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Chapter 23: Impacts of deforestation and climate change on biodiversity, ecological processes, and environmental adaptation

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Chapter 23

Impacts of deforestation and climate change on biodiversity, ecological processes, and environmental adaptation

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ACRONYMS AND ABBREVIATIONS

ABRACOS	Anglo Brazilian Amazonian Climate Observation Study
AOD	Aerosol Optical Depth
ARME	Amazon Region Micrometeorological Experiment
BPBES	Brazilian Platform for Biodiversity and Ecosystem Services
C	Carbon
CCN	Cloud Condensation Nuclei
CO_2	Carbon Dioxide
DOC	Dissolved Organic Carbon
DRF	Direct Radiative Forcing
ET	Evapotranspiration
GHG	Greenhouse Gas
GPP	Gross Primary Productivity
IN	Ice Nuclei
INPE	Brazilian National Institute for Space Research
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence Zone
LAI	Leaf Area Index
MgC	Megagrams of Carbon
NDCs	Nationally Determined Contributions
NEE	Net Ecosystem Exchange
NOx	Nitrogen Oxides
NPP	Net Primary Productivity

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O_3	Ozone
PAR	Photosynthetic Active Radiation
Rnet	Net surface radiation
SDM	Species Distribution Modeling
SPI	Standard Precipitation Index
SST	Sea Surface Temperature
TOA	Top of the Atmosphere
VOCs	Volatile Organic Compounds

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KEY MESSAGES

- The Amazon is one of the world’s most at risk regions, with a possibility that over 90% of species could be exposed to unprecedented temperatures by 2100.
- Knowledge gaps on carbon balance are significant, including the role of forest degradation and natural photosynthesis enhancements. Remote sensing of CO2 measurements, ground-based tower flux data, aircraft measurements, and modeling tools need to be integrated to close these gaps.
- Reducing emissions from biomass burning is critical to minimize the negative impacts on ecosystems and human health.

ABSTRACT

Climate change is already impacting critical mechanisms of the Amazonian ecosystem functioning. The observed increase in temperature, precipitation changes, increase in climate extremes affect ecosystem services, carbon uptake, and increase in the duration of the dry season, among other effects. It also affects biodiversity, selecting species that can adapt quickly to the changing climate, including freshwater fishes. Fisheries' yields are being impacted by climate change in unpredictable ways. Projections indicate significant adverse impacts of climate change on pollination and seed dispersal, essential ecosystem services for the maintenance of natural and agricultural ecosystems by changes in species distributions, and the decoupling of biotic interactions. Rainfall in the Amazon is sensitive to seasonal and interannual variations in sea surface temperature, as well as El Niño and La Niña. The increase in intensity and frequency of droughts and floods have important impacts on carbon cycling. Levels of water at Óbidos have increased significantly over the last 30 years. And runoff of Xingu catchment has risen by 10%, possibly due to 40% deforestation in the Xingu catchment. The Amazon was a carbon sink of about 0.5 tons of carbon per hectare per year, and recent data shows that the forest is more or less neutral in terms of carbon emissions. In dry years such as 2005 and 2010, the forest loses carbon to the atmosphere, increasing greenhouse gas concentrations. Increases in climate extremes are reducing carbon uptake by the Amazonian ecosystem. Biomass-burning emissions have significant negative impacts on the ecosystem, such as high ozone concentrations that affect the stomatal opening and human health. Aerosols from biomass burning alter the radiation balance, increasing diffuse radiation compared to direct radiation affecting carbon cycling. The increase in surface albedo associated with deforestation changes surface temperature and energy partitioning. Forest degradation could be as crucial as deforestation in terms of carbon emissions. Our current scientific understanding points to Amazonian forests becoming increasingly susceptible to wildfires and droughts. Feedbacks between climate change and Amazonian ecosystem functioning are substantial and must be better known and quantified, especially for carbon and water vapor feedback. We need more integrated studies involving biodiversity loss with the changing climate, including resilience. Additionally, there is a need for a comprehensive network of Amazonian environmental observations to provide society with diagnostic capabilities of the changes that terrestrial and aquatic ecosystems are already undergoing.

Keywords: Impacts of climate change, hydrological cycle, biodiversity, carbon cycling, precipitation, fisheries.

GRAPHICAL ABSTRACT

TBD

1. IMPACTS OF CLIMATE CHANGE ON BIODIVERSITY, INCLUDING FOREST DYNAMICS, CARBON CYCLING, FRESHWATER, AND COASTAL ECOSYSTEMS

Terrestrial ecosystems and climate interact in complex ways through changes in forcing and multiple biophysical and biogeochemical feedback across different spatial and temporal scales. Climate change is impacting tropical forest ecosystems in various ways, but the attribution is not always clear. Precise characterization of hydroclimate variability in the Amazon on various timescales is critical to understanding the link between climate change and biodiversity (Cheng et al., 2013). The natural variability of the climatic system sometimes makes it difficult to attribute changes to the climate. The increase in temperature, precipitation, and increase in climate extremes, tropical forests, and Amazonian forests are increasingly changing, possibly due to climate change impacts. The large biodiversity of the Amazon somewhat helps to protect the forest, but there are limits and thresholds for the environmental impacts. The complex forest dynamics are closely coupled to the carbon and water cycling, and changes in a single component affect the whole structure. Geologically, the Andean uplift was crucial for the evolution of Amazonian landscapes and ecosystems, and that current biodiversity patterns are rooted deep in the pre-Quaternary (Hoorn et al., 2010; see Chapters 1 and 2). Amazonian paleoclimate studies help to understand the formation and evolution of this rich environment and show evidence that human impact on the Amazonian ecosystem could have been substantial over the last few millennia (Maezumi et al., 2018, Maksic et al., 2018, Cordeiro et al., 2014, Anhuf et al., 2006).

Freshwater ecosystems also interact with the ecosystem in complex ways, and in the case of the Amazon, the Basin houses unparalleled aquatic biodiversity. Regarding fish, more than 2,500 species, belonging from old to modern groups, inhabit all kinds of water bodies, such as small streams, lakes, and large rivers, and many are adapted to challenging conditions. Some of these fish species are important sources of protein for local people. Other species are essential to maintain the biological equilibrium of local systems and floodplain forests' natural regeneration. However, the current challenging conditions of particular water bodies, such as low pH, high temperature, and low dissolved oxygen, could be worsened by the ongoing climate changes. As many fish species already live near their physiological limits, environmental impacts on those water characteristics would impact the local aquatic biota.

This chapter will discuss the observed and predicted impacts of climate change in the Amazonian terrestrial and aquatic ecosystems. We will focus on impacts on biodiversity, ecosystem services, carbon cycling, fisheries, and biomass burning emissions. All these aspects are closely linked, as can be observed in the schematic shown in Figure 23.1.

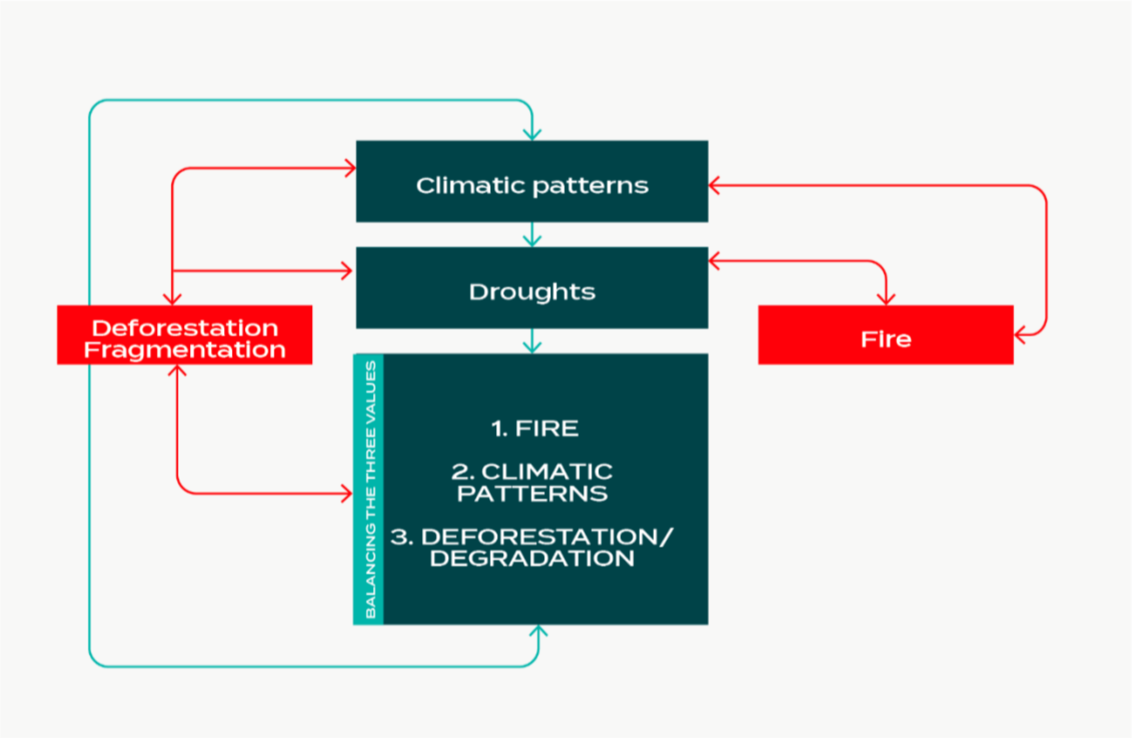

Figure 23.1 Links between climate, deforestation, forest degradation, and fire impacts on the Amazonian ecosystem, including biodiversity, carbon and water cycling, and economy and human well-being. To establish solid public policies on land-use change, it is necessary to have an integrated view of the main drivers and impacts.

1.1. Changes in biodiversity driven by climate change and deforestation

1.1.1. Lowland forests

An increasing body of literature indicates that global climate change can affect the future distribution of biodiversity and the composition of ecological communities, species range sizes, extinction probabilities, and species' local richness. Several paleoclimate studies show changes in biodiversity and ecological communities associated with climate change over a range of time scales (Anhuf et al., 2006, Cheng et al., 2013, Cordeiro et al., 2014). Climate variability associated with internal (such as ocean/atmosphere/land coupling) and external forcing (such as solar activity or volcanism) has altered the ecosystem for thousands of years. In particular, over the last 2000 years, the Amazon had relatively stable climate conditions and significant changes in the ecosystem.

In the case of the Amazon, while deforestation and forest degradation are currently the most significant threat to biodiversity, climate change is becoming an increasingly relevant driver. Climate change and deforestation combined could cause a decline of up to 58% in Amazon tree species richness. In comparison, deforestation alone would account for a decrease of 19–36% and climate change of 31–37% by 2050. Species may lose an average of 65% of their original environmentally suitable area, and a total of 53% are considered threatened (Gomes et al., 2019). Some Amazon regions are most likely to be affected by deforestation and climate changes synergetic impacts: eastern Amazon may suffer up to 95% of forest loss by 2050, followed by southwestern (81%) and southern Amazon (78%). Still, there is the influence of wildfire in the interactions between deforestation and climate change (Gomes et al., 2019).

The floristic and functional compositions of well-preserved lowland Amazonian forests have been changing according to records of long-term inventories covering 30 years. Tree communities have become increasingly dominated by large-statured taxa. Among newly recruited trees, drought-tolerant genera have become more abundant, while the mortality of wet tolerant genera has increased in plots where the dry season has intensified most (Esquivel-Muelbert et al., 2018). The results suggest a slow shift towards a drier Amazon, with changes in compositional dynamics (recruits and mortality) consistent with climate change drivers. The increase in atmospheric carbon dioxide (CO_2) is driving tree communities towards large statured species. Despite the impacts of climate change on the forest composition, the long generation times of tropical trees imply a lagged response of tree diversity to climate change (Esquivel-Muelbert et al., 2018).

While climate change affects biodiversity, plant trait diversity may enable the Amazon forests to adjust to new climate conditions protecting the Amazon's ecosystem functions (Sakschewski et al., 2016). However, the risks to biodiversity will increase over time with anthropogenic climate change progression, with future projections of potentially catastrophic global biodiversity loss. Projections (from 1850 to 2100) of temperature and precipitation to estimate the timing of exposure of a large group of species to potentially dangerous climate indicated that future disruption of ecological assemblages would be abrupt (Trisos et al., 2020) because of most species' simultaneous exposure to climate conditions beyond their realized niche limits. Under the RCP 8.5 scenario (high emissions), such abrupt exposure events will affect tropical forests by 2050.

Despite the lower level of warming relative to temperate regions, exposure is most significant in the tropics. Little historical climate variability and shallow thermal gradients mean that many species occur close to their upper realized thermal limits throughout their geographic range. The Amazon is one of the regions (together with the Indian subcontinent and Indo-Pacific) most at risk, with more than 90% of species in any assemblage exposed to unprecedented temperatures by 2100 (Trisos et al., 2020).

1.1.2. Lowlands connectivity with highlands

Amazon harbors one of the world's most diverse communities, and migration towards wetter and colder habitats as the lowlands become warmer is predicted for many species. Being the most extensive and highest mountain range on the continent, the Andes may represent the only refuge for many Amazonian species, potentially resulting in a net loss of species in lowland forests (Colwell et al., 2008).

Lowland Amazonian species are likely to be highly vulnerable to climate change because of their narrow thermal niche. Some areas in the Andes may increase in species richness due to the immigration of lowland species. However, these gains may be offset by other threats to biodiversity, such as habitat loss. In parts of the northern Andes, climate-driven shifts of bird, mammal, and amphibian species are predicted to lead to minimum average gains of 21% - 27% in species richness, based on two emissions scenarios (Lawler et al., 2009).

Since most tropical species might migrate to habitats that match their ecological requirements in response to climate change, protecting lowlands' connectivity to the cooler highlands may provide an escape route for many species from the megadiverse Amazon and Andean foothills. The forest belts are typically subdivided into upper montane (2500 m to timberline) and lower montane (1500 to 2500 m). However, very few elevational gradients of intact habitat extend from the lowlands on either side of the Andes to treeline or above. Because forests often remain in isolated belts at intermediate elevations, many species will face rising temperatures forcing them to shift upslope. Simultaneously, they are pushed downslope by the expansion of human population centers and the advancing agricultural frontier.

1.1.3. Aquatic ecosystems

A significant effect of climate change on the function of aquatic ecosystems and their biodiversity (see Chapter 3) is the disruption of the natural hydrological cycle due to unusually low and high peaks in water levels during extreme drought and flood events (Marengo and Espinoza, 2016; see also Chapter 22). Such extreme events affect plants and animals, causing changes at multiple levels, from individuals and populations to communities and ecosystems, at local and regional scales. In central Amazon’s floodplains, the extreme drought event of 2005 affected detritivore curimatids’ health (*branquinhas*), leading to thinner fish relative to their body length (Correia et al., 2015). It also caused shifts in fish abundance and the composition of fish communities, which were noticeable a decade later (Röpke et al., 2017). In western Amazon, the extreme drought of 2010 caused significant declines in wading birds, river dolphins, and populations (Bodmer et al., 2018). In contrast, extreme flood events in 2009 and 2011 to 2015 caused a 95% population decline of ground-dwelling mammals and altered predator-prey interactions. Such long-lasting reductions in game-wildlife abundance shifted local Indigenous people’s hunting effort to fishing and increased local fishing pressure during the flood period (Bodmer et al., 2018).

Many fish species in the Amazon are migratory, and their ability to migrate is threatened by climate change. Goliath catfishes (*Brachyplatystoma rousseauxii, B. platynemum, B. juruense,* and *B. vaillantii*) undertake the longest documented migrations freshwater fishes on Earth (Barthem et al., 2017). From headwater spawning habitats in/or near the Andes to nursery habitats in the Amazon Estuary on the Atlantic Ocean, their migratory journeys can expand to 11,600 km when older juveniles of *B. rousseauxii* return to their places of birth (Barthem et al., 2017). Low water levels during extreme drought events can lead to temporal river fragmentation, blockage of fish migrations, and local extinctions (Freitas et al., 2012). However, studies assessing the magnitude of climate change disruptions to migrations are needed.

Tectonics and climate changes are clear marks in the evolution of the Amazon biota. Amazonian fish experienced speciation booms over critical periods with regard to oxygen availability, high temperatures, and extreme levels of carbon dioxide (Albert et al., 2018). Environmental pressures in these geological periods contributed to shaping the biology of thousands of fish species in the Amazon, including the appearance of peculiar physiological, biochemical, and reproduction features in these species (Val and Almeida-Val, 1995). Three aspects deserve to be highlighted here, given their connections with the conservation of the Amazon biome in these times of the new scenarios imposed by the current climate changes and foreseen for the near future. These aspects are the availability of oxygen in the aquatic environment, water acidity due to the dissolution of CO_2, and an increase in temperature.

The availability of oxygen has always been a significant environmental challenge for fish in the Amazon that have developed a wide range of adaptations to transfer oxygen from the environment to the different organs (Val and Almeida-Val, 1995; Val et al., 1998). Some of these adaptations, such as aerial breathing as in Pirarucu (*Arapaima gigas)* (Brauner and Val, 1996) and the expansion of the lower lips of Tambaqui (*Colossoma macropomum)* (Saint-Paul, 1984) for breathing on the surface of the water column, among others, place these animals in contact with a modified atmosphere. The increase in temperature contributes to increased ventilation and, therefore, to increased contact of the gills and respiratory organs with water and air with modified properties (Almeida-Val and Hochachka, 1995).

