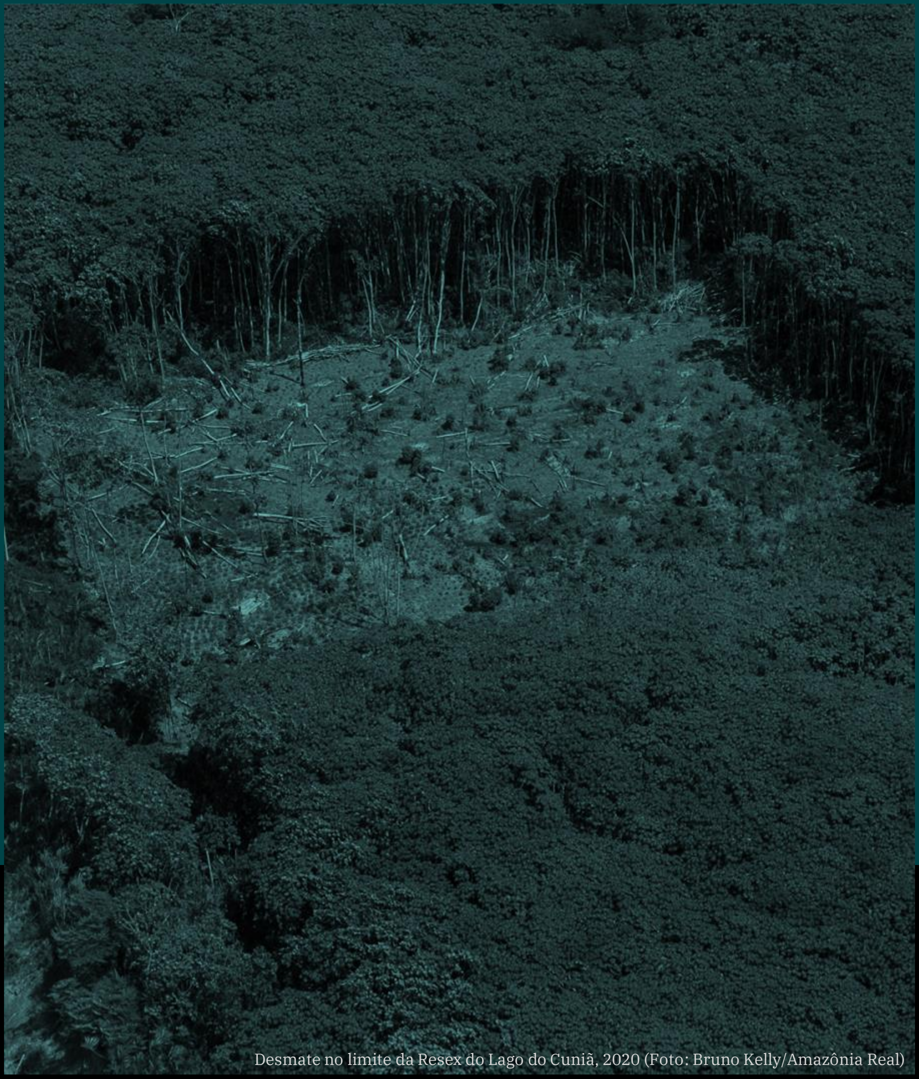
Amazon Assessment Report 2021

Chapter 23

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



Desmate no limite da Resex do Lago do Cuniã, 2020 (Foto: Bruno Kelly/Amazônia Real)

THE AMAZON WE WANT

Science Panel for the Amazon

SUSTAINABLE DEVELOPMENT SOLUTIONS NETWORK
A GLOBAL INITIATIVE FOR THE UNITED NATIONS

About the Science Panel for the Amazon (SPA)

The Science Panel for the Amazon is an unprecedented initiative convened under the auspices of the United Nations Sustainable Development Solutions Network (SDSN). The SPA is composed of over 200 preeminent scientists and researchers from the eight Amazonian countries, French Guiana, and global partners. These experts came together to debate, analyze, and assemble the accumulated knowledge of the scientific community, Indigenous peoples, and other stakeholders that live and work in the Amazon.

The Panel is inspired by the Leticia Pact for the Amazon. This is a first-of-its-kind Report which provides a comprehensive, objective, open, transparent, systematic, and rigorous scientific assessment of the state of the Amazon's ecosystems, current trends, and their implications for the long-term well-being of the region, as well as opportunities and policy relevant options for conservation and sustainable development.

