

Tipping Points of Amazonian Forests: Beyond Myths and Toward Solutions

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Keywords

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Abstract

Amazon forests are undergoing rapid transformations driven by deforestation, climate change, fire, and other anthropogenic pressures, leading to the hypothesis that they may be nearing a catastrophic tipping point—beyond which ecosystems could shift to a permanently altered state. This review revisits the concept of an Amazon tipping point and assesses the risk of forest collapse from an ecological perspective. We synthesize evidence showing that environmental stressors can drive critical ecosystem transitions, either gradually through incremental loss of resilience or abruptly via synergistic feedbacks. The interplay between climate and land-use change amplifies risks to biodiversity, ecosystem services, and livelihoods. Yet, there is limited evidence for a single, system-wide tipping point. Instead, the Amazon's resilience—although not unlimited—offers meaningful pathways for recovery. The most immediate and effective strategies to support this resilience include slowing forest loss, mitigating climate change, reducing fire activity, curbing defaunation, and restoring degraded ecosystems. Without decisive action to address direct threats, the Amazon system may be pushed beyond safe ecological-climatological operating limits—even in the absence of sharply defined thresholds—due to the scale and persistence of anthropogenic pressures. Preserving the Amazon's ecological integrity and its vital role in regulating the global climate requires urgent, sustained conservation efforts in collaboration with local and Indigenous communities.

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1. INTRODUCTION

Tropical forests have evolved under a range of natural climatic variability, soil compositions, and disturbance regimes. Over time, the species in these forests have developed mechanisms to cope with environmental factors and interacting biotic variables—ranging from species competition and seed dispersal to animal nutrient cycling (1–4). Thanks to these and other adaptations (5), most tropical forests have historically withstood and rebounded from natural disturbances, climatic fluctuations, and climate change (6) while maintaining their fundamental structure, biodiversity, and ecosystem functions (4). Over the past few decades, however, these forests have experienced an unprecedented array of stressors and disturbances driven by human activities and modern climate change (7–10), potentially pushing them beyond thresholds of resilience (11–14).

Given the scale and rate of current habitat loss, forest degradation, and climate change, the structure, composition, and functioning of contemporary Amazon forests could fundamentally diverge from those of primary old-growth forests (9, 12, 15, 16). Some forests risk entering a downward spiral of severe and widespread degradation (see sidebar titled Terminology for definitions), which would compromise key ecosystem services and natural regeneration and ultimately undermine the remaining forest's ability to sustain itself (17). Future climate change and direct human-induced degradation could lead to the collapse of 20–40% of the region's forests (15, 18), with changing wildfire regimes likely to accelerate and reinforce this process (19, 20).

If the Amazon crosses a tipping point, highly degraded and impoverished ecosystems are hypothesized to replace large expanses of old-growth forests (**Figure 1**), with profound socio-economic and ecological consequences (13, 15). The release of even a fraction of the 90–120 PgC currently stored in Amazonian forests would significantly accelerate global warming (21, 22). Additionally, the loss of evapotranspiration (ET) from the Amazon could further degrade adjacent forests, disrupt regional hydrological cycles, and amplify regional warming (23–25). These changes would threaten food security, public health, and economic stability across the region.

Critically, the degradation of Amazonian old-growth forests would erode the social, economic, cultural, and spiritual values deeply embedded in Indigenous and local communities (26). Such degradation, depending on its scale and intensity, could undermine much of the socioeconomic fabric that has evolved intertwined with the forest ecosystem over millennia (27). The complexity and irreplaceability of these biocultural relationships underscore the urgent need for effective conservation efforts, given that recovery is unlikely on human timescales. Even if recovery from degradation were possible, such an effort would certainly be much more costly and slower than deterring the tide of destruction now facing several Amazon forests (26).

TERMINOLOGY

Changes in forest properties encompass a wide range of processes and outcomes, often leading to confusion due to inconsistent terminology. This sidebar defines key terms as they apply to forest dynamics in the Amazon Basin.

Drivers of Change

Distinguishing natural dynamics from human-driven impacts is critical to understanding how forests function and recover under pressure. **Natural processes** describe stem turnover and forest responses to succession, natural disturbances, or long-term ecological shifts. These dynamics are an intrinsic part of forest ecosystems, supporting speciation, adaptation, and regeneration over time. **Human-driven impacts** describe measurable changes in the structural, functional, or compositional integrity of forests caused by human activities such as logging, human-ignited fires, defaunation, edge effects, and climatic events attributable to anthropogenic climate change. Unlike natural forest dynamics, human drivers often result in long-lasting changes that diminish ecological attributes and lead to impoverished or degraded forests. Interactions between natural and human factors can amplify impacts.

Outcomes of Change

Several terms are used to describe the outcomes of human-driven impacts. **Impoverished** or **degraded** forests refer to the state of the forests following human disturbances. While some definitions of degradation or impoverishment focus on carbon dynamics (e.g., reductions in biomass), we take a broader perspective that includes biodiversity, ecosystem function, and structural complexity. When human activities degrade or alter ecosystems beyond their historical baselines, **novel ecosystems** may emerge [but see Murcia et al. (28) for a critique of this concept]. Like degraded or impoverished forests, these will exhibit significant changes in structure, function, or biodiversity—but may also contain novel species combinations not found following natural disturbances (e.g., exotic grasses or other introduced species), novel species interactions, and an element of self-organization that makes recovery to historical baselines less likely. The term **savannization**, sometimes used to describe one end point of repeated Amazonian forest degradation, is misleading and diminishes the ecological importance of savannas as distinct and valuable biomes. However, the term **derived savannas** has been used to describe shifts to grass-dominated vegetation due to Anthropogenic action in some regions. **Forest collapse** or **forest dieback** describes near-total loss of structure, function, and biodiversity after severe disturbances. This differs mechanistically from **forest loss**, which refers to the active removal of tree cover as part of deforestation and land clearing. **Forest cover loss** is frequently used in satellite-based assessments and describes the combined outcomes of land clearing and impoverishment and degradation of the remaining forests, reducing leaf area.

Critical thresholds and tipping points are synonymous terms that involve pivotal changes in ecosystem conditions. Both refer to the combined set of environmental stressors leading to ecosystem shifts—often abrupt and nonlinear, such as sudden loss of aboveground biomass, diversity, and functions. Critical transitions are these types of system behavior when tipping points are crossed, triggering a shift in the state of the system. Whether a degraded forest recovers or transitions to a new state depends on its **resilience**. High resilience is indicated by a forest's ability to recover rapidly even after severe degradation, while low resilience results in slow recovery rates and potentially **irreversible critical transitions** maintained by **reinforcing feedbacks** that perpetuate and potentially amplify the ecosystem state shifts toward or beyond a critical transition, such as **climate-vegetation** interactions. The likelihood of critical transitions increases if systems exhibit **hysteresis**—the tendency for recovery pathways to differ from the processes that caused degradation, making a return to the original state more difficult once a threshold is crossed. Bistability refers to the existence of two or more ecosystem states that can persist under the same external conditions (e.g., precipitation levels).

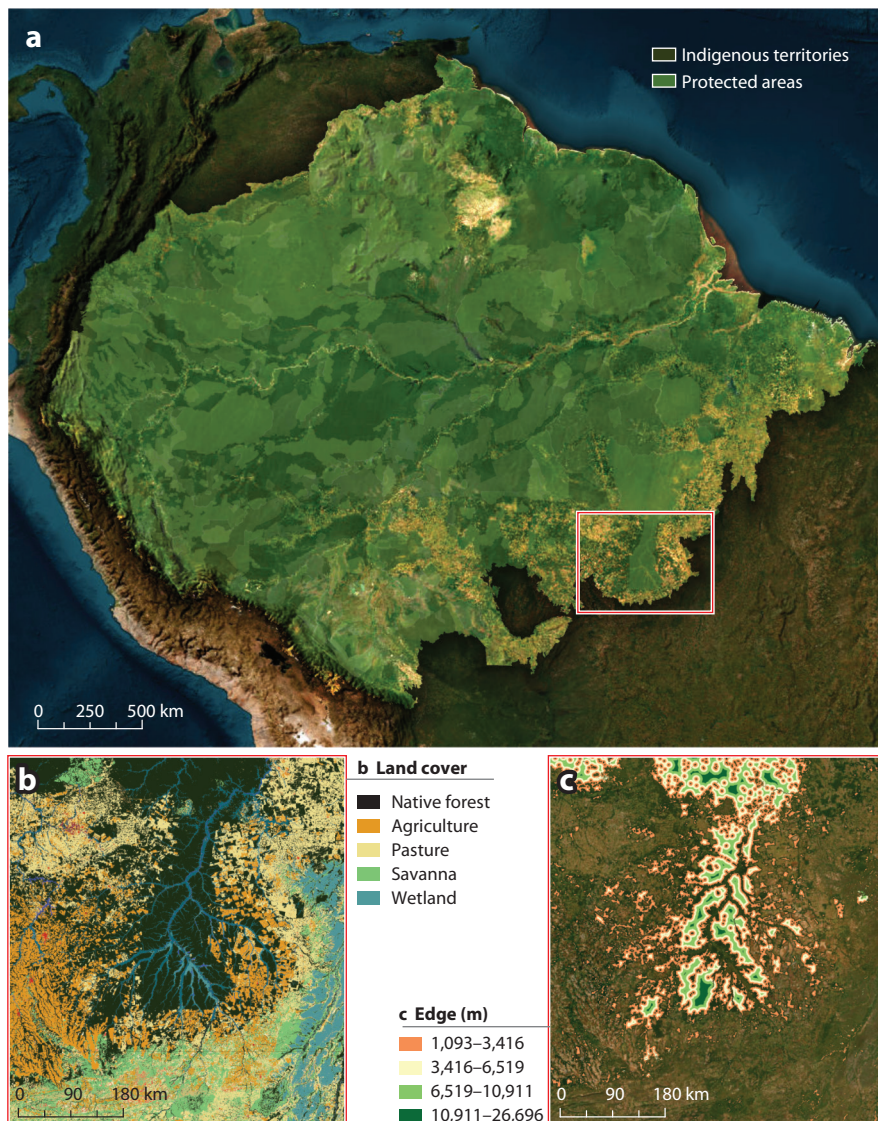


Figure 1

Map of the Amazon Basin showing (a) protected areas, (b) major land cover types (2023), and (c) edges created by habitat fragmentation. The maps show the upper Xingu region (denoted by the *white rectangle*), where forest edges near rivers are natural ecological boundaries but recent wildfires have expanded those edges, contributing to forest degradation and further fragmentation. In this region, rapid land-use change has drastically altered the landscape, with a large proportion of forests growing close to agricultural land. While the Xingu Indigenous Park has slowed forest cover loss due to deforestation, fires have decreased forest cover over the past two decades.

Despite broad scientific consensus about these mounting pressures, there are large uncertainties about the timing, scale, and intensity of potential tipping points in the Amazon, as well as the extent to which tipping points will compromise ecological and cultural resilience (15). This review (a) assesses the likelihood of forest collapse in different regions of Amazonia; (b) evaluates

the potential ecological consequences of such transformations; and (c) explores potential strategies for preventing forest losses and preserving the Amazon's ecosystem services, including climate regulation.

2. HISTORY OF TERMS AND CONCEPTS

2.1. Amazon Deforestation and Regional Climate Change

The hypothesis that Amazonian forests could collapse due to climate change originated from early research examining deforestation impacts on regional climate dynamics (23, 29) (**Figure 2**). These studies showed that converting forests to pastureland in idealized models could disrupt the regional energy balance by reducing the net energy available for ET shifting energy partitioning from latent heat to sensible heat. This shift was predicted to cause declines in relative humidity and precipitation and to drive regional warming. In some areas of the Amazon, these climatic shifts were predicted to cross critical thresholds that sustain the region's forests, potentially leading to a new equilibrium. As a result, it was hypothesized that 20–25% of the Amazon Basin could experience climatic conditions typical of savannas—a process dubbed savannization (23), highlighting the substantial climatic risks posed by large-scale deforestation through disruptions to the region's hydrological cycle.

2.2. Amazonian Forests and the Hydrological Cycle

Early research into forest–climate interactions underestimated ET by trees, as well as the strong relationship between the carbon and water cycles in tropical forests (20). The prevailing view in the 1980s and early 1990s stated that the region's nutrient-poor soils drove trees to optimize nutrient recycling by developing shallow root systems that could efficiently take up nutrients from leaf litter decomposition (48, 49). Deep-rooted trees were considered ecologically improbable. This assumption grossly underestimated the role of deep roots in accessing soil moisture and sustaining high ET throughout the year, the associated cooling effects, and the potential feedback between forests and climate. This knowledge gap also hampered our ability to properly quantify the susceptibility of tropical ecosystems to extreme climate events such as droughts and heat waves (50). Without deep root systems, trees in the Amazon were assumed to be much more vulnerable to drought. The long-held conceptual model of shallow-rooted Amazon forests began to shift with growing evidence that much of the region's rainfall is recycled by the trees via ET. Research in the mid-1980s estimated that 30–50% of the Amazon's rainfall is cycled through its vegetation (30, 51), suggesting that some Amazonian trees must access moisture from deeper soil layers than previously thought to sustain such elevated levels of transpiration during the dry season. Addressing this apparent paradox, Nepstad et al. (32) conducted a study, digging soil pits in search of deep-rooted Amazonian trees. While most roots were found near the soil surface, some extended as deep as 10 m into the soil profile, allowing trees to avoid dry season water stress and maintain high ET rates year round, especially in regions with high seasonality. The study also highlighted how deforestation and forest degradation can impair this water cycling capability.