As the water warms, it loses its ability to hold oxygen but at the same time triggers a greater oxygen demand in cold-blooded animals such as fish. Andean Amazon fish species, particularly those that inhabit high elevations and prefer cold water, are highly susceptible to contractions in their distribution range and eventually to extinction as they move upstream, searching for cooler water (Herrera et al., 2020). Increases in the metabolism of warm-water species in lowland habitats can trigger greater food intake and cause unforeseen consequences in local food webs. Tambaqui exposed to experimental conditions that mimic elevated air temperature and CO_2 predicted by climate change scenarios increased their food intake, but their growth decreased under the most extreme warming scenarios (Oliveira and Val, 2017). Such physiological responses of large and long-living fish such as Tambaqui can increase competition with other fish species and reduce aquatic ecosystems' carrying capacity.

Many fish species in the Amazon are susceptible to small temperature increases (Campos et al., 2018). These authors showed that the maximum critical temperature of some fish groups is already very close to the average maximum temperatures that currently occur. Small temperature increases affect multiple physiological processes. Studies with Tambaqui demonstrated that the most basic reproductive processes, such as fertilization, are sensitive to environmental conditions, including temperature and pH (Castro et al., 2020). Moreover, metabolic processes that provide the energy necessary to survive can express the increased environmental variability in Amazonian environments.

Acidic waters are common in the Amazon (see Chapter 3). The black waters of the Negro River, for example, are typically acidic, and some of its marginal lakes may have waters with pH as low as pH 3.5. Even so, hundreds of different fish species inhabit these waters, as are the hundreds of ornamental fish species that support a significant economy of some Amazonian villages. We are far from knowing the resilience of Amazonian fish to pH variations. Still, we see that they use different strategies to maintain ionic homeostasis in the face of challenging situations imposed by the acidity of the Negro River (Gonzalez et al., 2002). We also know that Tambaqui is remarkably resilient to acidic water exposure (Wood et al., 1998). Thus, the acidic pH, at least for the species studied so far and, except for fertilization, does not represent an expressive limiting factor. However, further studies involving other fish species of commercial interest are necessary.

We are far from understanding the effects of climate change on fish in the Amazon. Still, we already know that when exposed to simulated environmental scenarios for temperature, CO_2, and humidity for the year 2100, according to the Intergovernmental Panel on Climate Change (IPCC) models, they are significantly affected. In the case of Tambaqui, an important commercial species for the entire Amazon, we observed transcriptional readjustments (Prado-Lima and Val., 2016), intense vertebral disorders with increased levels of lordosis, kyphosis, and scoliosis (Lopes et al., 2018), and reduced feed conversion, with animals eating more and growing less in the most drastic climatic scenarios (Oliveira and Val, 2017). The disturbances also occur with ornamental fish species of Rio Negro (Fé-Gonçalves et al., 2018). Undoubtedly, fishing and fish farming will need to incorporate new technologies in the face of new climate scenarios to maintain protein production and ensure food security.

1.2. Forest dynamics in a changing climate

Forest dynamics are characterized by interactions between disturbances and demographic processes (e.g., recruitment, growth, and mortality), which together shape much of the structure, carbon content, and species composition of Amazonian forests. Despite their high resilience, anthropogenic climate change is severely altering forest dynamics across the entire basin. This includes old-growth, degraded, and secondary forests. Climate change exacerbates chronic drivers of forest change (e.g., rising temperature and CO_2) and the extent, frequency, and intensity of single and compounding disturbance events—including wildfire, drought, windthrow, and biotic attack. An outstanding question is whether such interactions between stressors and disturbances will be large enough to surpass tropical forests' capacity to resist and respond to such changes, especially as they interact with land-use change (see Chapter 24).

By changing the atmospheric composition and air temperature, global carbon emissions have impacted Amazon's most remote forests. The accumulation of atmospheric CO_2 has contributed to the increased growth of primary forests and mortality rates in the mid-2000s (Brienen et al., 2015). While this likely CO_2 effect has ultimately promoted forest carbon (C) gains, especially during the 1990s, carbon accumulation rates are now slowing down. One possible explanation for this change is that forest mortality losses are outpacing potential gains from forest enhanced growth. Another contributing factor to increasing mortality--other than CO_2--is the increases in air temperature occurring over the region. Many Amazonian trees operate close to their bioclimatic limit. Thus, when air temperatures rise, autotrophic respiration increases the carbon-related costs for tree growth, partially explaining why carbon accumulation in Amazonian forests decreases nearly 9 Mg C ha per increase degree Celsius (Hubau et al., 2020). Extreme daytime temperatures are critical in depressing tree growth rates.

Another characteristic of intact lowland forests that are changing is their floristic and functional composition. There is an apparent ongoing shift in tree species composition in the Amazon towards a more dry-affiliated community (Esquivel-Muelbert et al., 2019). These changes have been linked to climate-change drivers altering forest recruitment and mortality, with atmospheric CO_2 playing important roles. Overall, these ongoing changes in primary forest dynamics have been subtle, with their detection concentrated in field plots located in primary forests.

Unfortunately, the influences of climate change on Amazonian forests go beyond subtle forest dynamics and composition changes. Climate change is intensifying droughts, wildfires, and windstorms regimes and how these disturbances interact. While forests have evolved being exposed to some level of disturbances, these novel disturbance regimes can cause severe and prolonged forest degradation. This can sharply reduce forest species richness, reduce carbon storage capacity, and cause significant shifts in species composition (towards a more generalist, less diverse community of plants). The forests most susceptible to these disturbances grow along the driest southern and eastern margins of the Amazon, where drought, wildfires, and fragmentation already interact synergistically (Morton et al., 2013; Alencar et al., 2015). Lowland forests (e.g., igapos) are also particularly vulnerable to some of these disturbances, including fire and drought interactions (Flores et al., 2017). Despite the extensive degradation caused by drought-fire interactions in the Amazon, it is still unclear how much it is caused by climate change itself, given complex interactions involving land-use change.

Although forests disturbed by compounding extreme events may eventually recover, it is still unclear which time frame this happens. A single disturbance event such as drought may kill the most susceptible species and select more drought-resistant trees, which can potentially reduce tree mortality in successive events. Furthermore, previous studies suggest that even severely disturbed forests can recover some pre-disturbance characteristics (e.g., fluxes of H_2O) within decades (Chazdon et al., 2016). Yet, climate change is expected to increase the risks of new disturbances impacting the area, perhaps before recovery occurs. While higher levels of atmospheric CO_2 may facilitate forest recovery, more frequent disturbances would result in chronic impoverishment of biomass and biodiversity, especially in landscapes becoming more fragmented by deforestation. In fact, as regional climate changes, forest resilience is expected to decrease (Schwalm et al., 2017).

Our current scientific understanding points to Amazonian forests becoming increasingly susceptible to wildfires, droughts, windthrow events like climate change. Modeling studies indicate that climate changes have potentially significant effects in the near future, as more CO_2 accumulates in the atmosphere and the temperature continues to increase. Considering only primary forests, CO_2 could theoretically offset losses in carbon stocks from increased temperature. However, recent studies point that the CO_2 fertilization effect is limited mainly by the availability of other nutrients and diversity of functional strategies across species (Fleischer et al., 2019). Most predictive vegetation models or earth system models used to project potential trajectories of Amazonian forests are too sensitive to CO_2 fertilization and not very sensitive to variability in precipitation and lack disturbances such as drought-induced tree mortality and logging wildfire, and edge effects. Another priority for dynamic vegetation models is the representation of plant hydrodynamics, distribution of water and nutrients below-ground, and partitioning of solar radiation between competing plant canopies (Fisher et al., 2018).

Improving our understanding of the potential impacts of climate change in the near future requires long-term monitoring from individual trees to the entire continent. It also entails improving the current climate-global dynamic vegetation models, which are the primary tool used to forecast tropical forests' potential trajectories. Earth System Models (ESM) predicts too much of the Amazon to be water-limited, with very significant uncertainties in simulating Amazon climate, with an additional exacerbated sensitivity of vegetation models on the CO_2 effect (Ahlström et al., 2017). Although these models have rapidly advanced, the data and understating of an extraordinarily complex system with more than 16,000 tree species remains to be fully understood. The potential legacies of increased forest degradation by compounding disturbances can persist for long periods. This lends urgency in identifying potentially catastrophic thresholds of forest health declines associated with rising temperatures and changes in precipitation patterns (see Chapter 22).

1.3. Carbon cycling and storage

The long-term balance between carbon uptake during photosynthesis and carbon losses during respiration and tree mortality dictates how much carbon Amazonian forests can store. Of the total carbon assimilated by Amazon forests, between 30–40% are used for biomass accumulation. Most of the remainder is respired back to the atmosphere. Simultaneously, a smaller fraction is stored as sugars and starch, allocated for growth or to maintain physiological processes. The total gross primary productivity (GPP) allocated for growth (net primary productivity; NPP) range from 30 and 45%, with more of the NPP being used for wood increment (39%) than for leaf (34%) and fine root (27%) production (Malhi et al. 2011). However, few studies have quantified all these NPP components.

The spatial variability of C uptake and productivity of Amazonian forests strongly relates to climatic gradients across the Basin. Overall, photosynthesis is lower in regions with total annual precipitation averaging values < 2,000 mm and dry seasons longer >3.5 months (Guan et al., 2015). Extreme wet areas can constrain GPP due to high cloud cover and low light availability (Lee et al., 2013). Despite variability in GPP across the Amazon, most high-elevation primary forests average between 20 and 40 megagrams of carbon (MgC or 106 g)/ha per year (Malhi et al. 2011). NPP can follow similar spatial patterns to GPP, although differences are common due to the influences of autotrophic respiration on NPP (Brando et al., 2019a).

Currently, between 90-110 Pg of carbon is stored in Amazonian forests aboveground (Artaxo et al., 2021). Recent studies have shown that forest carbon cycling in the region is changing, with important implications for this large carbon reservoir. A few decades ago, primary forests of the Amazon were removing carbon from the atmosphere at a rate of about 50g/m/y (Ometto et al., 2005; Araujo et al., 2002; Chambers et al., 2001). However, the rate of carbon accumulation has sharply declined over the past two decades. One important reason for this reduction is significant droughts causing widespread reductions in tree growth and increases in tree mortality, especially the larger, carbon-rich ones, shown in Figure 23.2 (Brienen et al., 2015; Brando et al., 2019a). Another potential cause for the reduction is the increase in atmospheric CO_2, promoting higher forest turnover rates (McDowell *et al.* 2018). As a combined result of these changes, the carbon accumulation capacity of undisturbed forests is getting weaker for both the Amazon and tropical

Africa, with the possibility of forests becoming global carbon sources (Hubau et al., 2020; Brienen et al., 2015).

[A Figure will be inserted here, after being adapted from Brienen et al. 2015]

Figure 23.2. Long-term net above ground biomass change of old growth tropical forests in Amazonia. Trends in productivity and mortality across all sites from 1985 to 2010. in a), net biomass change is shown, in b) the productivity, and c) shows biomass mortality. It is possible to observe a decrease in net biomass change due to increase in biomass mortality (Brienen et al., 2015).

Given the strong controls of climate on the geography of carbon stocks and productivity of Amazon forests, ongoing climatic changes are expected to cause significant shifts in forest carbon cycling. Future temperature and precipitation changes, in addition to increases in climate extremes, will bring additional stress (Lovejoy and Nobre, 2018, 2019; Nobre et al., 2019; Aguiar et al., 2016). While intact tropical forests are estimated to be Earth's largest carbon sink (Pan et al., 2011; Phillips et al., 2009, Ometto et al., 2005), the stability of this sink is susceptible to a warming climate and disturbance processes (Lenton et al., 2008). For instance, Hubau et al. (2020) projected a decrease of 9 MgC/ha per increase in degree Celsius. Also, a change in drought regimes is expected to reduce the carbon storage capacity of tropical forests, especially those located in the southeast portion of the Basin. Such changes in climate-forest interactions will most likely change the emissions and atmospheric processes that have been discussed in previous sections, especially if global climate change is aggravated regionally by deforestation (Hoffmann et al., 2003).

The Amazon is currently subjected to pressures that go well beyond climate change (see Chapters 14-21). A wide range of severe disturbances, either natural or human-made, have directly or indirectly threatened the ecosystems' health, functions, and services in the Amazon, affecting biodiversity and carbon storage functions (Trumbore et al., 2015). A significant issue is that these disturbances interact with global climate change, having potentially compounding effects on forest carbon stocks. In southeast Amazon, forests become much more vulnerable to fire along their edges with agricultural fields, during droughts and heatwaves, and where logging removes canopy cover. Once forests burn, they tend to be more severely disturbed by windstorms than primary forests, explaining why forest carbon stocks can reduce by 90% when impacted by these disturbances (Brando et al., 2019b).

Unfortunately, the carbon stocks of Amazon forests are not threatened only by interactions between forest disturbances and climate change. Deforestation has also been an essential driver of carbon storage reductions. Over the last three decades, more than 400 Gm² of forests have been cleared in the Brazilian Amazon, representing 19% of the Brazilian Amazonian forested area. The annual rate of Amazonian deforestation was strongly reduced from 29 Gm² to 4 Gm² per year from 2004 to 2012, showing that it is possible and feasible to reduce tropical deforestation (Figure 23.3). Unfortunately, from 2012 to 2020, deforestation has increased significantly, and now the rate is at 11.1 Gm² in 2020, due to changes in Brazilian national policies for the Amazon region. The 2019 deforestation in the Brazilian Amazon released about 559 $MtCO_2$, according to estimates from Brazilian National Institute for Space Research (INPE, 2021), and the deforestation pressure is increasing carbon emissions. The remaining forest edges have become much more flammable and prone to burning (Brando et al., 2020). These emissions go against Brazilian Nationally Determined Contributions (NDCs) to the Paris Agreement, whose commitment is to eliminate illegal deforestation by 2030.

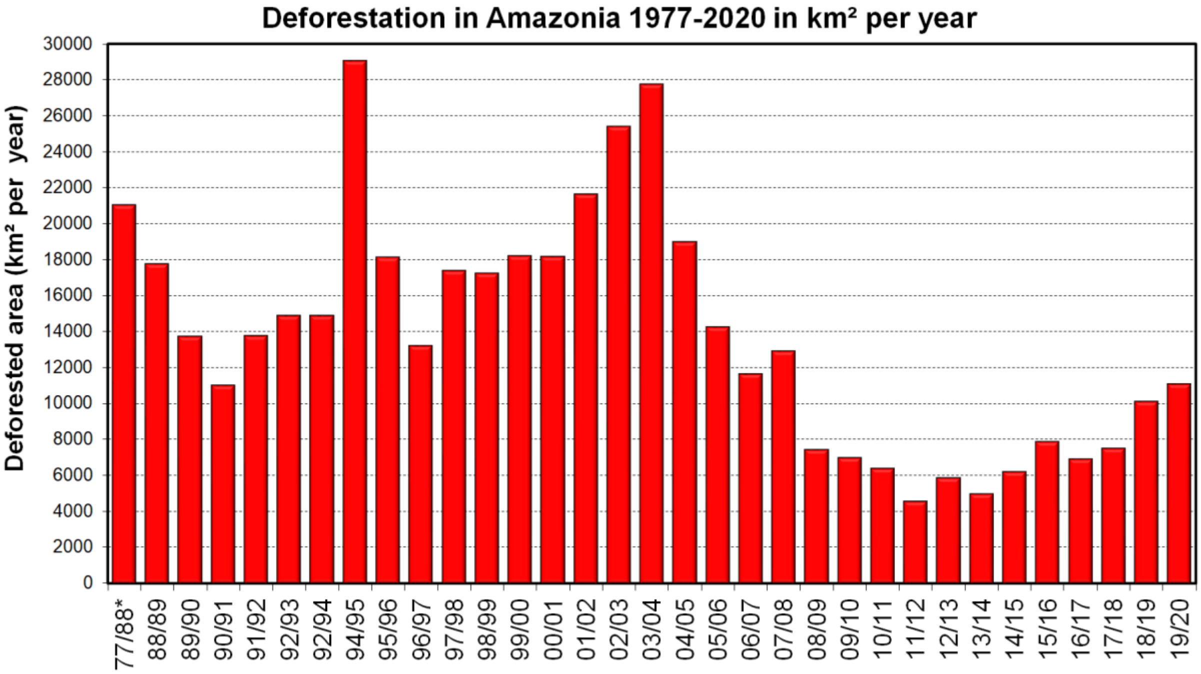

Figure 23.3. Time series of annual deforested area in the Brazilian Amazon, from 1977 to 2020. Data from the INPE PRODES program.