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INDEX

Graphical Abstract

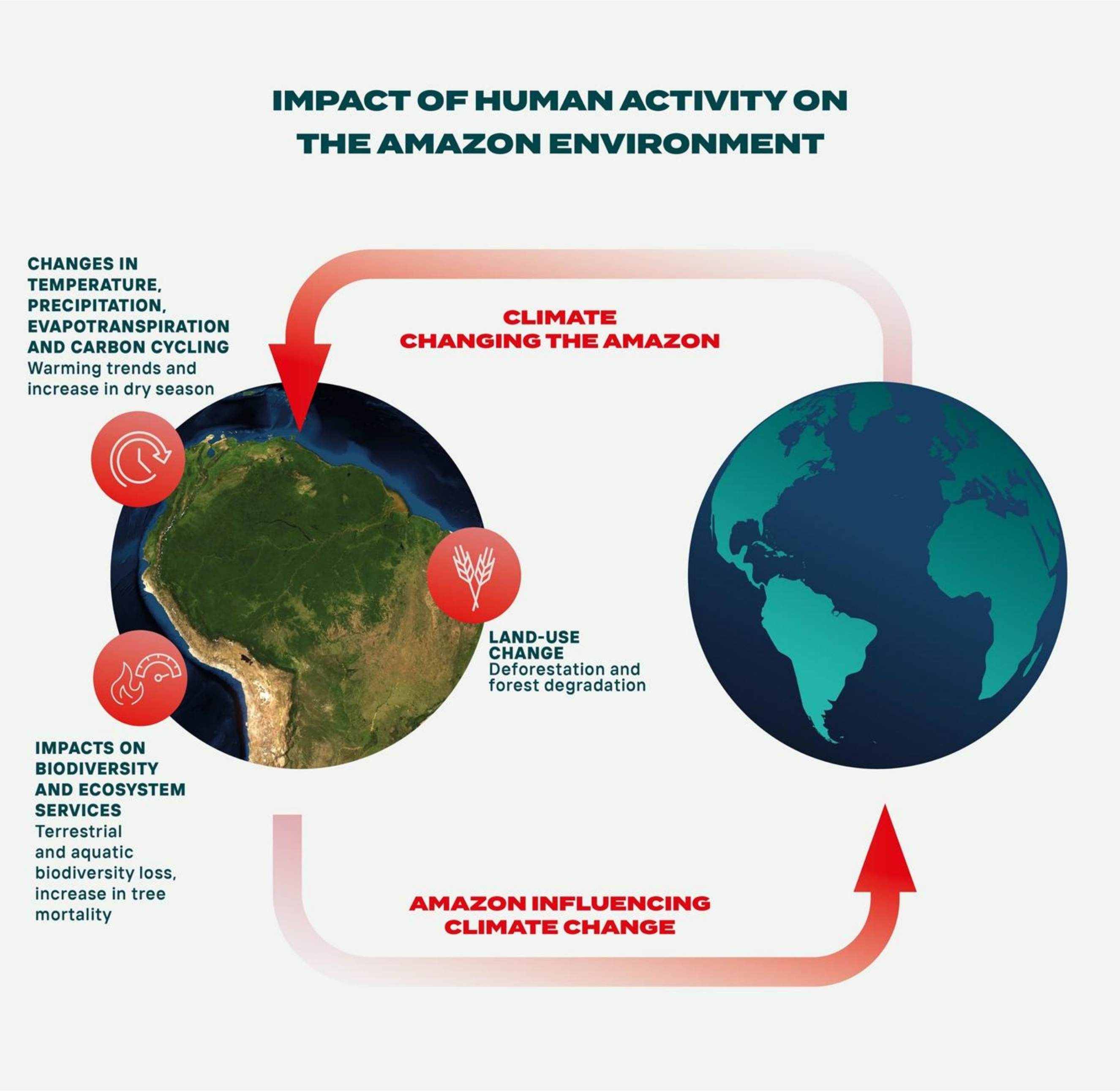

Figure 23.A Impact of human activities on the Amazon environment. Global climate changes affect the Amazon through temperature increase, altered precipitation patterns and climate extremes, leading to increased tree mortality and terrestrial and aquatic biodiversity loss. This, coupled with land-use change through deforestation and degradation, reduces evapotranspiration, changes carbon cycling dynamics, decreases the resilience of the ecosystems, and leads to further biodiversity loss and tree mortality, emitting greenhouse gases that impact not only the regional, but the global climate. On the other side, Amazonian deforestation enhances climate change.

Impacts of Deforestation and Climate Change on Biodiversity, Ecological Processes, and Environmental Adaptation

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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. To close these gaps, remote sensing of CO$_2$ measurements, ground-based tower flux data, aircraft measurements, and modeling tools must be integrated.
- 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 functioning of the Amazon's ecosystems. The observed increase in temperature, precipitation changes, and increase in climate extremes affect ecosystem services, carbon uptake, and 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 fish and other ectothermic groups able to do the same. In particular, fisheries' yields are important to food security and have been impacted by climate change in unpredictable ways. Moreover, projections indicate that climate change will have significant adverse impacts on pollination and seed dispersal, essential ecosystem services for the maintenance of natural and agricultural ecosystems because of changes in species distributions, and 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 significantly increased over the last 30 years, and the runoff of the Xingu catchment has risen by 10%, possibly owing to 40% deforestation in the Xingu catchment. The Amazon was a strong carbon sink in the 1980s, and recent measurements show a much weaker carbon sink in the forests. The mean net carbon uptake for the 1990s was -0.59 ± 0.18 Pg C y^{-1}, and the decade of 2010s had a carbon uptake of -0.22 ± 0.30 Pg C y^{-1}. 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

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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 with 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 ecosystems' 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

23.1 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 climate forcing and multiple biophysical and biogeochemical feedbacks across different spatial and temporal scales. Climate change impacts tropical forest ecosystems in various ways, but the attribution is not always clear because the climate system's natural variability can be large. 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 temperature, precipitation, and climate extremes are increasingly changing in tropical and Amazonian forests. 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 (see Chapters 1 and 2). Current biodiversity patterns are rooted deep in the pre-Quaternary period (Hoorn *et al.* 2010). Amazonian paleoclimate studies help to understand the formation and evolution of this rich environment and show evidence that human impact on the Amazonian ecosystems could have been substantial over the last few millennia (Maezumi *et al.* 2018; Maksic *et al.* 2019; Cordeiro *et al.* 2014; Anhuf *et al.* 2006).

Freshwater ecosystems also interact with the whole ecosystem in complex ways, and in the case of the Amazon, the Basin houses unparalleled aquatic biodiversity. Regarding fish, more than 2,400 species (see Chapter 3), 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 protein sources for local people (see Chapters 15 and 30). 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 (Braz-Mota and Almeida-Val 2021)

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

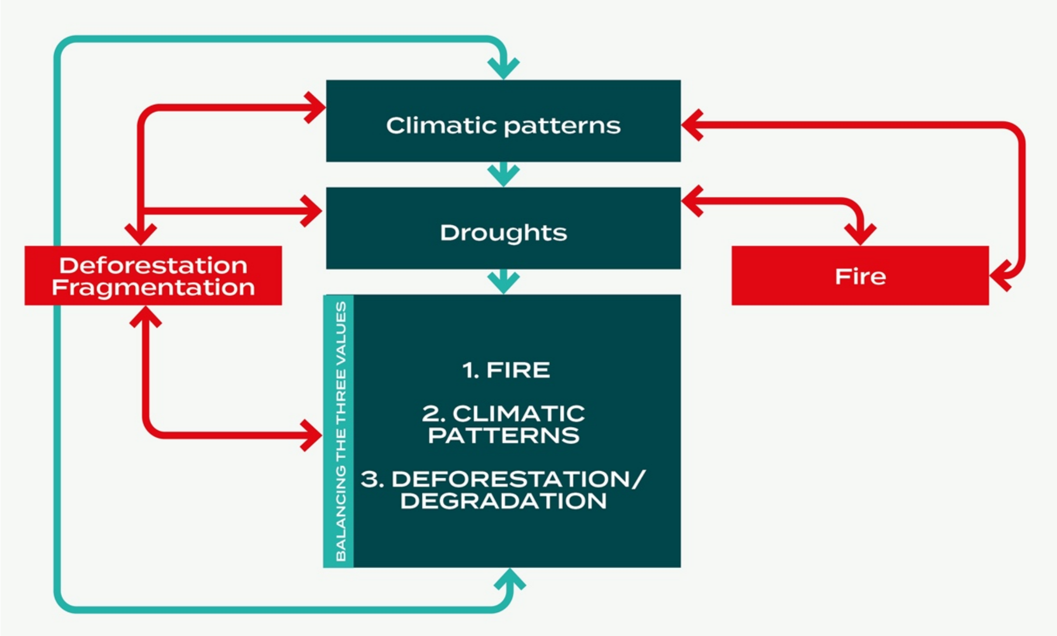

Figure 23.1. Links between climate, deforestation, forest degradation, and fire impacts on the Amazonian ecosystems. In order to establish solid public policies on land-use change, it is necessary to have an integrated view of the main drivers and impacts. Adapted from Luiz Aragão.

23.1.1 Changes in biodiversity driven by climate change and deforestation

23.1.1.1 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 have reported 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 ecosystems for thousands of years. But, over the last 20,000 years, the Amazon has had relatively stable climate.

Although deforestation and forest degradation are currently the most significant threat to biodiversity in the Amazon (see Chapters 19 and 20), 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 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 more likely to be affected by the synergetic impacts of deforestation and climate changes: eastern Amazon may suffer up to 95% of forest loss by 2050, followed by southwestern (81%) and southern Amazon (78%). Furthermore, 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. Among newly recruited trees, drought-tolerant genera have become more abundant, whereas the mortality of wet tolerant genera has increased in plots where the dry season has intensified most (Esquivel-Muelbert *et al.*

2019). 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.* 2019).

Although 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; see also Chapter 24). 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 have indicated that future disruption of ecological assemblages would be abrupt (Trisos *et al.* 2020) because of the simultaneous exposure of most species to climate conditions beyond their realized niche limits. Under the Intergovernmental Panel on Climate Change (IPCC) shared socioeconomic pathway SSP5-8.5 (high emissions), such events will affect tropical forests in the following decades.

