Chapter 24 In Brief

Resilience of the Amazon forest to global changes: Assessing the risk of tipping points

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Resilience of the Amazon forest to global changes: Assessing the risk of tipping points

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Key Messages & Recommendations

1) There are different hypotheses regarding Amazon tipping points related to regional rainfall, global temperature, and deforestation.
2) Different ecosystem configurations have been proposed to replace the forests impacted by deforestation and degradation resulting from compounding disturbances. In the future, broad areas may be covered by degraded, closed-canopy secondary forest.
3) Heterogeneity in forest responses and connectivity across the Amazon may increase the resilience of the system as a whole. However, if disturbances become widespread there is a higher risk of reaching a systemic tipping point.
4) There is a lack of observational and experimental evidence to improve climate-vegetation models' capacity to project the likelihood of crossing an Amazonian tipping point.
5) Investment and planning are needed for an effective transnational monitoring system to improve our knowledge on the dynamics of different Amazon ecosystems and their responses to environmental change.
6) Managing Amazonian resilience locally can reduce the risk of reaching a systemic tipping point. This requires protecting and restoring forest cover, biodiversity, agrobiodiversity, and cultural diversity, as well as improving fire management and fire early-warning systems. Managing Amazonian resilience also requires global action to halt greenhouse gas (GHG) emissions.

Abstract This chapter reviews and discusses existing evidence of ongoing changes in the Amazon forest system that may lead to resilience loss and the potential to cross tipping points in which the ecosystem may shift either gradually or abruptly to a persistent, environmentally degraded configuration.

Introduction The Amazon is a complex, dynamic, and extremely heterogeneous and biodiverse system, resulting from the interplay between natural and anthropogenic processes operating at different spatial and temporal scales (Chapters 1-13). Vegetation changes in the Amazon have accelerated in the past century, mostly due to anthropogenic activities that have led to unprecedented levels of disturbance to the region (See Chapters 14-23).

There exists broad concern over a potential ecological tipping point for the stability of the Amazon's forest ecosystems, which if passed would result in large scale forest dieback or collapse. However, despite increasing evidence of tree mortality caused by extreme rainfall events, fires, deforestation, and their combined effects[1–9] (see also Chapters 22 and

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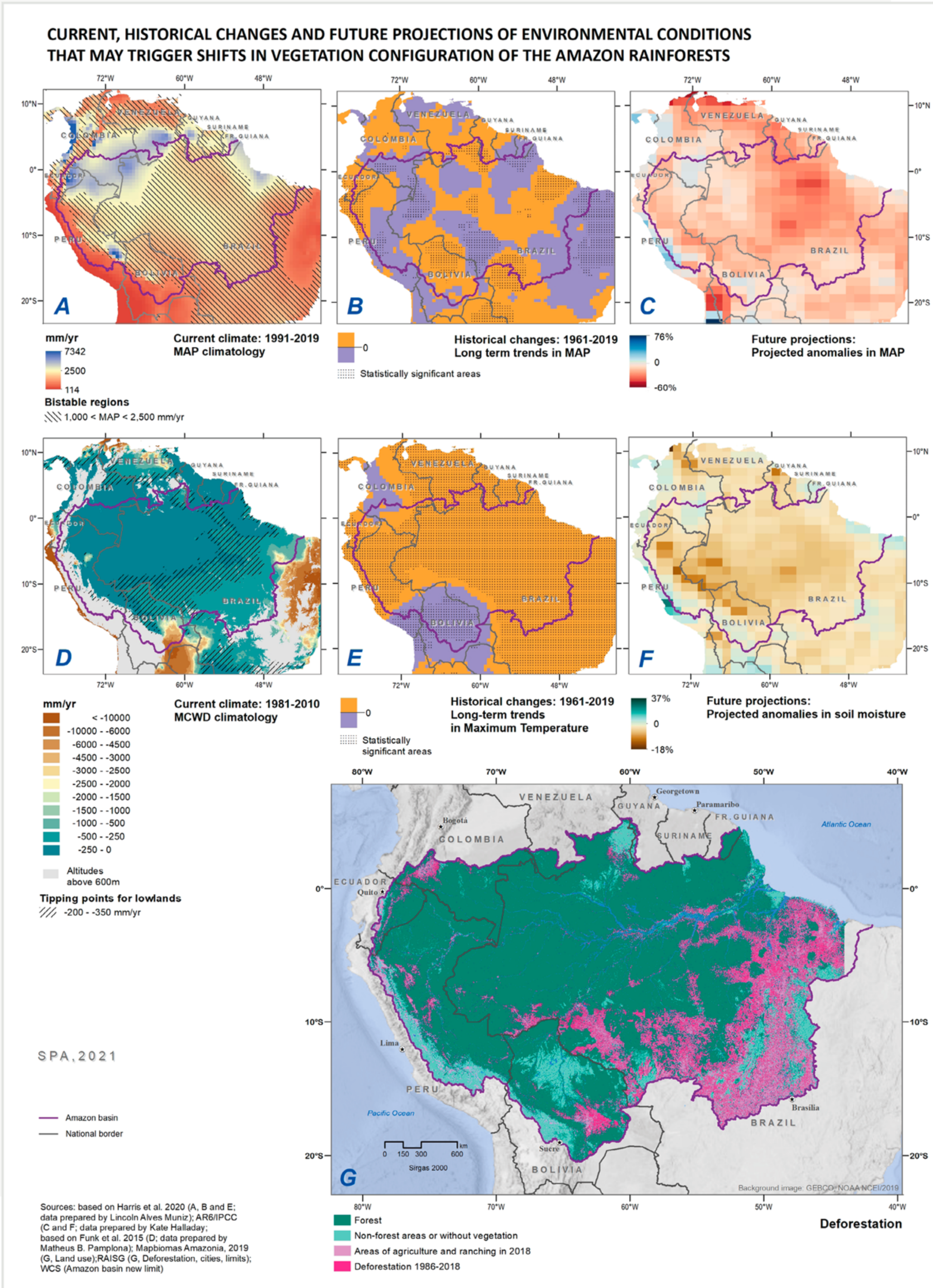