There is an ongoing debate about the net carbon flux between Amazonian forests and the atmosphere when the entire Basin is considered. Some studies indicate that the carbon accumulation of standing forests is large enough to offset carbon losses from disturbances and deforestation, while others point to Amazonian forests acting as carbon sources (e.g., Pan et al., 2011; Gloor et al., 2012; Baccini et al., 2017; Schimel et al., 2015; Brienen et al., 2015). This apparent disagreement is mainly because the net carbon flux is the difference between two large gross fluxes. The carbon emissions primarily result from deforestation, and the carbon uptake is due to forest growth, likely supported by the increasing CO_2 concentration in the atmosphere. Consequently, any change in the processes that affect atmosphere-biosphere interactions can significantly change the net carbon transfer between the tropical forests and the atmosphere, with substantial repercussions for atmospheric CO_2 levels and global climate (Lewis, 2006; Chambers and Silver, 2004). In other words, if deforestation, forest degradation, wildfires, edge effects were to be avoided, the net carbon uptake of Amazonian forests would contribute much more effectively to carbon removal from the atmosphere (Houghton et al., 2018).

1.4. Freshwater impacts

Amazon freshwater ecosystems have been impacted by changes in landscape during their formation and evolution (see Chapters 1 and 2). Although natural, these changes leave a signature that will be part of the several ecosystems, and all aquatic organisms are currently adapted to them. The highest evolutionary impact on recent freshwater evolution is the river captures due to geological changes (Val et al., 2014). River capture is a geomorphic mechanism of network reorganization by which a basin captures large portions of the network of an adjacent basin, thus creating a barrier for species dispersal. So**,** landscape changes in the Amazon water bodies, such as drainage network reorganization, influence the distribution range and connectivity of aquatic biota and, therefore, their evolution (Albert et al., 2018). Such natural changes have occurred in the Amazon since the Andean uplift resulting in many episodes causing loss of habitats. Loss of habitat is the primary driver to both the appearance of new species or their extinction, being the most substantial impact in freshwater systems. Ongoing impacts, though, give no time to fish assemblages, species, or populations to recover or adapt to the new condition, many times threatening those ecosystems.

Recent human activities have caused several habitat losses and many species extinction in the current evolutionary time. These changes are happening so fast that it is currently known as the 6th mass extinction (BPBES 2020). On top of the current Amazon Basin landscape, the impacts of mining, hydroelectric power plants, overfishing, the release of industrial, urban, and medical pollutants result in synergic effects over the aquatic biota. It is already adapted to acidic and hypoxic waters and lives at the upper limit of its critical temperature (Campos et al., 2019).

Fishes of the Amazon are, as already mentioned, adapted to extreme conditions such as low pH, variable dissolved oxygen (both spatial and day/night changes), and also periodic lack of oxygen, variable types of water, which have different amounts of DOC (dissolved organic carbon), and different pHs. Most anthropic actions induce changes in these characteristics, resulting in temperature increases, hypoxia, and acidification. Synergic effects of the release of herbicides cause tissue, cellular, and DNA damages that are acute and even worth when fish face hypoxia and higher temperatures (Silva et al., 2019; Souza et al., 2019).

The exposure of some species, particularly the Tambaqui (a model species) to climate rooms built to mimic the future scenario forecasted by IPCC for the year 2050, revealed many damages and some degree of mortality to fish adapted to different temperatures. The gene expression of the whole transcriptome showed that differentially expressed genes act to readjust or adapt protein expression and respond to changes in their metabolism (Fé-Gonçalves et al., 2020). Either they adjust their metabolism or die. These are few studies considering the effects of climate change on the dimension of aquatic biota in the Amazon. We are far from understanding the complex network of several impacts lately caused by men will modify the aquatic biota at several ecological and biological levels.

1.5. Climate change and hydrology

Several climate drivers perturb the hydrologic cycle of the Amazon basin. Rainfall in the Amazon is sensitive to seasonal and interannual variations in sea surface temperature (SST) in the tropical oceans (Fu et al. 2001; Liebmann and Marengo, 2001; Marengo et al., 2008a,b; see also Chapter 5). The warming of the tropical east Pacific during El Niño events suppresses wet season rainfall by modifying the (East-West) Walker Circulation. Teleconnections leading to simultaneous changes in the northern hemisphere extra-tropics alter moisture flow into the Amazon and induce drought events such as 1962, 1983, and 1998 (Williams et al., 2005; Ronchail et al., 2002). Moreover, variations in Amazonian precipitation are also known to be linked to SST in the tropical Atlantic (Liebmann and Marengo, 2001). A warming of the tropical North Atlantic relative to the south leads to a North-Westward shift in the Intertropical Convergence Zone (ITCZ) and compensating atmospheric descent over the Amazon, sometimes producing intense drought, as in 1963 and 2005 (Marengo et al., 2008a,b). Gloor et al. (2013) showed that the Amazon river discharge at Óbidos is increasing significantly at both dry and wet seasons. This could be caused by an increase in the input of water vapor from the tropical Atlantic due to the substantial sea surface temperature increase since the ’80s. Figure 23.4 below shows the time series of the Amazon river discharge at Óbidos.

[A Figure will be inserted here, after being adapted from Gloor et al. 2013]

Figure 23.4. Long term time series of the Amazon river discharge at Óbidos during dry season (blue), wet season (green) and whole year (red). Figure adapted from Gloor et al. (2013).

Observations and models suggest large-scale deforestation could cause a warmer and somewhat drier climate by altering the regional hydrologic cycle. Model results (Sampaio et al., 2007; Sampaio, 2008) suggest that if more than 40% of the original extent of the Amazon forest is lost, rainfall will decrease significantly across eastern Amazon. Complete deforestation could cause eastern Amazon to warm by more than 4ºC, and precipitation from July to November could decrease by up to 40%. Crucially, these changes would be in addition to any change resulting from increased greenhouse gas (GHG) emissions; reducing deforestation can offset the impacts of GHG. It has been suggested that 40% of deforestation may be a tipping point beyond which forest loss causes climate impacts which cause further forest loss (Sampaio et al., 2007).

A key question is whether a general long-term trend exists during recent decades toward drought conditions and, if so, to what degree it is associated with GHG emissions and deforestation. Li et al. (2008) show that the Standard Precipitation Index (SPI), a measure of changes in precipitation normalized by the standard deviation, does indeed suggest a more pervasive drying trend over the southern Amazon between 1970–1999. Previously, tendencies studied by Marengo (2009) for the period 1929–1998 suggested that no unidirectional rainfall trend existed in the entire Amazon region. Still, a slight negative/positive trend was identified in northern/southern Amazon. To understand discrepancies between these studies, it is necessary to evaluate the time scales over which the data were analyzed. Perhaps, the most critical aspect of natural Amazonian precipitation change is interannual and interdecadal variability in rainfall. Studies have identified a negative trend for southern Amazon during 1970–1999 coincided with the mid-1970s–1998 downward rainfall trend of the interdecadal rainfall variability in northern Amazon (Marengo, 2009). This decadal variability seems to be linked to interdecadal variations in the SST in the tropical Atlantic (see Chapter 22).

Despite some progress in reducing deforestation rates, some parts of the Amazon basin, such as the eastern Amazon region, a transition zone between rainforest and savanna environments, remain particularly vulnerable to feedback from ongoing land-use conversion to agriculture (Coe et al., 2013). The expansion and intensification of agriculture shift how incoming precipitation and radiation are partitioned among sensible and latent heat fluxes and runoff (Bonan, 2008; Coe et al. 2013; Foley et al. 2005; Neill et al. 2013). Relative to the forests they replace, crops and pasture grasses have reduced root density and depth and lower leaf area index (LAI). This decreases water demand and lower evapotranspiration (ET) (Coe et al., 2009, 2013; Costa et al., 2003; D’Almeida et al., 2007; De Moraes et al., 2006; Lathuillière et al., 2012; Nepstad et al., 1994; Pongratz et al., 2006; Scanlon et al., 2007). At local and regional scales (i.e., watersheds of 10-100,000 km2), such reductions in evapotranspiration lead to increased soil moisture and runoff (Coe et al., 2011, 2009; Hayhoe et al., 2011; Neill et al., 2006). At continental scales (i.e., Amazon Basin), these land cover changes may feedback on regional climate by reducing rainfall and decreasing runoff (D’Almeida et al., 2007; Davidson et al., 2012; Stickler et al., 2013).

2. IMPACTS OF CLIMATE CHANGE ON ECOSYSTEM SERVICES

2.1. Pollination and seed dispersal

Nature in the Amazon has a wealth of ecosystems and biodiversity that are indispensable to delivering ecosystem services across scales (Díaz et al., 2019). At landscape to regional scales, Amazon's forests regulate hydrological cycles (Salazar et al. 2018), water quality, and nutrient cycling that supports freshwater biodiversity and people (Menton et al., 2009). Ecosystem services result from the interactions between several biotic and abiotic components, with biodiversity supporting ecosystem functions that affect life on the planet (Mace et al., 2012). Anthropogenic climate change is one of the main current threats to biodiversity linked to species decline (Díaz et al., 2019). Among biotic interactions, pollination and seed dispersal play an essential role in determining plant diversity and distribution in natural ecosystems (Wang and Smith, 2002) and agricultural production. In this context, bees, birds, and bats that act as pollinators, seed dispersers, and pest controllers are crucial (Kremen et al., 2007). These groups are susceptible to spatially operating ecological factors, which makes the services provided by them highly contextual (Kremen, 2005; Mitchell et al., 2015).

Birds are good biological indicators of climate change impacts on ecosystem services. Their occupancy of all terrestrial habitats and the consumption of virtually all types of resources provide critical ecosystem functions and services such as pollination, seed, and nutrient dispersion predation, and scavenging. Miranda et al. (2019) compiled extensive species occurrence data representative of southeastern Amazon to assess the potential climate change impact on avian assemblages. Using Species Distribution Modeling (SDM), they analyzed how different climate change scenarios could affect the pattern of species distributions and assemblage compositions. They grouped species based on their primary diet (frugivores, insectivores, nectarivores, and others) as a proxy to ecosystem services (seed dispersion, pest control, and pollination). Considering the entire study area, they estimated that between 4 and 19% of the species would find no suitable habitat. Inside the currently established protected areas, species loss could be over 70% (Miranda et al., 2019). The results suggested that frugivores would be the most sensitive guild, bringing consequences on seed dispersal functions and natural regeneration. Moreover, they identified the western and northern parts of the study area as climatically stable. At the same time, climate change will potentially affect avian assemblages in southeastern Amazon with negative consequences to their ecosystem functions (Miranda et al., 2019).

Bats also have been reported to be associated with hundreds of plant species whose nectar or fruit they consume (Kunz et al., 2011; Ghanem and Voigt, 2012). They occupy different trophic niches and perform various functions in nature, acting as flower pollinators (nectarivores), seed dispersers (frugivores), and pest controllers (insectivores). Frugivorous bats work in a complementary way with birds with the same trophic habits, acting together to diversify the microhabitat where they deposit seeds, thus contributing a significant service when considering the quantity and quality of dispersion (Jacomassa and Pizo, 2010; Sarmento et al., 2014).

The effects of climate change on the distribution of bat species occurring in the Carajás National Forest (eastern Amazon, southeastern Pará state, Brazil) was examined by modeling species distributions (Costa et al., 2018). The authors evaluated a total of 83 species of bats for the years 2050 and 2070 to indicate the species potentially more sensitive to climate changes and if they would be able to find suitable areas in Carajás in the future. Besides, they assessed the priority areas that protect the most significant number of species from climate change. A considerable fraction (57%) of the analyzed species would not find suitable locations in Carajás under the climate change scenarios. Pollinators, seed dispersers, and more-generalist (omnivorous) bats would potentially be the most affected, suffering a 28–36% decrease in suitable areas under the 2070 scenario, affecting the plants that interact with bats. According to the scenarios, current protected areas in the Brazilian state of Pará would not protect most species in the future.

Both studies (Miranda et al., 2019 and Costa et al., 2018) emphasize that the possible effect of climate change and protected areas' location needs to be considered for conservation strategies of pollination and seed dispersal services future climate change.

Besides bats and birds, projections indicate the impacts of climate change on the distribution of bees in the Amazon, impacting crop pollination (Giannini et al., 2020). The analyses and projections of the distribution of 216 species occurring at the Carajás National Forest (Eastern Amazon, Pará, Brazil), using two different algorithms and geographically explicit data, showed that 95% of bee species would face a decline in their total occurrence area. Only 15 to 4% would find climatically suitable habitats in Carajás. Bees with medium and restricted geographic distributions and vital crop pollinators would experience significantly higher losses in occurrence areas while wide-range habitat generalists would remain. The decline in crop-pollinator species will probably pose negative impacts on pollination services.

Climate change will promote the redistribution of biodiversity, and species-specific differences in response to the changes can decouple the interacting species' distribution. Such pervasive and indirect effects of climate change may have spillover effects upon economies and human well-being. The extraction of Brazil nuts is the most important socio-economic activity associated with non-timber products in the Amazon (Peres and Lake, 2003; Zuidema and Boot, 2002). The potential effects of future distribution mismatch of seed dispersal and pollination Brazil nuts were studied by Sales et al. (2021). The projections indicated that Brazil nuts' pollinators would lose nearly 50% of their suitable distribution in the future, leading to an almost 80% reduction in co-occurrence potential. Local pollinator richness was predicted to diminish by 20%, potentially decreasing pollination redundancy and resilience to environmental changes. Another study pointed out the magnitude of the loss of seed dispersal services by primates as a function of the future redistribution of species. Primates are remarkable seed dispersers, comprising up to 40% frugivore biomass in tropical forests (Chapman, 1995). The projections indicate average contractions of 56% (23 to 100% reduction) on the studied primates' suitable areas (Sales et al., 2021).

2.2. Aquatic ecosystems

Climate change is predicted to affect ecosystem services provided by freshwater ecosystems, including access to drinking water, electricity derived from hydropower, navigation, and most important, fisheries (Castello and Macedo, 2016), the primary source of animal protein and major economic driver in the Amazon region. The monetary value of Amazonian fishing is estimated at US$200 million annually and involves 200,000 fishers (Barthem and Goulding, 2007). These figures, however, likely underestimate the actual value of Amazonian fisheries given that fish used for consumption at fisher households are not included in fisheries landing statistics and because small-scale fisheries are highly heterogeneous at natural, social, and economic scales (Castello et al., 2013).

Fisheries' yields are being impacted by climate change in unpredictable ways. For instance, over ten years (1994-2004), the body length of fish harvested in the central Amazon (Solimões), Madeira, and Purus rivers have declined in response to the intensification in drought. This change in fish yields reflects a decrease in the abundance of large predatory fish, which is compensated for by increasing the number of smaller fish that feed lower in the food chain (Fabré et al., 2017). Over the same period, fisheries' yields in the lower Amazon River (Óbidos, Santarém, and Monte Alegre) declined by 50% relative to those from adjacent floodplain lakes. Moreover, target fish species responded differently to local environmental stressors related to climate change, such as reduced discharge, elevated water temperature, and wind, but also to global-scale stressors such as sea surface temperature and climatic indices related to El Niño-Southern Oscillation events (Pinaya et al., 2016). Calculating the economic losses due to reductions in fisheries yields induced by climate change is challenging because of the sparse knowledge on fisheries yields per habitat type (e.g., floodplain lakes, flooded forests, flooded savannahs, etc.; Barros et al., 2020; Castello et al., 2018; Goulding et al., 2019) and the lack of reliable long-term fisheries statistics to assess trends across the basin.

Although aquatic ecosystems provide many more services to human populations beyond fisheries, the lack of quantification of many of those services hinders our ability to estimate losses. Extreme droughts likely will reduce access to fresh water for drinking and bathing, alter natural flow regimes, which in turn will affect riverine navigation and access to off-channel fishing, hunting, and farming grounds, and affect cultural services, including recreation and the persistence of sacred places, usually linked to river-rapids. Lastly, spatial gradients in the effects of climate change on ecosystem services are expected given the differences in flow regimes and precipitation patterns across the basin as one moves from north to south and west to east.

The aquaculture activities may be considered an environmental service when done in natural ponds or cages on the rivers. It is among the services that aim to protect wild fish populations and increase protein availability to humankind. Otherwise, this activity has some adverse effects on the natural water systems if not monitored by specialists. Familiar aquaculture facilities lack control and regulation and can use and release many toxic substances to the natural environment. Although this activity is considered essential to avoid overfishing and provides protein to local people, it is still considered a threat to the environment (Silva et al., 2019).

3. CLIMATE FEEDBACKS OF VEGETATION AND LAND USE CHANGES

The Amazon ecosystem is directly affected by climate and land-use changes in many ways, but also, there is feedback between these two processes that may amplify the negative impacts (Betts and Silva Dias, 2010). Deforestation for the expansion of agricultural lands affects climate through changes in the energy and water balance and the carbon cycle. For example, pasture and crops that typically replace forest have a lower capacity to cycle water through evapotranspiration, and the extra water tends to increase the runoff. A large amount of carbon emissions from Amazon deforestation contribute to increases in the atmospheric GHG and temperature globally, which are also expected to increase forest water use efficiency through CO_2 fertilization, and reduce the amount of water vapor recycled to the atmosphere. Recent studies showing an increased vapor deficit throughout the Amazon, but we do not know if this is a transient or permanent trend nor how this can affect the forest and drive feedback over the long term. The reduced ET can impact precipitation, but changes in response to deforestation depend on how large and where deforestation occurs. Therefore, the impact of deforestation and climate change on hydrology in any location will be a complex function of those competing impacts (Coe et al., 2009).

