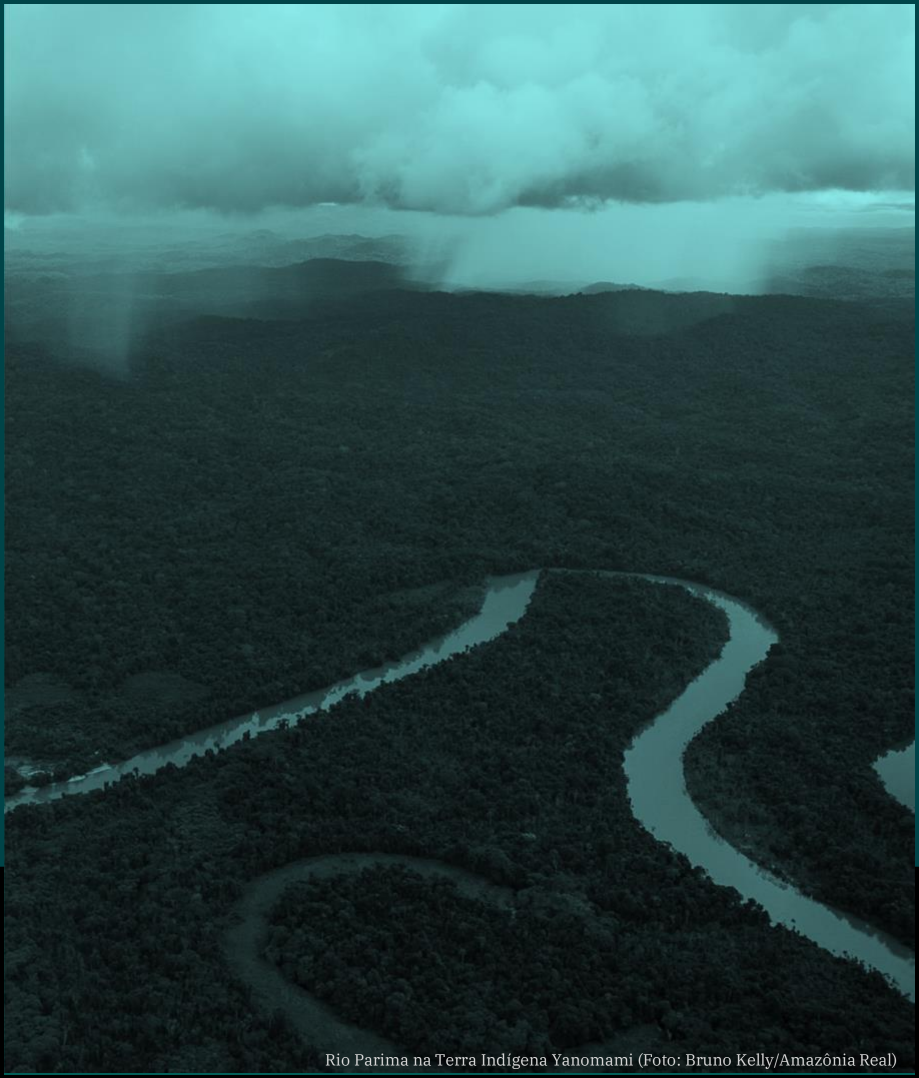
Chapter 7 In Brief

Biogeophysical Cycles: Water Recycling, Climate Regulation



Rio Parima na Terra Indígena Yanomami (Foto: Bruno Kelly/Amazônia Real)

THE AMAZON WE WANT
Science Panel for the Amazon

Biogeophysical Cycles: Water Recycling, Climate Regulation

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Key Messages & Recommendations