Figure 24.1 Tipping points and disturbances/perturbations which may affect the resilience of the Amazon. (A) 1991 - 2019 climatology of mean annual precipitation (MAP, mm/yr) showing bistable areas for tipping point range (tipping point 1 above) using CRU 4.04 dataset[16]; (B) long-term trends (Kendall τ) in MAP (hatched areas are statistically significant) using CRU 4.04[16]; (C) projected relative changes in MAP at 4°C global warming with the UKESM1 climate model[17]; (D) 1981-2010 MCWD climatology showing tipping points (-200 and -350 mm/yr for lowlands) (tipping point 3 above); (E) long-term trends (Kendall τ) in maximum temperatures (hatched areas are statistically significant) using CRU 4.04 dataset[16]; (F) projected relative changes in soil moisture at 4°C global warming with the UKESM1 climate model[17]; (G) deforestation according to MapBiomas.

23), the actual behavior of the Amazon system remains uncertain.

Potential tipping points and new configurations

Thresholds for tipping points proposed for the Amazon rainforests so far include (1) annual rainfall totals below 1,000 mm/yr[10,11] (Figure 24.1a-d)[12,13,14,15,16,17] or 1,500 mm/yr[18], (2) dry season length longer than seven months[11], (3) maximum cumulative water deficit values larger than 200 mm/yr[18] or 350 mm/yr[19] (Figure 24.1e); (4) an increase of 2°C of the equilibrium temperature of the Earth[20], and (5) surpassing 20-25% accumulated deforestation of the whole basin[21,22].

A major concern is that, once these possible tipping points are exceeded, large-scale forest loss will cause a positive feedback involving rainfall reduction, increased fire, and further forest mortality. Based on existing evidence, we identify four main configurations Amazonian forests may permanently shift to due to such self-reinforcing feedbacks (Figure 24.2).

