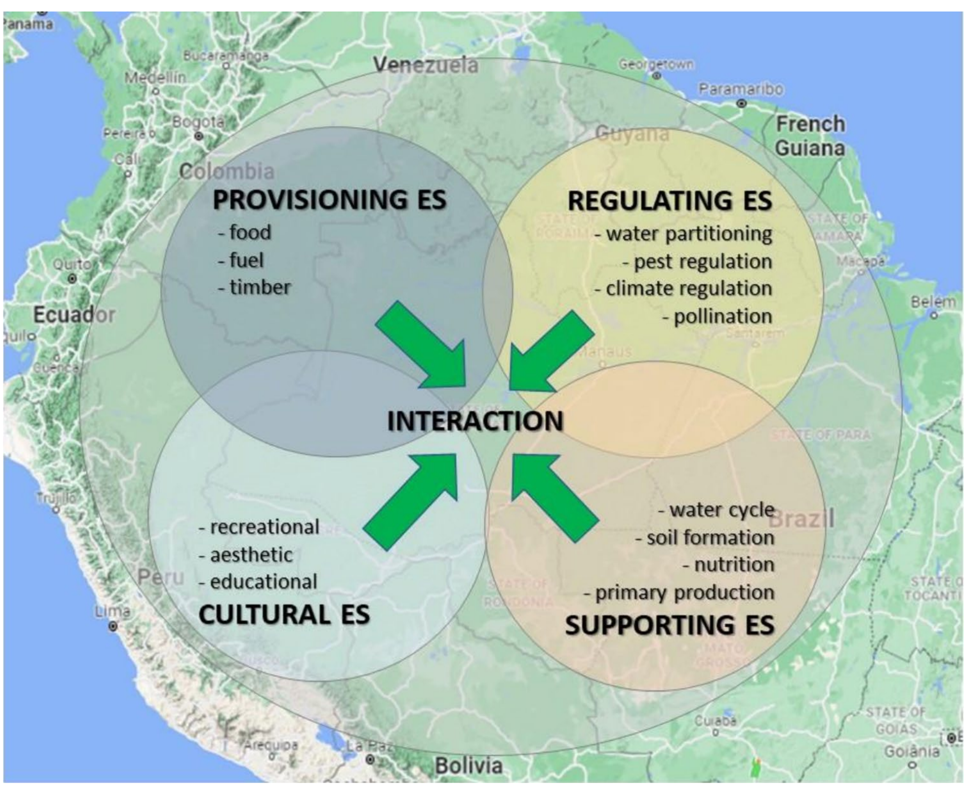

Fig. 1 A schematic view of some of the most relevant ecosystem services (ES) associated with the Amazon rain forest [Map data © 2021 Google]

this water transport is comparable to the total discharge from the Amazon river, and is responsible for almost 40% of the precipitation formation in the Amazon region (Nielsen et al. 2016, 2019; da Silva et al. 2019). This transport of moisture, known as 'flying rivers' by some authors (Getirana et al. 2021), plays a fundamental role in the maintenance of precipitation in the humid period of the midwest and southeast regions of Brazil. The water originating from the Amazon region also fills the largest and most important reservoirs for hydroelectric power generation in Brazil (Getirana et al. 2021).

This large extent of rain forest also plays an important role in the storage and sequestration of carbon (C), due to about 15% of global photosynthetic activity occurring here (Malhi and Grace 2000; Beer et al. 2010) that absorbs carbon dioxide (CO_2) from the atmosphere, thus contributing to the amelioration of the greenhouse effect on a global scale. The Amazon rain forest above-ground biomass (i.e. that stored in vegetation) is about 90 Pg C (Malhi et al. 2006; Fawcett et al. 2023) with a similar amount stored in soils.

Attributing economic values to ecosystem services provided by the Amazon rain forest are both controversial and challenging. However, without providing monetary values for unpriced services, quantifiable benefits from deforestation may be over-emphasized, thereby promoting exploitative land uses (Strand et al. 2018). In a meta-analysis, Brouwer et al. (2022) determined the mean value of C sequestration, water regulation, ecotourism, and recreation as about US\$ 410 ha^{-1} yr^{-1}. Strand et al. (2018) found that the central Amazon basin had greatest the ecosystem services values (sum of food production, raw material provision, greenhouse gas mitigation, and climate regulation), ranging up to US\$ 737 ha^{-1} yr^{-1}, but higher value areas were restricted to only 12% of the remaining forest. Yet, Lapola et al. (2018) estimate that loss of ecosystem services due to climate change in the Brazilian Amazon may lead to major losses, including non-market valued services of US\$ 7.7×10^{12} over a 30-year period, which is greater than the gross productivity of the region.

This paper primarily examines the issues of deforestation and forest degradation, with a specific focus on the Brazilian Amazon, one of the most ecologically important regions in the world. It explores how the ongoing destruction and degradation of the Amazon rain forest affects the ecosystem services that it provides, including regulating the climate, preserving biodiversity, maintaining water cycles, and supporting the livelihoods of local and Indigenous communities. This study provides an in-depth look at the scale of the problem, including the causes and drivers of deforestation, and the consequences these have for both local and global ecosystems. Furthermore, it discusses potential solutions and strategies to address these challenges, including policy interventions, conservation efforts, and reforestation initiatives. The main goal is to highlight not only the gravity of the issue but also the range of actions that can be taken to mitigate the damage and restore the health of the Amazon rain forest.