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).

23.1.1.2 Lowlands connectivity with highlands

Amazon harbors one of the world's most diverse biological communities (see Chapters 2–4), 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 owing 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 according to Nakicenovic and Swart (2000) (Lawler *et al.* 2009).

Because 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 (2,500 m to timberline) and lower montane (1,500 to 2,500 m). However, very few elevational gradients of intact habitat extend from the lowlands on either side of the Andes to the tree line 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.

23.1.1.3 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 owing 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 the western Amazon, the extreme drought of 2010 caused significant declines in wading birds, river dolphins, and fish populations (Bodmer *et al.* 2018). In contrast, extreme flood events in 2009 and 2011–2015 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).

Higher future sea levels will have important impacts on aquatic systems in Amazonia. Marine waters would be driven deep into the Central Amazon, altering shorelines, habitats, microclimates, and regional rainfall patterns (see Chapter 1). This large marine incursion would convert large areas of lowland Amazon rainforest to nearshore estuarine and marine habitats and possibly drive many species to extinction.

Many fish species in the Amazon are migratory (see Chapter 3), 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 of freshwater fish on Earth (Barthem *et al.* 2017). From headwater spawning habitats in/or near the Andean piedmont of Bolivia, Colombia, Ecuador, and Peru 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 change are clear marks in the evolution of the Amazon biota. Amazonian fish have experienced speciation booms during critical periods of oxygen availability, high temperatures, and extreme carbon dioxide levels (Albert *et al.* 2018). Environmental pressures in these geological periods shaped 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 water quality aspects deserve to be highlighted here, given their connections with the conservation of the Amazon biome in light of the new scenarios imposed by the current climate changes and foreseen for the near future. These aspects are oxygen availability in the aquatic environment, water acidity owing to the dissolution of CO_2, and temperature increase.

The availability of oxygen has always been a significant environmental challenge for fish in the Amazon; fish 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, 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 the Tambaqui can increase competition with other fish species and reduce the carrying capacity of aquatic ecosystems.

Many fish species in the Amazon are susceptible to small temperature increases (Campos *et al.* 2018). The maximum critical temperature of some fish groups is already very close to the current average maximum temperatures. 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, changes in metabolic processes that provide the energy necessary for fish survival under different situations may be an example of the increased environmental variability in Amazonian environments.

Acidic waters are common in the Amazon (see Chapter 4). The black waters of the Negro River, for example, are typically acidic, and some of its marginal lakes may have waters with pH values as low as 3.5. Even so, hundreds of different fish species inhabit these waters, including hundreds of ornamental fish species that support a significant economy of some Amazonian villages (see Chapter 30). We are far from knowing the resilience of Amazonian fish to pH variations. However, we know 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, at least for the species studied so far, except for fertilization, the acidic pH does not represent an expressive limiting factor. However, further studies involving other fish species are necessary.

We are far from understanding the effects of climate change on fish in the Amazon. However, according to IPCC models, we already know that fish are significantly affected when exposed to simulated environmental scenarios for temperature, CO_2, and humidity for the year 2100. In the case of Tambaqui, an important commercial species for the entire Amazon, 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), were observed. 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.

23.1.2 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 the capacity of tropical forests to resist and respond to such changes, especially as they interact with land-use change (see Chapter 24).

Global carbon emissions have impacted Amazon's most remote forests by changing the atmospheric composition and air temperature. 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). Although 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 increase in air temperature in 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 MgC ha per degree Celsius increase in air temperature (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, with an 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.

Although forests have evolved being exposed to some small level of disturbance, increased 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 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 how long it will take. 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). However, climate change is expected to increase the risks of new disturbances impacting the area, perhaps before recovery occurs. Although 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 (see Chapter 24). In fact, as the regional climate changes, forest resilience is expected to decrease (Schwalm *et al.* 2017).

Modeling studies indicate that climate changes will have potentially significant effects on forests in the near future. Considering only primary forests, increased atmospheric CO_2 concentration could theoretically offset losses in carbon stocks from increased temperature. However, recent studies suggest that the CO_2 fertilization effect is limited mainly by the availability of other nutrients and the diversity of functional strategies across species (Fleischer *et al.* 2019). Most predictive vegetation models or Earth System Models (ESM) used to project potential trajectories of Amazonian forests are too sensitive to CO_2 fertilization, lack adequate nutrient limitations, are 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 on forests 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. ESM predict the Amazon to be dryer than today, with an additional exacerbated sensitivity of vegetation models on the CO_2 fertilization effect (Ahlström *et al.* 2017). Although these models have rapidly advanced, this extraordinarily complex system with more than 15,000 tree species remains to be fully understood. The potential legacies of increased forest degradation by compounding disturbances can persist for long periods. This necessitates urgency in identifying potentially catastrophic thresholds of forest health declines associated with rising temperatures and changes in precipitation patterns (see Chapter 22).

23.1.3 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. The mature Amazonian ecosystem stores large amounts of carbon above and below ground (~150–200 Gt C; see Chapter 6). Production of woody biomass (longest-lived plant tissue and an important C stock) accounts for approximately 8–13% of the photosynthetic carbon uptake. 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) ranges from 30 to 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). There are relatively few direct measurements of NPP and GPP across Amazon. The magnitude of GPP varies significantly with rainfall and soil nutrient status, with the highest values found in the wet forests of northwestern Amazon and lower values found in regions with a long dry season (Malhi *et al.* 2015). However, few studies have quantified all these NPP components and their distribution between forest 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 an average total annual precipitation < 2,000 mm and dry seasons longer >3.5 months (Guan *et al.* 2015). Extreme wet areas can constrain GPP owing 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 because of the influence of autotrophic respiration on NPP (Brando *et al.* 2019a).

Recent studies have shown that forest carbon cycling in the region is changing, with important implications for this large global carbon reservoir. A few decades ago, primary forests of the Amazon were removing carbon from the atmosphere at a rate of approximately 0.5 tons per hectare per year (Ometto *et al.* 2005; Araujo *et al.* 2002; Chambers *et al.* 2001; Artaxo *et al.* 2021). 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, as 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; Gatti *et al.* 2021).

Given the significant impact of climate (precipitation, temperature, cloud cover) on the geography of carbon stocks and productivity of Amazon forests, ongoing climatic changes are expected to cause significant shifts in the 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). Although intact tropical forests are estimated to be Earth's largest carbon sink (Pan *et al.* 2011; Phillips *et al.*