2.3. Susceptibility of Amazonian Forests to Droughts

The droughts of the late 1990s and early 2000s provided valuable data to assess the sensitivity of Amazonian forests to extreme climate conditions (38, 52). Studies from field-based plot networks estimated that the widespread droughts of 2005 had a total impact of 1.5 PgC on the carbon cycling of Amazon forests (38), primarily due to increased tree mortality and, to a lesser extent, reduced growth. The 2010 drought had comparable impacts on carbon cycling, but the direct

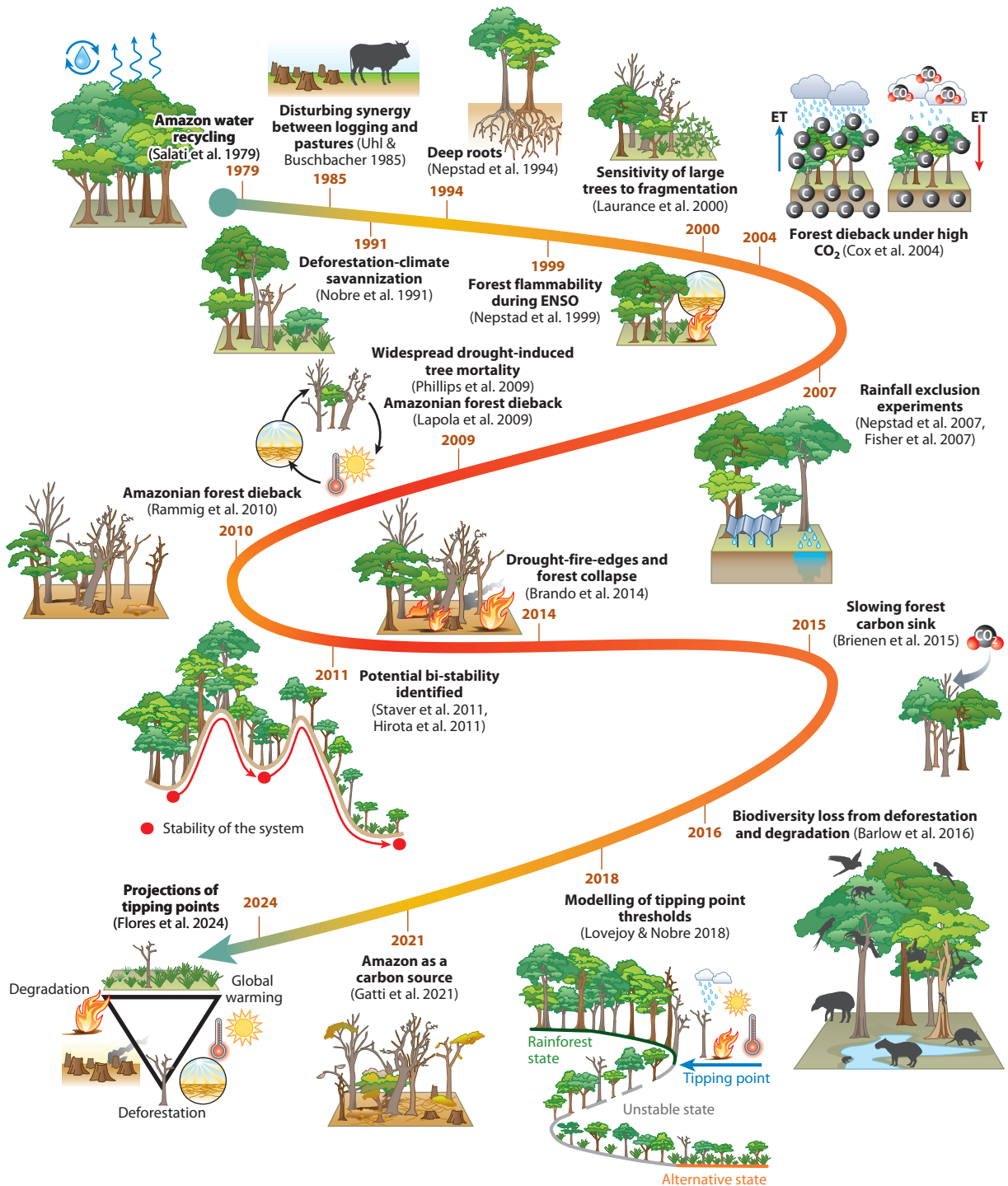


Figure 2

Timeline of key concepts related to evolution of the Amazonian tipping points. Abbreviations: ENSO, El Niño–Southern Oscillation; ET, evapotranspiration.

effects of climate on tree mortality differed from those of the 2005 drought (44, 53, 54). The observed mortality corresponded to the death of just a few additional large trees per hectare, but these droughts provided physical evidence of potential climate thresholds governing the survival of large trees under drier future conditions (38, 44, 55).

Rainfall exclusion experiments at two humid locations in the Brazilian Amazon partially corroborated these findings. These studies experimentally simulated a 50% decrease in precipitation over several years (36, 56), expecting forest trees to reach their hydraulic functional limits quickly. Surprisingly, large trees began to die at higher rates than the control only after 2 or 3 years of exclusion, indicating that they have several mechanisms to cope with extended soil drying [e.g., stomatal regulation, hydraulic lift, and deep soil water uptake (56–59)]. Despite these strategies for coping with plant water stress, once deeper parts of the soil profile reached low levels of plant-available water [272 mm lower than in normal primary forest (60)], large tree mortality increased markedly—from 1% to 9% in Santarém-Tapajós and from 3% to 8% in Caxiuanã (61, 62)—and aboveground live biomass declined by 20–30%. The elevated mortality drove substantial changes in species composition and richness, with surviving species tending to have drier fundamental niches (63). Results from these experiments suggest that, while adult trees can access deep soil moisture to survive seasonal water deficits, they are still susceptible to the extreme droughts projected under future climate (54, 59).

2.4. Hysteresis and Novel Ecosystems

Regional warming and extreme weather events can substantially alter forest dynamics, structure, and diversity. However, whether such climatic stressors could push these forests beyond a critical threshold remains uncertain, including whether transitions will result in a shift toward ecosystems characteristic of neighboring biomes (e.g., savannas) or the emergence of novel ecosystems. Observational studies have provided important insights into this issue (41, 42), promoting the hypothesis of bistability in the region, where forests and savannas can coexist under specific climatic conditions (e.g., 1,000–2,200 mm of annual precipitation). This could point to the existence of hysteresis between savannas and forests in parts of the tropics.

If hysteresis were present in the Amazon, it would support the theory that forests can transition into new stable states driven by global climate change, feedbacks between vegetation and climate, and/or disturbances. Biome distribution models suggest that most wet and moist forests in the region would likely persist under climate change alone, with minimal to no significant expansion of savanna ecosystems. However, although some regions in southeastern Amazonia are predicted to shift toward drier, transitional forest types (38, 64), climate change alone is unlikely to lead to a large-scale savannization (i.e., the expansion of savannas) in the Amazon.

Nonetheless, interactions among disturbances could erode forest resilience and increase the likelihood of forests giving way to ecosystems that fundamentally differ from their current structure and function (8, 65). Human-ignited wildfires, for instance, could accelerate this process, since fire-driven tree mortality creates open canopy conditions (33, 66) that favor early successional, light-wooded tree species; bamboos; and certain invasive or native grasses (67). This phenomenon, in which forests become progressively more degraded, could lead to novel, grass-dominated systems sometimes referred to as derived savannas (see sidebar titled Terminology for definitions).

2.5. Altered Fire Regimes in Amazonia

The interaction of climate change, droughts, previous forest disturbances, and heat waves has increased flammability across the Amazon Basin, reversing the region's historically low susceptibility

to wildfires (20, 68). During the 1998 drought, for example, Nepstad et al. (33) estimated that 30–40% of the Brazilian Amazon became vulnerable to understory fires, a finding later highlighted by the IPCC as a potential trigger for a forest tipping point [IPCC AR5 (69)]. As deforestation accelerated throughout the 1990s and 2000s, it increased the number of ignition sources and the overall extent of flammable forest edges, allowing uncontrolled fires across vast tracts of standing Amazonian forest (50). Between 1985 and 2020, an estimated 16% of Amazonian forests burned at least once (70), decreasing aboveground live carbon stocks by an average of $24.8 \pm 6.9\%$ compared to unburned forests (71). The increasingly hot and dry conditions in the southeast Amazon further elevated forest flammability, raising the likelihood of larger, more intense, and more severe fire events (43), as observed during the El Niño in 2023 and 2024.

In the wetter regions of the Amazon, fires are less frequent but can be far more severe than in drier areas when they do occur, typically under extreme dry and hot climatic conditions. Staver et al. (72) found that wetter upland forests in the Amazon are more vulnerable to fire due to thinner bark, a key trait that influences fire-induced tree mortality. In igapó forests, located in some of the wettest parts of the Amazon floodplain, fires have even more severe and lasting impacts, with postfire mortality sometimes reaching 100% and forest regeneration often stalling for decades (73). Nevertheless, there is a large variability in forest response to fires, with observations in less seasonal terra firme forests showing relatively low levels of tree mortality (74). Given the potential for extreme tree mortality under dry-hot climatic conditions (43), repeated fires could catalyze abrupt and severe changes in forest health (8).

Uncontrolled fires also impact atmospheric chemistry through emissions of ozone precursors and particulate aerosols, with potential feedbacks on forest ecosystems. Ozone has a large impact on net ecosystem exchange, and biomass-burning emissions of aerosol particles affect cloud formation, development, and precipitation, as well as the radiation balance over large areas of Amazonia (75).

3. FEEDBACK MECHANISMS

While climate change alone may lead to the rapid, widespread collapse of tropical forests (38, 64), feedback mechanisms could push ecosystems into alternative, degraded stable states (**Figure 3**). We highlight three potential feedback loops that could affect the future of Amazon forests (76): (a) hydrological (biosphere–atmosphere) feedbacks driven by deforestation and/or CO₂ effects on stomatal conductance; (b) temperature feedbacks on respiration and biomass loss; and (c) fire feedbacks, whereby the compounding effects of drought, fire, and reduced rainfall drive self-reinforcing cycles of forest degradation.

3.1. Hydrological Feedbacks

Structural changes in forest canopy cover (caused by deforestation or disturbances) and tree physiology (e.g., altered stomatal conductance and respiration rates) could drive climate–forest feedbacks, with important implications for the surrounding forests. Once initiated, these changes could disrupt forest–atmosphere water exchange and potentially reinforce degradation of the remaining forests through interactions with the regional climate system.

3.1.1. Forest cover loss. In the Amazon, deforestation is the primary cause of forest cover loss (see sidebar titled Terminology), leading to changes in climate that can influence forest dynamics locally and regionally via feedback loops. As forests are cleared and replaced by agricultural lands, declines in ET, net radiation, and surface roughness can reduce the availability of water, energy, and atmospheric mixing. These changes are expected to alter rainfall patterns, with climate models suggesting that deforestation of most of the Amazon could drive reductions in annual precipitation

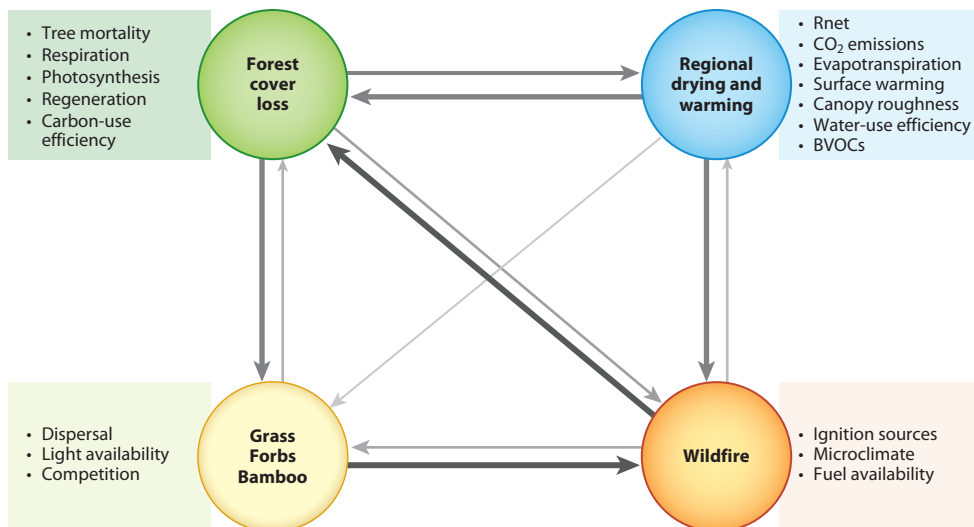


Figure 3

Hypothesized model illustrating how deforestation, land-use change, and the accumulation of CO₂ in the atmosphere may trigger potential positive feedback loops among forest cover loss, regional climate change, wildfire, and the proliferation of flammable vegetation (grasses, forbs, and bamboos). Text in rectangles highlights key mechanisms associated with these feedbacks. Darker and wider arrows represent hypothesized stronger interactions, indicating processes that may significantly reinforce ecosystem degradation and potential transitions. Although negative feedbacks may be present, we hypothesize that the net effect of these interactions leads to overall positive feedbacks. Abbreviations: BVOC, biogenic volatile organic compound; Rnet, net radiation flux.

of less than $16 \pm 13\%$ (77–79). Regions of the Amazon with high soil moisture recycling via forest ET may be particularly vulnerable to forest cover loss, further amplifying the climatic effects (79). Supporting this view, satellite observations identified reduced precipitation over deforested regions of the Amazon, with a projected 20% reduction in precipitation for complete Amazon deforestation (80).

While the overall decline in annual precipitation may appear modest, the timing of precipitation is crucial. Reductions in rainfall in the dry season could also increase forest water stress, often measured as the cumulative water deficit (ET minus precipitation). If reductions are concentrated in the transitional months between the dry and wet seasons, they could extend the dry season—an important factor influencing biome distributions. Natural climate variability complicates the direct attribution of deforestation as a driver of dry season lengthening. However, scientific evidence increasingly suggests that deforestation, along with the accumulation of greenhouse gases in the atmosphere, contributes to longer dry seasons (22, 78).