(i) Open-canopy, degraded state Because most trees in the Amazon forest are sensitive to fire, repeated fires often kill most of the tree community[23–27], particularly younger individuals, reducing tree recruitment[25]. Disturbances that open the forest structure immediately increase light availability at ground level, allowing herbaceous plants to invade[23,28,29]. As a result, disturbed forests may be trapped in an open state by repeated wildfires. Multiple studies in the Amazon show that shifts to an open degraded state are already occurring[24,26,30]. Because forests play a major role in maintaining the rainfall regime of the Amazon (Chapter 5), forest degradation will likely reduce rainfall in the central and western Amazon. A positive feedback between drought and deforestation is already

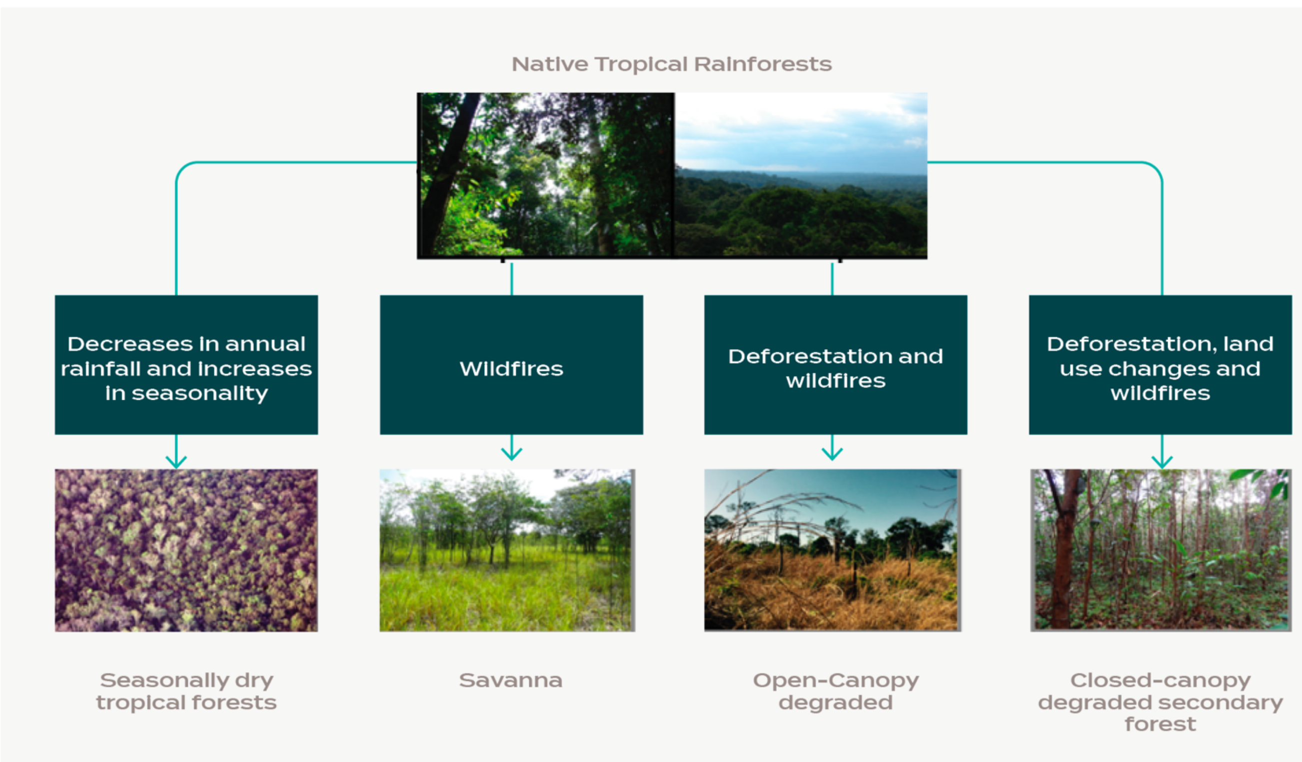

Figure 24.2 Potential alternative configurations and drivers. Photo credits: native tropical rainforests at ZF2 Station (AM, Brazil) by Marina Hirota; seasonally dry tropical forests at Maracá Island (RR, Brazil) by Marcelo Trindade Nascimento; savanna at Barcelos (AM, Brazil) by Bernardo M. Flores; open-canopy degraded at Fazenda Tanguro (MT, Brazil) by Paulo Brando; closed-canopy degraded secondary forest at Tefé (AM, Brazil) by Catarina Jakovac.

strengthening with accumulated deforestation, further increasing deforestation rates[7] and forest fires[31]. Deforestation also augments regional temperatures[32]. Due to these large-scale feedbacks, a tipping point (number 5 above) could cause major forest dieback within the Amazon basin[21,22].