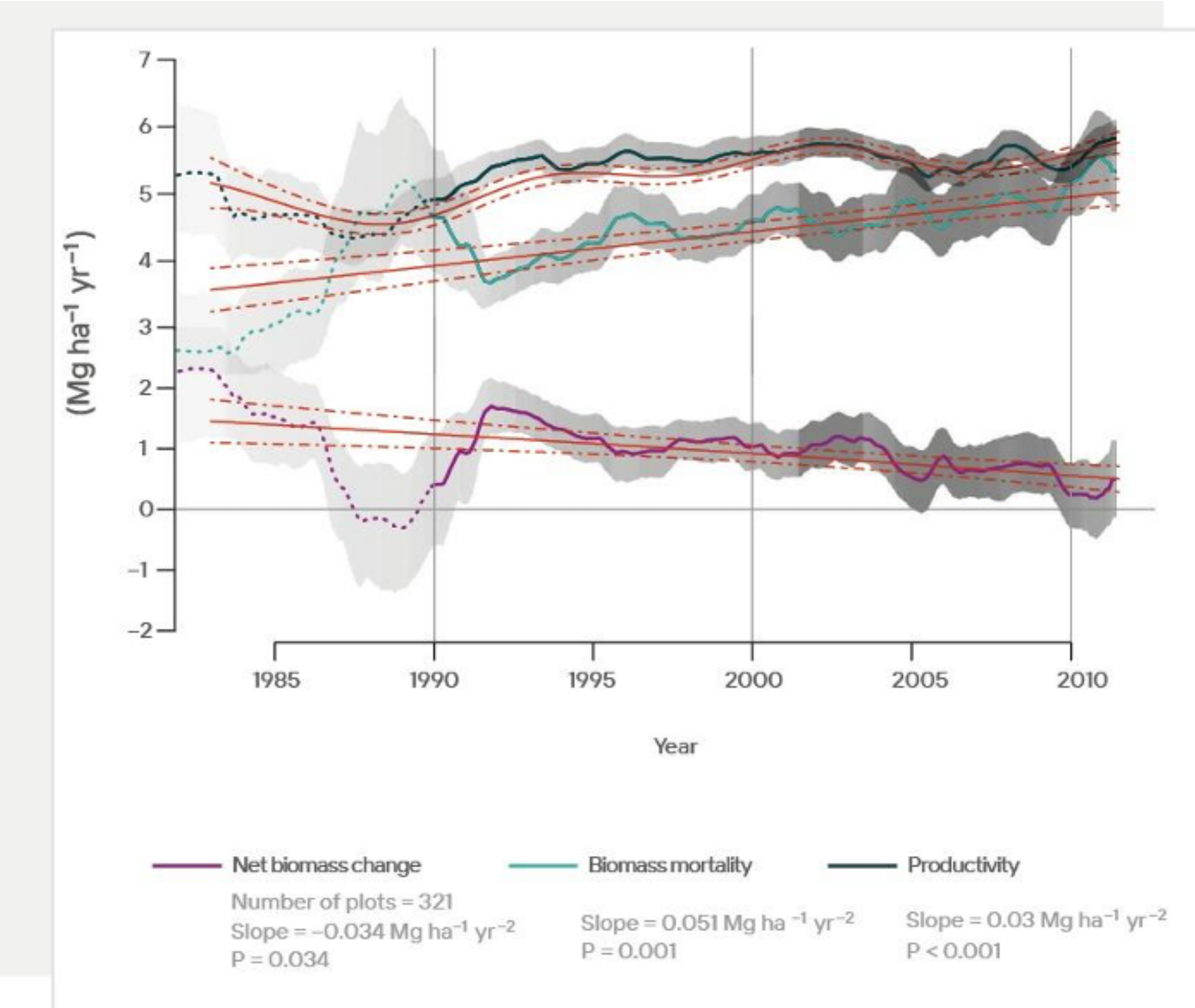

Figure 23.2. Long-term net above-ground biomass changes of old-growth tropical forests in the Amazon. Trends in productivity and mortality across all sites from 1985 to 2010. a) Net biomass change, b) biomass mortality, and c) forest productivity. It is possible to observe a decrease in net biomass change owing to an increase in biomass mortality. Adapted from Brienen et al. 2015.

2009; Ometto *et al.* 2005), the stability of this sink is susceptible to a warming climate and disturbance processes (Lenton *et al.* 2008). 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). Burned forests in the Amazon have 25% lower than expected carbon stocks 30 years after the fires, with no further recovery in growth and mortality dynamics (Silva *et al.* 2018, see also Chapter 19).

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 (see also Chapter 19). 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, the Brazilian Amazon forest has lost 741,759 km^2 of forests (MapBiomas 2020), representing 19% of the Brazilian Amazonian forested area. The annual rate of Amazonian deforestation was strongly reduced from 27,772 Km^2 to 4,571 Km^2 per year from 2004 to 2012, showing that it is possible and feasible to reduce tropical deforestation (Figure 23.3; see also Chapter 17). Unfortunately, from 2012 to 2020, deforestation has significantly increased, and the annual rate of deforestation in 2020 was 10,851 km^2 because of changes in Brazilian national policies for the Amazon region. The 2019 deforestation in the Brazilian Amazon released approximately 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.

There is an ongoing debate about the net carbon flux between Amazonian forests and the atmosphere when the entire Basin is considered (see SPA's Cross-Box on Carbon Budget). 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).

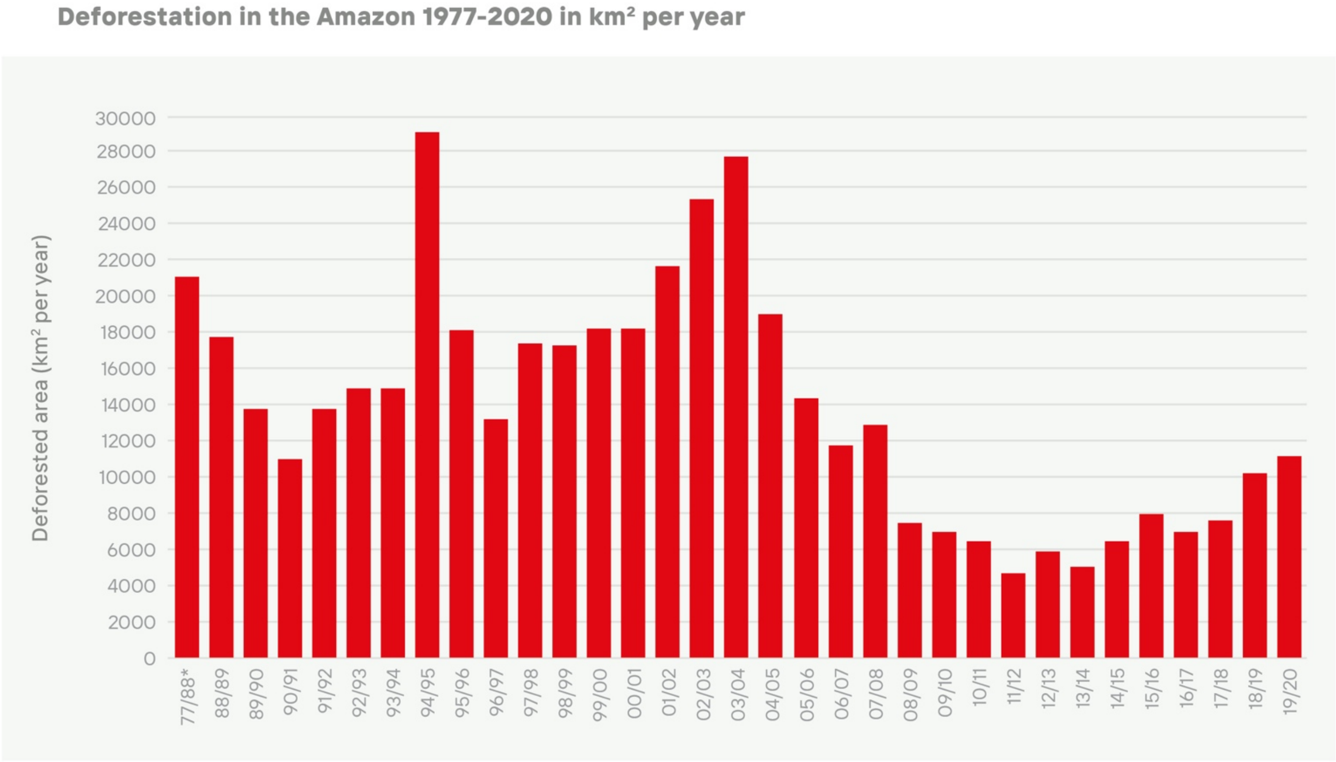

Figure 23.3 Time series of annual deforested area in the Brazilian Amazon, from 1977 to 2020. Data from the INPE PRODES program.