Forest cover loss can also potentially reduce rainfall via aerosol particles, which act as cloud condensation nuclei (CCN) that are essential for cloud production and development over Amazonia (75). Vegetation produces primary organic aerosol particles such as pollen and fungal spores, as well as volatile organic compounds (VOCs) like isoprene, which are crucial for producing particles feeding the CCN population over Amazonia (81, 82). Altering either VOCs or primary particle emissions can directly impact the hydrological cycle, although their contribution to long-term, large-scale changes in precipitation patterns remains unclear.

Forest loss can alter atmospheric circulation patterns, potentially reducing moisture convergence—the inflow of atmospheric moisture into the Amazon. This reduction may further

decrease precipitation, reinforcing positive feedback loops that exacerbate forest decline (83). However, climate models disagree as to whether Amazon forest loss leads to decreased or increased moisture convergence (84). Early modeling studies in the Amazon hypothesized that deforestation exceeding 40% could trigger a large-scale feedback loop and associated reductions in rainfall (23), potentially causing forest dieback across the region's remaining forests. More recently, it has been speculated that the threshold for this feedback loop causing dieback could be as low as 20–25% due to the compounding effects of local, regional, and global climate change interacting with local stressors (12). However, while deforestation-induced change in the regional climate may alter forest dynamics, carbon storage capacity, and diversity patterns, other studies suggest that the scale of these effects is unlikely to drive forest transitions to novel ecosystems (15, 85, 86).

3.1.2. CO₂ feedbacks. Modeling simulations suggest that elevated CO₂ levels could have a strong influence on the water-use efficiency (WUE) of remaining forests. As atmospheric CO₂ concentrations rise, stomatal conductance and ET decline. In response, some idealized models project feedbacks that would further alter rainfall and warm the region. For example, Li et al. (87) estimated that 40% of projected future changes in rainfall over the Amazon could be attributed to CO₂-induced alterations in stomatal conductance. However, the influence of this feedback on Amazonian forests remains poorly understood. While Earth system models (ESMs) appear to be too sensitive to elevated atmospheric CO₂, we have limited capacity to properly evaluate the accuracy of these model results. Many early studies predicted significant biomass losses in the Amazon due to positive feedbacks between vegetation physiology and reductions in precipitation, a phenomenon referred to as forest dieback (88, 89). In contrast, more recent ESMs suggest that higher CO₂ levels may enhance photosynthesis and improve WUE, a phenomenon known as the CO₂ fertilization effect. This effect is one potential explanation for observed increases in plot-level biomass in intact primary forests (e.g., 90), and it could partially offset the negative consequences of reduced ET and precipitation, adding uncertainty to projections of Amazon forest responses to climate change.

3.2. Temperature Feedbacks

As air temperatures rise, forests experience increased metabolic demands, potentially leading to higher carbon losses through respiration. Higher temperatures may also negatively impact photosynthesis through increased photorespiration and membrane damage (91). Combined, these processes can reduce biomass accumulation and the forest's capacity to maintain high canopy density, given that trees enter prolonged carbon deficits. A sparser canopy results in decreased ET, initiating a feedback loop of reduced rainfall, higher temperatures, and further biomass decline. Early ESMs overestimated the impact of respiration on forest biomass, predicting that rising temperatures would lead to rapid forest dieback (92). More recent refinements suggest that, while respiration does increase with temperature, the associated biomass loss occurs more gradually than previously thought.

3.3. Fire Feedbacks

The third feedback mechanism arises from interactions between drought, fire, and vegetation dynamics (33, 93). Under severe soil water stress, forest flammability increases due to drought-induced canopy loss. Such loss reduces the forest's ability to intercept light; increases air dryness in the understory; and accelerates the accumulation of flammable materials such as dead leaves, twigs, and other fine debris (94). Once ignited by human activities, these fires drastically alter forest structure, dynamics, and biodiversity, often killing more vulnerable, thin-barked tree species (72,

95, 96). Following a fire, forests become increasingly flammable during recovery due to fuel accumulation and increased canopy openness, which raise the likelihood of recurring fires at higher severity (e.g., 17).

This fire feedback loop is expected to intensify along forest edges, where most tropical forest fires occur (e.g., 97). Fires at forest edges are more intense and severe than those in forest interiors (43, 98, 99), creating environmental conditions favoring the establishment of flammable vegetation. For instance, forest edges invaded by grasses become much more flammable because grasses undergo annual senescence, contributing to high fine fuel loads even during nondrought conditions (67). The fire–grass feedback could slow the recovery of tree species, impeding succession and potentially trapping the ecosystem in a cycle of repeated burning and grass encroachment. It is estimated that grass invasion can occur when canopy leaf area density falls below 3 m²/m², roughly half the average canopy density of a primary Amazon forest (67).

Although this grass–fire cycle is well-established in other regions of the world (e.g., 100), its spatial and temporal dimensions are not fully understood in the Amazon. Spatially, these feedback loops are most likely to be observed in fragmented landscapes in southeast Amazonia, where disturbances are more frequent and intense, and the region already experiences a prolonged dry season. While currently operating at local scales [e.g., parts of the Xingu Basin (101)], these mechanisms have the potential to drive rapid, long-lasting forest degradation. In other Amazonian landscapes (e.g., Acre and Tapajós), fires can promote other pyrophytic vegetation such as bamboos and sedges (102). These reinforcing feedbacks appear to be strong enough to prevent tree recovery, but some studies have shown that forest canopy closure during recovery can outcompete grasses and other pyrophytic vegetation.

In addition to impacting vegetation dynamics, fires reduce precipitation through aerosol–radiation and aerosol–cloud interactions (75). Smoke aerosol reflects and absorbs shortwave radiation, resulting in surface cooling and warming in the lower atmosphere, which can suppress convection and reduce precipitation. Smoke aerosol increases the number of CCN, resulting in more numerous but smaller cloud droplets that can delay the onset of precipitation. The magnitude of the precipitation suppression is uncertain and complicated by multiple interconnected processes. Climate model simulations suggest that smoke aerosol can reduce precipitation over the Amazon by 5–10% (103–105). Analysis of satellite observations confirms that dense smoke, with aerosol optical depth exceeding 0.4, results in strong suppression of convection and a reduction in precipitation of up to 30% (106).

3.4. Synergies Between Feedback Mechanisms

The feedback mechanisms potentially operating in the Amazon can reinforce one another in complex ways. For instance, trees that reduce stomatal conductance to conserve water may avoid drought stress, but such trees risk overheating due to reduced transpirational cooling. However, closing stomata limits carbon assimilation, potentially leading to carbon starvation. Reduced ET from CO₂ effects or deforestation can also lead to increased fire risk owing to warmer and drier conditions (107). Finally, changes in air temperatures and precipitation from forest loss can exacerbate drought conditions, making forests more vulnerable to fire and subsequent invasion of flammable plant species.

4. QUANTIFYING RISK: EXPOSURE, SUSCEPTIBILITY, AND RESILIENCE

In this section, we highlight recent advances in understanding three interconnected factors that influence the risk of ecosystem collapse in the Amazon: (a) the region's exposure to climate change,

CONGO BASIN

The Congo Basin is the second largest contiguous tropical forest, after the Amazon. Both regions exhibit tightly coupled land–atmosphere interactions and depend strongly on recycled rainfall (108). Recent evidence suggests that Congo Basin tropical forests may rely even more heavily than the Amazon on moisture recycling to provide atmospheric moisture for rainfall (108, 109). Despite these similarities, the Congo Basin appears to be responding differently to global change than the Amazon (110, 111). For example, each basin responded differently to decadal drying trends (112, 113) and shows contrasting, albeit uncertain, projections in precipitation trends (114, 115). Moreover, forest plot data show that, despite long-term declines in the strength of the Amazonian carbon sink between 1990 and 2015, the strength of the carbon sink over the Congo Basin has remained relatively stable over the same period (116).

Several factors may account for why the Congo Basin is responding differently to global change. Differences in the ecological and evolutionary trajectory of the Congo Basin—including prolonged periods of drought during the evolution of Africa tropical forests (117), the presence of megafauna (118–120), and differences in plant species and trait composition (121, 122)—may play a role. Moreover, studies have suggested that the different patterns of land-use change found across the Congo Basin may make the region less vulnerable to global change pressures (110). Land-use change is driven primarily by small-scale agricultural expansion under rotational cropping systems to meet local food security and development needs (123, 124). While fires are a key part of the small-scale rotational agriculture practiced in the Congo Basin, current methods to monitor fire are likely missing the full impacts of fire across the region. More research is needed to understand how these different factors interact and how they may influence the current and future resilience of ecosystems in the Congo Basin.

extreme weather events, and human-driven disturbances; (b) the forest's ability to withstand these stressors, which is reflected in its ecological susceptibility to crossing critical thresholds; and (c) the resilience of ecosystems, or their capacity to recover and restore essential functions following disturbances such as deforestation, fires, or droughts. While the Amazon remains the primary focus of our review, the sidebar titled Congo Basin provides a brief comparative perspective from the Congo Basin, underscoring both shared challenges, such as vulnerability to climate change and land-use pressures, and key differences, including variations in climatic conditions, biodiversity, and the nature of human disturbances.

4.1. Climate Drivers of Change and Exposure

Amazonian forests are increasingly exposed to rising temperatures, prolonged droughts, extreme rainfall events, and wind disturbances—all of which are expected to intensify with ongoing climate change. These stressors have significant implications for forest structure, function, and resilience. Here, we briefly review the main regional climate trends and their potential interaction with land-use change and disturbances such as wildfires.

4.1.1. Regional climate change. The Amazon region has experienced significant climatic changes over the past few decades (15, 125). Regional warming averaged 0.2–0.3°C per decade and was most pronounced during the dry season in eastern Amazonia (0.49°C per decade) (125). Rising temperatures have contributed to increased air dryness in southeast Amazonia, as indicated by the rising vapor pressure deficit (125). Local deforestation has amplified these regional climatic changes. Fragmented landscapes often experience regional warming of 2–3°C, compounded by localized warming of an additional 2–4°C (126, 127). The cumulative effect may push temperatures up by 6°C or more during the dry season, exposing forest edge trees to extreme temperatures (16).

In addition to temperature changes, the Amazon has experienced significant shifts in its hydrological cycle. Since the 1980s, the dry season length in southern Amazonia has grown by 40 days, particularly in drier regions within the Arc of Deforestation (128). Together, changes in dry season length and regional warming likely increase plant water stress through higher atmospheric evaporative demand.

4.1.2. Extreme weather events. Severe droughts have further stressed Amazonian forests. Linked to variations in sea surface temperature, both the El Niño–Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation contribute to significant shifts in regional hydrodynamics. When these phenomena coincide, droughts can become more intense, prolonged, and widespread, leading to extended water deficits and major reductions in deep soil moisture, as seen during the 2005 and 2010 droughts (129–131). In southeastern Amazonia, full soil moisture recharge after a drought can take up to 2 years (132). In addition to changing hydroclimate, air temperatures can be considerably higher during ENSOs—including the 2015–2016 event, when air temperatures were 1°C higher than the long-term average, with some months surpassing 1.5°C. These droughts have increased in frequency and intensity over the past two decades (133).

4.2. Forest Susceptibility to Change

The likelihood of crossing a critical threshold depends on both the magnitude of exposure to stressors and the forest's inherent resistance (e.g., the inverse of susceptibility). Several studies have documented changes in forest composition, even in relatively undisturbed primary forests. The distributions of functional traits, such as wood density and leaf area index, are shifting, with drought- and heat-tolerant species becoming more dominant while more vulnerable species decline (63). Studies along elevation gradients have shown directional shifts in forest species composition toward species associated with lower, warmer elevations (e.g., thermophilization) (134). These findings can be interpreted either as detectable small changes in forest functioning due to global changes or as early signs of declining forest health, with potential near-term consequences.

One of the most comprehensive studies on Amazonian forest thresholds analyzed the current resilience of forests in relation to various climate and land-use variables (15). The study identified potential thresholds beyond which we risk ecological degradation from large-scale ecosystem transitions. They are based on conservative estimates as follows: annual precipitation below 1,800 mm (range: 1,000 to 1,800), maximum cumulative water deficit lower than −350 mm (range: −350 to 450), mean global air temperature increases exceeding 1.5°C (range: 2°C to 6°C), dry season lengths extending beyond 5 months (range: 5 to 8 months), and deforestation higher than 10% (range: 10% to 20%). Crossing these thresholds could signal irreversible alterations in key ecological properties of the region's forests, such as tree biomass and species composition. Depending on the context, vegetation may take many decades to equilibrate to novel conditions or may shift abruptly once thresholds are crossed. Examining vegetation responses to recent disturbances could provide clues about the likely trajectory and timing of future changes.

Recent extreme droughts provide insights into the critical limits of ecosystem properties, since they exceeded many of the thresholds defined by Flores et al. (15) (**Figure 4**). These droughts have led to reduced photosynthesis, lower ET, and diminished canopy greenness, coupled with increased tree mortality (**Supplemental Table 1**), particularly among large, dominant species. The species most vulnerable to drought-induced soil drying are often from wetter regions of the Amazon, suggesting that intensified drought conditions could lead to significant losses in biodiversity, functional traits, and ecosystem services. Despite causing localized abrupt changes in those characteristics, these extreme events have not yet triggered widespread ecosystem collapse, suggesting that primary forests species are mostly resistant to short-term climatic extremes.