1) The Amazon rainforest can cycle large amounts of water vapor from the soil to the atmosphere via evapotranspiration (ET). The Amazon basin's average recycling ratio varies from 24% to 35%, with a median value of 28%.
2) The central and northwestern Amazon export moisture to the Andes via atmospheric rivers that supply water for tropical glaciers, *páramos*, and cities. The southwestern part of the Amazon basin is an important year-round source of moisture for the La Plata basin, with moisture transported via the South American low-level jet.
3) The amount and timing of precipitation is regulated by the amount of forest cover, with forest loss or increase leading to reduction or increase in rainfall, respectively. If the rainforest is replaced with another land use, the Amazon would experience a hotter climate and the rate of ET would change, particularly during the dry season, affecting rainfall volumes and decreasing the duration of the rainy season, with implications for forest degradation, forest flammability, and regional crop yields.
4) The most important changes in the hydro-climate system occur in the transition between the dry and rainy seasons, with a lengthening of the dry season, which has important ecological and hydrological consequences. Future studies should focus on these particular seasons.
5) Very few (if any) of the new advancements in forest edge degradation have been included in Earth System Models (ESMs). Projecting the future of Amazonian forests requires a better representation of forest edge effects in ESMs.

Abstract This chapter assesses biogeophysical interactions between the Amazon rainforest and its hydrology and climate. A historical perspective is presented, highlighting breakthroughs which improved our understanding of the mechanisms by which the rainforest interacts with the atmosphere.

Introduction The rainforest interacts with the atmosphere in several ways, affecting the local, continental, and global climate. A major process is the recycling of water. Following the water cycle process, the winds near the ocean surface bring moisture from the tropical Atlantic Ocean into the Amazon (Figure 7.1). Part of this moisture falls as rain, and a portion of the fallen rain may quickly be returned to the atmosphere through ET. Some of this water vapor will come back as rainfall over the rainforest, and some will travel on to neighboring regions. This injection of water vapor does not present significant seasonal or interannual variability, which may be explained by several traits and processes associated with the rainforest.

The role of forests in water recycling Water recycling is the process by which ET in one location on the continent contributes to precipitation in another place on the continent[1]. The recycling ratio (ρ) is the ratio of precipitation of continental origin divided by the total precipitation. It depends on several conditions, including scale, the ratio of local ET to other water vapor sources, and the extension of the region downwind. A large region, such as the Amazon, tends to have a high recycling ratio, but regional recycling is more complex[2]. The Amazon

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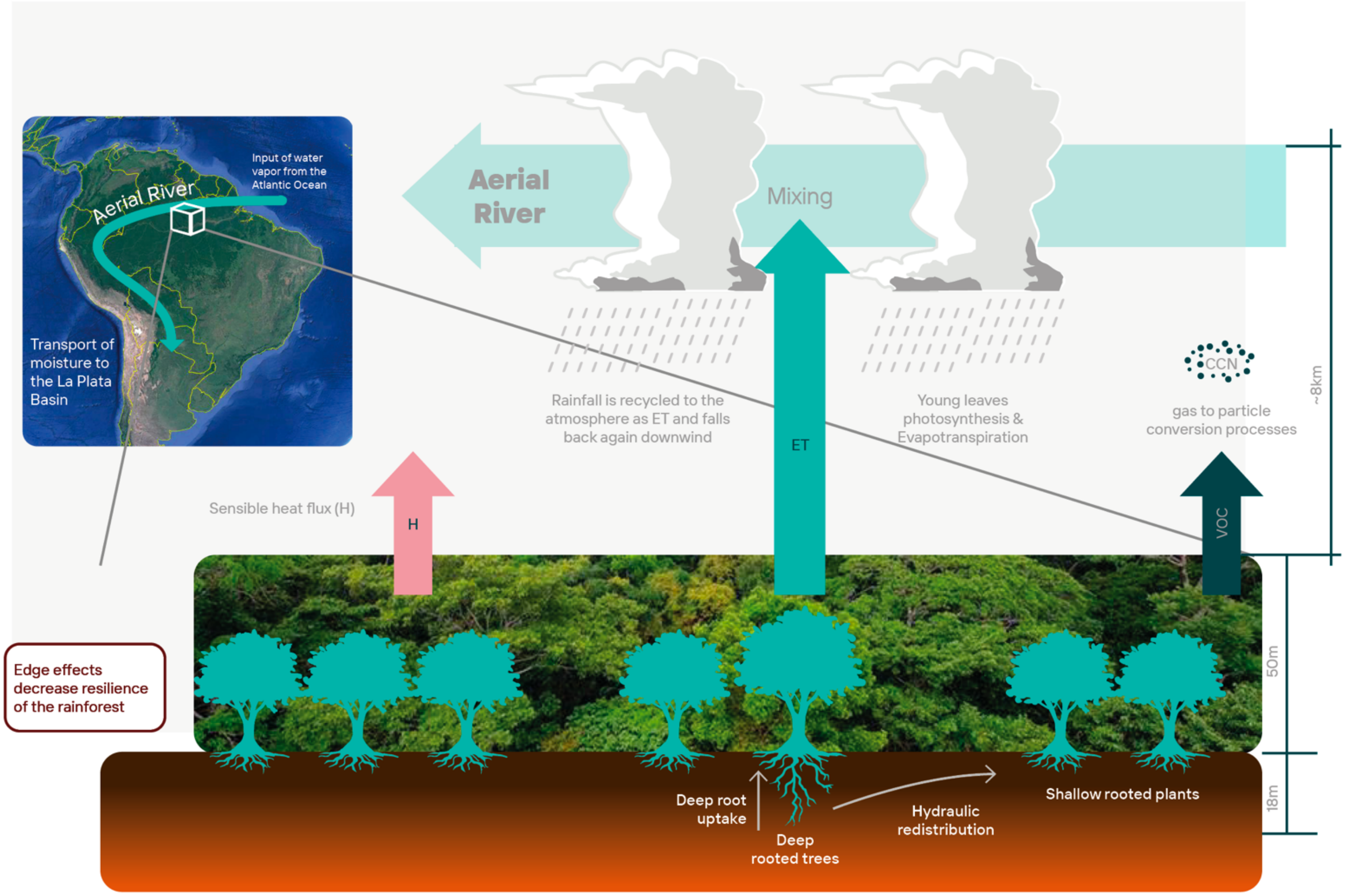