The Amazon under pressure

The Brazilian Amazon has been experiencing ongoing deforestation, largely driven by activities such as logging and land clearance for agriculture and cattle ranching. This deforestation has a significant impact on biodiversity and contributes to climatic change. But there are also other problems which are negatively impairing the ecosystem services it offers. Some of them are described herewith.

Forest loss and degradation

The unsustainable management of ecosystems in the Amazon rain forest feeds into global climate changes and alters ecosystem service provision with their combined effects exposing and increasing the socio-environmental vulnerabilities of its populations (Brondízio et al. 2016; Garrett et al. 2021, 2024; Reygadas et al. 2023). The Amazon rain forest has already lost around 15% of its 6×10^6 km^2 surface area reported in the 1970s (Amigo 2020; Marques 2024). Rates of deforestation in Brazil have been declining from those seen in the early 2000s, although clearly increased under the Bolsonaro administration from 2019 to 2022 indicating the importance of political and economic forces on rates of forest loss (Fig. 2).

A recent study by the Joint Research Centre (JRC) of the European Commission (Beuchle et al. 2022), based on the JRC Tropical Moist Forest (TMF) dataset, reported that, from 1990 to 2021, the pan-Amazon (i.e. Amazonia

Fig. 2 Rates of deforestation in the Brazilian Legal Amazon using data from the INPE PRODES satellite. [Data were obtained from INPE (2025)]

sensu stricto and Guiana regions; Eva et al. 2005) lost more than 820,000 km^2 (14.5%) of undisturbed humid forest. An example extracted from the JRC-TMF dataset for an area in the Brazilian Amazon is shown in Fig. 3. Amazonian deforestation not only reduces the forest's carbon sequestration capacity but also contributes significantly to greenhouse gas emissions. For example, in 2020, CO_2 emissions from the Amazon forest increased by approximately 140% compared to the lowest levels recorded in 2012, reflecting an increasing pattern of biomass loss (Kruid et al. 2021; Rosan et al. 2024).

On top of forest loss, forest degradation emerges as a critical source of CO_2 emissions, with the area of forest degraded being similar or slightly greater than that already deforested (Matricardi et al. 2020; Qin et al. 2021; Beuchle et al. 2022; Coelho-Junior et al. 2022; Lapola et al. 2023) depending on how 'degradation' is defined. For example, Qin et al. (2021) reported that between