(ii) Closed-canopy, secondary forest state In this configuration, different feedback mechanisms trap forests in an early successional stage (Figure 24.2). Under optimal conditions, secondary forests gradually change and mature in species and functional composition, increase in species diversity and biomass, and plant-animal interactions recover complexity and biomass[33,34]. However, secondary forests are almost twice as likely to be cleared than mature forests, possibly due to lower governmental restrictions and higher accessibility[35], leading secondary forests to persist in an early-successional state[24]. The capacity of secondary forests to fully recover depends on the impacts of activities applied prior to abandonment, as well as on the landscape context[36]. The use of fire to clean pastures and fertilize cropping fields reduces soil fertility and consequently the rates of forest recovery[36–38]. Forest fragmentation and overhunting reduce seed dispersal, further reducing tree recruitment[39].

(iii) Native savanna state The Amazon forest is often assumed to shift into a savanna-like state once it passes the aforementioned tipping points[10,11,20,22,40]. However, evidence for such shifts at the local scale is lacking, mostly because disturbed forests are commonly invaded by alien grasses[41]. Recent evidence, however, reveals that this is already happening in remote parts of the basin, far from the agricultural frontier, where floodplain forests are being replaced by white-sand savannas after repeated wildfires[42] (Figure 24.2). Such local shifts are happening abruptly, within 40 years, likely accelerated by flood-related erosion that alters plant-soil interactions and favors savanna species.

(iv) Closed-canopy, seasonally dry tropical forest Considering the observed trends towards a drier climate in some parts of the Amazon (Chapter 22), there is a possibility that forests over nutrient-richer soils may shift into a closed-canopy state that resembles, in terms of structure and functioning, a seasonally dry tropical forest (SDTF)[18,43], dominated by fast-growing deciduous trees with a higher tolerance to drought conditions and a higher demand for nutrients. A shift to semi-deciduous forest would probably not follow catastrophic non-linear dynamics, or associated tipping points, because of the long distance for species to migrate from STDFs regions[44].

Evidence of Amazonian ecosystem dynamics since the Last Glacial Maximum (20 ka) Paleoecological evidence reveals two important processes for understanding future dynamics. Firstly, forests have undergone local and regional shifts to dry secondary forests or savannas[45], particularly in peripheral parts of the basin. However, they have not experienced an abrupt, basin-wide dieback, even during significantly warmer and drier periods that may be analogous to hypothesized climate-related tipping points (those numbered 1-4 above). Secondly, forest recovery capacity depends on its disturbance history; the more the forest is adapted to disturbance, the faster the recovery rates. However, some caveats need to be addressed when using paleo-data as reference for future dynamics: (i) the rates and magnitudes of projected climatic changes, combined with disturbance events which act synchronously, are unprecedented and may hamper forest recovery; (ii) baseline conditions are not analogs of ecophysiological drivers, such as the enhanced atmospheric CO_2 concentrations of the 21st century; and (iii) long-term ecological data are still limited in the basin and concentrated primarily along the Amazon's margins; thus, more work is needed for unraveling the dynamics of such heterogeneous ecosystems[46].

Drivers of Amazon forest resilience Despite the uncertainties, current findings suggest that, in the absence of deforestation and degradation, for instance due to wildfires, Amazonian forests may change both compositionally and functionally in response to climatic changes, but still remain as closed-canopy forests. Furthermore, if climate-related tipping points (those numbered 2-4 above) are crossed, shifts may be sparse and local because of the high heterogeneity and diversity of forest types. Increased tree mortality caused by human-induced disturbances, and maintained due to increased vulnerability of degraded forests to new disturbance, may lead to increased destabilization of the Amazon forest[47], increasing the likelihood that forests will be trapped in an open-canopy degraded state at larger scales, and that the system as a whole will cross the tipping point (5).

Uncertainties associated with tipping points within the Amazon system

How does forest heterogeneity affect large-scale tipping points? Species diversity is generally expected to increase the resilience of Amazonian ecosystems. Firstly, because diversity has a positive impact on forest productivity[48] and carbon storage[49], potentially accelerating regrowth after disturbances. Secondly, as the number of species is related to the number of strategies and potential responses to disturbances, diversity increases the resilience of the forest overall[50–52].