Figure 7.1 Diagram of the main biogeophysical processes of biosphere-atmosphere interactions in the Amazon, at different scales. Deep root systems, hydraulic redistribution, and young leaf photosynthesis maintain high ET rates that release water vapor into the atmosphere; it is then recycled as rainfall. Forests emit volatile organic compounds (VOCs) that become cloud condensation nuclei (CCN) that favor the formation of rain droplets. The Amazon is also an important source of moisture for several regions over South America, especially the La Plata River basin and adjacent areas.

basin's average recycling ratio varies from 24% to 35%, with a median value of 28%, or about half of what was estimated in the 1970s and 80s. van der Ent *et al*. (2010)[3] and Zemp *et al*. (2014)[1] show that ρ is close to zero near the mouth of the Amazon, where moisture from the ocean enters the Amazon, to >50% close to the Andes (Figure 7.2). The mechanical uplift from the mountains and the Andes' concave shape induces low-level convergence several hundred kilometers before the Andes, facilitating high rates of precipitation and hindering moisture from crossing the Andes and leaving the basin.

Recycling is also higher during the dry season than during the wet season. During the dry season, the input of moisture from the ocean decreases, and the steady flux of water from the rainforest increases the importance of this local source. In most of the Amazon, ET is not controlled by the availability of soil moisture but rather by the availability of energy to evaporate water, hence the low seasonal variability. This is because Amazonian trees have access to water stored deep in the ground and consequently do not suffer much water stress. The more complex seasonal ET dynamics of moisture-limited upland forests in the southern Amazon indicates joint regulation by environmental (e.g., net radiation, vapor pressure deficit) and biological (forest canopy conductance) factors in these forests[4–6].

The stability of local ET is also associated with variability of ρ at interannual and decadal time scales. Costa and Foley (1999)[7] found a weakening of the trade winds that transport water vapor from the tropical Atlantic into the Amazon basin during 1976-1996, which caused a decrease in the input of water vapor in the Amazon basin. In this case, where the main source of water vapor to the basin has decreased by about 720 mm yr^{-1} in 20 years (from 3430 mm yr^{-1} in 1976-77 to 2710 mm yr^{-1} in 1995-96, or 36 mm yr^{-1}), the Amazon basin maintained constant precipitation and runoff by increasing the relative contribution of local source water vapor (regional ET) from 28% in 1976-77 to 33% in 1995-96.