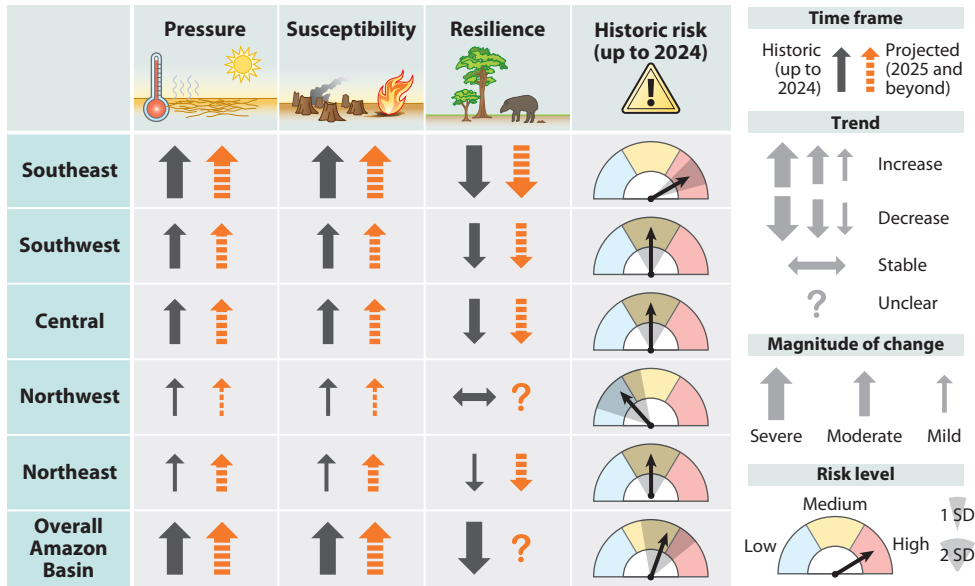


Figure 4

Historical (up to 2024) and future (2025 and beyond) trends, derived from the literature (**Supplemental Table 1**) for pressure, susceptibility, and resilience to disturbance, and how these metrics interact to determine the total risk of vegetation collapse for each region of the Amazon Basin, qualitatively categorized by cardinal directions. The direction of trends was determined by the quantity of studies indicating an increase, decrease, or no change. The magnitude of change was ascertained using the relative quantity of studies supporting a given trend in a particular direction, compared to other regions, and the content of the studies.

Furthermore, many of the drought impacts were short-lived, with vegetation recovering after a few years, although some impacts can last for more than a decade (112). However, forest resistance can be broken if wildfires occur during these extreme droughts, as these lead to abrupt and prolonged alterations in vegetation dynamics during drought conditions (19) (**Supplemental Table 1**).

The largest fire experiment in the Amazon uncovered key mechanisms behind the varied impacts of fire. Initial fires during nondrought years caused lower-than-expected mortality, mostly affecting smaller trees (135), and in some cases even temporarily boosting forest productivity (136). However, when fires coincided with droughts, tree mortality increased sharply, reaching 90% along the forest edges. The resulting changes in forest structure facilitated the spread of invasive flammable grasses—first C3 Cerrado species, then C4 African exotic species. Windstorms further impacted the areas that had been most severely damaged by the experimental fires, probably due to fire-weakened trees (137). Such interactions among droughts, fires, and fragmentation have the potential to transform forested systems into novel ecosystems—characterized by lower diversity, reduced capacity to store carbon, an altered hydrological cycle, and pronounced changes in ecosystem functioning (7, 138). Indeed, such rapid transitions have been witnessed outside of experimental conditions, including forests in the Xingu Basin and moist forests across the eastern Amazon that burned multiple times (17, 66, 95, 101).

4.3. The Resilience of Amazonian Forests

Despite significant transformations driven by disturbances and stressors, Amazonian forests may still retain the ability to recover fundamental characteristics. While this ecological resilience

Supplemental Material >

capacity is largely underpinned by natural regeneration and ecological succession, growing evidence suggests that resilience across the Basin is declining, as reflected in various proxies for forest health.

4.3.1. Loss of ecological complexity. In the Amazon's Arc of Deforestation, forest fragmentation is compounded by increasingly frequent and intense disturbances such as severe droughts, fires, and blowdowns (7, 20, 139). Extensive fragmentation in this region has created small, isolated forest patches with large perimeters exposed to edge effects (43, 140, 141). These edge zones are highly susceptible to extreme climatic events and disturbances (137). Tall canopy trees, which play a critical role in maintaining forest structure and function, are especially vulnerable in these fragmented landscapes, with their loss exacerbating structural changes in forest fragments (142). Fragmentation also disrupts animal-mediated seed dispersal, as defaunation driven by overhunting and habitat loss diminishes the populations of key seed-dispersing species (143). This disruption significantly hinders forest regeneration and the inclusion of species with functional traits essential for full ecosystem recovery (144). In fragmented forests, the proliferation of woody vines can further slow recovery by competing with trees for resources and reducing overall forest growth. While these factors may not individually signify resilience loss, the collective decline of multiple proxies of forest resilience is concerning.

4.3.2. Critical slowing down. Time-series data from remote sensing techniques provide some insights into resilience patterns across the Amazon and global tropics. For instance, an increase in autocorrelation within these time series—indicating how closely an ecosystem's current state mirrors its past conditions—could suggest a critical slowing down (145) and reduced capacity for recovery from disturbances. According to this metric, estimates suggest that between 37% and 80% of the Amazon Basin may be experiencing some loss of resilience, particularly in areas heavily impacted by logging, fragmentation, and natural disturbances such as drought (65, 146–148). These findings consistently indicate southeastern Amazonia as a region where resilience is in decline. However, these proxies of forest resilience are coarse, likely fail to capture the detailed ecological processes associated with resilience, and may represent degradation rather than loss of forest resilience.

4.3.3. From carbon sink to source. Assessments of changes in forest resilience have also considered the forest's carbon cycling capacity. Airborne measurements of CO₂ concentrations have indicated that the western Amazon continues to function as a carbon sink, while the eastern Amazon has become carbon neutral or, in some cases, a weak carbon source (45). This divergence is primarily attributed to higher fire activity and longer, more intense dry seasons in the eastern region. Furthermore, the eastern Amazon is warming at a faster rate than the global average, largely due to reduced evaporative cooling caused by deforestation and forest degradation, although forests degraded by repeated fires have been shown to rapidly recover ET (99). While the reduced capacity to absorb carbon may signal an early decline in resilience, widespread deforestation may also be obscuring the carbon sink function of remaining old-growth forests. Forest plot networks in the Amazon show a decline in the rate of carbon accumulation over time in primary forests associated with higher mortality rates, but they remain a net carbon sink due to rapid wood increment (116, 149, 150).

4.3.4. Postclearing recovery. The capacity of forests to recover after deforestation can provide insights into their resilience. Most secondary forests rapidly regenerate, and because they are below the ecosystem potential for tree heights and densities, they often achieve net carbon uptake rates significantly higher than those of primary forests over the first decades. On average, secondary forests can recover approximately 90% of the biomass stocks of primary forests

within 66 years after being clear cut (151). However, recovery rates vary widely, occurring faster where rainfall is high and slower in regions with prolonged dry seasons and high-water deficits, poorer soils, or more frequent natural or human disturbances (152). In addition, recovery of diversity measures such as species composition can be much slower, potentially taking more than 200 years (151). The recovery of ET after deforestation can occur even sooner, compared to carbon accumulation. However, these forests remain vulnerable to droughts for decades during recovery.

The recovery of degraded forests depends on the input of seeds from surrounding areas. Because many plants in tropical forests, including several tall canopy trees, are dispersed by animals, forest resilience may vary according to how the fauna responds to forest degradation. As large frugivores decline, small-seeded plants may become overrepresented. Seed dispersal limitation of old-growth forest trees may thus strengthen positive feedbacks that reduce forest diversity or resilience, especially in defaunated areas (144, 153). However, in some parts of the Amazon, the abundance of animal dispersed tree species has increased (153).

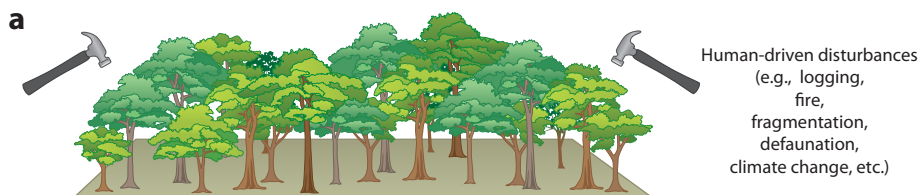
While most forests embedded in a matrix with high forest cover may rapidly recover biomass and species tree richness, deforested areas within fragmented landscapes may become arrested in succession, given limited seed dispersal and an overabundance of lianas (154). Similarly, areas dominated by grasses often face suppressed regeneration, as grasses outcompete tree seedlings and saplings, making recovery slow or impossible without human intervention, especially near water bodies (155, 156). Despite these challenges, vast areas of the Amazon have high potential for regrowth after deforestation. Roughly 19% of the deforested region is currently in some stage of regrowth, although most secondary growth is young with high turnover rates (157).

5. THE AMAZON'S FUTURE

5.1. The Domino and the Hammer

The uncertainty surrounding the concept of an Amazon tipping point can be illustrated using the analogies of a domino effect set and a hammer (**Figure 5**). The domino effect illustrates the potential for cascading impacts that may be triggered when climate changes cross specific thresholds, fundamentally disrupting the climate, ecology, and natural disturbance regimes of Amazon forests. This chain of events can alter species competition, increase flammability, and reduce the forest's resistance and resilience to external stressors, leading to a downward spiral of degradation and, ultimately, the collapse of large forest areas.

The hammer effect, in contrast, can be used to describe direct human-driven impacts such as deforestation and land-use change, rather than a self-sustaining feedback loop. In this analogy, the degradation of the Amazon results from repeated hammer blows to the ecosystem. The key distinction is that stopping destructive activities would halt these impacts, allowing for recovery. In contrast, the domino effect implies that, even if direct impacts stopped immediately, forest degradation or impoverishment would continue because the forest's climate and ecology are already committed to future change. A third scenario is also possible, whereby repeated hammer blows degrade forest health to the point at which they initiate a domino effect (**Figure 5**). While the domino effect often receives much of the attention in discussions about tipping points and may operate across certain areas of the Amazon, we speculate that the hammer effect remains the primary driver of forest impoverishment. These two different pathways—domino and hammer—would have direct policy and conservation implications since stopping the blows could halt forest loss and drastically reduce the likelihood of a domino effect (**Figure 5**).

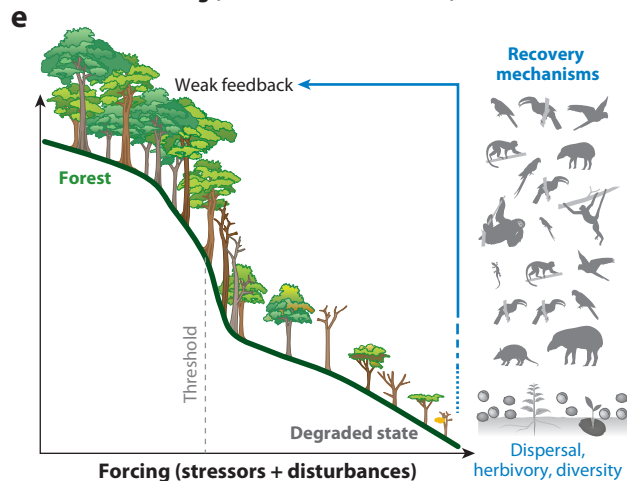
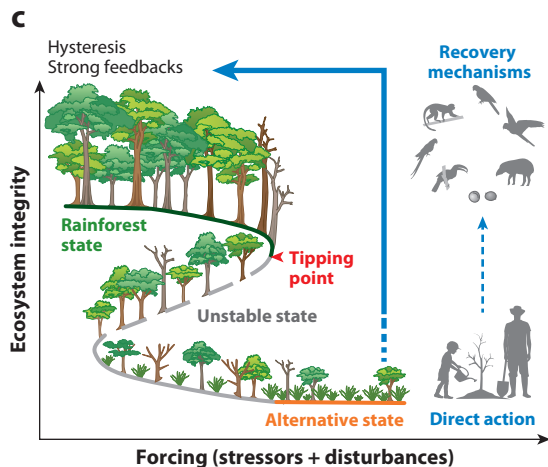
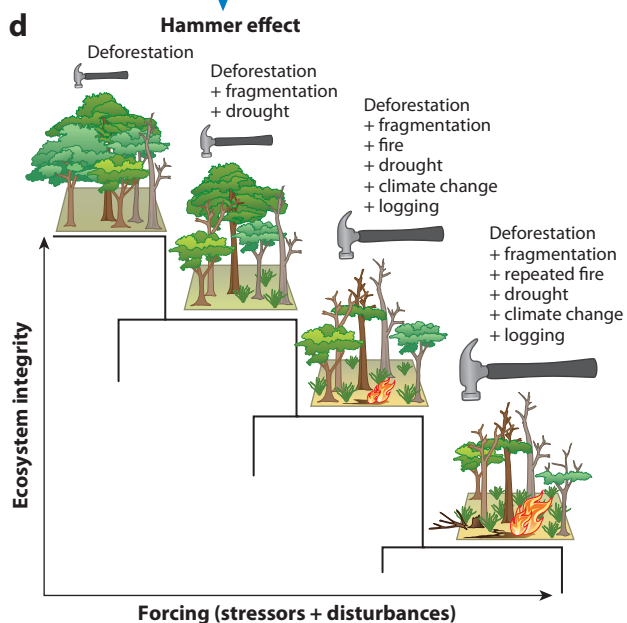
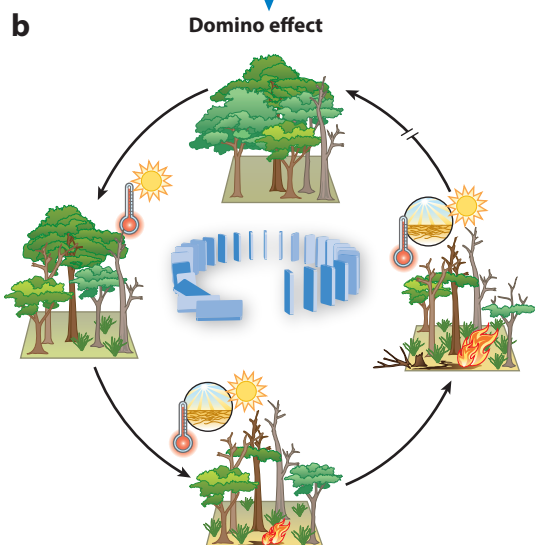


Resilience lost

Climate
change

Drought

Fire



(Caption for Figure 5 appears on following page)

Figure 5 (Figure appears on preceding page)

Potential pathways of forest recovery. Forests have been degraded by several drivers (*a*), or hammer blows. As a result, two conceptual models of ecosystem trajectories could occur in the Amazon. First, the degraded state (*b*) illustrates the domino effect, which assumes tipping points and nonlinear responses in response to stressors, whereby small changes in a driver (e.g., climate) may trigger irreversible ecosystem shifts due to strong feedbacks. While the system can fluctuate within boundaries, significant stress can push it into a degraded state, making recovery challenging. Second, the resilient state (*d*) illustrates the hammer effect, which assumes that human-driven disturbances (hammer blows) are the primary drivers of Amazon ecosystem degradation. Repeated blows can cause the ecosystem to cross thresholds beyond which recovery is difficult but possible. These two conceptual models can also be represented as a system having hysteresis (*c*) or nonlinear transformations associated with different potential drivers (*e*).