23.1.4 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 several ecosystems, and all aquatic organisms are adapted to them. The highest evolutionary impact on recent freshwater evolution is river capture owing 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. 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 a change in the landscape and causing habitat loss (Wittmann and Householder 2016). Loss of habitat is the primary driver of both the appearance and extinction of new species, the latter being the most substantial impact in freshwater systems. Ongoing impacts, though, do not give sufficient time for fish assemblages, species, or populations to recover or adapt to the new conditions, threatening the persistence of species in those ecosystems.

Recent human activities have caused several habitat losses and the extinction of many species in the current evolutionary time. These changes are happening so fast that it is currently known as the 6th mass extinction (Ceballos et al. 2017). On top of the current extinction rates, the impacts of mining, hydroelectric power plants, overfishing, and the release of industrial, urban, and medical pollutants result in synergic effects over the aquatic biota in the Amazon Basin landscape (see Chapter 20). Fish 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 and variable types of water that have different amounts of dissolved organic carbon (DOC). Most anthropic actions induce changes in these water quality 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 worse 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 forecast by IPCC for the year 2050 revealed many damages and some degree of mortality to fish subjected to warmer temperatures. The whole transcriptome gene expression 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 how the complex network of impacts caused by humans in the recent past will modify the aquatic biota at several ecological and biological levels.

23.1.5 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 Chapters 5 and 22). The warming of the tropical east Pacific during El Niño events suppresses wet season rainfall by modifying the (East–West) Walker Circulation. Large-scale teleconnections lead to simultaneous changes in the northern hemisphere extratropics, altering moisture flow into the Amazon, inducing drought events (Williams *et al.* 2005; Ronchail *et al.* 2002). Moreover, variations in Amazonian precipitation are also 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 northwestward shift in the Intertropical Convergence Zone (ITCZ) and compensating atmospheric dry air mass descent over the Amazon, sometimes producing intense droughts such as those in 1963 and 2005 (Marengo *et al.* 2008a,b). Gloor *et al.* (2013) showed that the Amazon river discharge at Óbidos is significantly increasing during dry and wet seasons. This could be caused by an increase in the input of water vapor from the tropical Atlantic owing to the substantial sea surface temperature increase since the 1980s. A time series of the Amazon river discharge at Óbidos is shown in Figure 23.4.

Observations and models suggest large-scale deforestation could cause a warmer and somewhat drier climate by altering the regional hydrologic cycle (see also Chapter 22). 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 significantly decrease across the eastern Amazon. Complete deforestation could cause the eastern Amazon to warm by more than 4°C, and precipitation from July to November could decrease by 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 20–25% of basin-wide deforestation may be a tipping point beyond which forest loss causes climate impacts that cause further forest loss (see Chapter 24; 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

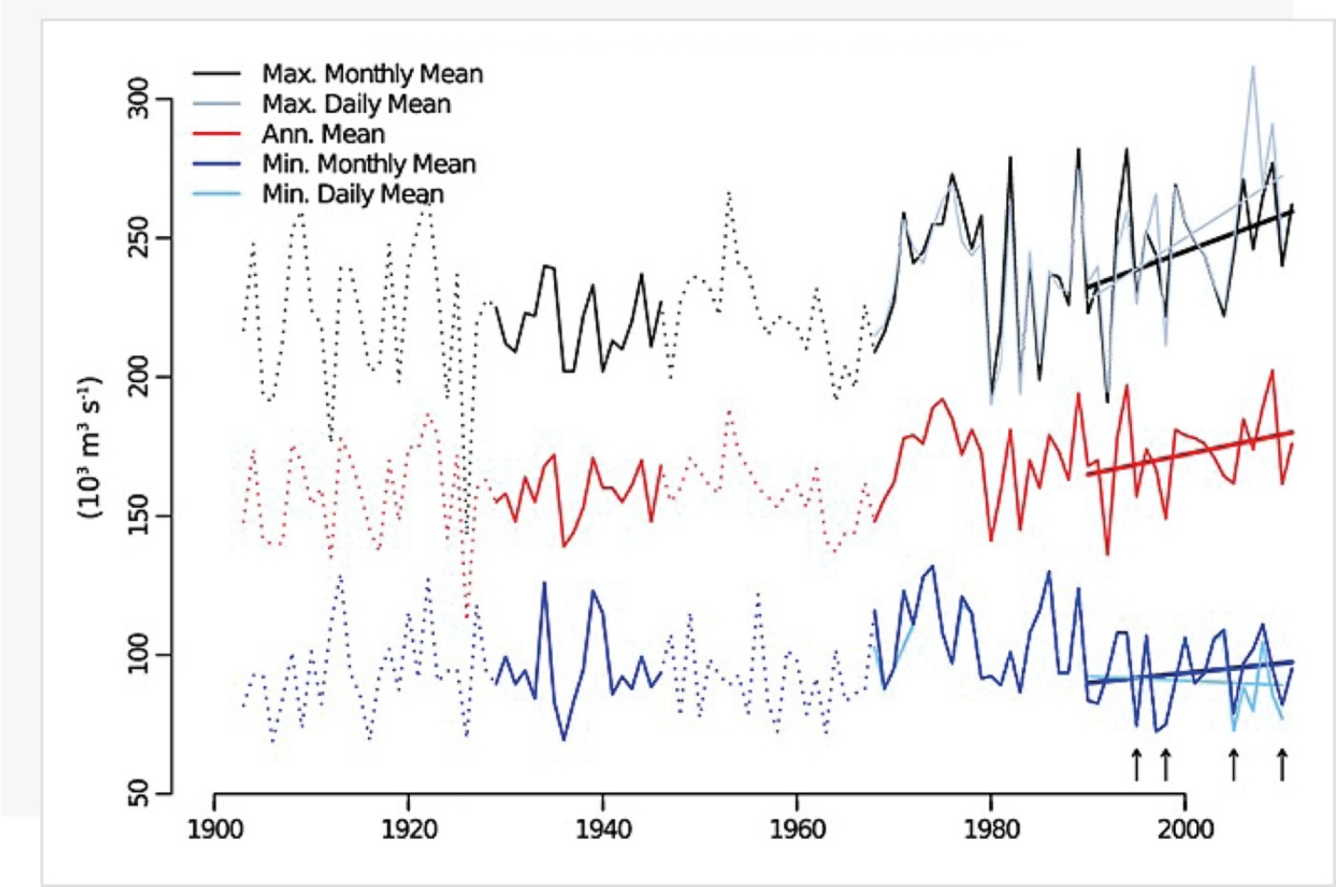

Figure 23.4. Long-term time series of the Amazon river discharge at Óbidos during the dry season (blue), wet season (green), and whole year (red). Source: Gloor et al. (2013).

rainfall trend existed in the entire Amazon region. However, a slight negative/positive trend was identified in the northern/southern Amazon. To understand the discrepancies between these studies, it is necessary to evaluate the timescales 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 from 2002 to 2011, after 2005, some parts of the Amazon Basin, such as the eastern Amazon region, a transition zone between rainforest and savanna environments, remain particularly vulnerable to feedbacks from ongoing land-use conversion to agriculture (Coe *et al.* 2013). The expansion and intensification of agriculture (see Chapter 15) 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 evapotranspiration (ET) (Coe *et al.* 2009, 2013; Costa *et al.* 2003; D'Almeida *et al.* 2007; 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 km^2), 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 reduce rainfall and decrease runoff (D'Almeida *et al.* 2007; Davidson *et al.* 2012; Stickler *et al.* 2013).