Capture of deep soil moisture by trees Several studies have proposed different mechanisms to explain the drought (seasonal or extreme) tolerance of the Amazon rainforest. These mechanisms include deep-root water uptake, plant hydraulic lift, and leaf regeneration in the dry season. Very deep (> 6 m) fine roots, although rare, have been found in a few sites in the eastern[8] and central Amazon[9,10]. In the eastern Amazon, where precipitation is more seasonal, Nepstad *et al.* (1994)[8] found roots reaching 18 m. The existence of these roots, in association with low plant-available water in the upper (< 1 m) soil layers, gives rise to the understanding of the role of deep roots as the primary strategy of plants to deal with seasonal and, potentially, severe droughts[8,11–13]. However, despite the documented occurrence of deep roots, it is well recognized that, in the Amazon, shallow roots (< 1 m) are much more abundant[8,9]. Although deep roots have low density, research done by Hodnett *et al.* (1995)[12] near Manaus has

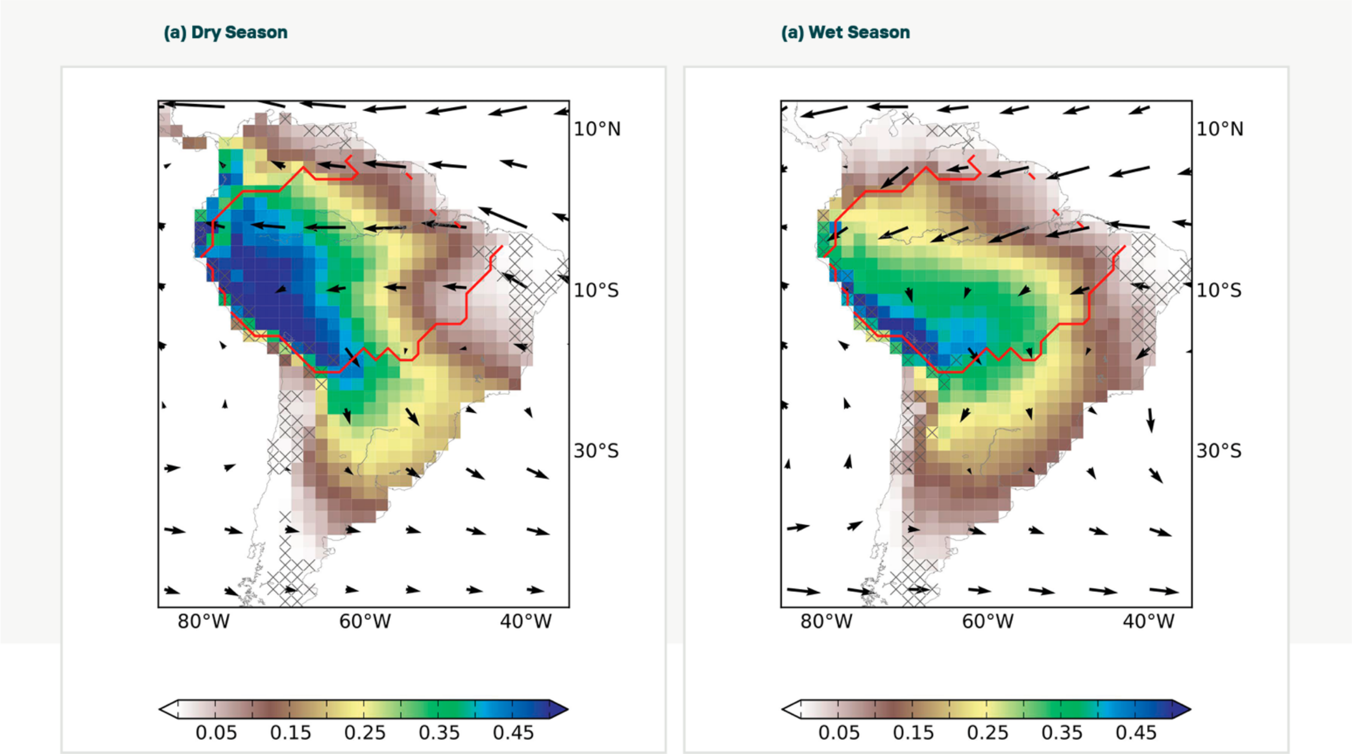

Figure 7.2 Fraction of precipitation originating inside the Amazon basin (contour in red), using MOD16 evapotranspiration data and TRMM precipitation data for the period 2001-2010, and direct moisture recycling calculations. (a) Dry season (Jun-Sep), (b) Wet season (Dec-Mar). Redrawn from Figure 8 of Zemp *et al.* (2014)[1].