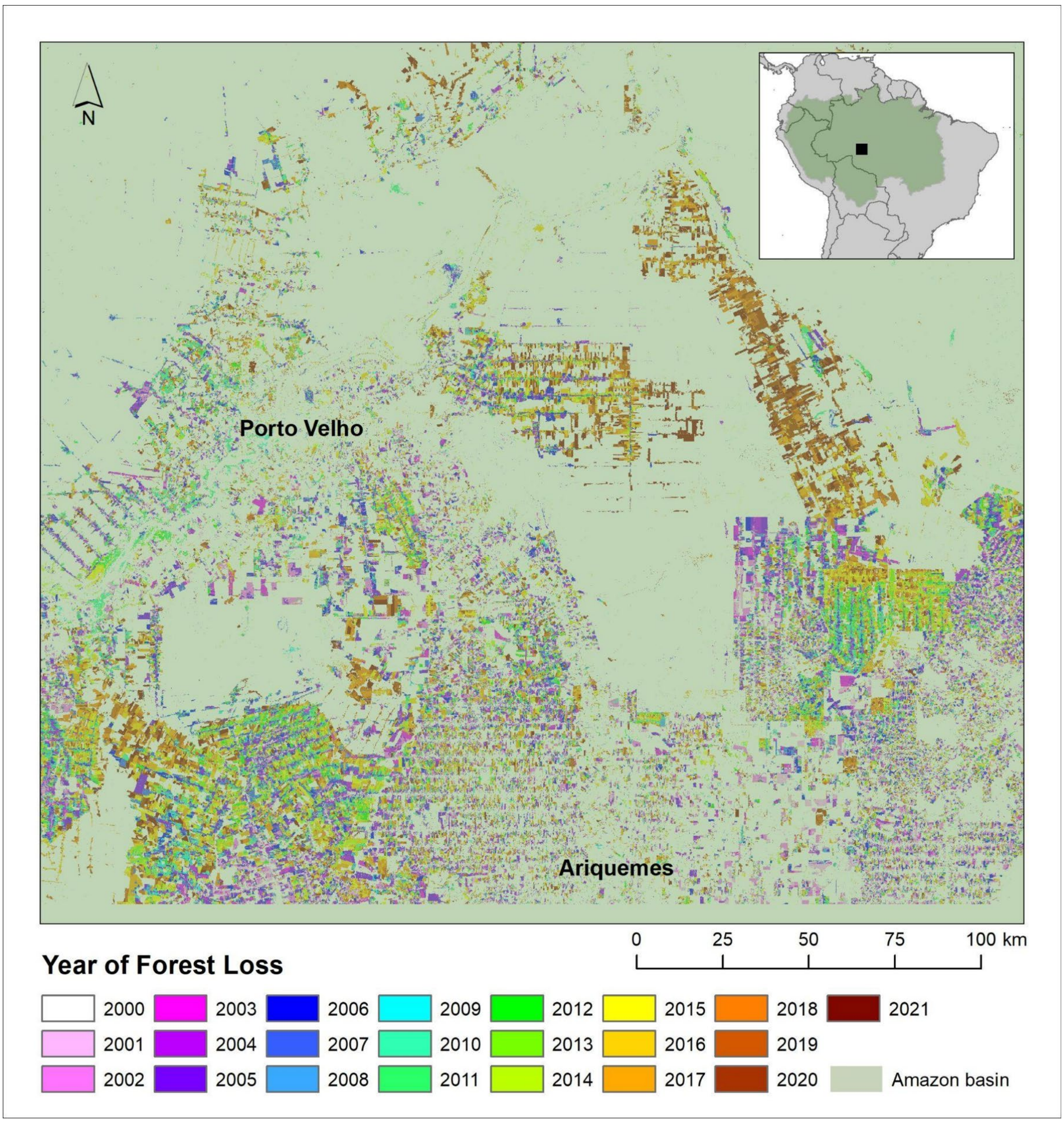

Fig. 3 An example of forest loss in the Brazilian Amazon estimated using the Joint Research Centre's Tropical Moist Forest dataset which provides high-resolution Landsat-derived information on forest cover change from 1990 to 2023. [Authors' own work showing land cover change to distinguish between intact and deforested areas illustrating deforestation patterns on a yearly basis, based on data from Vancutsem et al. (2021)]

2010 and 2019, the Brazilian Amazon recorded a net loss of 0.67 Pg of C, with 73% of this loss attributed to forest degradation, exceeding the impact of direct deforestation. This forest loss and degradation comes from a history of anthropogenic occupancy and actions in the last 50 years, such as timber extraction, road building, hydropower projects, mining, agricultural expansion, and fires (Soares-Filho et al. 2006; Davidson et al. 2012; Athayde et al. 2019; Garrett et al. 2021; Souza-Filho et al. 2021; Lapola et al. 2023). Forest fires, often exacerbated by severe droughts and human activities, play a central role and extreme climatic events, such as the 2015–2016 El Niño, resulted in substantial carbon losses due to drought-induced fires in the eastern Amazon (Berenguer et al. 2021).

Agricultural expansion

Agricultural demands at larger scales and changes in the local way of life have resulted in the conversion of natural ecosystems to cattle ranching and soy cropland and which together form the main drivers of deforestation in the Brazilian Amazon (Marques 2024). Expansion of agricultural production still occurs at the expense of illegally deforested land (Rajão et al. 2020) even though it is well known that millions of hectares of idle and non-productive lands in the Amazon region could be used for agriculture (Nobre 2019; Ferrante and Fearnside 2022b). In fact, it has been shown that conversion of land in the cerrado would lead to less C emissions than in the Amazon (Cerri et al. 2018).

Mining in Indigenous lands

A multitude of other studies have also shown that the Amazon region continues to face an overexploitation of natural resources. Illegal activities including illegal mining and logging have been increasing despite environmental laws and regulations, causing the exploitation and degradation of land (Ferrante and Fearnside 2020; Garrett et al. 2021). This has been notably challenging in Indigenous lands (Duarte et al. 2023) which are particularly important as Indigenous peoples and local communities (IPLCs) play a key role in enhancing socio-ecological resilience at larger scales because their livelihoods and cultural identity are intrinsically interlinked to biodiversity and ecological systems, thus establishing 'biocultural' landscapes (Athayde and Silva-Lugo 2018). Furthermore, the clearing of forest areas for livestock, crop farming, and mining projects also threaten the livelihoods of IPCLs who rely on these areas for their livelihoods. The increased illegal mining in Amazonia is of particular concern as it causes environmental degradation and pollution. There is evidence that mercury used for gold extraction has been bioaccumulated in aquatic food chains as detected at high concentrations in the hair of local communities (Gerson et al. 2022).

Wildfires

Considering that deforestation is a driver of fire activity (Libonati et al. 2021; Silva et al. 2021), the increase in deforestation may also promote an increase in fires in the Amazon region, with a consequential loss of forest and an increase in C emissions to the atmosphere. This is compounded by the effects of droughts that amplify fire occurrence (Campanharo et al. 2019; Berenguer et al. 2021). When the forest is removed through burning, a large amount of particulate matter is also released to the atmosphere, causing pollution (Forbes et al. 2006) with negative health effects (Urrutia-Pereira et al. 2021; Damm et al. 2024) and reducing local precipitation due to increase in the production of aerosols (Andreae et al. 2004; Barkhordarian et al. 2019). Campanharo et al. (2019) estimated the economic cost of fires in southwestern Amazonia to be US\$ 2.43×10^8 during the 2010 drought period, representing 7% of the region's gross domestic product.