5.2. Model Projections

The Amazon is projected to undergo substantial continued warming and shifts in precipitation patterns because of global climate change. Projections from the Coupled Model Intercomparison Project (CMIP) indicate that, without considering the effects of CO₂ fertilization on the vegetation, we expect substantial losses in forest biomass (85, 158, 159). For example, Uribe et al. (64) estimated that climate change alone could drive net biomass losses in tropical ecosystems of 5.9–9.8 PgC per degree Celsius of warming without CO₂ fertilization, with 40% of these losses concentrated in the eastern Amazon. Model projections also indicate that fire activity in the Amazon is likely to increase in southeast Amazonia, potentially impacting 16% of the forests along the Arc of Deforestation (20).

A major uncertainty in projecting the future of Amazon forest responses to climate change relates to how climate models represent CO₂ fertilization. In CMIP6 simulations, rising atmospheric CO₂ concentrations are responsible for 70–90% of projected changes in precipitation and temperature patterns, primarily through alterations in atmospheric circulation (50%) and vegetation–climate hydrological feedbacks (30–40%)—with the remaining attributable to deforestation (87). While empirical studies suggest that increased atmospheric CO₂ may reduce plant ET, many ESMs likely overestimate the magnitude of these reductions. If so, projected precipitation declines in the eastern Amazon—where CO₂-driven reductions in ET are strongest—could also be overestimated.

5.3. Potential Ecological Pathways

Current ESMs also lack mechanisms to adequately represent the synergistic effects of fragmentation, logging, wildfires, and loss of ecosystem function, including defaunation and the breakdown of interactions between plants and animals (15). These compounding factors, exacerbated by climate change, could push the Amazon into unpredictable and potentially dangerous trajectories. Considering these interactions and model limitations, Flores et al. (15) outlined three potential future outcomes for the Amazon, emphasizing that different parts of the basin may experience varying drivers and respond differently:

1. degraded forests, driven by competition between trees and opportunistic plants, compounded by interactions between deforestation, fire, and seed dispersal limitation;
2. degraded open-canopy ecosystems, characterized by interactions among low tree cover, fire, soil erosion, seed dispersal limitation, invasive grasses, and opportunistic plants, with regional feedbacks between forest loss and reduced atmospheric moisture flow; and
3. white-sand savannas, associated with feedbacks among low tree cover, fire, soil erosion, and seed limitation, particularly in flooded forests.

We explore two possible end-member outcomes, recognizing that these are not mutually exclusive and that impoverished forests may be an intermediate stage toward more severe transitions.

5.3.1. Impoverished forests. Observational studies and experiments provide ample evidence of Amazon forest impoverishment due to global changes, including the loss of large, dominant trees during drought events (38, 43, 62); reductions in average wood density from human disturbances (160); and a shift to small-seeded species dispersed by birds and bats along deforestation and degradation gradients (144, 153). Certain ecosystem features, such as large trees, are particularly vulnerable to compounding stressors. While many large trees have adapted to survive past droughts by growing deep roots to access deep groundwater, increasing soil dryness in some regions may render this strategy insufficient. Furthermore, large trees are sensitive to additional stressors such as windstorms (137); logging (161); edge effects (34); and a breakdown of certain seed dispersal modes such as synzoochory (144, 153), which is prevalent among some of the Amazon's most distinctive tree families such as the Lecythidaceae.

Widespread impoverishment of Amazonian forests could alter their ability to resist or respond to further environmental changes. The loss of large trees, for instance, could cause decreased forest rooting depth, thereby decreasing access to deep soil water and leading to forests becoming more seasonal in drier parts of the Amazon (32). In addition, these forests could become increasingly dominated by fast-growing, short-lived generalist species typical of secondary forests, which may be more sensitive to extreme drought or temperatures (e.g., 63, 162) and which tend to be less resistant to disturbances such as fires (95). The loss of large-seeded tree species may also drive changes in faunal communities that depend on these fruits, although the potential for strong feedbacks may be ameliorated by a high level of redundancy in fruit–frugivore interactions (163, 164).

5.3.2. Transition to nonforests. A more extreme scenario of forest response to stressors and disturbances involves the replacement of forests with nonforest vegetation. This is already occurring due to large-scale deforestation—driven by land speculation, cattle ranching, and agro-industrial expansion—with economic interests suppressing vegetation regrowth. However, it is important to distinguish this deforestation-driven forest loss from a potential transition of the remaining (uncleared) forest (see sidebar titled Terminology), which we focus on in this review.

Interactions and compounding effects of co-occurring disturbances—including deforestation, climate change, and fire—could facilitate transitions into ecosystems dominated by nonforest species, including grasses or shrubs. To date, such transitions are rare, having been observed only in experimentally burned areas subjected to frequent fire return intervals rarely seen outside experimental settings—or in repeatedly burned flooded forests (73). Thus, (*a*) how widespread these changes might become without further anthropogenic intervention and (*b*) whether recovery is possible over longer timescales remain uncertain. Nonetheless, climate change and ongoing deforestation create scenarios in which further changes are inevitable and large-scale forest degradation is possible. In extreme cases, novel ecosystems may also emerge from widespread degradation (e.g., 7).

6. MANAGING POTENTIAL TRANSITIONS

From a management perspective, there is little immediate difference between an impoverished forest and one that is transitioning into a nonforest state. Both are highly undesirable outcomes with far-reaching consequences for people, nature, and climate. These outcomes can be extreme in both scenarios and are unlikely to be reverted on timescales relevant to current decision-making. Moreover, both are initiated by similar drivers, so management actions designed to counter them are the same. Finally, observed changes in both scenarios can be either linear (e.g., incremental losses of biomass from successive droughts) or highly nonlinear (e.g., fires leading to sharp losses of aboveground biomass and biodiversity).

6.1. Halting Forest Loss and Degradation

Strong governance provides the foundation for designing and implementing strategic measures to prevent undesirable transitions in the Amazon. Effective governance should orchestrate the wide range of actors involved in forest stewardship and conservation by establishing robust institutions, mechanisms, and regulatory frameworks (165). International actors play a pivotal role since significant land-use changes are driven by globalization and demand from distant markets (11).

Reducing deforestation is the first line of defense to prevent the impoverishment or complete collapse of Amazonian forests (11, 15). The significant decline in deforestation rates (>80%) in the Brazilian Amazon between 2004 and 2014 is emblematic of the potential for such coordinated efforts (166, 167). This reduction was achieved through a combination of national government policies (e.g., establishment of protected areas, monitoring and enforcement of environmental laws), supply chain interventions, and financial incentives (166). However, without fundamental changes in the rationale behind the drivers of deforestation, it tends to rebound with shifts in markets or political will.

Lessons from Brazil and Colombia demonstrate that success in reducing deforestation lies in multiple, complementary interventions—combining disincentives and incentives implemented by public and private actors across different scales (168). Governments can enable conditions that support market-based incentives (e.g., supply chain initiatives) by imposing regulations, formalizing land rights, orchestrating actors, and monitoring compliance. Initiatives targeting specific commodity sectors—e.g., the soy and cattle moratoria in Brazil and zero-deforestation agreements for palm oil, beef, cocoa, and timber sectors in Colombia (167)—are relevant for scaling up zero-deforestation efforts. Successful deforestation commitments by national governments can also attract new financial streams via REDD+, which supports forest conservation and sustainable management (169).

Coordinated action to strengthen and support Indigenous land rights is among the most effective strategies to maintain healthy forests and associated ecosystem services. Indigenous territories account for almost half of all remaining land with high ecological integrity (wilderness) across the Amazon (170). Securing and enhancing their collective systems of tenure, governance, and livelihoods will be essential for achieving socioecological resilience in Amazonian forests (171, 172).

Indigenous and traditional Amazonian communities have played key roles in shaping regionally important forest-based economies. These sustainable sociobioeconomies could deliver substantial socioecological benefits, provided that they are built upon sustainable harvesting and land-use practices and are implemented with a strong foundation of social justice and equity (173–175). Although currently limited to niche markets, sociobioeconomies can be expanded through investments in improved infrastructure, value chains, and social organization (176). Scaling up sustainable activities—such as ecotourism; gastronomy; and diversified production of fruits, nuts, oils, medicines, fish, and other products derived from sociobiodiversity—requires dismantling environmentally destructive sectors through strategic disincentives (176) and the ending of the many subsidies that encourage them. Viable socioeconomic solutions are essential to incentivize the conservation of standing forests and to reduce the appeal of deforestation for short-term economic gain (177).

Proposals for more sustainable forest management have called for adaptive approaches that mitigate the risk of ecological transitions while providing a wide range of social, economic, and ecological benefits (178). Such approaches often shift away from the traditional view of forests as a predictable source of harvestable products, focusing instead on the comprehensive provision of diverse ecosystem services (179). In times of climate extremes, the overexploitation of resources

such as timber can help push ecosystems beyond their limits, rendering them more flammable and ecologically less resilient (31).

6.2. Managing Altered Fire Regimes

Addressing the escalating threats posed by fire in the Amazon will require ambitious adaptation strategies and comprehensive management approaches. The new Brazilian Integrated Fire Management Law (180) offers opportunities to manage fire ignitions proactively and to prevent burning of fire-sensitive Amazon forests. Effective wildfire prevention depends on targeted policies, incentives, and capacity building to encourage fire-free land management, particularly for stakeholders with financial resources such as capitalized cattle ranchers (11). At the same time, it is crucial to support family farmers, Indigenous Peoples, and traditional communities who rely on fire for their livelihoods and cultural traditions (181). These groups should be provided with information and assistance to gradually and autonomously adapt their agricultural practices, minimizing fire use during periods when climatic conditions pose significant risks (182, 183). They should also be supported when their forests burn, as fires lead to strong reductions in material benefits (e.g., nontimber forest products) and relational values (e.g., land rights of place attachment). Proactive strategies to minimize ignition sources—including regulation of deforestation, slash-and-burn practices, and arson—are also critical, especially during periods when forests are most flammable.

Mitigating future wildfires also demands advancement on several fronts. As the climate becomes warmer and drier in Amazonia, human-ignited forest fires are likely to produce much larger wildfires (**Figure 6**). Reducing this risk would require improving seasonal fire forecasting systems and shifting the focus from ignition probabilities to the risk of fire spread. Enhanced real-time monitoring of fire types and locations using satellite sensors, airborne surveys, and ground-based networks of tower-mounted cameras is critical. Although Amazonia's size and remoteness make fire emergency response (i.e., firefighting) challenging, it is a key management component and requires sustained investment in training and equipping local firefighting teams (e.g., 183). Finally, quantifying the socioeconomic impacts of forest fires—such as damage to infrastructure, health risks from smoke exposure, and loss of ecosystem services—is essential for raising public awareness and driving action. This is particularly important because understory fires not only devastate forests and biodiversity but also have immediate and far-reaching consequences for human livelihoods, public health, and regional stability.

6.3. Promoting Large-Scale Landscape Restoration

Landscape restoration, alongside efforts to reduce deforestation and degradation, is a vital strategy for strengthening the socioecological resilience of fragmented forest regions such as Brazil's Arc of Deforestation. While national policy initiatives aspire to transform the region into an Arc of Restoration through financial mechanisms, to be effective they should include strategic spatial planning with cost-benefit analyses that balance multiple benefits such as carbon, biodiversity, and social and economic indicators (184, 185). Risks related to water and food security, and the potential for irreversible forest transitions, should be carefully evaluated.