demonstrated that, in many years, it is impossible to close the dry season water balance of the Amazonian rain forest without using water stored at depths greater than 2 m. The 250-550 cm layer contributed ~20% of water demand, while the deepest layers (550–1150 cm) contributed ~10%.

Other studies have suggested the existence of mechanisms to transport water upward from deep to shallow soil layers, either through the root system, i.e., plant hydraulic lift[14,15], or through the capillary rise mechanism in fine-textured soils[16,17]. Some have suggested a third mechanism, root niche partitioning[18,19], by which plants uptake soil water from different sources, as a function of their height, root depth, and plant hydraulic attributes such as resistance to xylem vessels embolism[20].

Mechanisms like deep root development, plant hydraulic uplift, and leaf regeneration in the dry season suggest that Amazonian forests can be resilient to extreme droughts, and that this evolution trace might have been selected in paleoclimates with strong interannual variability. With these mechanisms, the rainforest may have access to around 800-3000 mm of water stored in soil[8,21]. These mechanisms may not be available to every tropical forest; further, we do not know if the ability to grow deep roots is limited to a few species or shared by many.

Roots’ access to soil water is linked to the regulation of water loss through leaves. The stomata in leaves regulate ET and facilitate dry-season forest ET[22]. Christoffersen *et al.* (2014)[23] highlight the important and complementary roles of roots and leaves in regulating ET.

The role of Amazonian tropical forests in producing their own hydroclimate Rainforests and warm, humid climates are strongly connected, forming a two-way reinforcing system. In other words, the humid tropical climate allows the rainforest's existence, which, by its turn, helps to produce the rainy climate it needs. On an annual average basis in the Amazon, around 72% of the water vapor that enters the atmosphere is of oceanic origin, and 28% is evaporated locally. In addition to its role as a water vapor source, the evergreen tropical forest has yet another role in the local climate. Theoretical[24,25] and modeling studies[26] demonstrate that the rainforest's low albedo favors convection over the basin, while an increase in the surface albedo causes a subsidence anomaly over the region. In addition, forests also emit volatile organic compounds (VOCs) that become cloud condensation nuclei (CCN) that favor the formation of rain droplets (see Chapter 6). Because water vapor and convection are the key contributors to precipitation, large-scale rainforests likely have some ability to maintain their own climate.

The role of forest in the onset of the rainy season High ET during the dry season stimulates an earlier return of the wet season than would otherwise be expected[27]. Specifically, rainforest transpiration increases shallow convection that moistens and destabilizes the atmosphere during the initial stages of the dry-to-wet season transition, conditioning the regional atmosphere for a rapid increase in rain-bearing deep convection. In turn, this process drives moisture convergence and wet season onset 2–3 months before the arrival of the main monsoon-like convergence over the Amazon. Recent evidence using both rain gauge and remotely sensed precipitation data (TRMM-NASA/JAXA) empirically demonstrates the role of rainforests in several critical features of the southern Amazon rainy season. Leite Filho *et al.* (2020)[28] have shown that forests' presence is associated with an earlier onset and later end of the rainy season, i.e., a longer rainy season. Moreover, Leite-Filho *et al.* (2019)[44] have shown that higher forest cover is associated with a lower frequency of dry spells in September, October, April, and May, the transition months between the dry and rainy seasons. In other words, in well-preserved forests, the rainy season begins earlier and is less likely to be interrupted by a long dry spell in its initial days. On the other hand, in heavily deforested areas, the rainy season starts late and is more likely to be interrupted by a long dry spell.