Forest conversion and degradation impact climate through two pathways. The first is through the carbon cycle. Globally, photosynthesis removes almost 30% of all global anthropogenic CO_2 emissions each year. Tropical forests are the most significant fraction of that sequestration. With an area of 6.1 million km², the carbon stored in the Amazon's forests (~100-120 Pg of carbon) is equivalent to ten years of current global carbon fossil-fuel emissions. More than ½ of all CO_2 emissions from Amazon nations result from deforestation and degradation, and the total contribution to global atmospheric CO_2 content has been significant (Global Carbon Project, 2019). The net emissions from 2003 to 2016 alone were estimated at 4.7 Gt CO_2 (Walker et al., 2020).

The second mechanism by which deforestation and degradation affect climate is through the energy and water balance. Tropical forests have a low albedo, high evapotranspiration, and high roughness compared to croplands and pastures that often replace them (see Chapter 7). Those characteristics firmly control the local and, less strongly, global climate. The low albedo results in a significant fraction of incoming solar radiation being absorbed and high net energy in the forest system. Much of that energy is used in the cooling process of evapotranspiration, which is generally high throughout the year because of relatively abundant sunshine and rainfall or stored soil moisture. The relatively high surface roughness and aerodynamic conductance increase the atmospheric mixing of ET and energy into the troposphere (Panwar et al., 2020). As a result, >60% of all rainfall is transpired back to the atmosphere. This has the immediate effect of cooling the land surface by 2-5°C (Lawrence and Vandecar, 2015; Silvério et al., 2015). The relatively high surface roughness increases atmospheric mixing of ET and energy into the troposphere. Those conditions provide atmospheric moisture that increases rainfall, particularly at the onset of the rainy season (Wright et al., 2017). Deforestation and degradation reduce evapotranspiration by 30% or more, increase the surface temperature (e.g., Silverio et al. 2015), and if large enough, reduce rainfall regionally (e.g., Butt et al. 2011, Spracklen and Garcia-Carreras, 2015; Leite-Filho et al., 2019). The type of land use that follows from deforestation has a lesser but still important impact, with crops having a relatively greater impact than pasture (Silverio et al., 2015).

The high deforestation and forest degradation rates have impacted biodiversity, forest resilience, and climate over the past few decades (Davidson et al., 2012). By 2018, 724,000 km² of forests was lost in the pan-Amazônia (Mapbiomas Amazonia 2.0, 2020). In addition to large-scale deforestation, the Amazon has experienced large amounts of forest degradation, which is hard to detect and measure. Still, there is strong evidence to suggest that it occurs at the same or more significant scale than deforestation (Walker et al., 2020). For example, between 1992 and 2014, a larger area of Amazon forest in Brazil was degraded (337,400 km^2) than deforested (308,300 km²) (Matricardi et al., 2020). This may only get worse in the near future. Deforestation and degradation coupled with greenhouse gas-driven climate changes will likely lead to a significantly warmer and drier climate over much of the eastern Amazon and could cause a significant portion of the Amazon to shift from broadleaf evergreen to drought-deciduous or savanna environments (e.g., Nobre et al., 1991; Malhi et al., 2008, 2009).

3.1. Surface albedo and radiation balance

Deforestation to expand agriculture has permanent changes on the surface radiation balance, impacting climate at local and regional scales. Crops and pasture that typically replace forest have shallow roots system and a seasonal growing season, which tend to decrease the net surface radiation (Rnet), which is the sum of solar shortwave and net longwave radiation fluxes absorbed by the land surface (Coe et al., 2016). Rnet reduction is linked to increases in the surface albedo and the outcoming flux of longwave radiation, limiting the system's capacity to cycle water through evapotranspiration. These local changes in the Rnet and water balance alter circulation and shorten the rainy season (Butt et al., 2011; Knox et al., 2011), affecting crop productivity over the agricultural frontier over the Amazon and Cerrado regions.

Surface albedo is the ratio of reflected incident radiation in the total solar in a short wavelength spectrum. It is the main factor that affects the land radiation balance and has frequently been considered in studies of global and regional climate. The primary identified sources of variation of land surface albedo are land cover, solar elevation angle, canopy wetness, and cloud cover (Pinker et al., 1980; Bastable et al., 1993; Culf et al., 1995).

The albedo of different tropical land covers has been studied for over 40 years. The first measurements in the Amazon during ARME – Amazon Region Micrometeorological Experiment indicated an average albedo of 12.3±0.2% for a tropical forest near Manaus, Brazil (Shuttleworth et al., 1984). Later, during ABRACOS – Anglo Brazilian Amazonian Climate Observation Study, Bastable et al. (1993) verified an average albedo of 13.1% for the same site and 16.3% for a nearby pasture, a difference of 3.2%. Synthesizing the measurements at three Amazonian forest sites and three pasture sites, Culf et al. (1996) found average albedos of 13.4% and 18%, respectively (4.6% difference).

Figure 23.5 shows seasonal albedo for the rainforest, pastures, and soybeans cropping systems typical of the Amazon. Rainforest and pasture albedo are from Culf et al. (1996). While the forest albedo is more conservative throughout the year, presenting low variability according to the elevation of the sun and the moisture of leaves and soil, the pasture albedo is more sensitive to these factors, showing large variability along the year. Canopy height, vegetation density, the proportion of the exposed bare soil, or the predominantly vertical inclination of the leaves probably explain the wider variability of the pasture albedo. It is important to observe the significant difference between the forest albedo (about 13%) to pasture albedo (17%), while soybean shows much higher albedo.

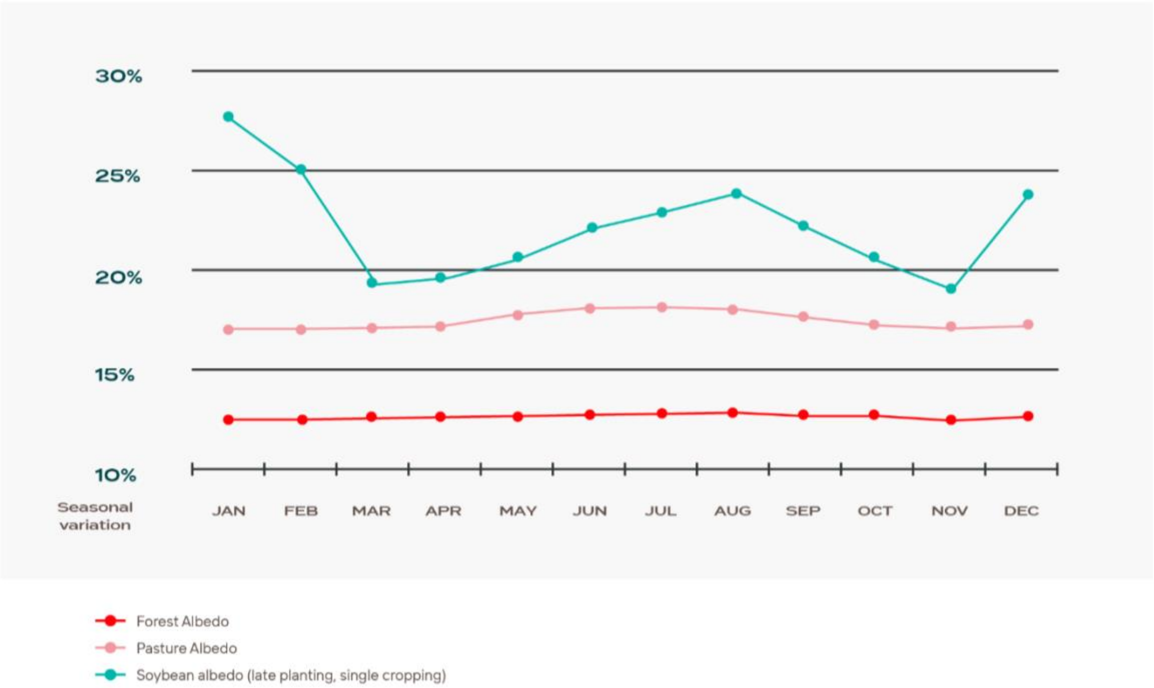

Figure 23.5. Seasonal variation of forest, pasture and soybean albedo. A single soybean growing season is represented. Strong increase in surface albedo can be observed when forest is changed to pasture or soybean. Figure adapted from Costa et al. (2007).

The seasonal variability of crop albedo depends on several factors, including the cropping system adopted (single cropping or double cropping), to the crop itself (soybean, maize), to the planting date, and to the presence of crop residues on the field after harvest, the albedo of the soil itself, and whether or not the field is plowed before planting. Here we present soybean albedo data from Costa et al. (2007), adjusted for a late planting date (November). The soybean albedo (for the growing season only) indicates an increased albedo as the crop grows and decreasing albedo as the crop drops leaves and dries out. For the period between growing seasons, albedo rises again due to crop residues (straw) on the ground, decreasing as straw decomposes and the field is prepared for planting. Although many details of this seasonal curve will vary according to the factors listed above, crop albedo is typically much higher than pasture albedo and forest albedo.

Sena et al. (2013) analyzed surface albedo changes from land-use change radiative forcing over Rondonia from 2000 to 2009. The top of the atmosphere (TOA) flux for aerosol optical depth (AOD)=0 (no aerosols) for forest areas was 147.3 W/m², and over deforested areas, this value is 160.2 w/m². The difference of 12.9 w/m² is the radiative forcing due to change in surface reflectance from forest to deforested regions of Rondonia. Evapotranspiration has also changed significantly, from forest areas to pasture with 0.35 cm column water vapor smaller at the pasture. This is about 10% of the total column of water vapor, a very significant change.

3.2. Changes in soil moisture and evapotranspiration

Roughly two-thirds of the precipitation in the Amazon is transferred back to the atmosphere through evapotranspiration, consuming a lot of the energy and cooling the surface (see Chapter 5). However, land-use transitions can disrupt this system by dramatically reducing evapotranspiration. Thus, changes in evapotranspiration and soil moisture associated with land use and land cover change, including deforestation and degradation, are crucial to understanding possible trajectories of Amazon forests in the coming years. Pasture and cropland that typically replace forests do not access deep soil moisture or groundwater and have a much shorter growing season than the forests they replace (Coe et al., 2016; Costa et al., 2007; Negrón Juárez et al., 2007; Pongratz et al., 2006). For example, crops and pastures in the southern Amazon evapotranspire at rates equivalent to forests but only for 2-3 months per year at the peak of the growing season (von Randow et al., 2012). At the same time, forests evapotranspire at near-peak rates (>100mm/month) for up to 10 months per year because of their access to the ample stored soil moisture in the top 10m of the soil column.

These differences have a profound impact on the seasonal distribution of evapotranspiration and the annual total. This has been studied extensively at large and small spatial scales throughout the Amazon and Cerrado environments. Conversion of the native vegetation results in a decrease in mean annual ET of about 30%, with a dry season decreases being much greater (Arantes et al., 2016; Lathuillière et al., 2012; Panday et al., 2015; Spera et al., 2016). The changes to ET directly impact other variables that influence the surface water balance, soil moisture, and groundwater storage increase by as much as 30% locally and streamflow by 3-4-fold in small headwater streams and as much as 20% in very large rivers such as the Tocantins/Araguaia (Coe et al., 2011; Hayhoe et al., 2011; Heerspink et al., 2020; Levy et al., 2018; Neill et al., 2013).

Much of the precipitation in the Amazon is a result of moisture recycled by the forest (Salati and Vose, 1984, Maeda et al., 2017). Thus, the decreased ET that results from deforestation directly impacts the amount, location, and timing of rainfall. Numerous observational and numerical modeling studies have shown a clear link between deforestation and delayed onset and an earlier end to the rainy season (Butt et al., 2011; Debortoli et al., 2015; Fu et al., 2013). In numerical modeling studies, Li and Fu (2004) and Wright et al. (2017) showed that evapotranspiration, by increasing humidity throughout the atmosphere during the late dry season, is the crucial factor needed to initiate rainfall, with initiation being hastened by 2-3 months compared to simulations without forest ET. Evidence indicates that dry season humidity in the Amazon decreases, making the dry season more severe (Barkhordarian et al., 2019). Via an analysis of rain gauge data in the southern Amazon, Leite-Filho et al. (2019) estimate that for every 1% increase in deforestation, the onset of the rainy season is delayed by 0.12-0.17 days, which has amounted to an 11-18-day average delay in the rainy season onset in Rondônia, Brazil (Butt et al., 2011).

Concerning evapotranspiration, GHG emissions and deforestation have opposite effects. Increased emissions (and associated increased atmospheric temperatures) tend to increase ET, while deforestation (and associated land conversion to agriculture) decreases ET. It has been suggested that an overall reduction in the area of Amazonian forest will push much of the Amazon into a permanently drier climate regime (Malhi et al., 2008). At an annual scale, deforestation-reduced ET only partly offsets the positive effect of GHG emissions on ET, resulting in a net increase of runoff by the end of the century. In southeastern Amazon, model simulations with 50% forest area loss combined with climate change led to a consistent ET decrease which offsets positive ET changes due to climate change alone. For instance, model projections of the water budget in the Xingu basin (Guimberteau et al., 2017) are consistent with Panday et al. (2015), who found opposite effects of deforestation and GHG impacts during the past 40 years using a combination of long-term observations of rainfall and runoff/discharge.

Generally, the resulting increase of runoff due to deforestation (i.e., ET decreases are associated with runoff increases) is consistent with other studies at local and regional scales (e.g., Sterling et al., 2013; Rothacher, 1970; Hornbeck et al., 2014). For instance, the increase of annual runoff in the Xingu catchment (+8%; Guimberteau et al., 2017) due to deforestation is of the same order as the results of Stickler et al. (2013), who found a 10 to 12% runoff increase given 40% deforestation in this catchment. Yet, during August to October, in the southeastern catchments, deforestation amplifies the effect of climate change in reducing ET, particularly in the south of the Tapajós catchment and in the north of the Madeira and Xingu catchments where deforested areas are the largest. Thus, deforestation contributes to the increase in runoff (+27 % in the Tapajós) and thus balances.

In summary, the initial significant decrease in ET initiated by deforestation has already impacted much of the Amazon, particularly the south, and has the potential through large-scale feedback to precipitation and fundamentally alter the region’s climate. The changes in hydrology in response to deforestation depend on where and how large deforestation is (Coe et al., 2009; Heerspink et al., 2020). However, evidence suggests that the climate changes can be expected to be of the same scale as changes associated with increasing greenhouse gases and the same direction – significantly increased temperatures, decreased rainfall, and reduced length of the rainy season.

4. BIOGENIC AND FIRE AEROSOL EMISSIONS AND IMPACT IN AND OUTSIDE THE REGION

The Amazonian atmosphere is dominated by two clear seasons. In the wet season, the atmosphere is dominated by natural primary biogenic aerosol particles emitted directly by the vegetation (Prass et al., 2021, Whitehead et al., 2016, Poschl et al., 2010). In the dry season, biomass burning emissions have strong impacts on the Amazonian ecosystem and atmospheric properties (Davidson et al., 2012; Andreae et al., 2004, Andreae et al., 2012; Andreae 2019). Significant emissions of carbon monoxide, ozone precursors, nitrogen oxides, aerosol particles, and other compounds alter the atmospheric composition significantly over large areas of South America, and they can travel for thousands of kilometers (Andreae et al., 2001; Freitas et al., 2005; Reddington et al., 2016). Critical ingredients of the forest emissions such as biogenic volatile organic compounds (VOCs) are changing, possibly associated with higher temperatures (Yáñez-Serrano, 2020). These emissions have significant impacts on the ecosystem, including the radiation balance, atmospheric chemistry, and human health (Forster et al., 2007; Artaxo et al., 2013; Bela et al., 2015, Butt et al., 2020). Fire emissions are calculated with fire burned area derived from remote sensing data and emission factors measured in field experiments (van Marle et al., 2017; Randerson et al., 2012). Future climate variability is expected to enhance the risk and severity of fires in tropical rainforests. In the Amazon, most fires are human-driven. A way to assess the aerosol column in the atmosphere is by looking at the so-called aerosol optical depth that expresses the total amount of particles in the whole aerosol column. AOD can be measured using MODIS or with sun photometers from the NASA AERONET network.

The drivers of Amazonian fires are complex and very diverse. Figure 23.6 shows a schematic view of the complex relationship between the main fire drivers. The impacts are also various, and fire emissions influence regional carbon and water cycle, human health, and ecosystem health, besides being a significant contributor to global warming. Global deforestation is responsible for 13% of greenhouse gas emissions.

[Figure 23.6 will be inserted here]

Figure 23.6. Schematic view of the complex relationship between the main fire drivers in Amazonia.

4.1. Impacts of biomass burning emissions on the radiation balance

The high loading of aerosols from biomass burning impacts direct radiative forcing (DRF) over large areas in tropical forests (Procópio et al., 2003; Eck et al., 2003). The geographical distribution of DRF follows the sources and transport of biomass burning aerosols and impacts in areas outside the Amazon region, such the central and southern Brazil, north of Argentina, Pantanal, and other regions. As most biomass-burning aerosols scatter light, the impact on the temperature is to cool down the surface. Black carbon emissions from Amazonian biomass burning changes the snow and ice albedo in the tropical glaciers, im-pacting the melting of Andean glaciers. The black carbon component absorbs solar radiation and has a heating effect on the top of the boundary layer. The average surface radiative forcing can be as high as -36 Wm-2 (Sena et al.; 2015, Reddington et al., 2016). Just for comparison, the global anthropogenic forcing that drives climate change is +2.3 W/m² (Boucher et al., 2013).