Regional deforestation drivers in the Amazon

Although around 60% of the Amazon rain forest is in Brazil, indicating the importance of Brazilian policies and initiatives in conserving the forest, it is also relevant to consider deforestation in other neighbouring countries. In a recent literature review, Hänggli et al. (2023) analysed deforestation drivers and the effectiveness of deforestation-control policies across Amazonian countries. This comprehensive review highlighted the diversity of deforestation dynamics across the region, revealing distinct patterns and causes specific to each country and sub-region. Agricultural expansion, including both cattle ranching and commodity crop cultivation, remains the primary proximate cause of deforestation across the Amazon (excepting the Guianas). In Brazil, Bolivia, Ecuador, and Colombia, pasture expansion has been consistently identified as the leading driver of deforestation (Arima et al. 2011; Barona et al. 2010). The main area of deforestation in Brazil is in the southern Amazon known as 'the Arc of Deforestation' that spreads from south-west Maranhão, through the states of Pará, Mato Grosso and Rondônia (Csillik et al. 2024; Marques 2024). In the Arc of Deforestation, the rise of commodity crops such as soybeans became a dominant force for forest loss. Studies in the Brazilian Amazon reported a considerable indirect effect of soy expansion, which displaces pasture, into new frontier areas (Arima et al. 2011; Song et al. 2021). In Peru, oil palm expansion is linked to deforestation, while in Brazil (primarily Pará) this relationship is not as pronounced (Rojas Briceño et al. 2019). Small-scale or subsistence agriculture, although a minor driver compared to large-scale activities, consistently contributes to forest loss in Bolivia, Peru, and Brazil, especially in Brazilian states like Roraima and Amapá (Tyukavina et al. 2017). Although mining has a limited direct impact on deforestation in Brazil, it facilitates forest loss through road construction, which opens new areas to agricultural expansion (Sonter et al. 2017). Large-scale hydropower projects in the Brazilian Amazon further exacerbate deforestation by encouraging agricultural and urban expansion (Siqueira-Gay et al. 2020). Similarly, the construction of the Interoceanic Highway in Peru has been linked to increased deforestation driven by agriculture and mining in surrounding areas (Armenteras et al. 2013; Sánchez-Cuervo et al. 2020).

Impacts on an Amazon under pressure

An Amazon under pressure has far-reaching impacts on the local environment and communities, as well as the global atmospheric system. These impacts include:

Loss of species and cultural ecosystem services

Biodiversity is under threat as the Amazon rain forest is home to more than 10% of the Earth's terrestrial biodiversity (Guayasamin et al. 2021; WWF 2022). Loss of forest and forest degradation cause ecosystem disruption and loss of species. The removal of forests contributes greatly to habitat loss and places pressure on the fauna and fauna—some of which are unique species—living within the region. Reports indicate that over the past five decades, wildlife populations in Latin America and the Caribbean have declined by 95%, reflecting the severity of the biodiversity crisis in the region (WWF 2022). Based on species distribution modelling, Gomes et al. (2019) predicted that deforestation and climate change could lead to a loss of 58% of Amazonian tree species by 2050. These predicted losses will not only threaten the survival of numerous species but also undermine essential ecosystem services that sustain IPLCs and regulate the global climate. The already existing food insecurity in the region (Cerri et al. 2018) is exacerbated, and the quality of life of the IPLCs who rely on the Amazon forest for their subsistence is reduced, forcing their displacement to larger cities and plunging them further into poverty (Maisonnave 2023). The extraction of non-timber forest products—a typical practice of local communities—that are derived from ecosystem services related to wild food, ornamental resources, and natural medicines, becomes more difficult due to their increasing scarcity with the clearing of forest (Antunes et al. 2021; Brandão et al. 2022). Brandão et al. (2022) estimated the loss of trees in the Amazon to lead to economic losses of between US\$ 7.0×10^8 to 8.7×10^9 per year. As the forest provides cultural services for the Amazonian Indigenous populations, supporting their livelihoods, beliefs, and rituals, forest loss and/or conversion implies a major impact on cultural ecosystem service provision (Angarita-Baéz et al. 2017; Lessmann Escalona 2021).

Potential loss of the Amazon carbon sink

Apart from its socio-economic impacts, deforestation and forest degradation lead to a release of substantial amounts of CO_2 into the atmosphere, with significant long-term effects on climate change at global scales through reducing the C sink in the Amazon. Around 16.4% of Brazil's greenhouse gas emissions in 2019 were caused by deforestation and fires occurring in the Amazonian region alone (Silva et al. 2021). One of the reasons that the Amazon region is losing its C sink capability is the increase in the intensities of extreme droughts resulting in a decline in C sink strength (Machado-Silva et al. 2021). Recent work has shown how increases in tree mortality due to hotter and drier conditions during the 2015–2016 El Niño led to a shutdown of the Amazon C sink during this period (Bennett et al. 2023); this was, in fact, more marked in areas of the Amazon that already had a drier climate and indicates a concerning trend under a future warmer and drier climate.