Observational studies of Spracklen *et al.* (2012)[45] confirm the dependence of rainfall on vegetation.

They used satellite remote-sensing data of tropical precipitation and leaf area index (LAI), combined with simulated atmospheric transport patterns, and concluded that air that has passed over extensive vegetation in the preceding 10 days produces at least twice as much rain as air that has passed over little vegetation. This empirical correlation is consistent with ET maintaining atmospheric moisture in air that passes over extensive vegetation.

These mechanisms imply active, positive feedback. The amount of forest cover regulates the amount and timing of precipitation received by those forests, with forest loss or increase leading to respective reductions or increases in rainfall and subsequent impacts on forest cover

The role of the forest as a source of water vapor to other regions The Amazon region is an important source of moisture for several regions of South America, such as the Andes, providing moisture and rainfall to glaciers, *páramos*, and major cities[31], and also to the La Plata River basin[1,32–35]. Over this basin, and possibly over the Pantanal and Andean regions, the Amazon is the second-highest continental contributor of annual mean precipitation[36], with local water recycling over the La Plata basin being the main source. Over the La Plata basin region, several authors agree that continental areas are the main source of water vapor[37]. Water vapor transport happens in relatively narrow spaces of the atmosphere nicknamed “aerial rivers”. Moreover, external sources from the southern Pacific and the tropical Atlantic also contribute to precipitation in the basin[37]. Drumond *et al*. (2008)[37] highlighted the influence of the tropical Atlantic Ocean, which varies seasonally from the northern regions in the austral summer months[36].

The southwestern part of the Amazon basin is an important direct source of incoming moisture over the La Plata basin, the Andean Amazon, and the Pantanal regions year-round. Water from the Amazon is exported out of the basin, transported via the South American low-level jet (SALLJ) along the Andes[3,32–34,37]. This warm-season regional circulation represents a nucleus of strong low-level winds in the middle of moisture transport by the trade winds coming from the tropical Atlantic. This system transports and distributes moisture from the entire Amazon basin into the La Plata basin and the Andean Amazon region, producing rainfall, as well as over the Pantanal and the agricultural lands of west-central Brazil. Previous studies examined the role of this low-level jet in moisture transport and occasional extreme precipitation events[35,38,39]. This system also transports smoke and aerosols from biomass burning in the Amazon to adjacent regions, exacerbating atmospheric pollution over cities in those areas[40].

Climate regulation provided by the forests Why are Amazonian forests much cooler than the land uses that often replace them? Recent studies on land surface temperature regulation indicate that Amazonian forests act like a giant air-conditioner[41,42]. This relates primarily to forests’ ability to cycle large amounts of water vapor from the soil to the atmosphere via evapotranspiration[43]. Compared with most crops cultivated in the region, Amazon forests have rougher canopies, denser canopy cover throughout most of the year, deeper roots, and an overall higher capacity to absorb solar energy and return it back to the atmosphere overwhelmingly as latent heat[58] (Figure 7.1). Combined with the high net surface radiation and precipitation inherent to the region, these characteristics give forests a disproportional capacity to cool their leaves. For instance, the daytime land surface temperature in forested areas of the southeast Amazon tends to be 5°C lower than deforested areas during the dry season, a result of ET decreasing, on average, by a third as forests are replaced by pasture and cropland[41].

The relatively cool surface of Amazonian forests relates to complex interactions between biological, physical, and chemical processes[45]. Most Amazonian tree species prevent leaf temperatures from increasing above critical levels, to avoid over-heating and reductions in growth and carbon storage, which influence plant survival[46]. Some studies suggest that the optimal temperature for leaf photosynthesis is less than 30°C, with leaf photosynthesis dropping abruptly when temperatures rise above 35ºC[47], though there is debate about whether the mechanism is driven by temperature or vapor pressure deficit, which is also temperature-dependent[48]. A recent long-term study found that South America's rainforest carbon stocks and carbon gains decreased significantly ($P < 0.001$) with the mean daily maximum temperature in the warmest month[49]. This process helps to explain why the average surface temperature of Amazonian forests is usually below 30ºC[44]. While ET controls the much of the capacity to regulate surface temperatures, leaf angle, pubescence, size, shape, canopy position, number of leaves per stem, and canopy structure all play a role[45].