Figure 23.7 shows a long time series (2000-2020) of aerosol optical depth over five sites in the Brazilian Amazon. In the wet season, very low atmospheric aerosol loading is observed, with a very clean atmosphere. AOD is among the highest values observed everywhere in the dry season, with important year-to-year variability. This high variability is driven by climate and public policies toward reducing deforestation and biomass burning (Morgan et al., 2019).

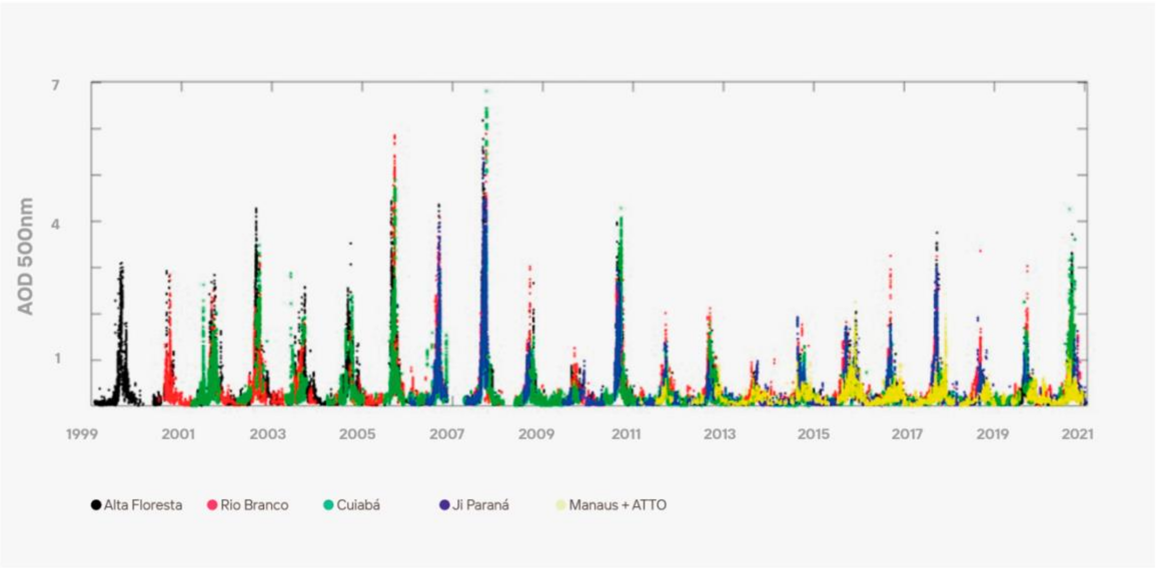

Figure 23.7. Long time series (2000-2020) of aerosol optical depth over 5 sites in the Brazilian Amazonia. Significant year-to-year variability, is driven by climate as well as public policies toward reducing deforestation and biomass burning emissions.

Clouds and aerosols influence the flux of photosynthetic active radiation (PAR) critical for carbon assimilation (Net Ecosystem Exchange - NEE) by the forests. Also, the ratio of diffuse to direct radiation is controlled by clouds, and aerosols and plants do photosynthesis more efficiently with diffuse radiation because of the more extensive penetration of radiation into the forest canopy (Rap et al., 2015; Procópio et al., 2004). Analysis about the change in NEE from LBA tower data from 1999 to 2002 in Rondônia shows a 29% increase in NEE when the AOD increased from 0.10 to 1.5 at 550 nm. In Manaus (ZF2 tower), the aerosol effect on NEE accounted for a 20% increase in NEE. High aerosol loading (AOD above 3 at 550 nm) or high cloud cover leads to reductions in total solar flux and a substantial decrease in photosynthesis up to the point where NEE approaches zero (Cirino et al., 2014). Large-scale modeling studies show similar results in terms of strong aerosol effects on carbon uptake for the Amazon. Model simulations with 3 times the BB emissions of 2012 show significant scale increases of 20 to 40% in diffuse radiation, GPP, and NPP, especially in August at the peak of the biomass burning season (Rap et al., 2015).

4.2. Impacts of ozone from biomass burning precursors on the ecosystem

The Amazon in the wet season shows very low background ozone (O_3) concentrations (<20ppb), and the ecosystem is adjusted to this low O_3 concentration. However, in the dry season, high values of 40 to 80 ppbv were observed downwind of biomass burning plumes (Bela et al., 2015), and at this level of ozone, damage to vegetation occurs. Biomass burning emits significant amounts of ozone precursors, nitrogen oxides (NOx), and VOCs that lead to surface ozone formation downwind of the plumes (Bela et al., 2015; Artaxo et al., 2013). Tropospheric ozone is an important air pollutant, which causes adverse effects on human health, crops, and natural vegetation (Jacobson et al., 2014; Reddington et al., 2015; Pacifico et al., 2015). Simulations with a global chemistry transport model show that NO_2 increased in concentration by 1 ppbv per decade and ozone by 10 ppbv per decade, a substantial increase (Pope et al., 2020). Pacifico et al. (2015) used the UK HadGEM2 earth system climate model to assess the impact of biomass burning on surface ozone and its effect on vegetation. The impact of ozone damage from present-day biomass burning on vegetation productivity is about 230 TgC yr-1. This ozone damage impact over the Amazon forest is of the same order of magnitude as the release of carbon dioxide due to fire in South America, showing that the effect is significant. The enhanced ozone will further damage natural vegetation and reduce photosynthesis (Pacifico et al., 2015; Sitch et al., 2007), leading to reductions in crop yields downwind of forest fires, including in the area of Mato Grosso and Goiás (Brazil), with large agribusiness areas. These effects combined could substantially impact natural vegetation, agriculture, and public health, with potential degradation in ecosystem services and economic losses. Ozone is also an important greenhouse gas, so biomass burning emissions also contribute to the global temperature increase and radiative forcing.

4.3. Impacts of biomass burning emissions on clouds and precipitation

Clouds are formed from 3 main ingredients: water vapor, aerosol particles that act as cloud condensation nuclei (CCN), and atmospheric thermodynamic conditions (Boucher et al., 2013). The complex physical-chemical interaction seen in the Amazon basin includes the processes of rainfall formation, diurnal, seasonal, inter-annual cycles, cloud spatial organization, the mechanisms controlling CCN, the interaction between vegetation, boundary layer, clouds, and upper troposphere (Liu et al., 2020). These processes were all in perfect combination, defining a stable climate that produces rainfall equivalent to 2.3 meters over the area of the Amazonas basin, equivalent to $14\cdot10^6$ km^3 of rain each year on average. However, these unique nonlinear complex mechanisms have been modified by human activities (Silva Dias et al., 2002, Poschl et al., 2010). Biomass burning with the significant aerosol particle emissions alters the CCN concentrations, changing cloud microphysics, cloud lifetime, and precipitation (Andreae et al., 2004). With plenty of water vapor, these extra CCN enhance the numbers of droplets with reduced size. These smaller initial droplets reduce the efficiency of droplets to grow to precipitable size, increasing cloud lifetime and reduce precipitation close to cloud formation. The effect of deep convective clouds is difficult to predict because of our lack of knowledge on mixed-phase and ice cloud microphysics (Artaxo et al., 2020; Machado et al., 2018). The primary biogenic aerosol particles are quite efficient Ice Nuclei (IN) particles necessary to produce the deep ice clouds (Schrod et al., 2020, Patade et al., 2021). There are significant differences among cloud droplets from pristine and biomass-burning polluted environments, as was observed in the GoAmazon2014/15 experiment (Martin et al., 2010, Nascimento et al., 2021), including differences in the vertical distribution of the cloud droplet number concentrations, especially in convective clouds (Wendisch et al., 2016).

Evapotranspiration provides a significant component of the atmospheric moisture over the Amazon, which becomes increasingly critical towards the western part of the basin (Spracklen et al., 2012; Molina et al., 2019). Deforestation and increasing atmospheric CO_2 reduce evapotranspiration, reduce the amount of water available for rainfall in the western Amazon Basin, and adversely impact rainforest resilience (Zemp et al., 2017). This effect even extends beyond the Amazon Basin into the Rio de la Plata region, for which Amazonian evapotranspiration is a vital moisture source (Camponogara et al., 2014, 2018; Zemp et al., 2014).

In terms of biomass burning, aerosol impacts precipitation and monsoon circulation, where many confounding factors make it difficult to establish causality from purely observational studies (Zhang et al., 2009). Changes in surface properties, evapotranspiration, albedo, thermodynamic conditions, and others, make predicting aerosol effects on precipitation very difficult (Artaxo et al., 2020). One of the few observational studies of the impacts of biomass burning on rainfall was Camponogara et al. (2014). Combining Reanalysis, TRMM, and AERONET data from 1999 up to 2012 during September–December, a clear relationship between aerosols and precipitation was derived. Results show that high aerosol concentrations tend to suppress precipitation. A significant reduction in rainfall at the La Plata basin was observed with increasing biomass burning aerosols in the Amazon.

The lack of a significant meteorological observation network in Amazonia assesses changes in precipitation quite tricky and inaccurate. The same for an extended aerosol observation network.

5. CONCLUSIONS

There is no question that the impacts from climate change and deforestation in the Amazon are strong, diverse, and well documented. From biodiversity, carbon cycling, hydrological cycles, biomass burning, wherever we look, climate change and anthropogenic land-use change are already having an impact on the Amazonian ecosystems. And the reverse is also true, especially in terms of carbon emissions due to deforestation. Tropical deforestation is responsible for 13% of global CO_2 emissions (Global Carbon Project, 2020), and Brazil, Colombia, Bolivia, and Peru are among the 10 top tropical deforestation countries. Reducing tropical deforestation is the faster and cheapest way to mitigate greenhouse gas emissions, with many co-benefits. Tropical forests suffer from significant stress from climate change, particularly an increase in temperature, altered hydrological cycle, and increase in climate extremes. Reducing biomass burning is essential to minimize several negative aspects associated with high concentrations of aerosols, ozone, carbon monoxide, and nitrogen oxides over large areas of South America. Three main effects of climate changes in aquatic systems (both marine and freshwater) are ocean and hydrographic basins warming, acidification, and oxygen loss. If we consider only these effects, we can preview habitat loss, changes in fish migration, disturbances in fish assemblages, changes in spatial fish species distribution. These are the main impacts climate changes will cause for aquatic systems biota. We might consider deforestation, road building and consequent urban increase, and mining as one of the highest impacts contributing to climate change in the Amazon Basin. The loss of biodiversity is expected not only from direct deforestation but also from different sensitivities of plant species to increased temperature and reduced precipitation. It is important to emphasize that in addition to reducing deforestation is also essential to reduce fossil fuel burning, which is the leading cause of global warming.

6. RECOMMENDATIONS

- A comprehensive network of Amazonian environmental observatories and a system for sharing comparable data is needed to diagnose ongoing terrestrial, freshwater, and estuarine ecosystems changes.
- More integrated studies on biodiversity loss and climate change, for example, on species resilience, are needed.
- More studies on the feedbacks between climate change and Amazonian ecosystem functioning are vital and must be better known and quantified, especially for carbon and water vapor feedbacks.
- It is necessary to perform studies on the basin-wide water balance considering evapotranspiration, rain off aerial rivers, and all water balance components in the Amazon, looking for closure on water balance in the Amazon.
- Studies on the ecosystem and species resilience to increased temperatures and reduced water supply are needed.
- It is important to emphasize that in addition to reduce deforestation, is also essential to reduce fossil fuel burning that is the main cause of global warming.
- Paleoclimate studies are needed to look at the past climate to help understand natural climate variability and better understand the historical role of humans shaping the landscape over several timescales.

7. REFERENCES

Ahlström, A., Canadell, J.G., Schurgers, G. *et al.* Hydrologic resilience and Amazon productivity. *Nat Commun* **8,** 387 (2017). https://doi.org/10.1038/s41467-017-00306-z.

Albert, J., Val, P., and Hoorn, C. (2018). The changing course of the Amazon River in the Neogene: center stage for Neotropical diversification. Neotropical Ichthyology, 16(3). doi:10.1590/1982-0224-20180033

Aguiar, L.M.S., Bernard, E., Ribeiro, V., Machado, R.B., Jones, G., 2016. Should I stay or should I go? Climate change effects on the future of Neotropical savannah bats. Global Ecology and Conservation, 5, 22-33.

Alencar, A. A. C. et al. (2015) 'Landscape Fragmentation, Severe Drought and the New Amazon Forest Fire Regime, Ecological Applications. p. 150123115009002. doi: 10.1890/14-1528.1.

Almeida-Val VMF and Hochachka PW. Air-breathing fishes: metabolic biochemistry of the first diving vertebrates. In: Biochemistry and molecular biology of fishes. 1ed. Amsterdam – the Netherlands. Elsevier 1995, v5, p. 45-55.

Andreae, M.O. 2019. Emission of trace gases and aerosols from biomass burning–an updated assessment. Atmospheric Chemistry and Physics, 19, 8523-8546.

Andreae M. O., Rosenfeld, D., Artaxo, P., Costa, A. A., Frank, G. P., Longo, K. M., and Silva Dias, M. A. F.: Smoking rain clouds over the Amazon, Science, 303, 1337–1342, doi:10.1126/science.1092779, 2004.

Andreae, M. O., Artaxo, P., Beck, V., Bela, M., Freitas, S., Gerbig, C., Longo, K., Munger, J. W., Wiedemann, K. T., and Wofsy, S. C.: Carbon monoxide and related trace gases and aerosols over the Amazon Basin during the wet and dry seasons, Atmos. Chem. Phys., 12, 6041–6065, doi:10.5194/acp-12-6041-2012, 2012.

Andreae, M. O., Artaxo, P., Fischer, H., Freitas, S. R., Grégoire, J.-M., Hansel, A., Hoor, P., Kormann, R., Krejci, R., Lange, L., Lelieveld, J., Lindinger, W., Longo, K., Peters, W., de

Reus, M. Scheeren, B., Silva Dias, M. A. F., Stroem, J., van Velthoven, P. F. J., and Williams, J.: Transport of biomass burning smoke to the upper troposphere by deep convection in the equatorial region, Geophys. Res. Lett., 28, 951–954, 2001.

Anhuf, M.-P. Ledru, H. Behling, F.W. Da Cruz, R.C. Cordeiro, T. Van der Hammen, I. Karmann, J.A. Marengo, P.E. De Oliveira, L. Pessenda, A. Siffedine, A.L. Albuquerque, P.L. Da Silva Dias, Paleo-environmental change in Amazonian and African rainforest during the LGM, Palaeogeography, Palaeoclimatology, Palaeoecology, Volume 239, Issues 3–4, 2006, Pages 510 527, ISSN 0031-0182, https://doi.org/10.1016/j.palaeo.2006.01.017.

Arantes, A.E., Ferreira, L.G., Coe, M.T., 2016. The seasonal carbon and water balances of the Cerrado environment of Brazil: Past, present, and future influences of land cover and land use. ISPRS J. Photogramm. Remote Sens. 117, 66–78. https://doi.org/10.1016/j.isprsjprs.2016.02.008,

Araújo, A.C., Nobre, A.D., Kruijt, B., Elbers, J.A., Dallarosa, R., Stefani, P., von Randow, C., Manzi, A.O., Culf, A.D., Gash, J.H.C., Valentini, R., Kabat P. 2002. Comparative measurements of carbon dioxide fluxes from two nearby towers in a central Amazonian rainforest: The Manaus LBA site. Journal of Geophysical Research, 107, D20 doi.org/10.1029/2001JD000676.

Artaxo, P., Hans-Christen Hansson, Meinrat O. Andreae, et al., Tropical and Boreal Forest – Atmosphere Interactions: A Review. In press at Tellus-B, April 2021.

Artaxo, P., Rizzo, L. V., Brito, J. F., Barbosa, H. M. J., Arana, A., Sena, E. T., et al. (2013). Atmospheric aerosols in Amazonia and land-use change: From natural biogenic to biomass burning conditions. Faraday Discussions, 165, 203–235. https://doi.org/10.1039/C3FD00052D.

Artaxo, P., Doerffer, R., Consult, B., Ahn, G.J.H., Frouin, et al. 2020. Atmospheric Correction of Satellite Ocean-Color Imagery During the PACE Era, From the Satellite to the Earth's Surface: Studies Relevant to NASA’s Plankton, Aerosol, Cloud, Ocean Ecosystems (PACE) Mission.

Baccini, A., Walker, W., Carvalho, L., Farina, M., Sulla-Menashe, D., Houghton, R.A. 2017. Tropical forests are a net carbon source based on aboveground measurements of gain and loss. Science, 358, 230-234. DOI: 10.1126/science.aam5962.

Barkhordarian, A., Saatchi, S.S., Behrangi, A., Loikith, P.C., Mechoso, C.R., 2019. A Recent Systematic Increase in Vapor Pressure Deficit over Tropical South America. Sci. Rep. 9. https://doi.org/10.1038/s41598-019-51857-8

Barros, D. de F., M. Petrere Jr, V. Lecours, D. Butturi-Gomes, L. Castello, and V. J. Isaac. 2020. Effects of deforestation and other environmental variables on floodplain fish catch in the Amazon. Fisheries Research 230:105643.