Brazil included a restoration target of 12 million hectares by 2030 in its intended nationally determined contributions, with approximately half of this slated to occur in the Amazon. A multistakeholder restoration network has emerged within Brazil in response to international and national institutional mechanisms (186). Among the restoration drivers are regulatory frameworks such as the Protection of Native Vegetation Law (Forest Code), which requires landowners to restore lands that are out of compliance; this framework is supported by global funds for forest

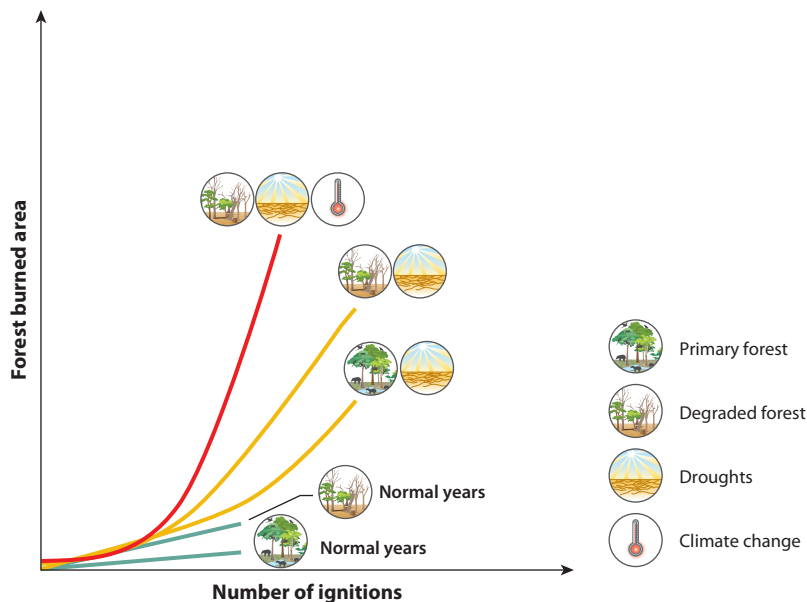


Figure 6

Relationships between ignition sources and burned area across forest conditions and climate scenarios. In primary forests, increases in ignition sources have limited effects on wildfire extent during nondrought years. However, under drought conditions, more of these ignitions spill over into flammable forest edges, triggering larger fires and greater burned area. In degraded forests—altered by logging, edge effects, or other disturbances—even a small number of ignitions can lead to disproportionately large fires due to faster spread and longer burn durations. These dynamics are further amplified by climate change, which increases drought frequency and reduces ecosystem resilience. While degraded forests are more fire-prone, primary forests may still experience larger burned areas during extreme droughts simply because they encompass larger patches. Together, these patterns illustrate how fire regimes respond nonlinearly to interacting stressors, with critical thresholds shaped by both forest condition and climate. To reduce future wildfire risk, ignition sources may need to be reduced disproportionately, as forests become increasingly flammable under the combined pressures of disturbance and climate change.

restoration and conservation. Carbon markets offer promising funding mechanisms for climate mitigation and large-scale restoration, yet critical knowledge gaps in spatial planning, environmental impact assessments, and regulatory frameworks must be addressed to ensure an equitable distribution of benefits and to prevent greenwashing. Given the current challenges, however, only a small fraction of deforested areas has actively been restored (187).

Naturally regenerating areas offer another strategic approach to achieving large-scale restoration with a favorable cost–benefit balance, given the high cost of active forest restoration in remote regions of Amazonia. In 2017, naturally regenerating forests covered 234,795 km² of land across the Amazon, representing approximately 4% of the biome’s total forest cover, with approximately 75% of this area located in Brazil (188). These figures demonstrate the region’s inherent capacity for recovery, despite regional differences in recovery rates (189). However, forest regrowth is often short-lived, lasting an average of 8 years before being cleared again (188), so it is not widely recognized as a restoration strategy. Some communal territories such as Indigenous and Quilombola territories have contributed significantly to native vegetation regrowth (190). This situation highlights that, in many regions, the main issue is the lack of effective governance to enforce or incentivize conservation of these high-value forests (175).

Forest landscape restoration involves integrating trees into various systems (including agricultural lands) to restore and enhance ecological properties and diverse human benefits. Pastures are key, since they account for most of the converted areas in Amazonia [70% in the case of Brazil (191)] and are associated with environmental degradation, low income, and marginal productivity (192). Incentives promoting the resurgence of integrated agriculture, including agroforestry and other crop and livestock systems, could be developed through research programs, credit systems, payments for ecosystem services, and food safety regulations (193). Integrated production systems enhance biodiversity, ecosystem services, and ecological resilience of landscapes. Assisted natural regeneration, including enrichment planting with commercially viable species, is yet another promising approach that enhances biodiversity while providing economic benefits to local communities (175, 194).

Regardless of the chosen strategy, restoration initiatives must take into account the plurality of social actors involved (including gender, age, and power diversity), their interests, their capacities, and their level of participation. Biocultural restoration integrates ecological restoration with cultural practices and Indigenous knowledge, emphasizing the vital connection between biodiversity conservation and the cultural values of local communities (195). This approach has been proposed to restore Amazonian sustainable-use reserves degraded by fires (196). Because ecosystems and human cultures in the Amazon are deeply intertwined through a long evolutionary history (197), efforts to prevent undesirable ecological transitions must be codesigned with and implemented by those who manage and possess a deep understanding of Amazonian forests (196).

7. CONCLUSION: NAVIGATING A BETTER FUTURE FOR THE AMAZON

Numerous studies have documented substantial ecological shifts in the Amazon region, driven by deforestation, climate change, fire, and other anthropogenic stressors. In some landscapes, current levels of pressure are exceeding the capacity of Amazonian forests to regenerate and sustain their fundamental ecological functions. While the intensity, pace, and outcome of these transformations vary in different regions and contexts, the overall trajectory is clear: Without sustained conservation efforts and policy incentives, much larger portions of the forest will become impoverished.

From a scientific perspective, the critical questions are not whether changes to the health of tropical forests will occur, but whether these changes will unfold gradually or abruptly and whether they are transient or irreversible. Contemporary evidence suggests that multiple scenarios may unfold simultaneously in different regions. Some forests may remain largely intact, while others experience progressive declines in ecological integrity in response to stressors. Still others may undergo nonlinear responses, with feedback loops accelerating degradation severity. This underscores a critical point: There is little evidence for a single, basin-wide tipping point, but rather a series of localized changes in forest condition may differ substantially in scale, drivers, intensity, and timing. Recognizing this complexity highlights the urgency of every action—large or small, immediate or long term—to slow forest loss and enhance resilience.

Beyond the scientific debate on whether and how tipping points may unfold in the Amazon, a critical practical question remains: How does the concept of an Amazon tipping point—and the variability and uncertainty surrounding it—shape conservation strategies and policy decisions? While the term effectively conveys urgency, its broad and sometimes ambiguous usage can reduce its practical impact (198). Overemphasizing its imminence could inadvertently foster fatalism, reducing proactive responses (199), while framing it as a distant, catastrophic threshold downplays the reality that major ecological disruptions are already occurring. If the tipping point concept

is to meaningfully inform policy and conservation, it must be communicated in a way that not only highlights risks but also clarifies actionable pathways for intervention. The most effective messaging should strike a balance—conveying the immediacy of the threats while emphasizing the possibilities to act and implement solutions.

Regardless of whether changes occur gradually or abruptly, the environmental solutions remain consistent and require interventions that stabilize the global climate, strengthen environmental governance, curb local warming through deforestation control and restoration, and manage fire. These strategies are well-known, but implementing and sustaining them at scale remain a formidable challenge. Brazil's success in reducing deforestation serves as a positive example, but its subsequent setbacks in later governments provide a cautionary tale about the fragility of environmental gains. It also stresses the need for enduring political commitment involving Amazonia's decision-makers, a transformation of the region's economy, and grassroots leadership and social legitimacy.

While climate change and local disturbances are already driving large-scale negative transformations in the Amazon, the lack of evidence pointing to an imminent climate-driven forest collapse (in the absence of fire) also offers a crucial window of opportunity. The Amazon's fate is not preordained by a single tipping point, and the choices, policies, and actions taken today can steer the regions toward a more sustainable future.

SUMMARY POINTS

1. Amazonian forests are undergoing rapid and large-scale transformations, driven by the combined pressures of deforestation, climate change, fire, selective logging, and defaunation. These stressors interact across spatial and temporal scales, reshaping ecosystem structure, function, and dynamics.
2. There is no empirical evidence for a single, basin-wide tipping point, but critical thresholds are being crossed at regional and local levels. These include accelerated regional warming, shortened fire return intervals, cumulative canopy loss below thresholds needed to exclude flammable vegetation, high level of fragmentation that isolates forest patches and increases their exposure to edge effects, and defaunation that disrupts seed dispersal and overall forest regeneration. Crossing these thresholds undermines forest resilience and increases the likelihood of transitions toward degraded states.
3. Two distinct processes drive Amazonian forest to degraded states: the hammer effect—in which repeated, direct human disturbances such as deforestation, fire, and fragmentation progressively erode forest integrity—and the domino effect, in which feedbacks between vegetation and climate could trigger widespread, self-reinforcing degradation. While the domino effect remains a long-term concern, the hammer effect is the most immediate and preventable threat—and lies within the scope of national and subnational governance.
4. Ecological resilience remains high across much of the Amazon but is increasingly compromised in regions subject to repeated disturbances, to loss of ecological complexity, and to isolation of the remaining native vegetation. Most Earth system models likely underestimate this resilience by omitting key ecological information such as deep rooting trees, variation in species responses to disturbance, and animal–plant interactions that buffer against abrupt ecological shifts.

5. A critical window of opportunity remains open for safeguarding Amazon's resilience: Halting deforestation, managing fire, securing Indigenous land rights, and scaling up ecological restoration are viable and proven strategies that reduce the risk of irreversible change and enhance the Amazon's role in regulating global climate and sustaining biodiversity.

FUTURE DIRECTIONS

1. Forest–climate interactions: Further research should quantify mechanistically the climatic consequences of Amazon deforestation, incorporating the combined effects of evapotranspiration, biogenic volatile organic compounds, aerosols, cloud formation, and atmospheric moisture transport. Improved models and observational networks are needed to capture these interactions across spatial and temporal scales.
2. Forest sensitivity and adaptive capacity: Investigations should assess how past exposure to climate averages, climate variability, and disturbances influences species traits and adaptive capacity and how these combine with natural gradients in soils and edaphic conditions to govern forest sensitivity to future climate change and other disturbances.
3. Forest resilience and recovery: Further studies are needed to investigate how the ecological simplification resulting from deforestation, defaunation, and land-use intensity affects forest resilience and recovery potential, particularly through effects on regeneration dynamics, flammability, and heat and drought susceptibility and any resulting feedback loops. Distinguishing areas where natural regeneration is likely from those requiring active intervention is critical for prioritizing conservation and restoration efforts.
4. People–forest interactions: Future efforts should advance understanding of socioecological interactions that shape forest resilience, recognizing that, even where ecological conditions permit recovery, human decisions ultimately determine outcomes. Research should focus on how land-use practices, governance systems, and cultural values influence forest regeneration, fire use, and long-term ecosystem stability.
5. Solutions: Landscape-scale interventions that strengthen resilience, including targeted restoration, fire management, land-use zoning, and regulation of hunting and resource use, should be designed and evaluated. Research should identify social and institutional conditions that enable these interventions to succeed without compromising local livelihoods.

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AUTHOR CONTRIBUTIONS

P.M.B., J.B., M.N.M., D.S., H.S., and J.F. led the writing of the article. All authors contributed to the conceptualization and editing of the article. L.M., B.S., S.J., and N.P. contributed to analysis and figures.

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LITERATURE CITED

1. Chazdon RL. 2003. Tropical forest recovery: legacies of human impact and natural disturbances. *Perspect. Plant Ecol. Evol. Syst.* 6(1–2):51–71
2. Connell JH. 1978. Diversity in tropical rain forests and coral reefs: High diversity of trees and corals is maintained only in a nonequilibrium state. *Science* 199(4335):1302–10
3. Marra DM, Trumbore SE, Higuchi N, Ribeiro GHM, Negrón-Juárez RI, et al. 2018. Windthrows control biomass patterns and functional composition of Amazon forests. *Glob. Change Biol.* 24(12):5867–81
4. Lewis SL, Edwards DP, Galbraith D. 2015. Increasing human dominance of tropical forests. *Science* 349(6250):827–32
5. Chazdon RL, Arroyo-Mora JP. 2013. Tropical forests as complex adaptive systems. In *Managing World Forests as Complex Adaptive Systems in the Face of Global Change*, ed. C Messeier, KJ Puettmann, KD Coates, pp. 35–59. Routledge
6. Bush M, Flenley J, Gosling W, eds. 2011. *Tropical Rainforest Responses to Climatic Change*. Springer
7. Lapola DM, Pinho P, Barlow J, Aragão LEOC, Berenguer E, et al. 2023. The drivers and impacts of Amazon forest degradation. *Science* 379(6630):eabp8622
8. Nepstad DC, Stickler CM, Soares-Filho B, Merry F. 2008. Interactions among Amazon land use, forests and climate: prospects for a near-term forest tipping point. *Philos. Trans. R. Soc. B* 363(1498):1737–46
9. Trumbore S, Brando P, Hartmann H. 2015. Forest health and global change. *Science* 349(6250):814–18
10. Artaxo P, Hansson HC, Machado LAT, Rizzo LV. 2022. Tropical forests are crucial in regulating the climate on Earth. *PLOS Clim.* 1(8):e0000054
11. Barlow J, França F, Gardner TA, Hicks CC, Lennox GD, et al. 2018. The future of hyperdiverse tropical ecosystems. *Nature* 559(7715):517–26
12. Lovejoy TE, Nobre C. 2019. Amazon tipping point: last chance for action. *Sci. Adv.* 5(12):eaba2949
13. Nobre CA, Sampaio G, Borma LS, Castilla-Rubio JC, Silva JS, Cardoso M. 2016. Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. *PNAS* 113(39):10759–68
14. Malhi Y, Gardner TA, Goldsmith GR, Silman MR, Zelazowski P. 2014. Tropical forests in the Anthropocene. *Annu. Rev. Environ. Resour.* 39:125–59
15. Flores BM, Montoya E, Sakschewski B, Nascimento N, Staal A, et al. 2024. Critical transitions in the Amazon forest system. *Nature* 626(7999):555–64
16. Doughty CE, Keany JM, Wiebe BC, Rey-Sanchez C, Carter KR, et al. 2023. Tropical forests are approaching critical temperature thresholds. *Nature* 621(7977):105–11
17. Cochrane MA, Alencar A, Schulze MD, Souza CM, Nepstad DC, et al. 1999. Positive feedbacks in the fire dynamic of closed canopy tropical forests. *Science* 284(5421):1832–35
18. Staal A, Fetzer I, Wang-Erlandsson L, Bosmans JHC, Dekker SC, et al. 2020. Hysteresis of tropical forests in the 21st century. *Nat. Commun.* 11:4978