Additionally, higher mean annual precipitation (above 2,500 mm/yr) increases forest resilience[10,11], while forests exposed to higher average seasonality and interannual variability seem to be more drought tolerant, compensating for lower resilience[53]. Nonetheless, tipping points (those numbered 2 and 3 above) imply that in forests where climate is already drier, increases in rainfall seasonality could potentially cause more forest loss. Increases in the frequency of extreme drought events, together with wildfires, may also prevent forest recovery[54,55]. Amazonian floodplains, covering 14% of the basin, were shown to be less resilient than upland forests, with a potential tipping point of forest collapse at approximately 1,500 mm/yr of rainfall[56].

How does forest connectivity affect large-scale tipping points? Connectivity may theoretically increase systemic forest resilience, because spatial interactions facilitate recovery of disturbed sites. For instance, the climatic, hydrological, and bio-geochemical connections between the Andes and the low-lying Amazon are undeniably key factors in determining the functioning of the current and future system on the large scale (Chapter 22)[57]. However, as conditions change and disturbance regimes intensify, increasing landscape fragmentation and wildfires, disturbances may become contagious, resulting in systemic collapse[58]. Managing the various processes that connect different parts of the Amazon is therefore critical for enhancing its resilience.

The interplay between the CO_2 fertilization effect and nutrient availability Two other uncertainties are related to the potential plant physiological effects of increased atmospheric CO_2 ("the CO_2 fertilization effect") and the hypothetical limitations to forest productivity and biomass accumulation imposed by soil nutrient constraints. On the one hand, the CO_2 fertilization effect could, theoretically, increase forest productivity, biomass accumulation rates[59], and water use-efficiency[60]. On the other hand, the lack of availability of key nutrients for plant metabolism reduces biomass gains under elevated CO_2 conditions[61]. These interactions need to be further studied in highly-diverse forests. Elevated CO_2 also has the potential to interfere with moisture fluxes from trees to the atmosphere.

Without productivity enhancements and with a reduction in forest canopy transpiration due to increased atmospheric CO_2, the Amazon forest and its current community compositions and functional relations are thought to become less resilient to climatic changes, deforestation, degradation, and other anthropogenic disturbances. Such long-term degradation can have pervasive regional socioeconomic impacts[62].

Modeling resilience and tipping points of the Amazon Modeling and evaluating the likelihood and mechanisms of an Amazon tipping point requires closer integration of models, data, and field experiments. Field data show that community dynamics play a key role in the impact of climate change and climatic extremes in the Amazon[6,63,64]. Thus, improving the representation of such recruitment and mortality dynamics and its driving causes is one priority for modeling. Other processes, such as the role of plant hydraulics[65] and increased plant functional diversity[51,66], as well as large scale heterogeneities related to climate, hydrology, and soil chemistry, should be explored in more depth. The potential CO_2 fertilization effect on photosynthesis and water use, as well as possible limitations of forest productivity by soil nutrients, represent a quasi-complete gap in existing models of Amazonian forest vegetation. Narrowing down the uncertainties of rainfall projections for the region would also be critical for better modeling studies of the Amazon tipping point.

Conclusions Due to novel feedbacks associated with invasive plants and human-modified landscapes, we consider the open degraded state and the closed-canopy secondary forest state as more likely to occur over broad areas, particularly across the 'arc of deforestation'. New evidence, however, indicates that in remote parts of the Amazon basin far from the agricultural frontier, the native savanna state could be replacing seasonally inundated forests disturbed by wildfires. Ecological features, including differential tree growth, recruitment, and survival among Amazonian species, are key to promoting forest resistance to, as well as recovery from, disturbances at local scales. The lack of ecological information for many Amazonian species, uncertainty of potential feedbacks, and need for further improvements in climate change projections hamper the development of robust models for anticipating the potential shifts that Amazonian forests may undergo in the near future, either gradually or abruptly. Even with models where a tipping point is not met, and accounting for the uncertainty due to the limited data available, it is crucial to protect, maintain, and sustainably manage the resilience of Amazonian forests.

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