Barthem, R. B., Goulding, M., Leite, R. G., Cañas, C., Forsberg, B., Venticinque, E., ... & Mercado, A. (2017). Goliath catfish spawning in the far western Amazon confirmed by the distribution of mature adults, drifting larvae, and migrating juveniles. Scientific Reports, *7*, 41784.

Barthem, R., & Goulding, M. (2007). An unexpected ecosystem: The Amazon as revealed by fisheries. Lima, Peru: Gráfico Biblos & Missouri Botanical Garden.

Bastable, H.G., W. J. Shuttleworth, R. L. G. Dallarosa, G. Fisher, and C. A. Nobre, 1993: Observations of climate, albedo and surface radiation over cleared and undisturbed Amazonia forest. Int. J. Climatol., 13, 783-796.

Bela, M. M., Longo, K. M., Freitas, S. R., Moreira, D. S., Beck, V., Wofsy, S. C., et al. (2015). Ozone production and transport over the Amazon basin during the dry-wet and wet-dry transition seasons. Atmospheric Chemistry and Physics, 15(2), 757–782. 2015

Betts, Alan K.; Silva Dias, Maria Assunção F. Progress in Understanding Land-Surface-Atmosphere Coupling from LBA Research. Journal of Advances in Modeling Earth Systems, v. 2, p. 1-20, 2010.

Bodmer, R., P. Mayor, M. Antunez, K. Chota, T. Fang, P. Puertas, M. Pittet, M. Kirkland, M. Walkey, C. Rios, P. Perez-Peña, P. Henderson, W. Bodmer, A. Bicerra, J. Zegarra, and E.

Docherty. 2018. Major shifts in Amazon wildlife populations from recent intensification of floods and drought. Conservation Biology 32:333–344.

Bonan, G.B., (2008) Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science 320 (5882), 1444–1449.

Boucher, O., D. Randall, P. Artaxo, C. Bretherton, G. Feingold, P. Forster, V.-M. Kerminen, Y. Kondo, H. Liao, U. Lohmann, P. Rasch, S. K. Satheesh, S. Sherwood, B. Stevens and X. Y. Zhang, 2013: Clouds and Aerosols. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change - IPCC [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Pg. 571- Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

BPBES - Plataforma Brasileira de Biodiversidade e Serviços Ecossistêmicos. https://www.bpbes.net.br/, 2020. Reference to be confirmed.

BPBES (2018) 1o Diagnóstico Brasileiro de Biodiversidade e Serviços Ecossistêmicos. Sumário para tomadores de decisão. Disponível em: https://www.bpbes.net.br/wp-content/uploads/2018/11/Sum%C3%A1rio-para-Tomadores-de-Decis%C3%A3oBPBES-1.pdf. Reference to be confirmed.

Brando et al. 2019a. Droughts, Wildfires, and Forest Carbon Cycling: A Pantropical Synthesis. Annual Review of Earth and Planetary Sciences 47.

Brando et al. 2019b. Prolonged tropical forest degradation due to compounding disturbances: Implications for CO2 and H2O fluxes. 25(9)

Brando et al. 2020. Amazon wildfires: scenes from a foreseeable disaster. Flora 268, 151609. https://doi.org/10.1016/j.flora.2020.151609

Brauner CJ, Val AL. The interaction between O2 and CO2 exchange in the obligate air breather, Arapaima gigas, and the facultative air breather Liposarcus pardalis. In: Val AL, Almeida-

Val VMF, Randall DJ, editors. Physiology and Biochemistry of the fishes of the Amazon. Manaus: INPA; 1996. p. 101-10.

Brienen, Roel & Phillips, Oliver & Feldpausch, et al. (2015). Long-term decline of the Amazon carbon sink. Nature. 519. 344. 10.1038/nature14283.

Butt, Edward; Conibear, Luke; Reddington, Carly; Darbyshire, Eoghan; Morgan, William; Coe, Hugh; Artaxo, Paulo; Brito, Joel; Knote, Christoph; Spracklen, Dominick. Large air quality and human health impacts due to Amazon forest and vegetation fires. Article reference: ERC-100344. Environmental Research Communications, 2 (9) 095001. https://doi.org/10.1088/2515-7620/abb0db. 2020.

Butt, N., de Oliveira, P.A., Costa, M.H., 2011. Evidence that deforestation affects the onset of the rainy season in Rondonia, Brazil. J. Geophys. Res. 116, D11120.

Camponogara, G., Silva Dias, M. A. F., and Carrió, G. G., Relationship between Amazon biomass burning aerosols and rainfall over the La Plata Basin: Atmos. Chem. Phys., 14, 4397-4407, doi:10.5194/acp-14-4397-2014, 2014.

Camponogara, G., Silva Dias, M. A. F., and Carrió, G. G.: Biomass burning CCN enhance the dynamics of a mesoscale convective system over the La Plata Basin: a numerical approach, Atmos. Chem. Phys., 18, 2081–2096, 2018.

Campos, D.F., Braz-Mota, S., Val, A.L., Almeida-Val, V.M.F. 2019. Predicting thermal sensitivity of three Amazon fishes exposed to climate change scenarios Ecological Indicators 101, 533-540.

Campos D, Val AL, Almeida-Val VMF. The influence of lifestyle and swimming behavior on metabolic rate and thermal tolerance of twelve Amazon forest stream fish species. Journal of Thermal Biology. 2018;72:148-54.

Castello, L., & Macedo, M. N. (2016). Large-scale degradation of Amazonian freshwater ecosystems. Global change biology, 22(3), 990-1007.

Castello, L., D. G. McGrath, C. C. Arantes, and O. T. Almeida. 2013. Accounting for heterogeneity in small-scale fisheries management: The Amazon case. Marine Policy 38:557–565.

Castello, L., L. L. Hess, R. Thapa, D. G. McGrath, C. C. Arantes, V. F. Renó, and V. J. Isaac. 2018. Fishery yields vary with land cover on the Amazon River floodplain. Fish and Fisheries 19:431–440.

Castro J, Braz-Mota S, Campos D, Souza S, Val A. High Temperature, pH, and Hypoxia Cause Oxidative Stress and Impair the Spermatic Performance of the Amazon Fish Colossoma macropomum. Frontiers in Physiology. 2020; 11:772.

Chambers, J.Q., Higuchi, N., Tribuzy, E.S., Trumbore, S.E. 2001.Carbon sink for a century. Nature, 410, 429-429.

Chambers, J. Q. & Silver, W. L. 2004 Some aspects of ecophysiological and biogeochemical responses of tropical forests to atmospheric change. Phil. Trans. R. Soc. Lond. B 359, 463–476. Doi 10.1098/rstb.2003.1424.

Chapman, C. A. (1995). Primate seed dispersal: coevolution and conservation implications. Evolutionary Anthropology: Issues, News, and Reviews, 4(3), 74-82.

Chazdon, R. L. et al. (2016) ‘Carbon sequestration potential of second-growth forest regeneration in the Latin American tropics’, Science Advances. American Association for the Advancement of Science, 2(5), p. e1501639. doi: 10.1126/sciadv.1501639.

Cheng, H.; Sinha, A.; Cruz, F. W. ; Wang, X. ; Edwards, R. L. ; D'Horta, F.M. ; Ribas, Camila C. ; Vuille, M. ; Stott, Lowell D. ; Auler, A.S. 2013. Climate change patterns in Amazonia and biodiversity. Nature Communications, 4, 1411.

Cirino GG, Souza RAF, Adams DK et al. 2014. The effect of atmospheric aerosol particles and clouds on net ecosystem exchange in the Amazon. Atmospheric Chemistry and Physics, 14, 6523– 6543.

Coe, M.T. et al. (2013) Deforestation and climate feedbacks threaten the ecological integrity of south–southeastern Amazonia. Philos. Trans. R. Soc. B: Biol. Sci. 368 (1619).

Coe, M.T., Costa, M.H., Soares-Filho, B.S. (2009) The influence of historical and potential future deforestation on the stream flow of the Amazon River-Land surface processes and atmospheric feedbacks. J. Hydrol. 369 (1), 165–174.

Coe, M.T., Latrubesse, E.M., Ferreira, M.E., Amsler, M.L., 2011. The effects of deforestation and climate variability on the streamflow of the Araguaia River, Brazil. Biogeochemistry 105, 119–131.

Coe, M.T., Macedo, M.N., Brando, P.M., Lefebvre, P., Panday, P., Silvério, D., 2016. The Hydrology and Energy Balance of the Amazon Basin, in: Nagy, Z. (Ed.), Interactions Between Biosphere, Atmosphere and Human Land Use in the Amazon Basin. Springer Berlin Heidelberg, Berlin, pp. 35–53.

Colwell, R. K., Brehm, G., Cardelús, C. L., Gilman, A. C., & Longino, J. T. (2008). Global warming, elevational range shifts, and lowland biotic attrition in the wet tropics. science, 322(5899), 258-261.

Cordeiro, R. C. et al. Palaeofires in Amazon: Interplay between land-use change and palaeoclimatic events. Palaeogeogr. Palaeoclimatol. Palaeoecol.415, 137–151 (2014).

Correia, G. B., Siqueira-Souza, F. K., & Freitas, C. E. D. C. (2015). Intra-and inter-annual changes in the condition factors of three Curimatidae detritivores from Amazonian floodplain lakes. Biota Neotropica, 15(4).

Costa, M. H., S. N. M. Yanagi, P. J. O. P. Souza, A. Ribeiro, E. J. P. Rocha (2007) Climate change in Amazonia caused by soybean cropland expansion, as compared to caused by pastureland expansion. Geophys. Res. Lett. 34, L07706. doi:10.1029/2007GL029271.

Costa, M.H., Botta, A., Cardille, J.A. (2003) Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. J. Hydrol. 283 (1), 206–217.

Costa, W. F., Ribeiro, M., Saraiva, A. M., Imperatriz-Fonseca, V. L., & Giannini, T. C. (2018). Bat diversity in Carajás National Forest (Eastern Amazon) and potential impacts on ecosystem services under climate change. Biological Conservation, 218, 200-210.

Culf, A. D., J. L. Esteves, A. O.Marques Filho, H. R. Rocha, 1996: Radiation, temperature and humidity over forest and pasture in Amazonia. In: Gash, J. H. C., Nobre, C. A., Roberts, J. M., Victoria, R. L. Amazonian deforestation and climate. New York: John Wiley & Sons, 175-191.

Culf AD, Fisch G and Hodnett MG. 1995. The albedo of Amazonian forest and ranch land. Journal of Climate 8.

D'Almeida, C. et al. (2007) The effects of deforestation on the hydrological cycle in Amazonia: a review on scale and resolution. Int. J. Climatol. 27 (5), 633–647.

Davidson, E. A., de Araujo, A. C., Artaxo, P., Balch, J. K., Brown, I. F., Bustamante, M. M. C., et al. (2012). The Amazon Basin in transition. Nature, 481(7381), 321–328. https://doi.org/10.1038/nature10717.

De Moraes, J.M., Schuler, A.E., Dunne, T., Figueredo, R.D.O., Victoria, R.L. (2006) Water storage and runoff processes in plinthic soils under forest and pasture in eastern Amazonia. Hydrol. Process. 20 (12), 2509–2526.

Debortoli, N.S., Dubreuil, V., Funatsu, B., Delahaye, F., Oliveira, C.H. De, Rodrigues-filho, S., 2015. Rainfall patterns in the Southern Amazon : a chronological perspective (1971 – 2010). https://doi.org/10.1007/s10584-015-1415-1

Díaz, S., Settele, J., Brondizio, E., Ngo, H. T., Guèze, M., Agard, J., & Zayas, C. (2019). IPBES global assessment summary for policymakers.

Eck, T.F., Holden, B.N., Ward, D.E. et al. 2003. Variability of biomass-burning aerosol optical characteristics in southern Africa during SAFARI 2000 dry season campaign and a comparison of single scattering albedo estimates from radiometric measurements, J. Geophys. Res., 108(D13), 8477, doi:10.1029/2002JD002321.

Esquivel-Muelbert, A. et al. (2019) ‘Compositional response of Amazon forests to climate change’, Global Change Biology. Blackwell Publishing Ltd, 25(1), pp. 39–56. doi: 10.1111/gcb.14413.

Fabré, N. N., Castello, L., Isaac, V. J., & Batista, V. S. (2017). Fishing and drought effects on fish assemblages of the central Amazon Basin. Fisheries research, 188, 157-165.

Fé-Gonçalves LM, Paula-Silva MN, Val AL, Almeida-Val VMF. Differential survivorship of congeneric ornamental fishes under forecasted climate changes are related to anaerobic potential. Genetics and Molecular Biology. 2018;41:107-18.

Fé-Gonçalves, L.M., Araújo, J.D.A., Santos, C.H.A., Almeida-Val, V.M.F. 2020. Transcriptomic evidences of local thermal adaptation for the native fish Colossoma macropomum (Cuvier, 1818). Genetics and molecular biology 43

Fisher, R. A. et al. (2018) ‘Vegetation demographics in Earth System Models: A review of progress and priorities’, Global Change Biology. Blackwell Publishing Ltd, pp. 35–54. doi: 10.1111/gcb.13910.

Fleischer, K. et al. (2019) ‘Amazon forest response to CO2 fertilization dependent on plant phosphorus acquisition’, Nature Geoscience. Nature Publishing Group, 12(9), pp. 736–741. doi: 10.1038/s41561-019-0404-9.

Flores, B. M. et al. (2017) ‘Floodplains as an Achilles’ heel of Amazonian forest resilience’, Proceedings of the National Academy of Sciences of the United States of America. National Academy of Sciences, 114(17), pp. 4442–4446. doi: 10.1073/pnas.1617988114.

Foley, J.A. et al. (2005) Global consequences of land use. Science 309 (5734), 570– 574.

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland, 2007: Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D.

Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Freitas, C. E. de Carvalho, Rivas, A. A., Campos, C. P., Sant'Ana, I., Khan, J. R., de Almeida Correa, M. A., & Catarino, M. F. (2012). The potential impacts of global climatic changes and dams on Amazonian fish and their fisheries. In New advances and contributions to fish biology (pp. 176-195). InTech Rijeka, Croatia.

Freitas, S., Longo, K., Silva Dias, M., Silva Dias, P., Chatfield, R., Prins, E., Artaxo, P., Grell, G., and Recuero, F.: Monitoring the transport of biomass burning emissions in South America, Environ. Fluid Mech., 5, 135–167, doi:10.1007/s10652-005-0243-7, 2005.

Fu, R., Dickinson, R. E., Chen, M. X., and Wang, H. (2001) How do tropical sea surface temperatures influence the seasonal distribution of precipitation in the equatorial Amazon? J. Climate, 14, 4003–4026.

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., 2013. Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection. Proc. Natl. Acad. Sci. U.S.A. 110, 18110–5.

Ghanem, S. J., & Voigt, C. C. (2012). Increasing awareness of ecosystem services provided by bats. Advances in the Study of Behavior, 44, 279-302.

Giannini, T. C., Costa, W. F., Borges, R. C., Miranda, L., da Costa, C. P. W., Saraiva, A. M., & Fonseca, V. L. I. (2020). Climate change in the Eastern Amazon: crop-pollinator and occurrence-restricted bees are potentially more affected. Regional Environmental Change, 20(1), 1-12.

Global Carbon Project - Carbon budget and trends 2019 - Pierre Friedlingstein, Matthew W. Jones, Michael O'Sullivan, et al., (2019), Earth System Science Data, 11, 1783-1838, 2019, DOI: 10.5194/essd-11-1783-2019.

Global Carbon Project - Carbon budget and trends 2020. Friedlingstein, P., O'Sullivan, M., Jones, M., Andrew, R., Hauck, J., Olsen, A., et al. 2020. Global Carbon Budget 2020. Earth System Science Data vol. 12issue 4(2020) 3269-3340.

Gloor, M., Gatti, L., Brienen, R. et al. 2012. The carbon balance of South America: a review of the status, decadal trends and main determinants. Biogeosciences, 9, 5407–5430.

Gloor M et al. 2013. Intensification of the Amazon hydrological cycle over the last two decades. Geophysical Research Letters 40(9), p. 1729-1733.

Gomes, V. H., Vieira, I. C., Salomão, R. P., & ter Steege, H. (2019). Amazonian tree species threatened by deforestation and climate change. Nature Climate Change, 9(7), 547-553.

Gonzalez RJ, Wilson RW, Wood CM, Patrick ML, Val AL. Diverse strategies for ion regulation in fish collected from the ion-poor, acidic Rio Negro. Physiological and Biochemical Zoology. 2002;75(1):37-47.

Goulding, M., E. Venticinque, M. L. d. B. Ribeiro, R. B. Barthem, R. G. Leite, B. Forsberg, P. Petry, U. Lopes da Silva-Júnior, P. S. Ferraz, and C. Cañas. 2019. Ecosystem-based management of Amazon fisheries and wetlands. Fish and Fisheries 20:138–158.

Guan K et al. 2015. Photosynthetic seasonality of global tropical forests constrained by hydroclimate. Nature Geoscience 8, 284-289.