ET and land surface temperatures appear to be relatively constant across the Amazon basin. Yet, there are important fine-scale spatial and temporal variability in canopy properties, ET, and land surface temperature. The main environmental process controlling this spatial variability is solar radiation[50]. Although potential incoming short-wave radiation is high across the entire region, some portions of the Amazon (e.g., near the Andes) receive less radiation due to cloudier conditions than others (e.g., the southeastern Amazon). The second factor relates to soil water availability. Where there is an intense dry season (or in extremely dry years like the 2015-2016 El Niño), low soil water availability towards the late dry season can constrain ET and cause related increases in land surface temperature[51]. In the Cerrado, dry-season ET may be less than half that of wet-season ET[52], with surface temperatures increasing proportionally to decreases in ET during the late dry season. Similarly, when soil moisture drops below critical levels during drought years, plant water stress can trigger reductions in stomatal conductance and ET, resulting in increased land surface temperatures[53]. Thus, while the climate over much of the Amazon is adequate for plants maintaining a high ET and associated cooler temperatures, broad patterns across the region exist.

Air temperature and land surface temperature, although with the same tendency, often diverge, with variations resulting from differences in the specific heat values of air, soil, and water, and from complex interactions between atmospheric properties, soil moisture, net radiation, and elevation. In general, air and land surface temperatures converge to similar values during the night but diverge during the hotter parts of the day, when land surface temperatures usually surpass air temperature by several degrees[45]. As large tracts of Amazon forests are clear cut, we expect major increases in surface temperatures[41], given that deforestation results in decreased evapotranspiration. This warming can be larger than the cooling effects that deforestation causes by increasing albedo.

Edge effects on temperature and moisture More than 70% of the world's remaining forest is less than 1 km from an edge (border adjacent to a field), and 20% is less than 100 m from an edge[54]. In human-dominated tropical landscapes, forest edges and their effects are pervasive[55,56]. In the southeastern Amazon, nearly 14% of forests now grow less than 100 m from a deforested area[57].

Forest edges adjacent to cleared fields are subject to prolonged forest degradation. These edges and forest patches are exposed to hotter, dryer, and windier conditions[58,59]. These edge effects degrade forests over time and have important implications for forest structure, especially because they tend to disproportionately increase mortality of canopy-dominant trees over the short-term[60]. The resulting changes in microclimate then facilitate the establishment of light-wooded (low wood density), small-sized, fast-growing pioneer species[61], causing regional reductions in forest carbon stocks over the long-term[62,63].

Tropical forests are highly resilient to occasional disturbances, but the combined effects of continued deforestation and a changing climate places large areas of the Amazon forest at risk of greater degradation in the coming decades[64], particularly along forest edges neighboring deforested fields and in isolated forest patches[65,66].

Quantifying the drivers of forest degradation in the Amazon is key to developing, validating, and parameterizing earth system models (ESM) that mechanistically simulate changes in carbon pools and fluxes between the biosphere and atmosphere[67]. Advances in mapping forest degradation and its drivers have permitted substantial improvements in ESM's ability to project potential pathways of Amazon forests. However, very few (if any) of these new advancements have addressed the issue of forest edge degradation. Hence, projecting the future of Amazonian forests requires a better representation of forest edge effects in ESMs.

Conclusions Internal biogeophysical processes strongly control the hydrological and climatic system of the Amazon basin. This is possible because the rainforest has developed several mechanisms to access water stored in deep soil layers and provide the energy necessary to trigger and maintain convection. These combined mechanisms lead to a rainier climate on average and a longer rainy season. Simultaneously, they maintain the temperature of surface air so that it is warm enough for convection but does not exceed plants' limits. Such mechanisms, along with the microclimate temperature and humidity control at the edges of the forest, are fundamental features of the coupled biosphere-atmosphere system in the Amazon, helping define the Amazon's climate and the climate of other parts of South America. Moreover, these mechanisms ensure this coupled system's ability to endure the dry season along its southern border and provide a steady source of water vapor to the atmosphere when the input of water vapor from the Atlantic weakens.

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