Hydrological disruption

Additionally, the loss of trees disrupts hydrological cycles. Water vapour produced by transpiration forms the 'flying rivers' and is transported by wind to drier South American regions, particularly those with a strong agroindustry and is therefore directly responsible for roughly 70% of the continent's gross domestic product (Getirana et al. 2021). If the Amazon rain forest continues to decline in area, this moisture transport process may be greatly reduced, since much of the moisture in this region comes from evapotranspiration from the forest, further compromising the occurrence of precipitation during the wet season of the central and southeast regions of Brazil and aggravating the current water crisis. Conversely, the regions where there is the most notable agricultural expansion (e.g. Brazilian Amazonian states of Rondônia, Mato Grosso, and Pará) are those where the largest decrease in yields due to reduced precipitation are predicted (Leite-Filho et al. 2021). Lejeune et al. (2015) analysed several studies involving numerical simulations that reduce or remove the entire Amazon forest and assessed the impact on the precipitation in South America, with an occurrence of more rain in the southern region of the continent and less rain in other

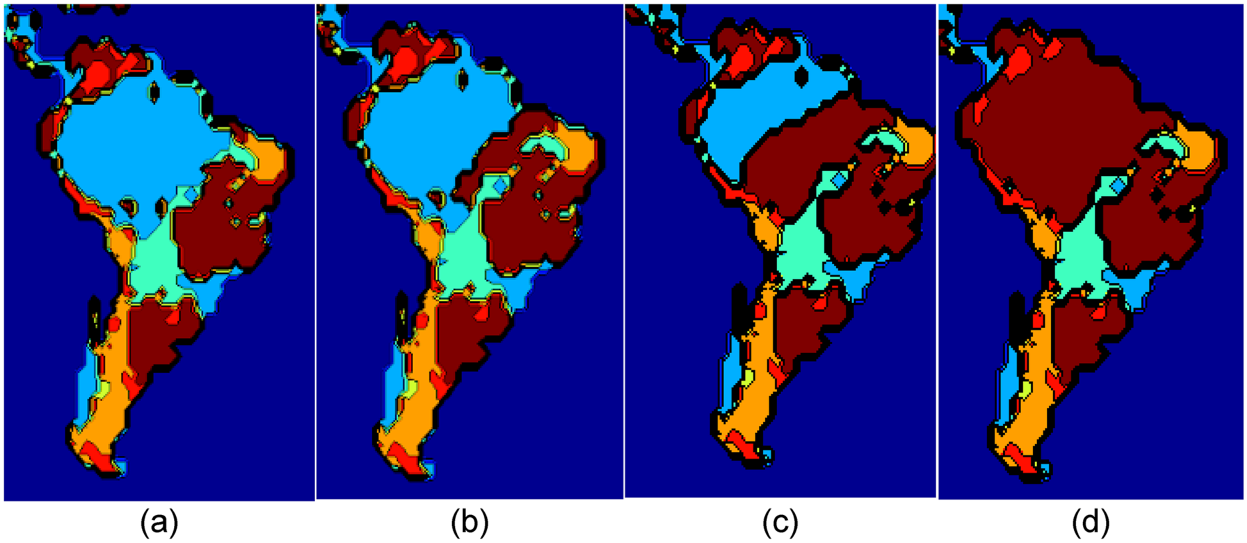

Fig. 4 Changes in the functional types of vegetation for the simulations carried out in the NCAR/CAM 3.1 model, where the light blue represents regions of equatorial forest or rain forest and the brown colour represents areas of agricultural land. Control case map (**a**) and replacement of (**b**) 15%, (**c**) 50%, and (**d**) 100% of the Amazon forest area with agricultural land in the simulations

regions. This result was also observed in more recent studies, such as the work of Amorim et al. (2019). The current rates of deforestation could lead to a climate tipping point in the near future (Lovejoy and Nobre 2019; Amigo 2020; Marques 2024). Forest reduction decreases the region's albedo, increasing surface heat retention and, consequently, generating a positive feedback for global warming. It has been suggested that if 40% of the Amazon basin is deforested, a tipping point may be reached (Nobre and Borma 2009), leading to movement of the forest–savanna boundary or, in a worse-case scenario, large-scale forest dieback. Other authors feel that the tipping point has already been reached (Lovejoy and Nobre 2019) which is of great concern. In addition, it is necessary to assess whether the loss of moisture associated with deforestation in the Amazon forest will have an effect on the precipitation regime in other parts on the planet, since this change in evapotranspiration may compromise the global mass balance, given the size and thus importance of the Amazon rain forest.

Local climatic imbalances

In order to assess the influence of different deforestation scenarios in the Amazon on the precipitation regime in Brazil and South America, we conducted simulations using the Community Atmosphere Model (CAM 3.1) of the National Center for Atmospheric Research (Collins et al. 2004), removing 15%, 50%, and 100% of the Amazon rain forest and replacing it with agricultural land in the simulations (Fig. 4). These three deforestation scenarios represent the current extent of forest loss (15%), a high-pressure scenario (50%), and a worst-case scenario (100%). This model is part of the set of General Circulation Models of the atmosphere used by the Intergovernmental Panel on Climate Change (IPCC) and considers the functional types of vegetation for the year 2004 (Oleson et al. 2010). To assess the impact of deforestation on precipitation in Brazil and South America, we initiated the model using average sea surface temperature (SST) conditions and integrated it over 17 months so that the differences in precipitation between a typical January with an intact (100%) Amazon rain forest (called the control case) and the same January with the three deforestation scenarios could be compared. The month of January was chosen because it is the month with the greatest amount of precipitation in the centre-west and southeast regions of Brazil, which have the greatest population densities in the country, the greatest rates of water withdrawal for irrigation, and the largest reservoirs for electricity generation, and which have recently experienced water crises (Nielsen et al. 2019; Getirana et al. 2021). It is also important to note that the CAM 3.1 model only needs about three months of integration to be able to enter equilibrium with the ocean and generate the planetary cloud cover required for this type of study. The simulations considered all the other parameters of the earth system, such as SST, ice and cover, to be the same in all the simulations; thus, the only forcing evaluated and altered was the vegetation cover.