Guimberteau, M., Ciais, P., Ducharne, A., Boisier, J. P., Dutra Aguiar, A. P., Biemans, H., De Deurwaerder, H., Galbraith, D., Kruijt, B., Langerwisch, F., Poveda, G., Rammig, A., Rodriguez, D. A., Tejada, G., Thonicke, K., Von Randow, C., Von Randow, R. C. S., Zhang, K., and Verbeeck, H. (2017) Impacts of future deforestation and climate change on the hydrology of the Amazon Basin: a multi-model analysis with a new set of land-cover change scenarios, Hydrol. Earth Syst. Sci., 21, 1455–1475.

Hayhoe, S.J., Neill, C., Porder, S., Mchorney, R., Lefebvre, P., Coe, M.T., Elsenbeer, H., Krusche, A. V., 2011. Conversion to soy on the Amazonian agricultural frontier increases streamflow without affecting stormflow dynamics. Glob. Chang. Biol. 17, 1821–1833.

Heerspink, B.P., Kendall, A.D., Coe, M.T., Hyndman, D.W., 2020. Trends in streamflow, evapotranspiration, and groundwater storage across the Amazon Basin linked to changing precipitation and land cover. J. Hydrol. Reg. Stud. 32, 100755. https://doi.org/10.1016/j.ejrh.2020.100755

Herrera-R, G. A., Oberdorff, T., Anderson, E. P., Brosse, S., Carvajal-Vallejos, F. M., Frederico, R. G., ... & Ortega, H. (2020). The combined effects of climate change and river fragmentation on the distribution of Andean Amazon fishes. Global Change Biology.

Hoffmann WA, Schroeder W and Jackson RB. 2003. Regional feedbacks among fire, climate, and tropical deforestation. Journal of Geophysical Research 108(D23). https://doi.org/10.1029/2003JD003494

Hoorn C, Wesselingh FP, ter Steege H, Bermudez MA, Mora A, Sevink J, Sanmartín I, Sanchez-Meseguer A, Anderson CL, Figueiredo JP, Jaramillo C, Riff D, Negri FR, Hooghiemstra H, Lundberg J, Stadler T, Särkinen T, Antonelli A. Amazonia through time: Andean uplift, climate change, landscape evolution, and biodiversity. Science. 2010 Nov 12;330(6006):927-31. doi: 10.1126/science.1194585. PMID: 21071659.

Hornbeck, J. W., Bailey, A. S., Eager, C., and Campbell, J. L. (2014) Comparisons with results from the Hubbard Brook Experimental Forest in the northern Appalachians, Long-term response of a forest watershed ecosystem, in: Clearcutting in the southern Appalachians, Oxford University Press, Oxford, 213–228.

Houghton, R.A., Baccini, A., Walker, W.S. 2018. Where is the residual terrestrial carbon sink?. Global change biology. 24, 3277-3279.

Hubau, W. et al. (2020) ‘Asynchronous carbon sink saturation in African and Amazonian tropical forests’, Nature. Nature Research, 579(7797), pp. 80–87. doi: 10.1038/s41586-020-2035-0.

INPE. 2021. INPE Emission Model. Available at http://inpe-em.ccst.inpe.br/en/home/

Jacobson, L. S. V., Hacon, S. S., Castro, H. A., Ignotti, E., Artaxo, P., Saldiva, P. H. N., & de Leon, A. C. M. P. (2014). Acute effects of particulate matter and black carbon from seasonal fires on peak expiratory flow of school children in the Brazilian Amazon. Public Library of Science, 9(8), 1, e104177–14.

Jacomassa, F. A. F., & Pizo, M. A. (2010). Birds and bats diverge in the qualitative and quantitative components of seed dispersal of a pioneer tree. Acta Oecologica, 36(5), 493-496.

Knox R, Bisht G, Wang J and Bras R. 2011. Precipitation Variability over the Forest-to-Nonforest Transition in Southwestern Amazonia. Journal of Climate 24. DOI: 10.1175/2010JCLI3815.1

Kremen, C. (2005). Managing ecosystem services: what do we need to know about their ecology? Ecology letters, 8(5), 468-479.

Kremen, C., Williams, N. M., Aizen, M. A., Gemmill-Herren, B., LeBuhn, G., Minckley, R., ... & Ricketts, T. H. (2007). Pollination and other ecosystem services produced by mobile organisms: a conceptual framework for the effects of land-use change. Ecology letters, 10(4), 299-314.

Kunz, T. H., De Torrez, E. B., Bauer, D., Lobova, T., & Fleming, T. H. (2011). Ecosystem services provided by bats. Europe, 31, 32.

Lathuillière, M.J., Johnson, M.S., Donner, S.D. (2012) Water use by terrestrial ecosystems: temporal variability in rainforest and agricultural contributions to evapotranspiration in Mato Grosso, Brazil. Environ. Res. Lett. 7 (2), 024024.

Lawler, J. J., Shafer, S. L., White, D., Kareiva, P., Maurer, E. P., Blaustein, A. R., & Bartlein, P. J. (2009). Projected climate-induced faunal change in the Western Hemisphere. Ecology, 90(3), 588-597.

Lawrence, D., Vandecar, K., 2015. Effects of tropical deforestation on climate and agriculture. Nat. Clim. Chang. https://doi.org/10.1038/nclimate2430.

Lee, J-E., Frankenberg, C., van der Tol, C., Berry, J.A., Guanter, L., Boyce, C.K., Fisher, J.B., Morrow, E., Worden, J.R. & Asefi. S. 2013. Forest productivity and water stress in

Amazonia: observations from GOSAT chlorophyll fluorescence Proc. R. Soc. Lond. B Biol. Sci., 280, 20130171.

Leite-Filho, A.T., Sousa Pontes, V.Y., Costa, M.H., 2019. Effects of Deforestation on the Onset of the Rainy Season and the Duration of Dry Spells in Southern Amazonia. J. Geophys. Res. Atmos. 124, 5268–5281. https://doi.org/10.1029/2018JD029537

Lenton, TM. Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S., & Schellnhuber, J.H. 2008. Tipping elements in the Earth's climate system. PNAS, 105, 1786-1793.

Levy, M.C., Lopes, A. V., Cohn, A., Larsen, L.G., Thompson, S.E., 2018. Land Use Change Increases Streamflow Across the Arc of Deforestation in Brazil. Geophys. Res. Lett. 45, 3520–3530. https://doi.org/10.1002/2017GL076526.

Lewis, Simon. 2006. Tropical Forests and the Changing Earth System. Phil Trans R Soc B 361: 195-210.

Li W and Fu R. 2004. Transition of the large-scale atmospheric and land surface conditions from the dry to the wet season over Amazonia as diagnosed by the ECMWF re-analysis. J Clim17:2637–2651Li, W., Fu, R., Negron Juarez, R. N., and Fernandes, K. (2008) Observed change of the standardized precipitation index, its potential cause and implications to future climate change in the Amazon region. Philosophical Trans. Royal Society London B, 363, 1767–1772.

Liu, L., Cheng, Y., Wang, S., Wei, C., Pöhlker, M. L., Pöhlker, C., Artaxo, P., Shrivastava, M., Andreae, M. O., Pöschl, U., and Su, H.: Impact of biomass burning aerosols on radiation, clouds, and precipitation over the Amazon: relative importance of aerosol–cloud and aerosol–radiation interactions, Atmos. Chem. Phys., 20, 13283–13301, https://doi.org/10.5194/acp-20-13283-2020, 2020

Liebmann, B. and Marengo, J. (2001) Interannual variability of the rainy season and rainfall in the Brazilian Amazon Basin. J. Climate, 14, 4308–4318.

Lopes IG, Ataújo-Daikiri TB, Kojima JT, Val AL, Portella MC. Predicted 2100 climate scenarios affects growth and skeletal development of Tambaqui (Colossoma macropomum) larvae. Ecology and Evolution. 2018;2018:1-10.

Lovejoy, T.E. & Nobre, C. 2018. Amazon Tipping Point. Science Advances, 4, 2,eaba2340. Doi: 10.1126/sciadv.aat2340

Lovejoy, T.E. & Nobre, C. 2019. Amazon Tipping Point: Last chance for action. Science Advances, 5, 12,eaba2949. Doi: 10.1126/sciadv.aba2949.

McDowell et al., Drivers and mechanisms of tree mortality in moist tropical forests. New Phytologist (2018) 219: 851–869doi: 10.1111/nph.15027

Mace, G. M., Norris, K., & Fitter, A. H. (2012). Biodiversity and ecosystem services: a multilayered relationship. Trends in ecology & evolution, 27(1), 19-26.

Machado, L.A.T., Calheiros, A.J.P., Biscaro, T. et al., 2018. Overview: Precipitation characteristics and sensitivities to environmental conditions during GoAmazon2014/5 and ACRIDICON-CHUVA. Atmos. Chem. Phys., 18, 6461–6482. https://doi.org/10.5194/acp-18-6461-2018

Maeda, E.E., Ma, X., Wagner, F., Kim, H., Oki, T., Eamus, D., Huete, A., 2017. Evapotranspiration seasonality across the Amazon basin. Earth Syst. Dyn. Discuss. 8, 1–28. https://doi.org/10.5194/esd-2016-75.

Maezumi, S. Y. et al. The legacy of 4,500 years of polyculture agroforestry in the eastern Amazon. Nat. Plants4, 540–547 (2018).

Maksic, Jelena; Shimizu, Marilia Harumi; De Oliveira, Gilvan Sampaio; Venancio, Igor Martins ; Cardoso, Manoel; Ferreira, Felipe Alexandre. Simulation of the Holocene climate over South America and impacts on the vegetation. HOLOCENE, v. 28, p. 095968361881040, 2018.

Malhi, Y., Doughty, C. and Galbraith, D. 2011. The allocation of ecosystem net primary productivity in tropical forests. Philosophical Transactions of the Royal Society, B, 366, 3225-3245.

Malhi Y et al. 2009. Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. PNAS.

Malhi, Y., Roberts, J. T. R., Betts, R. A., Killeen, T. J., Li, W., and Nobre, C. A. (2008) Climate change, deforestation, and the fate of the Amazon. Science, 319, 169–172, doi: 10.1126/ science.1146961.

Marengo, J. A., and J. C. Espinoza. 2016. Extreme seasonal droughts and floods in Amazonia: Causes, trends and impacts. International Journal of Climatology 36:1033–1050.

Marengo, J. A. (2009) Long-term trends and cycles in the hydrometeorology of the Amazon Basin since the late 1920s. Hydrological Processes, 23, 3236–3244.

Marengo, J. A., Nobre, C. A., Tomasella, J., Cardoso, M. F., and Oyama, M. D. (2008b) Hydro-climatic and ecological behaviour of the drought of Amazonia in 2005. Philo- sophical Trans. Royal Society London B, 363, 1773–1778.

Marengo, J. A., Nobre, C. A., Tomasella, J., Oyama, M. D., De Oliveira, G. S., Oliveira, R., Camargo, H., Alves, L. M., and Brown, I. F. (2008a) The drought of Amazonia in 2005. J. Climate, 21, 495–516.

Martin, S. T., M. O. Andreae, P. Artaxo, et al., Sources and Properties of Amazonian Aerosol Particles. Review of Geophysics, Vol. 48, Article number RG2002, DOI: 10.1029/2008RG000280, 2010.

Matricardi EAT et al. 2020. Long-term forest degradation surpasses deforestation in the Brazilian Amazon. Science 369, 1378-1382.

Menton, M. C., Merry, F. D., Lawrence, A., & Brown, N. (2009). Company–community logging contracts in Amazonian settlements: impacts on livelihoods and NTFP harvests. Ecology and Society, 14(1).

Miranda, L. S., Imperatriz-Fonseca, V. L., & Giannini, T. C. (2019). Climate change impact on ecosystem functions provided by birds in southeastern Amazonia. Plos one, 14(4), e0215229.

Mitchell, M. G., Bennett, E. M., & Gonzalez, A. (2015). Strong and nonlinear effects of fragmentation on ecosystem service provision at multiple scales. Environmental Research Letters, 10(9), 094014.

Molina, R. D., Salazar, J. F., Martínez, J. A., Villegas, J. C., & Arias, P. A. (2019). Forest-induced exponential growth of precipitation along climatological wind streamlines over the Amazon. Journal of Geophysical Research: Atmospheres, 124, 2589–2599. https://doi.org/ 10.1029/2018JD029534

Morgan, William T., Eoghan Darbyshire, Dominick V. Spracklen, Paulo Artaxo & Hugh Coe. Non-deforestation drivers of fires are increasingly important sources of aerosol and carbon dioxide emissions across Amazonia. Scientific Reports Nature 9:16975 https://doi.org/10.1038/s41598-019-53112-6, 2019.

Morton, D. C. et al. (2013) 'Understorey fire frequency and the fate of burned forests in southern Amazonia'.

Nascimento, J. P., Bela, M. M., Meller, B., Banducci, A. L., Rizzo, L. V., Vara-Vela, A. L., Barbosa, H. M. J., Gomes, H., Rafee, S. A. A., Franco, M. A., Carbone, S., Cirino, G. G., Souza, R. A. F., McKeen, S. A., and Artaxo, P.: Aerosols from anthropogenic and biogenic sources and their interactions: modeling aerosol formation, optical properties, and impacts over the central Amazon Basin, Atmos. Chem. Phys. Discuss. https://doi.org/10.5194/acp-2020-1002 , 2021.

Negrón Juárez, R.I., Hodnett, M.G., Fu, R., Gouden, M.L., von Randow, C., 2007. Control of dry season evapotranspiration over the Amazonian forest as inferred from observation at a Southern Amazon forest site. J. Clim. 20, 2827–2839. https://doi.org/10.1175/JCLI4184.1

Neill, C. et al. (2006) Hydrological and biogeochemical processes in a changing Amazon: results from small watershed studies and the large-scale biosphere-atmosphere experiment. Hydrol. Process. 20 (12), 2467–2476.

Neill, C., Coe, M.T., Riskin, S.H., Krusche, A. V, Elsenbeer, H., Macedo, M.N., Mchorney, R., Lefebvre, P., Davidson, E.A., Scheffler, R., Michela, A., Porder, S., Deegan, L.A., Neill, C., 2013. Watershed responses to Amazon soya bean cropland expansion and intensification. Philos. Trans. R. Soc. B: Biol. Sci. 368 (1619).

Nepstad, D.C. et al. (1994) The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. Nature 372, 666–669.

Nobre C, Sellers PJ and Shukla J. 1991. Amazonian Deforestation and Regional Climate Change. Journal of Climate 4. Available at: https://www.jstor.org/stable/26196408

Nobre, C., Marengo, J.A., Soares, W.R. 2019. Climate change risks in Brazil. Springer International Publishing. ISBN 978-3-319-92880-7. Doi.org/10/1007/978-3-319-92881-4

Oliveira, A. M., & Val, A. L. (2017). Effects of climate scenarios on the growth and physiology of the Amazonian fish tambaqui (Colossoma macropomum) (Characiformes: Serrasalmidae). Hydrobiologia, 789(1), 167-178.

Ometto, J.P.H.B., Nobre, A.D., Rocha, H.R., Artaxo, P., Martinelli, L.A. 2005. Amazonia and the modern carbon cycle: lessons learned. Oecologia, 143, 483-500.

Pacifico, F., Folberth, G. A., Sitch, S., Haywood, J. M., Rizzo, L. V., Malavelle, F. F., & Artaxo, P. (2015). Biomass burning related ozone damage on vegetation over the Amazon forest: A model sensitivity study. Atmospheric Chemistry and Physics, 15, 2791–2804. 2015.

Pan, Y., Birdsey, R., Fang, J. et al. 2011. A large and persistent carbon sink in the world’s forests. Science, 333, 988–992.

Panday, P.K., Coe, M.T., Macedo, M.N., Lefebvre, P., Castanho, A.D. de A., 2015. Deforestation offsets water balance changes due to climate variability in the Xingu River in eastern Amazonia. J. Hydrol. 523, 822–829. https://doi.org/10.1016/j.jhydrol.2015.02.018

Panwar, A., Renner, M., Kleidon, A., 2020. Imprints of evaporative conditions and vegetation type in diurnal temperature variations. Hydrol. Earth Syst. Sci. 24, 4923–4942. https://doi.org/10.5194/hess-24-4923-2020

Patade, S., Phillips, V. T. J., Amato, P., Bingemer, H. G., Burrows, S. M., DeMott, P. J., Goncalves, F. L. T., Knopf, D. A., Morris, C. E., Alwmark, C., Artaxo, P., Pöhlker, C., Schrod, J., & Weber, B. (2021). Empirical formulation for multiple groups of primary biological ice nucleating particles from field observations over Amazonia, Journal of the Atmospheric Sciences. Vol. 79, 1-25, https://doi.org/10.1175/JAS-D-20-0096.1 2021.

Peres, C. A., & Lake, I. R. (2003). Extent of nontimber resource extraction in tropical forests: accessibility to game vertebrates by hunters in the Amazon basin. Conservation Biology, 17(2), 521-535.

Phillips, O.L., Aragão, L.E.O.C., Simon L.L. et al. 2009. Drought sensitivity of the Amazon rainforest, Science, 323, 1344–1347.

Pinaya, W. H. D., Lobon-Cervia, F. J., Pita, P., Buss de Souza, R., Freire, J., & Isaac, V. J. (2016). Multispecies fisheries in the lower Amazon River and its relationship with the regional and global climate variability. PLoS One, 11(6), e0157050.