19. Aragão LEOC, Anderson LO, Fonseca MG, Rosan TM, Vedovato LB, et al. 2018. 21st century drought-related fires counteract the decline of Amazon deforestation carbon emissions. *Nat. Commun.* 9:536
20. Brando PM, Soares-Filho B, Rodrigues L, Assunção A, Morton D, et al. 2020. The gathering firestorm in southern Amazonia. *Sci. Adv.* 6(2):eaay1632
21. Gatti LV, Gloor M, Miller JB, Doughty CE, Malhi Y, et al. 2014. Drought sensitivity of Amazonian carbon balance revealed by atmospheric measurements. *Nature* 506(7486):76–80
22. Malhi Y, Roberts JT, Betts RA, Killeen TJ, Li W, Nobre CA. 2008. Climate change, deforestation, and the fate of the Amazon. *Science* 319(5860):169–72
23. Nobre CA, Sellers PJ, Shukla J. 1991. Amazonian deforestation and regional climate change. *J. Clim.* 4(10):957–88
24. Coe MT, Macedo MN, Brando PM, Lefebvre P, Panday P, Silvério D. 2016. The hydrology and energy balance of the Amazon Basin. In *Interactions Between Biosphere, Atmosphere and Human Land Use in the Amazon Basin*, ed. L Nagy, BR Forsberg, P Artaxo, pp. 35–53. Springer
25. Tavares JV, Oliveira RS, Mencuccini M, Signori-Müller C, Pereira L, et al. 2023. Basin-wide variation in tree hydraulic safety margins predicts the carbon balance of Amazon forests. *Nature* 617(7959):111–17
26. Cámara-Leret R, Fortuna MA, Bascompte J. 2019. Indigenous knowledge networks in the face of global change. *PNAS* 116(20):9913–18
27. Nascimento MN, Aukes TFN, McMichael CNH. 2024. Indigenous and colonial influences on Amazonian forests. *Plants People Planet* 6(4):803–23
28. Murcia C, Aronson J, Kattan GH, Moreno-Mateos D, Dixon K, Simberloff D. 2014. A critique of the “novel ecosystem” concept. *Trends Ecol. Evol.* 29(10):548–53
29. Shukla J, Nobre C, Sellers P. 1990. Amazon deforestation and climate change. *Science* 247(4948):1322–25
30. Salati E, Dall’Olio A, Matsui E, Gat JR. 1979. Recycling of water in the Amazon Basin: an isotopic study. *Water Resour. Res.* 15(5):1250–58
31. Uhl C, Buschbacher R. 1985. A disturbing synergism between cattle ranch burning practices and selective tree harvesting in the Eastern Amazon. *Biotropica* 17(4):265
32. Nepstad DC, De Carvalho CR, Davidson EA, Jipp PH, Lefebvre PA, et al. 1994. The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. *Nature* 372(6507):666–69
33. Nepstad DC, Verssimo A, Alencar A, Nobre C, Lima E, et al. 1999. Large-scale impoverishment of Amazonian forests by logging and fire. *Nature* 398(6727):505–8
34. Laurance WF, Delamônica P, Laurance SG, Vasconcelos HL, Lovejoy TE. 2000. Rainforest fragmentation kills big trees. *Nature* 404(6780):836–36
35. Cox PM, Betts RA, Collins M, Harris PP, Huntingford C, Jones CD. 2004. Amazonian forest dieback under climate-carbon cycle projections for the 21st century. *Theor. Appl. Climatol.* 78(1–3):137–56
36. Nepstad DC, Tóhver IM, Ray D, Moutinho P, Cardinot G. 2007. Mortality of large trees and lianas following experimental drought in an Amazon forest. *Ecology* 88(9):2259–69
37. Fisher RA, Williams M, Da Costa AL, Malhi Y, Da Costa RF, et al. 2007. The response of an Eastern Amazonian rain forest to drought stress: results and modelling analyses from a throughfall exclusion experiment. *Glob. Change Biol.* 13(11):2361–78
38. Phillips OL, Aragão LEOC, Lewis SL, Fisher JB, Lloyd J, et al. 2009. Drought sensitivity of the Amazon rainforest. *Science* 323(5919):1344–47
39. Lapola DM, Oyama MD, Nobre CA. 2009. Exploring the range of climate biome projections for tropical South America: the role of CO₂ fertilization and seasonality. *Glob. Biogeochem. Cycles* 23(3):2008GB003357
40. Rammig A, Jupp T, Thonicke K, Tietjen B, Heinke J, et al. 2010. Estimating the risk of Amazonian forest dieback. *New Phytol.* 187(3):694–706
41. Staver AC, Archibald S, Levin SA. 2011. The global extent and determinants of savanna and forest as alternative biome states. *Science* 334(6053):230–32
42. Hirota M, Holmgren M, Van Nes EH, Scheffer M. 2011. Global resilience of tropical forest and savanna to critical transitions. *Science* 334(6053):232–35
43. Brando PM, Balch JK, Nepstad DC, Morton DC, Putz FE, et al. 2014. Abrupt increases in Amazonian tree mortality due to drought-fire interactions. *PNAS* 111(17):6347–52

44. Brienens RJW, Phillips OL, Feldpausch TR, Gloor E, Baker TR, et al. 2015. Long-term decline of the Amazon carbon sink. *Nature* 519(7543):344–48
45. Gatti LV, Basso LS, Miller JB, Gloor M, Gatti Domingues L, et al. 2021. Amazonia as a carbon source linked to deforestation and climate change. *Nature* 595(7867):388–93
46. Barlow J, Lennox GD, Ferreira J, Berenguer E, Lees AC, et al. 2016. Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation. *Nature* 535(7610):144–47
47. Lovejoy TE, Nobre C. 2018. Amazon tipping point. *Sci. Adv.* 4(2):eaat2340
48. Gholz HL, Ewel KC, Teskey RO. 1990. Water and forest productivity. *Forest Ecol. Manag.* 30(1–4):1–18
49. Jordan CF. 1982. The nutrient balance of an Amazonian rain forest. *Ecology* 63(3):647–54
50. Nepstad D, Carvalho G, Barros AC, Alencar A, Capobianco JP, et al. 2001. Road paving, fire regime feedbacks, and the future of Amazon forests. *Forest Ecol. Manag.* 154(3):395–407
51. Salati E, Vose PB. 1984. Amazon Basin: a system in equilibrium. *Science* 225(4658):129–38
52. Lewis SL, Brando PM, Phillips OL, van der Heijden GMF, Nepstad D. 2011. The 2010 Amazon drought. *Science* 331:554
53. Anderson LO, Ribeiro Neto G, Cunha AP, Fonseca MG, Mendes De Moura Y, et al. 2018. Vulnerability of Amazonian forests to repeated droughts. *Philos. Trans. R. Soc. B* 373(1760):20170411
54. Feldpausch TR, Phillips OL, Brienens RJW, Gloor E, Lloyd J, et al. 2016. Amazon forest response to repeated droughts. *Glob. Biogeochem. Cycles* 30(7):964–82
55. McDowell N, Allen CD, Anderson-Teixeira K, Brando P, Brienens R, et al. 2018. Drivers and mechanisms of tree mortality in moist tropical forests. *New Phytol.* 219(3):851–69
56. Da Costa ACL, Galbraith D, Almeida S, Portela BTT, Da Costa M, et al. 2010. Effect of 7 yr of experimental drought on vegetation dynamics and biomass storage of an eastern Amazonian rainforest. *New Phytol.* 187(3):579–91
57. Brum M, Vadeboncoeur MA, Ivanov V, Asbjornsen H, Saleska S, et al. 2019. Hydrological niche segregation defines forest structure and drought tolerance strategies in a seasonal Amazon forest. *J. Ecol.* 107(1):318–33
58. Oliveira RS, Dawson TE, Burgess SSO, Nepstad DC. 2005. Hydraulic redistribution in three Amazonian trees. *Oecologia* 145(3):354–63
59. Markewitz D, Devine S, Davidson EA, Brando P, Nepstad DC. 2010. Soil moisture depletion under simulated drought in the Amazon: impacts on deep root uptake. *New Phytol.* 187(3):592–607
60. Brando PM, Nepstad DC, Davidson EA, Trumbore SE, Ray D, Camargo P. 2008. Drought effects on litterfall, wood production and belowground carbon cycling in an Amazon forest: results of a throughfall reduction experiment. *Philos. Trans. R. Soc. B* 363(1498):1839–48
61. Meir P, Mencuccini M, Dewar RC. 2015. Drought-related tree mortality: addressing the gaps in understanding and prediction. *New Phytol.* 207(1):28–33
62. Rowland L, Da Costa ACL, Galbraith DR, Oliveira RS, Binks OJ, et al. 2015. Death from drought in tropical forests is triggered by hydraulics not carbon starvation. *Nature* 528(7580):119–22
63. Esquivel-Muelbert A, Baker TR, Dexter KG, Lewis SL, Brienens RJW, et al. 2019. Compositional response of Amazon forests to climate change. *Glob. Change Biol.* 25(1):39–56
64. Uribe MDR, Coe MT, Castanho ADA, Macedo MN, Valle D, Brando PM. 2023. Net loss of biomass predicted for tropical biomes in a changing climate. *Nat. Clim. Change* 13(3):274–81
65. Longo M, Keller M, Kueppers LM, Bowman KW, Csillik O, Ferraz A, et al. 2025. Degradation and deforestation increase the sensitivity of the Amazon Forest to climate extremes. *Environ. Res. Lett.* 20(5):054024
66. Rappaport DI, Morton DC, Longo M, Keller M, Dubayah R, dos-Santos MN. 2018. Quantifying long-term changes in carbon stocks and forest structure from Amazon forest degradation. *Environ. Res. Lett.* 13(6):065013
67. Silvério DV, Brando PM, Balch JK, Putz FE, Nepstad DC, et al. 2013. Testing the Amazon savannization hypothesis: fire effects on invasion of a neotropical forest by native cerrado and exotic pasture grasses. *Philos. Trans. R. Soc. B* 368(1619):20120427
68. Brando P, Macedo M, Silvério D, Rattis L, Paolucci L, et al. 2020. Amazon wildfires: scenes from a foreseeable disaster. *Flora* 268:151609

69. IPCC. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC
70. Alencar AAC, Arruda VLS, Silva WVD, Conciani DE, Costa DP, et al. 2022. Long-term Landsat-based monthly burned area dataset for the Brazilian biomes using deep learning. *Remote Sens.* 14(11):2510
71. Silva CVJ, Aragão LEOC, Barlow J, Espirito-Santo F, Young PJ, et al. 2018. Drought-induced Amazonian wildfires instigate a decadal-scale disruption of forest carbon dynamics. *Philos. Trans. R. Soc. B* 373(1760):20180043
72. Staver AC, Brando PM, Barlow J, Morton DC, Paine CET, et al. 2020. Thinner bark increases sensitivity of wetter Amazonian tropical forests to fire. *Ecol. Lett.* 23(1):99–106
73. Flores BM, Fagoaga R, Nelson BW, Holmgren M. 2016. Repeated fires trap Amazonian blackwater floodplains in an open vegetation state. *J. Appl. Ecol.* 53(5):1597–603
74. Pontes-Lopes A, Silva CVJ, Barlow J, Rincón LM, Campanharo WA, et al. 2021. Drought-driven wildfire impacts on structure and dynamics in a wet Central Amazonian forest. *Proc. R. Soc. B* 288(1951):20210094
75. Artaxo P, Hansson H-C, Andreae MO, Bäck J, Alves EG, et al. 2022. Tropical and boreal forest-atmosphere interactions: a review. *Tellus B* 74(1):24–163
76. Flores BM, Staal A. 2022. Feedback in tropical forests of the Anthropocene. *Glob. Change Biol.* 28(17):5041–61
77. Zemp DC, Schleussner C-F, Barbosa HMJ, Hirota M, Montade V, et al. 2017. Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks. *Nat. Commun.* 8:14681
78. Spracklen DV, Garcia-Carreras L. 2015. The impact of Amazonian deforestation on Amazon basin rainfall. *Geophys. Res. Lett.* 42(21):9546–52
79. Berbet MLC, Costa MH. 2003. Climate change after tropical deforestation: seasonal variability of surface albedo and its effects on precipitation change. *J. Clim.* 16(12):2099–104
80. Smith C, Baker JCA, Spracklen DV. 2023. Tropical deforestation causes large reductions in observed precipitation. *Nature* 615(7951):270–75
81. Curtius J, Heinritzi M, Beck LJ, Pöhlker ML, Tripathi N, et al. 2024. Isoprene nitrates drive new particle formation in Amazon's upper troposphere. *Nature* 636(8041):124–30
82. Machado LAT, Unfer GR, Brill S, Hildmann S, Pöhlker C, et al. 2024. Frequent rainfall-induced new particle formation within the canopy in the Amazon rainforest. *Nat. Geosci.* 17(12):1225–32
83. Bochow N, Boers N. 2023. The South American monsoon approaches a critical transition in response to deforestation. *Sci. Adv.* 9(40):eadd9973
84. Luo X, Ge J, Guo W, Fan L, Chen C, et al. 2022. The biophysical impacts of deforestation on precipitation: results from the CMIP6 model intercomparison. *J. Clim.* 35(11):3293–311
85. Li Y, Brando PM, Morton DC, Lawrence DM, Yang H, Randerson JT. 2022. Deforestation-induced climate change reduces carbon storage in remaining tropical forests. *Nat. Commun.* 13:1964
86. Wunderling N, Von Der Heydt AS, Aksenov Y, Barker S, Bastiaansen R, et al. 2024. Climate tipping point interactions and cascades: a review. *Earth Syst. Dyn.* 15(1):41–74
87. Li Y, Baker JCA, Brando PM, Hoffman FM, Lawrence DM, et al. 2023. Future increases in Amazonia water stress from CO₂ physiology and deforestation. *Nat. Water* 1(9):769–77
88. Cox PM, Betts RA, Jones CD, Spall SA, Totterdell IJ. 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature* 408(6809):184–87
89. Cox PM, Betts RA, Betts A, Jones CD, Spall SA, Totterdell IJ. 2002. Modelling vegetation and the carbon cycle as interactive elements of the climate system. *Int. Geophys.* 83:259–79
90. Phillips OL, Lewis SL, Baker TR, Chao K-J, Higuchi N. 2008. The changing Amazon forest. *Philos. Trans. R. Soc. B* 363(1498):1819–27
91. Slot M, Winter K. 2016. The effects of rising temperature on the ecophysiology of tropical forest trees. In *Tropical Tree Physiology*, ed. G Goldstein, LS Santiago, pp. 385–412. Springer International Publishing
92. Galbraith D, Levy PE, Sitch S, Huntingford C, Cox P, et al. 2010. Multiple mechanisms of Amazonian forest biomass losses in three dynamic global vegetation models under climate change. *New Phytol.* 187(3):647–65
93. Alencar AA, Brando P, Asner GP, Putz FE. 2015. Landscape fragmentation, severe drought, and the new Amazon forest fire regime. *Ecol. Appl.* 25(6):1493–505