In the scenario with 15% deforestation, there is a sharp decline in precipitation in the states of Rio de Janeiro, Espírito Santo, Minas Gerais, Mato Grosso do Sul, and Pará, with an increase in precipitation in the southern region of Brazil and in the states of Goiás, Tocantins, and part of Bahia (Fig. 5a). As deforestation increases, the regions with the least precipitation become more noticeable on the map, illustrating the importance of moisture from the Amazon rain forest in the country's precipitation balance. In the scenarios with 50% and 100% deforestation, in general, we see that only the east of southern Brazil, northern Goiás, south-central Tocantins and parts of Bahia, and Piauí show an increase in precipitation, with a decrease throughout the rest of the country, reaching a deficit of more than 100 mm month^{-1} in most of the southeast region of Brazil (Fig. 5b, c), which, if it were to occur persistently over a few years, could create an unprecedented water deficit in this region. This decrease in precipitation in the southeast is associated with the possible weakening of the Atlantic Convergence Zone, which is responsible for around 40% of the summer precipitation in this region (Nielsen et al. 2016). It is important to emphasize that this trend of decreasing precipitation across a large part of the country, associated with deforestation in the Amazon, was noticed not only in this study but also in numerous others (Lejeune et al. 2015; Ruiz-Vásquez et al. 2020; Moreira 2024). The hypothesis explored in this study, as well as in others (Amorim et al. 2019; Smith et al. 2023), suggests that complete forest loss in the Amazon leads to an increase in surface temperature and a reduction in total precipitation. Furthermore, both the present study and that of Lejeune et al. (2015) observed a local-scale decline in latent heat flux as a direct consequence of deforestation. Despite variations in model configurations, spatial resolutions, and methodologies, a consistent pattern emerges, highlighting the strong sensitivity of the regional climate to deforestation. The primary mechanism behind these findings is linked to alteration of the vegetation cover, whereby the replacement of forests with cropland or pasture leads to a decrease in surface roughness, leaf area index, and rooting depth. This, in turn, limits the amount of water vapour recycled into the atmosphere, reducing evapotranspiration and latent heat flux, which ultimately leads to a decline in precipitation (Foley et al. 2003; Cao et al. 2020; Moreira 2024). Additionally, the increase in albedo associated with land cover changes, combined with the decrease in latent heat flux, is often offset by a rise in sensible heat flux, leading to a local increase in near-surface air temperature. The removal of roughness elements such as trees reduces surface obstacles that would otherwise facilitate heat transfer from the land surface to the atmosphere. Lejeune et al. (2015) also highlighted a relationship between heat fluxes and surface air temperature, demonstrating that while surface warming persisted year-round, the most pronounced anomalies occurred at the end of the dry season, when soil moisture levels were lowest. This aligns with von Randow et al. (2004), who found that during the dry season, forested areas maintained evapotranspiration, whereas pastures, with shallow root systems, were unable to access deeper soil moisture reserves. While the simulated annual precipitation reduction was relatively small, the seasonal