23.2 Impacts of climate change on ecosystem services

23.2.1 Pollination and seed dispersal

Nature in the Amazon has a wealth of ecosystems and biodiversity, which 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, which supports freshwater and forest biodiversity (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 their services 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). They estimated that between 4–19% of the species would find no suitable habitat considering the entire study area. Inside the currently established protected areas, species loss could be over 70%. 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 have also been associated with hundreds of plant species (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 83 species of bats to identify the species potentially more sensitive to climate changes and if they would be able to find suitable areas in the Carajás area 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 in the case of 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). Using two different algorithms and geographically explicit data, the analyses and projections of the distribution of 216 species occurring at the Carajás National Forest showed that 95% of bee species would face a decline in their total occurrence area. Only 4–15% 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, açai, guarana, cocoa, and others can be critical socio-economic activities associated with non-timber products in the Amazon (Peres and Lake 2003; Zuidema and Boot 2002; see also Chapter 30). The potential effects of future distribution mismatch of seed dispersal and pollination of 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).

23.2.2 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 importantly, fisheries (Castello and Macedo 2016), the primary source of animal protein and major economic driver in the Amazon region. The monetary value of Amazonian fisheries is estimated at more than USD 400 million annually, and just in the Brazilian Amazon, it involves more than 200,000 fishers (Barthem *et al.* 1997; Barthem and Goulding 2007; Duponchelle *et al.* 2021). 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 example, 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 owing 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; 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 will likely 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 (see Chapter 22).

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. However, this activity has some adverse effects on the natural water systems if not monitored by specialists. Household-based 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).

23.3 Climate feedbacks of vegetation and land-use changes

The Amazon ecosystem is directly affected by climate and land-use changes in many ways, but there is also 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 forests 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 have shown an increased vapor deficit throughout the Amazon, but it is still unknown 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 carbon sequestration. With an area of 7.3 million km^2, the carbon stored in the Amazon's forests (~150-200 billion tons of carbon stores in soils and vegetation) is equivalent to more than ten years of current global carbon fossil-fuel emissions. More than half 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 with 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 the absorption of a significant fraction of incoming solar radiation and the production of 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). Deforestation and degradation reduce evapotranspiration, increase the surface temperature (e.g., Silvério *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 more significant impact than pasture (Silvério *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). In addition to large-scale deforestation, the Amazon has experienced large amounts of forest degradation, calculated as 1,036,080 km² over the last 30 years (Mapbiomas 2020). By 2018, 870,000 km² of forests have been lost in the Pan Amazon (Mapbiomas 2020). However, there is strong evidence to suggest that it occurs at the same or more significant scale than deforestation (Walker *et al.* 2020).

23.3.1 Surface albedo and radiation balance

Deforestation to expand agriculture results in permanent changes to the surface radiation balance, impacting climate at local and regional scales. Crops and pastures that typically replace forests have shallow roots systems 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 radiation to the incident total solar in the short wavelength spectrum. It is the main factor affecting the land radiation balance and has frequently been considered in global and regional climate studies. 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 Amazon Region Micrometeorological Experiment (ARME) indicated an average albedo of 12.3±0.2% for a tropical forest near Manaus, Brazil (Shuttleworth 1984). Later, during Anglo Brazilian Amazonian Climate Observation Study (ABRACOS), 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).

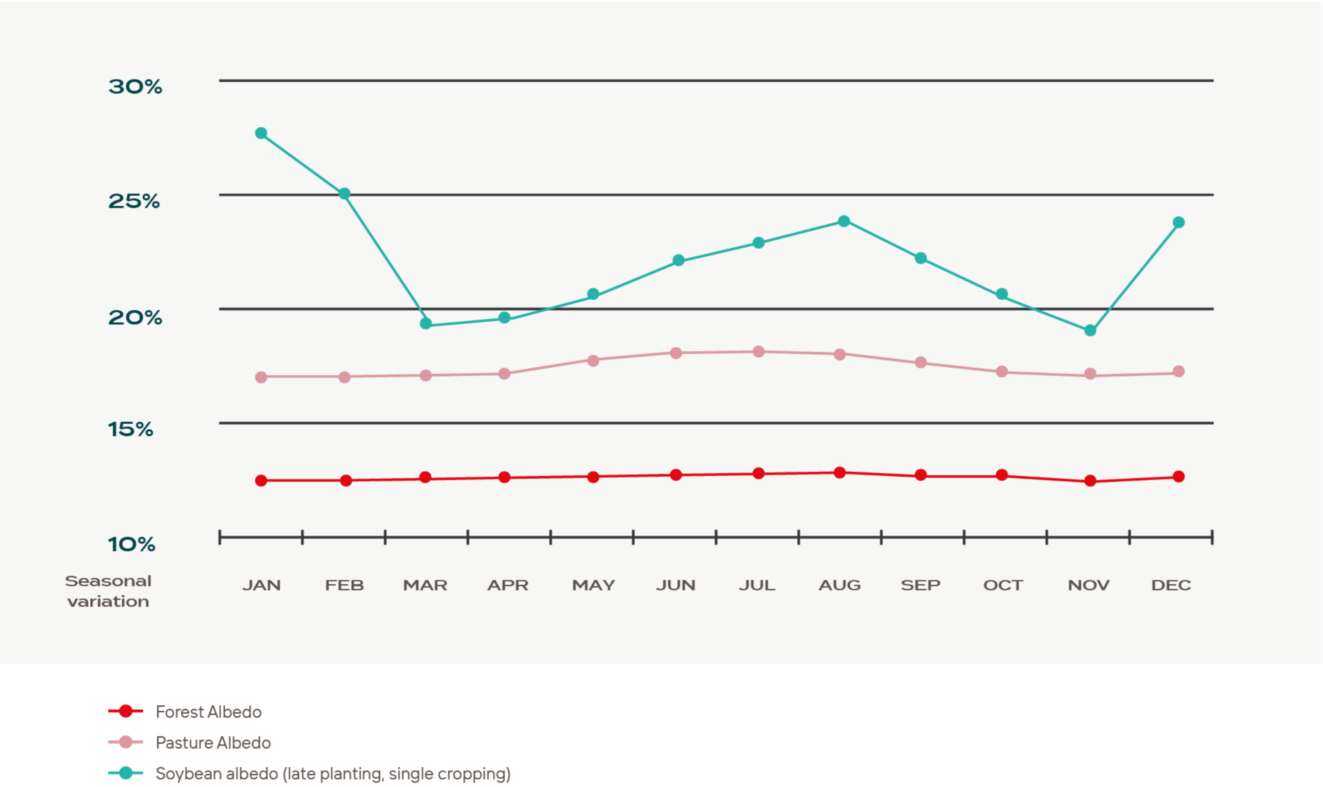

Figure 23.5. Seasonal variation of the forest, pasture, and soybean albedo. A single soybean growing season is represented. A strong increase in surface albedo can be observed when the forest is changed to pasture or soybean. Figure adapted from Costa et al. (2007).