Pinker, R. T., O. E. Thompson, and T. F. Eck, 1980: The albedo of a tropical evergreen forest. Q. J. Roy. Meteor. Soc., 106, 551-558.

Pongratz, J., Bounoua, L., Defries, R.S., Morton, D.C., Anderson, L.O., Mauser, W., Klink, C.A., 2006. The Impact of Land Cover Change on Surface Energy and Water Balance in Mato Grosso, Brazil. Earth Interact. 10, 1–17.

Pope, R. J., Arnold, S. R., Chipperfield, M. P., Reddington, C. L. S., Butt, E. W., Keslake, T. D., et al. (2020). Substantial increases in Eastern Amazon and Cerrado biomass burning-sourced tropospheric ozone. Geophysical Research Letters, 47, e2019GL084143.

Pöschl, U., S. T. Martin, B. Sinha, et al. Rainforest aerosols as biogenic nuclei of clouds and precipitation in the Amazon. Science, Vol. 329, 1513-1516, doi: 10.1126/science.1191056, 2010.

Prado-Lima M, Val AL. Transcriptomic characterization of Tambaqui (Colossoma macropomum, Cuvier, 1818) exposed to three climate change scenarios. PLoS ONE. 2016.

Prass, M., Andreae, M. O., de Araùjo, A. C., Artaxo, P., Ditas, F., Elbert, W., Franco, M. A., Hrabe de Angelis, I., Kesselmeier, J., Klimach, T., Kremper, L. A., Thines, E., Walter, D., Weber, J., Weber, B., Fuchs, B. M., Pöschl, U., and Pöhlker, C.: Bioaerosols in the Amazon rain forest: Temporal variations and vertical profiles of Eukarya, Bacteria and Archaea, Biogeosciences Discuss. https://doi.org/10.5194/bg-2020-469 , 2021.

Procopio, A. S., L. A. Remer, P. Artaxo, Y. J. Kaufman, and B. N. Holben(2003), Modeled spectral optical properties for smoke aerosols in Ama-zonia, Geophys. Res. Lett., 30, 2265, doi:10.1029/2003GL018063.

Procopio, A., Artaxo, P., Kaufman, Y.J., Remer, L.A., Schafer, J.S., Hoben, B.N. 2004. Multiyear analysis of Amazonian Biomass Burning Smoke Radiative Forcing of Climate. Geophysical Research Letters, vol. 31(3) https://doi.org/10.1029/2003GL018646.

Randerson, J.T., Chen, Y., van der Werf, G.R., Rogers, B.M. & Morton, D.C. 2012. Global burned area and biomass burning emissions from small fires, J. Geophys. Res., 117, G04012, https://doi.org/10.1029/2012JG002128.

Rap, A., Spracklen, D.V., Mercado, L., Reddington, C.L., Haywood, J.M., Ellis, R.J., Phillips, O.L., Artaxo, P., Bonal, D., Coupe, N.R. & Butt, N. 2015. Fires increase Amazon forest productivity through increases in diffuse radiation, Geophys. Res. Lett., 42, 4654–4662, doi:10.1002/2015GL063719, 2015.

Reddington, C. L., Butt, E. W., Ridley, D. A., Artaxo, P., Morgan, W. T., Coe, H., & Spracklen, D. V. (2015). Air quality and human health improvements from reductions in deforestation-related fires in Brazil. Nature Geoscience, 8, 768–773. https://doi.org/10.1038/ngeo2535

Reddington, C. L., Spracklen, D. V., Artaxo, P., Ridley, D. A., Rizzo, L. V., & Arana, A. (2016). Analysis of particulate emissions from tropical biomass burning using a global aerosol model and long-term surface observations. Atmospheric Chemistry and Physics, 16(17), 11083–11106.

Ronchail, J., Cochonneau, G., Molinier, M., Guyot, J. L., Gorreti, A., Guimara˜ es, V., and de Oliveira, E. (2002) Interannual rainfall variability in the Amazon Basin and sea surface temperatures in the equatorial Pacific and the tropical Atlantic Oceans. Int. J. Climatol., 22, 1663–1686.

Röpke, C. P., S. Amadio, J. Zuanon, E. J. G. Ferreira, C. P. De Deus, T. H. S. Pires, and K. O. Winemiller. 2017. Simultaneous abrupt shifts in hydrology and fish assemblage structure in a floodplain lake in the central Amazon. Scientific Reports 7:1–10.

Rothacher, J. (1970) Increases in water yield following clear-cut logging in the Pacific northwest, Water Resour. Res., 6, 653–658, doi:10.1029/wr006i002p00653.

Saint-Paul U. Physiological adaptation to hypoxia of a neotropical characoid fish Colossoma macropomum, Serrasalmidae. Environmental Biology of Fishes. 1984;11(1):53-62.

Sakschewski, B., Von Bloh, W., Boit, A., Poorter, L., Peña-Claros, M., Heinke, J., ... & Thonicke, K. (2016). Resilience of Amazon forests emerges from plant trait diversity. Nature Climate Change, 6(11), 1032-1036.

Salati, E., Vose, P.B., 1984. Amazon Basin : A System in Equilibrium. Science (80-.). 225, 129–139. https://doi.org/10.1126/science.225.4658.129.

Salazar, J. F., Villegas, J. C., Rendón, A. M., Rodríguez, E., Hoyos, I., Mercado-Bettín, D., & Poveda, G. (2018). Scaling properties reveal regulation of river flows in the Amazon through a “forest reservoir”. Hydrology and Earth System Sciences, 22(3), 1735-1748.

Sales, L. P., Rodrigues, L., & Masiero, R. (2021). Climate change drives spatial mismatch and threatens the biotic interactions of the Brazil nut. Global Ecology and Biogeography, 30(1), 117-127.

Sampaio, G. (2008) Climatic consequences of gradual conversion of Amazonian tropical forests into degraded pasture or soybean cropland: A GCM simulation study, Ph.D. thesis in Meteorology (INPE-15263-TDI/1346, 417 pp.). Instituto Nacional de Pesquisas Espaciais, São José dos Campos, Brazil. Available at http: //urlib.net/sid.inpe.br/mtc-m17@80/2008/ 02.28.17.17

Sampaio, G., Nobre, C. A., Costa, M. H., Satyamurthy, P., Soares-Filho, B. S., and Cardoso, M. (2007) Regional climate change over eastern Amazonia caused by pasture and soybean cropland expansion. Geophys. Res. Lett., 34, L17709.

Sarmento, R., Alves-Costa, C. P., Ayub, A., & Mello, M. A. (2014). Partitioning of seed dispersal services between birds and bats in a fragment of the Brazilian Atlantic Forest. Zoologia (Curitiba), 31(3), 245-255.

Scanlon, B.R., Jolly, I., Sophocleous, M., Zhang, L. (2007) Global impacts of conversions from natural to agricultural ecosystems on water resources: quantity versus quality. Water Resour. Res. 43 (3).

Schimel, D., Stephens, B.B., & Fisher, J.B. 2015. Effect of increasing CO2 on the terrestrial carbon cycle. PNAS, 112, 436-441.

Schwalm, C. R. et al. (2017) 'Global patterns of drought recovery', Nature. Nature Publishing Group, 548(7666), pp. 202–205. doi: 10.1038/nature23021.

Schrod, J., Thomson, E. S., Weber, D., Kossmann, J., Pöhlker, C., Saturno, J., Ditas, F., Artaxo, P., Clouard, V., Saurel, J.-M., Ebert, M., Curtius, J., and Bingemer, H. G.: Long-term deposition and condensation ice-nucleating particle measurements from four stations across the globe, Atmos. Chem. Phys., 20, 15983–16006, https://doi.org/10.5194/acp-20-15983-2020, 2020.

Sena, E. T., & Artaxo, P. (2015). A novel methodology for large-scale daily assessment of direct radiative forcing of smoke aerosols. Atmospheric Chemistry and Physics, 15, 5471–5483. https://doi.org/10.5194/acp-15-5471-2015

Sena, E. T., Artaxo, P., and Correia, A. L. 2013. Spatial variability of the direct radiative forcing of biomass burning aerosols and the effects of land-use change in Amazonia. Atmos. Chem. Phys. 13, 1261–1275. https://doi.org/10.5194/acp-13-1261-2013.

Shuttleworth, W.J., J. H. C. Gash, C. R. Lloyd, J. M. Roberts, A. O. Marques, G. Fisch, P. Silva, M. N. G. Ribeiro, L. C. B. Molion, L. D. A. Sá, C. A. Nobre, O. M. R. Cabral, S. R. Patel, and J. C. Moraes, 1984: Observations of radiation exchange above and below Amazonian forest. Q. J. Roy. Meteor. Soc., 110, 1163-1169.

Silva Dias, M.A.F.; Rutledge, S. ; Kabat, P. ; Dias, Pedro Leite Da Silva ; Nobre, C. A. ; Fisch, Gilberto ; Dolman, A J ; Zipser, E. ; Garstang, M.; Manzi, A. O. ; Fuentes, J. ; Rocha, H. R. ; Marengo, Jose ; Planafattori, A. ; Sá, L. ; Alvalá, R. ; Andreae, M. ; Artaxo, Paulo ; Gielow, R. ; Gatti, Luciana. Clouds and rain processes in a biosphere atmosphere interaction context in the Amazon Region. Journal of Geophysical Research, Estados Unidos, v. 107, n.D20, p. 46.1-46.23, 2002.

Silvério, D. V., Brando, P.M., Macedo, M.N., Beck, P.S.A., Bustamante, M., Coe, M.T., 2015. Agricultural expansion dominates climate changes in southeastern Amazonia: The overlooked non-GHG forcing. Environ. Res. Lett. 10, 104015. https://doi.org/10.1088/1748-9326/10/10/104015.

Silva, G.S.D., Matos, L.V., Freitas, J.O.D.S., Campos, D.F., Almeida, E., Val, V.M.F. 2019. Gene expression, genotoxicity, and physiological responses in an Amazonian fish, Colossoma macropomum (CUVIER 1818), exposed to Roundup® and subsequent acute hypoxia. Comp Biochem Physiol C Toxicol Pharmacol., 222:49-58. doi: 10.1016/j.cbpc.2019.04.010.

Sitch, S., Cox, P.M., Collins, W.J. & Huntingford C. 2007. Indirect radiative forcing of climate change through ozone effects on the land-carbon sink, Nature, 448, 791– 794.

Souza, S.S., Silva, G.S., Almeida-Val, V.M.F. 2019. Ecophysiology, genotoxicity, histopathology, and gene responses of naphthalene injected *Colossoma macropomum* (Cuvier, 1818) exposed to hypoxia. Genetics and molecular biology, 42, 411-424

Spera, S.A., Galford, G.L., Coe, M.T., Macedo, M.N., Mustard, J.F., 2016. Land-use change affects water recycling in Brazil's last agricultural frontier. Glob. Chang. Biol. 22. https://doi.org/10.1111/gcb.13298.

Spracklen DV and Garcia-Carreras L. 2015. The impact of Amazonian deforestation on Amazon basin rainfall. Geophys. Res. Lett., 42, doi:10.1002/2015GL066063.

Spracklen DV, Arnold SR and Taylor CM. 2012. Observations of increased tropical rainfall preceeded by air passage over forests. Nature 489.

Sterling, S., Ducharne, A., and Polcher, J. (2013) The impact of global land-cover change on the terrestrial water cycle, Nat. Clim. Change, 3, 385–390, doi:10.1038/nclimate1690.

Stickler, C. M., Coe, M. T., Costa, M. H., Nepstad, D. C., McGrath, D. G., Dias, L. C., Rodrigues, H. O., and Soares-Filho, B. S. (2013) Dependence of hydropower energy generation on forests in the Amazon Basin at local and regional scales, P. Natl. Acad. Sci. USA, 110, 9601–9606.

Trisos, Christopher & Merow, Cory & Pigot, Alex. (2020). The projected timing of abrupt ecological disruption from climate change. Nature. 580. 1-6. 10.1038/s41586-020-2189-9.

Trumbore S, Brando P and Hartmann H. 2015. Forest health and global change. Science 349 (6250), p. 814-818. DOI: 10.1126/science.aac6759

Val P., Silva CL, Harbor D, Morales N, Amaral FR, Maia TFA (2014) Erosion of an active fault scarp leads to drainage capture in the Amazon region, Brazil. Earth Surf Proc Land, 39: 1062-1074. https://doi.org/10.1002/esp.3507

Val A. L., Almeida-Val VMF. Fishes of the Amazon and their environments. Physiological and biochemical features. Heidelberg: Springer Verlag; 1995. 224 p.

Val A. L., Silva MNP, Almeida-Val VMF. Hypoxia adaptation in fish of the Amazon: a never-ending task. South African Journal of Zoology. 1998;33(2):107-14.

van Marle, M.J.E., Field, R.D., van der Werf, G.R., Estrada de Wagt, I.A., Houghton, R.A., Rizzo, L.V., Artaxo, P. & Tsigaridis, K. 2017. Fire and deforestation dynamics in Amazonia (1973–2014), Global Biogeochem. Cy., 31, 24–38, https://doi.org/10.1002/2016GB005445.

von Randow, R.C.S., von Randow, C., Hutjes, R.W.A., Tomasella, J., Kruijt, B., 2012. Evapotranspiration of deforested areas in central and southwestern Amazonia. Theor. Appl. Climatol. 109, 205–220. https://doi.org/10.1007/s00704-011-0570-1.

Wang, B. C., & Smith, T. B. (2002). Closing the seed dispersal loop. Trends in ecology & evolution, 17(8), 379-386.

Wayne S. Walker, Seth R. Gorelika , Alessandro Baccinia , Jose Luis Aragon-Osejob,c, Carmen Josseb,c, Chris Meyerd , Marcia N. Macedo, Cicero Augusto, Sandra Rios, Tuntiak Katan , Alana Almeida de Souza, Saul Cuellarc, Andres Llanos, Irene Zagerc, Gregorio Díaz Mirabal, Kylen K. Solvika, Mary K. Farinaa, Paulo Moutinho, and Stephan Schwartzman. The role of forest conversion, degradation, and disturbance in the carbon dynamics of Amazon indigenous territories and protected areas. PNAS 2020.

Wendisch, M., Pöschl, U., Andreae, M. O., et al. (2016). The ACRIDICON-CHUVA campaign: Studying tropical deep convective clouds and precipitation over Amazonia using the new German research aircraft HALO. Bulletin of the American Meteorological Society, 97(10), 1885-1908. doi:10.1175/BAMS-D-14-00255.1

Whitehead, J. D., Darbyshire, E., Brito, J., Barbosa, H. M. J., Crawford, I., Stern, R., Gallagher, M. W., Kaye, P. H., Allan, J. D., Coe, H., Artaxo, P., and McFiggans, G.: Biogenic cloud nuclei in the central Amazon during the transition from wet to dry season, Atmos. Chem. Phys., 16, 9727–9743, https://doi.org/10.5194/acp-16-9727-2016, 2016.

Williams, E., Dall'Antonia, A., Dall'Antonia, V., De Almeida, J., Suarez, F., Liebmann, B., and Malhado, A. (2005) The drought of the century in the Amazon Basin: An analysis of the regional variation of rainfall in South America in 1926. Acta Amazônica, 35, 231–238.

Wood CM, Wilson RW, Gonzalez RJ, Patrick ML, Bergman HL, Narahara A, et al. Responses of an Amazonian teleost, the tambaqui (Colossoma macropomum) to low pH in extremely soft water. Physiological Zoology. 1998;71(6):658-70.

Wright et al. 2017. Rainforest-initiated wet season onset over the southern Amazon. PNAS 114(32)

Yáñez-Serrano, Ana; Bourtsoukidis, Efstratios; Alves, Eliane; Bauwens, Maite; Stavrakou, Trissevgeni; Llusia, Joan; Filella, Iolanda; Guenther, Alex, Artaxo, Paulo; Kesselmeier, Jurgen; Penuelas, Josep. Amazonian BVOC emissions under global change: a review of current research, and future directions Journal: Global Change Biology, 26 (9), 4722-4751, DOI: 10.1111/gcb.15185, 2020.

Zemp, D.C., Schleussner, C.F., Barbosa, H.M.J., van der Ent, R.J., Donges, J.F., Heinke, J., Sampaio, G., Rammig, A., 2014. On the importance of cascading moisture recycling in South America. Atmospheric Chemistry and Physics 14, 13337–13359.

Zemp, D.C., Schleussner, C.F., Barbosa, H.M.J., Rammig A. 2017. Deforestation effects on Amazon forest resilience. Geophysical Research Letters, 44, 6182-6190

Zhang, Yan ; FU, Rong ; Yu, Hongbin ; Qian, Yun ; Dickinson, robert ; Silva Dias, Maria Assunção F. ; da Silva Dias, Pedro L. ; Fernandes, Kátia . Impact of biomass burning aerosol on the monsoon circulation transition over Amazonia. Geophysical Research Letters, v. 36, p. L10814, 2009.

Zuidema, P. A., & Boot, R. G. (2002). Demography of the Brazil nut tree (Bertholletia excelsa) in the Bolivian Amazon: impact of seed extraction on recruitment and population dynamics. Journal of Tropical Ecology, 1-31.

8. CORE GLOSSARY

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