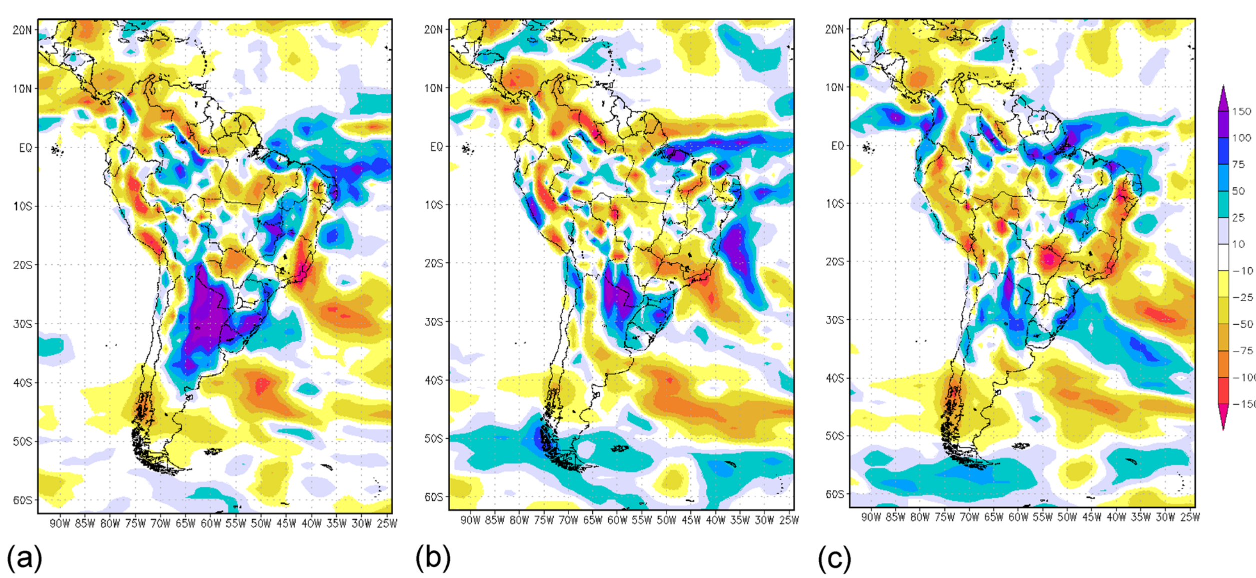

Fig. 5 Difference between accumulated rainfall (mm month^{-1}) in the month of January between the scenarios with (**a**) 15%, (**b**) 50%, and (**c**) 100% deforestation compared to the scenario with the original Amazon rain forest intact

differences in climate responses to deforestation were significant for local ecosystems, particularly during the dry season, as was also observed in the studies by Swann et al. (2015) and Smith et al. (2023); in the latter case, these patterns were observed using present climate data rather than numerical simulations. The reality is that the simulations in this study, based on 15% deforestation, already mirror the unfortunate state of the Amazon, as current estimates indicate that deforestation has surpassed this threshold (Lapola et al. 2023). This allows for a meaningful comparison between our simulation results and present-day directly observed climatic data.

Beyond local impacts, this study also assessed the effects of deforestation on other regions of Brazil, considering the influence of large-scale atmospheric circulation patterns across South America. The findings indicate the presence of non-linear climate patterns in response to deforestation, likely driven by interactions between altered climate variables and changes in atmospheric circulation. These, in turn, generate further variations at the local scale, reinforcing feedback loops that exacerbate climate imbalances (Butt et al. 2023). Finally, all studies consistently indicate a clear trend of rising temperatures and declining precipitation in the region, reinforcing the urgent warning about the detrimental impacts of deforestation on the regional climate.

The way forward for the Amazon

Recent years have seen increased environmental challenges, especially in Brazil since the weakening of the Forest Code and with much previous (Bolsonaro) governmental anti-environmental rhetoric, weakening of environmental laws, and increase in rates of deforestation (Nobre 2019; Silva Junior et al. 2021; Dutra da Silva and Fearnside 2022; Rodrigues 2022). The current Lula government faces many environmental challenges (Fearnside 2023) and the 2023 Amazon Summit was a step in the right direction despite a lack of clear forward plans (Moutinho 2023; Marques 2024). The cumulative effects of deforestation can have far-reaching consequences for both the environment and human well-being, emphasizing the importance of sustainable forest management and conservation efforts. One of the most effective ways to preserve the ecosystem services provided by the Amazon rain forest is to address inappropriate land-use changes. This will help maintain the Amazon region´s position as the largest planetary biodiversity hotspot. A significant decrease in Amazon deforestation could prevent it from turning into a savannah, and return this region to its capacity as a global C sink and not a C source, as it is progressively becoming.

The preservation of the Amazon forest in Brazilian territory depends on the political will of the government in office. More sustainable 'green' policies led to a decrease in deforestation rates in the period 2004 to 2014, whereas an increase was seen from 2015 and particularly from 2019 onwards. Already, a downturn in the rates of deforestation is occurring since the new Lula administration (Fig. 2; Watts 2023). Policy responses to deforestation have shown varied effectiveness. Protected areas and public policy interventions, such as environmental enforcement and land tenure regularization, have demonstrated relative success in curbing deforestation in Brazil (Merkus 2024). For instance, federal enforcement policies, including fines and embargoes, have effectively weakened the relationship between global commodity markets and deforestation, particularly in critical regions like Pará and Mato Grosso (Assunção and Rocha 2019). An effective way to motivate the current government to embrace the preservation agenda is via embargos or trade restrictions on commodities (notably soy and beef) that are produced illegally or in recently deforested areas (Gibbs et al. 2015; Ferrante and Fearnside 2022a). The Soy Moratorium, implemented in 2006, whereby signatory companies agreed not to buy soybeans cultivated in recently deforested areas, was a successful example of this, as was the beef Zero Deforestation Commitment (Rudorf et al. 2012; Vallim and Leichsenring 2025). Currently, Pará state is implementing the 'Sustainable Livestock Program' to make the products from the cattle ranching traceable and guarantee that they are not leading to an increase in deforestation rates in the state (Pará 2023).

Another pathway is the active movement towards private conservation areas, as shown in several Brazilian ecosystems (e.g. da Silva et al. 2021; Stabille et al. 2022), where conserving native vegetation on private lands is an important mechanisms to protect biodiversity (De Marco Jr. et al. 2023). An equally effective approach could be for local communities to formally commit to the preservation of given areas. Integrating privately conserved areas into a national protected area system can increase the success of large-scale conservation initiatives (da Silva et al. 2021) such as is required for the Amazon basin. However, because private protected areas are dependent upon the financial commitment of non-governmental actors, and their legal status is unclear, their long-term role in forest conservation remains to be fully realized (López de la Lama et al. 2023), but should be explored and promoted further.