Seasonal albedo for the rainforest, pastures, and soybean cropping systems typical of the Amazon are shown in Figure 23.5. Rainforest and pasture albedo are from Culf *et al.* (1996). Although the forest albedo is more stable 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 during 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 (approximately 13%) to pasture albedo (17%), whereas soybean shows much higher overall and seasonally variable albedo.

The seasonal variability of crop albedo depends on several factors, including the cropping system adopted (single cropping or double cropping), the crop itself (soybean, maize), and the planting date. Other factors are 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, the 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 aerosol particles) for forest areas was 147 W/m², and over deforested areas, this value was 160 W/m². The difference of 13 W/m² is the radiative forcing due to a 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 approximately 10% of the total column water vapor, a very significant change.

23.3.2 Changes in soil moisture and evapotranspiration

More than half 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. Therefore, changes in evapotranspiration and soil moisture associated with land use and land cover change, including deforestation and degradation, are crucial to understanding the possible trajectories of Amazon forests health in the coming years. Pasture and cropland that typically replace forests have smaller roots and 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 (>100 mm/month) for up to 10 months per year because of their access to the ample stored soil moisture in the top 10 m of the soil column.

These differences have a profound impact on the seasonal distribution of evapotranspiration and the annual total. This has been extensively studied at large and small spatial scales throughout the Amazon and Cerrado environments. Conversion of the native vegetation results in a decrease in the mean annual ET of approximately 30%, and during the dry season, this decrease is much larger (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). Therefore, the decrease in ET resulting 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 a crucial factor needed to initiate rainfall, with initiation being hastened by 2–3 months compared with simulations without forest ET. Evidence indicates that dry season humidity in the Amazon decreases, making the dry season more severe (Barkhordarian *et al.* 2019). Using detailed analysis of rain gauge data in the southern Amazon, Leite-Filho *et al.* (2019) estimate that for every 10% increase in deforestation, the onset of the rainy season is delayed by approximately 4 days (see also Chapter 22), which has amounted to an 11–18-day average delay in the rainy season onset in Rondônia, Brazil (Butt *et al.* 2011).

GHG emissions and deforestation have opposite effects on evapotranspiration. Increased emissions (and associated increased atmospheric temperatures) tend to increase ET, whereas 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 this 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 owing 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 owing 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) owing to deforestation is of the same order as the results of Stickler *et al.* (2013), who found a 10–12% runoff increase given 40% deforestation in this catchment. From 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. Therefore, deforestation contributes to the increase in runoff (+27 % in the Tapajós).

In summary, the initial significant decrease in ET initiated by deforestation has already impacted much of the Amazon, particularly the south of the basin, and has large-scale feedback to precipitation. 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.

23.4 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; Pöschl *et al.* 2010). In the dry season, biomass burning emissions have strong impacts on the Amazonian ecosystems 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 significantly alter the atmospheric composition 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 forest emissions, such as biogenic volatile organic compounds (VOCs), are changing, possibly associated with higher temperatures (Yáñez-Serrano *et al.* 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 increase 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, which expresses the total amount of particles in the whole aerosol column. AOD can be measured using a moderate-resolution imaging spectroradiometer (MODIS) sensor or sun photometers from the NASA AERONET network.

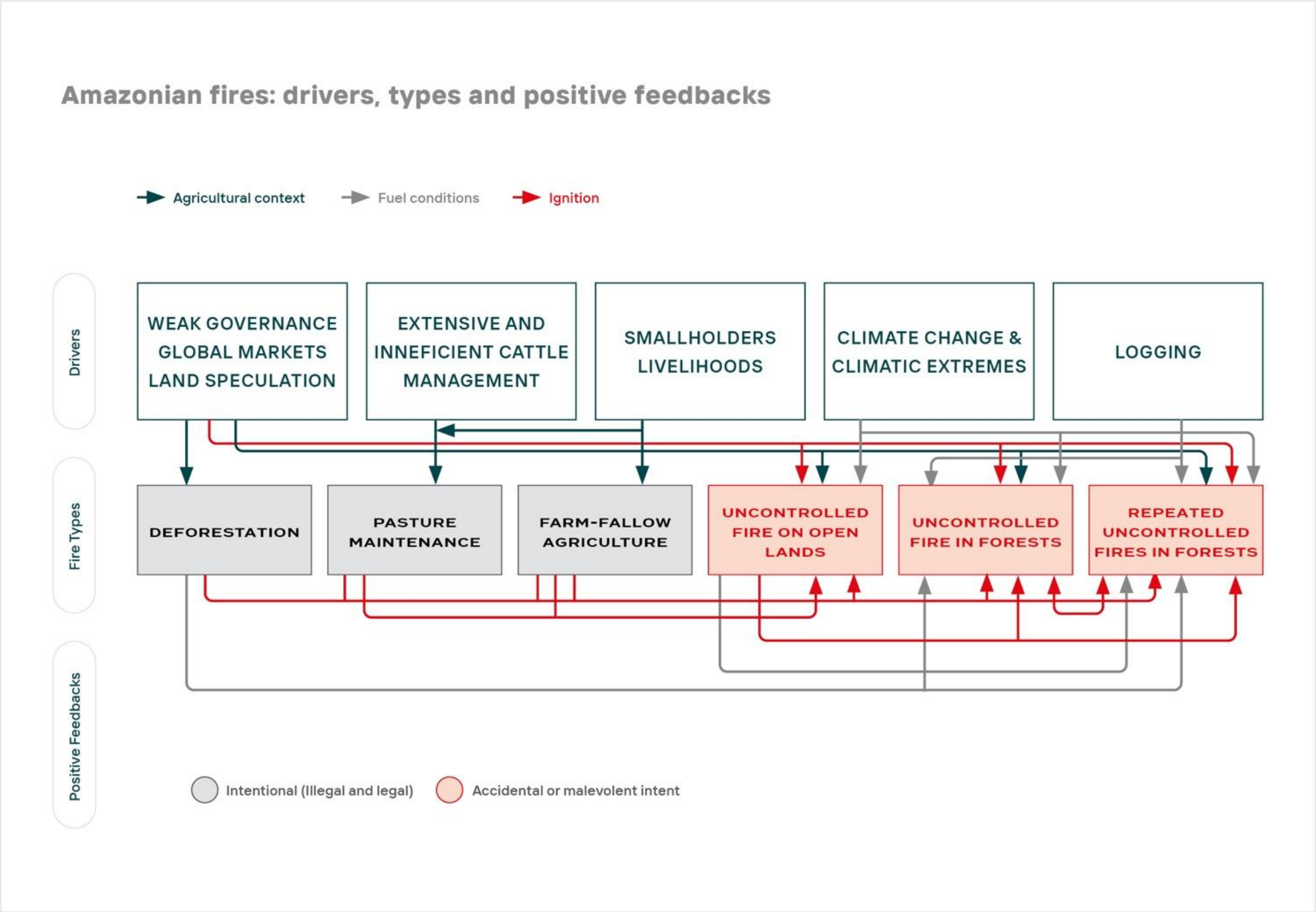

Figure 23.6. Schematic diagram of the complex relationship between the main fire drivers in the Amazon. Figure adapted from Barlow et al. 2020.