Moving forward, the value of the rain forests in the Brazilian Amazon to global biodiversity, climate regulation, and the well-being of IPLCs means that their conservation needs to be prioritized and implemented through a combination of local and international efforts. This includes some key measures. The first is that Brazil should reinforce and enforce its environmental laws to protect the Amazon. This includes strict regulations against illegal logging, land encroachment, and deforestation. Also, efforts should also be made to prevent illegal activities with improved enforcement, and to hold accountable those responsible for environmental crimes (Coelho-Junior et al. 2022). Secondly, there is a particular need to strengthen laws that protect Indigenous peoples and their lands given the worrying increase in encroachment on these protected areas (Begotti and Peres 2019, 2020; Silva Junior et al. 2023). These lands cover about one-fifth of the Brazilian Amazon and are an effective protection against deforestation although the effect of this barrier has been weakened in recent years. It is therefore important to restore, expand, and strengthen protection of these areas. There is also a need to support Indigenous communities´ land rights through involving these communities in decision-making processes, and provide resources to protect their territories. Moreover, implementing advanced monitoring systems, including satellite imagery and remote sensing technologies, can help identify and respond to deforestation in real time (Coelho-Junior et al. 2022). A further key element is financing. Here, there is a need to develop financial mechanisms that reward rain forest conservation efforts. For example, creating incentives for landowners, farmers, and local communities to protect and restore the rain forest can help reduce deforestation rates. Payments for ecosystem services and C offset programs can be explored to incentivise conservation activities.

In recent years, the 'bioeconomy' concept has gained traction—this is the use of renewable biological and biotechnological resources for economic growth, while using these to address environmental challenges (Bugge et al. 2016; Garrett et al. 2024). Clearly, the Amazon region is abundant in such resources and the Brazilian government has instituted the National Bioeconomy Strategy (Brasil 2024). However, bioeconomies are not simply based on unsustainable extraction or cultivation of forest resources and need to consider the needs of IPLCs and harness their knowledge, while also reconfiguring economic models (Garrett et al. 2024). For the Amazon rain forest, the most appropriate conception would involve a bio-ecological bioeconomy defined as an economic system in which the criterion of sustainability is inextricably linked to the criterion of economic growth. The Amazon bioeconomy should be substantiated in an economy encompassing diversity of territories, peoples, knowledge, products, and markets. The forest products and services can be expanded, connecting the forest to people and entrepreneurs (Abramovay et al. 2021; Gebara et al. 2023). As an example, rural communities of Mamirauá Sustainable Development Reserve have been using and managing species with medicinal properties that are on the pharmacology list of interest of the Brazilian National Health Surveillance Agency (Benitz et al. 2023).

Forest restoration is now firmly on the political agenda (e.g. the UN Decade on Restoration: https://www.decadeonrestoration.org, and the Bonn Challenge: https://www.bonnchallenge.org) and has a role in improving biodiversity metrics, ecosystem functioning, and human well-being in degraded forests of the Amazon. This may be through various approaches including natural regeneration, assisted regeneration, agroforestry, and plantations (Gastauer et al. 2020; da Silva et al. 2023). However, the rate of forest restoration in the Amazon is currently slow and we need more information on appropriate socio-economic conditions for successful regeneration with a focus on governance, management, and market issues as well as basic ecological understanding of which tree species should be planted where to obtain maximum benefits from restoration schemes. Restoration will only likely be successful with synergies among local governments, local people, and the private sector (Gastauer et al. 2020).

We emphasize that rain forest conservation is a global concern as the Amazon rain forest plays a vital role in regulating the Earth's climate, since we were able to determine how the deforestation of the Amazon had a significant influence on the climate of the whole of Brazil in just 10 years of model integration (Fig. 5). In this way, studies involving earth system models should be carried out to better understand how this influence can spread to the climate of the entire planet over a longer timeframe.

Finally, greater international cooperation between Brazil and other countries is needed, both in terms of funding and expertise. Organizations, such as the United Nations, the World Bank, non-governmental organizations, and bi-lateral (country-to-country) support, can facilitate collaborative efforts. It is important to note that rain forest conservation requires a multi-faceted approach involving various stakeholders, including government bodies, local communities, NGOs, and the international community. We underscore the need for region-specific policy interventions that account for the diverse socio-economic, environmental, and institutional drivers of deforestation. Tailoring approaches to address the unique deforestation dynamics in each region is crucial to enhancing the effectiveness of conservation efforts and mitigating further forest loss. By combining strategies and stakeholders working effectively together, it is possible to protect the rain forests in Brazil and ensure their long-term sustainability.

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WLF: Conceptualization, Ideas, Writing—Original Draft, Writing—Review and Editing, Project administration, Funding acquisition. MAPD: Writing—Original Draft, Writing—Review and Editing, Visualization. MAC: Writing—Original Draft, Writing—Review and Editing. MC: Formal analysis, Computational simulations, Writing—Original Draft, Visualization. GASdC: Formal analysis, Computational simulations, Visualization. AEP: Writing—Original Draft, Writing—Review and Editing. ES: Formal analysis, Writing—Original Draft, Writing—Review and Editing, Visualization. FQB: Ideas, Writing—Original Draft, Writing—Review and Editing, Visualization, Project administration.

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Declarations

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