The drivers of Amazonian fires are complex and very diverse (see Chapter 19). A schematic view of the complex relationship between the main fire drivers is shown in Figure 23.6. The impacts are also various, and fire emissions influence the 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 (Global Carbon Project 2020).

23.4.1 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 as central and southern Brazil, north of Argentina, Pantanal, and other regions. As most biomass-burning aerosols scatter sunlight, the impact on the temperature is to cool down the surface. Black carbon (an absorbing aerosol component) emissions from Amazonian biomass burning changes the snow and ice albedo in the tropical glaciers, impacting the melting of Andean glaciers (Aliaga *et al.* 2021; Bianchi *et al.* 2021). 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 W/m^2 (Sena and Artaxo 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).

A long time series (2000–2021) of aerosol optical depth over five sites in the Brazilian Amazon is shown in Figure 23.7. 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 world during the dry season, with significant year-to-year variability. This high year-to-year variability is partially driven by climate and also by policies affecting deforestation and biomass burning (Morgan *et al.* 2019).

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 of the change in NEE from the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (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 three times the biomass burning emissions of 2012 show significant increases of 20 to 40% in surface diffuse radiation, GPP, and NPP, especially in August at the peak of the biomass burning season (Rap *et al.* 2015).

23.4.2 Impacts of ozone from biomass burning precursors on the ecosystem

The Amazon in the wet season shows very low background ozone (O_3) concentrations (<20 ppbv), 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

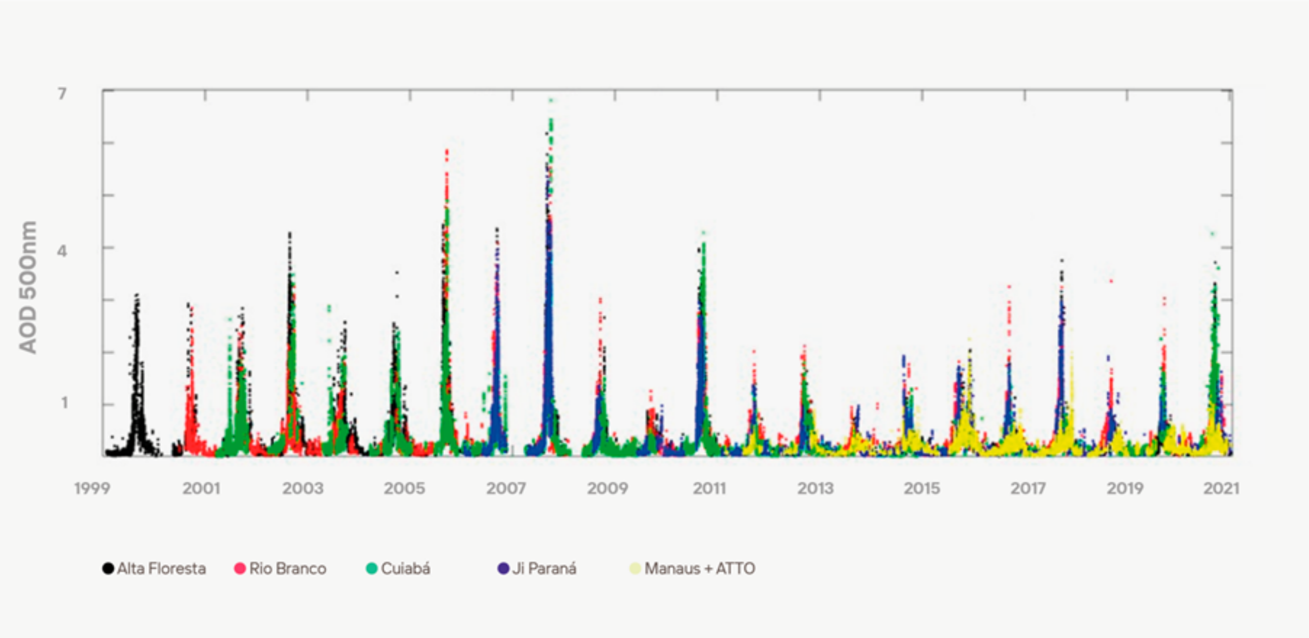

Figure 23.7. Long time series (2000–2021) of aerosol optical depth (AOD) over 5 sites in the Brazilian Amazon. Significant year-to-year variability is driven by climate and public policies toward reducing deforestation and biomass burning emissions.

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 approximately 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 increase in 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 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.

23.4.3 Impacts of biomass burning emissions on clouds and precipitation

Clouds are formed from three 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 Amazon Basin, equivalent to 14×10^6 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; Pöschl *et al.* 2010). Biomass burning with 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 number of droplets with a reduced size. These smaller initial droplets reduce the efficiency of droplets to grow to precipitable size, increasing cloud lifetime and reducing precipitation. The effect of deep convective clouds is difficult to predict because of insufficient knowledge available on mixed-phase and ice cloud microphysics (Artaxo *et al.* 2021; Machado *et al.* 2018). The primary biogenic aerosol particles are quite efficient ice nuclei (IN) particles necessary to produce deep ice clouds (Prenni *et al.* 2009; 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 proportion of the atmospheric moisture over the Amazon, becoming 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, the amount of water available for rainfall in the western Amazon Basin, and adversely impact rainforest resilience (Zemp *et al.* 2017). This effect 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 other parameters make predicting the effects of aerosols on precipitation very difficult (Artaxo *et al.* 2020). One of the few observational studies of the impacts of biomass burning on rainfall was by Camponogara *et al.* (2014). Combining Reanalysis, data from the Tropical Rainfall Measuring Mission (TRMM), and AERONET data from 1999 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 the Amazon makes assessing changes in precipitation quite tricky and inaccurate. The same is true for an extended aerosol and trace gases observation network.

23.5 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 impacting the Amazonian ecosystems. And the reverse is also true, especially in terms of carbon emissions owing 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 top 10 tropical deforestation countries. Reducing tropical deforestation is the fastest 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 an 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 expect habitat loss, changes in fish migration, disturbances in fish assemblages, and changes in spatial fish species distribution. These are the main impacts climate change will cause for aquatic systems biota. However, other effects may be an important driver for biodiversity loss but occur either in continental or marine water systems. 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 tropical deforestation, it is also essential to reduce fossil fuel use to reduce the rate of climate change.

23.6 Recommendations

- A comprehensive network of Amazonian environmental observatories and a system for sharing comparable data is needed to detect changes in ongoing terrestrial, freshwater, and estuarine ecosystems.
- More integrated studies on biodiversity loss and climate change, such as species resilience, are needed.
- The possible effect of climate change and protected areas location needs to be considered for conservation strategies, taking into account pollination and seed dispersal services.
- 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, aerial rivers, and all water balance components in the Amazon.

- Studies on the ecosystem and species resilience to increased temperatures and reduced water supply are needed.
- In addition to reducing deforestation, it is also essential to reduce fossil fuel burning, which is the leading cause of climate change.
- Paleoclimate studies are needed to investigate past climate variations to help understand natural climate variability and better understand the historical role of humans shaping the landscape over several timescales.

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