94. Ray D, Nepstad D, Moutinho P. 2005. Micrometeorological and canopy controls of fire susceptibility in a forested Amazon landscape. *Ecol. Appl.* 15(5):1664–78
95. Barlow J, Peres CA. 2008. Fire-mediated dieback and compositional cascade in an Amazonian forest. *Philos. Trans. R. Soc. B* 363(1498):1787–94
96. Brando PM, Nepstad DC, Balch JK, Bolker B, Christman MC, et al. 2012. Fire-induced tree mortality in a neotropical forest: the roles of bark traits, tree size, wood density and fire behavior. *Glob. Change Biol.* 18(2):630–41
97. Nepstad D, Soares-Filho B, Merry F, Lima A, Moutinho P, et al. 2008. The end of deforestation in the Brazilian Amazon. *Science* 326:1350–51
98. Balch JK, Brando PM, Nepstad DC, Coe MT, Silvério D, et al. 2015. The susceptibility of southeastern Amazon forests to fire: insights from a large-scale burn experiment. *BioScience* 65(9):893–905
99. Brando PM, Silvério D, Maracahipes-Santos L, Oliveira-Santos C, Levick SR, et al. 2019. Prolonged tropical forest degradation due to compounding disturbances: implications for CO₂ and H₂O fluxes. *Glob. Change Biol.* 25(9):2855–68
100. D'Antonio CM, Vitousek PM. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. *Annu. Rev. Ecol. Syst.* 23:63–87
101. Silvério DV, Oliveira RS, Flores BM, Brando PM, Almada HK, et al. 2022. Intensification of fire regimes and forest loss in the Território Indígena do Xingu. *Environ. Res. Lett.* 17(4):045012
102. Pereira CA, Barlow J, Tabarelli M, Giles AL, Ferreira AEDM, Vieira ICG. 2024. Recurrent wildfires alter forest structure and community composition of terra firme Amazonian forests. *Environ. Res. Lett.* 19(11):114051
103. Tosca MG, Randerson JT, Zender CS. 2013. Global impact of smoke aerosols from landscape fires on climate and the Hadley circulation. *Atmos. Chem. Phys.* 13(10):5227–41
104. Kolusu SR, Marsham JH, Mulcahy J, Johnson B, Dunning C, et al. 2015. Impacts of Amazonia biomass burning aerosols assessed from short-range weather forecasts. *Atmos. Chem. Phys.* 15(21):12251–66
105. Magahey S, Kooperman GJ. 2023. Isolating the effect of biomass burning aerosol emissions on 20th century hydroclimate in South America and Southeast Asia. *Environ. Res. Lett.* 18(10):104029
106. Herbert R, Stier P. 2023. Satellite observations of smoke-cloud-radiation interactions over the Amazon rainforest. *Atmos. Chem. Phys.* 23(7):4595–616
107. Longo M, Saatchi S, Keller M, Bowman K, Ferraz A, et al. 2020. Impacts of degradation on water, energy, and carbon cycling of the Amazon tropical forests. *JGR Biogeosci.* 125(8):e2020JG005677
108. Baker JCA, Spracklen DV. 2022. Divergent representation of precipitation recycling in the Amazon and the Congo in CMIP6 models. *Geophys. Res. Lett.* 49(10):e2021GL095136
109. Worden J, Saatchi S, Keller M, Bloom AA, Liu J, et al. 2021. Satellite observations of the tropical terrestrial carbon balance and interactions with the water cycle during the 21st century. *Rev. Geophys.* 59(1):e2020RG000711
110. Saatchi S, Longo M, Xu L, Yang Y, Abe H, et al. 2021. Detecting vulnerability of humid tropical forests to multiple stressors. *One Earth* 4(7):988–1003
111. Liu J, Bowman KW, Schimel DS, Parazoo NC, Jiang Z, et al. 2017. Contrasting carbon cycle responses of the tropical continents to the 2015–2016 El Niño. *Science* 358(6360):eaam5690
112. Saatchi S, Asefi-Najafabady S, Malhi Y, Aragão LEOC, Anderson LO, et al. 2013. Persistent effects of a severe drought on Amazonian forest canopy. *PNAS* 110(2):565–70
113. Asefi-Najafabady S, Saatchi S. 2013. Response of African humid tropical forests to recent rainfall anomalies. *Philos. Trans. R. Soc. B* 368(1625):20120306
114. Cook BI, Mankin JS, Marvel K, Williams AP, Smerdon JE, Anchukaitis KJ. 2020. Twenty-first century drought projections in the CMIP6 forcing scenarios. *Earth's Future* 8(6):e2019EF001461
115. Dobler A, Benestad RE, Lussana C, Landgren O. 2024. CMIP6 models project a shrinking precipitation area. *NPJ Clim. Atmos. Sci.* 7(1):239
116. Hubau W, Lewis SL, Phillips OL, Affum-Baffoe K, Beeckman H, et al. 2020. Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature* 579(7797):80–87
117. Malhi Y, Adu-Bredu S, Asare RA, Lewis SL, Mayaux P. 2013. African rainforests: past, present and future. *Philos. Trans. R. Soc. B* 368(1625):20120312

118. Berzaghi F, Verbeeck H, Nielsen MR, Doughty CE, Bretagnolle F, et al. 2018. Assessing the role of megafauna in tropical forest ecosystems and biogeochemical cycles: the potential of vegetation models. *Ecography* 41(12):1934–54
119. Berzaghi F, Longo M, Ciais P, Blake S, Bretagnolle F, et al. 2019. Carbon stocks in central African forests enhanced by elephant disturbance. *Nat. Geosci.* 12(9):725–29
120. Campos-Arceiz A, Blake S. 2011. Megagardeners of the forest: the role of elephants in seed dispersal. *Acta Oecol.* 37(6):542–53
121. ForestPlots.net, Blundo C, Carilla J, Grau R, Malizia A, et al. 2021. Taking the pulse of Earth's tropical forests using networks of highly distributed plots. *Biol. Conserv.* 260:108849
122. Cooper DLM, Lewis SL, Sullivan MJP, Prado PI, Ter Steege H, et al. 2024. Consistent patterns of common species across tropical tree communities. *Nature* 625(7996):728–34
123. Shapiro A, d'Annunzio R, Desclée B, Jungers Q, Kondjo HK, et al. 2023. Small scale agriculture continues to drive deforestation and degradation in fragmented forests in the Congo Basin (2015–2020). *Land Use Policy* 134:106922
124. Tyukavina A, Hansen MC, Potapov P, Parker D, Okpa C, et al. 2018. Congo Basin forest loss dominated by increasing smallholder clearing. *Sci. Adv.* 4(11):eaat2993
125. Marengo JA, Jimenez JC, Espinoza J-C, Cunha AP, Aragão LEO. 2022. Increased climate pressure on the agricultural frontier in the Eastern Amazonia–Cerrado transition zone. *Sci. Rep.* 12(1):457
126. Silvério DV, Brando PM, Macedo MN, Beck PSA, Bustamante M, Coe MT. 2015. Agricultural expansion dominates climate changes in southeastern Amazonia: the overlooked non-GHG forcing. *Environ. Res. Lett.* 10(10):104015
127. Almada HK, Macedo MN, Lenza E, Maracahipes L, Silvério DV. 2024. Indigenous lands and conservation units slow down non-GHG climate change in the Cerrado-Amazon ecotone. *Perspect. Ecol. Conserv.* 22(2):177–85
128. Marengo JA, Souza CM, Thonicke K, Burton C, Halladay K, et al. 2018. Changes in climate and land use over the Amazon region: current and future variability and trends. *Front. Earth Sci.* 6:228
129. Chen Y, Randerson JT, Morton DC, DeFries RS, Collatz GJ, et al. 2011. Forecasting fire season severity in South America using sea surface temperature anomalies. *Science* 334(6057):787–91
130. Chen Y, Morton DC, Andela N, Giglio L, Randerson JT. 2016. How much global burned area can be forecast on seasonal time scales using sea surface temperatures? *Environ. Res. Lett.* 11(4):045001
131. Libonati R, Geirinhas JL, Silva PS, Russo A, Rodrigues JA, et al. 2022. Assessing the role of compound drought and heatwave events on unprecedented 2020 wildfires in the Pantanal. *Environ. Res. Lett.* 17(1):015005
132. Panday PK, Coe MT, Macedo MN, Lefebvre P, de Almeida Castanho AD. 2015. Deforestation offsets water balance changes due to climate variability in the Xingu River in eastern Amazonia. *J. Hydrol.* 523:822–29
133. Chiang F, Mazdiyasi O, AghaKouchak A. 2021. Evidence of anthropogenic impacts on global drought frequency, duration, and intensity. *Nat. Commun.* 12:2754
134. Duque A, Stevenson PR, Feeley KJ. 2015. Thermophilization of adult and juvenile tree communities in the northern tropical Andes. *PNAS* 112(34):10744–49
135. Balch JK, Nepstad DC, Brando PM, Curran LM, Portela O, et al. 2008. Negative fire feedback in a transitional forest of southeastern Amazonia. *Glob. Change Biol.* 14(10):2276–87
136. Brando P, Oliveria-Santos C, Rocha W, Cury R, Coe MT. 2016. Effects of experimental fuel additions on fire intensity and severity: unexpected carbon resilience of a neotropical forest. *Glob. Change Biol.* 22(7):2516–25
137. Silvério DV, Brando PM, Bustamante MMC, Putz FE, Marra DM, et al. 2019. Fire, fragmentation, and windstorms: a recipe for tropical forest degradation. *J. Ecol.* 107(2):656–67
138. De Faria BL, Brando PM, Macedo MN, Panday PK, Soares-Filho B, Coe MT. 2017. Current and future patterns of fire-induced forest degradation in Amazonia. *Environ. Res. Lett.* 12(9):095005
139. Davidson EA, De Araújo AC, Artaxo P, Balch JK, Brown IF, et al. 2012. The Amazon basin in transition. *Nature* 481(7381):321–28

140. Da Silva SS, Numata I, Fearnside PM, De Alencastro Graça PML, Ferreira E JL, et al. 2020. Impact of fires on an open bamboo forest in years of extreme drought in southwestern Amazonia. *Reg. Environ. Change* 20(4):127
141. Matricardi EAT, Skole DL, Costa OB, Pedlowski MA, Samek JH, Miguel EP. 2020. Long-term forest degradation surpasses deforestation in the Brazilian Amazon. *Science* 369(6509):1378–82
142. Laurance WF, Curran TJ. 2008. Impacts of wind disturbance on fragmented tropical forests: a review and synthesis. *Austral Ecol.* 33(4):399–408
143. Carvalho CDS, García C, Lucas MS, Jordano P, Côrtes MC. 2021. Extant fruit-eating birds promote genetically diverse seed rain, but disperse to fewer sites in defaunated tropical forests. *J. Ecol.* 109(2):1055–67
144. Pinho BX, Melo FPL, Ter Braak CJF, Bauman D, Maréchaux I, et al. 2025. Winner-loser plant trait replacements in human-modified tropical forests. *Nat. Ecol. Evol.* 9:282–95
145. Scheffer M, Bascompte J, Brock WA, Brovkin V, Carpenter SR, et al. 2009. Early-warning signals for critical transitions. *Nature* 461(7260):53–59
146. Boulton CA, Lenton TM, Boers N. 2022. Pronounced loss of Amazon rainforest resilience since the early 2000s. *Nat. Clim. Change* 12(3):271–78
147. Van Passel J, Bernardino PN, Lhermitte S, Rius BF, Hirota M, et al. 2024. Critical slowing down of the Amazon forest after increased drought occurrence. *PNAS* 121(22):e2316924121
148. Wang H, Ciais P, Sitch S, Green JK, Tao S, et al. 2024. Anthropogenic disturbance exacerbates resilience loss in the Amazon rainforests. *Glob. Change Biol.* 30(1):e17006
149. Berenguer E, Lennox GD, Ferreira J, Malhi Y, Aragão LEOC, et al. 2021. Tracking the impacts of El Niño drought and fire in human-modified Amazonian forests. *PNAS* 118(30):e2019377118
150. Silva CHL Jr., Aragão LEOC, Anderson LO, Fonseca MG, Shimabukuro YE, et al. 2020. Persistent collapse of biomass in Amazonian forest edges following deforestation leads to unaccounted carbon losses. *Sci. Adv.* 6(40):eaaz8360
151. Poorter L, Craven D, Jakovac CC, Van Der Sande MT, Amissah L, et al. 2021. Multidimensional tropical forest recovery. *Science* 374(6573):1370–76
152. Elias F, Ferreira J, Lennox GD, Berenguer E, Ferreira S, et al. 2020. Assessing the growth and climate sensitivity of secondary forests in highly deforested Amazonian landscapes. *Ecology* 101(3):e02954
153. Hawes JE, Vieira ICG, Magnago LFS, Berenguer E, Ferreira J, et al. 2020. A large-scale assessment of plant dispersal mode and seed traits across human-modified Amazonian forests. *J. Ecol.* 108(4):1373–85
154. Vieira DLM, Scariot A. 2006. Principles of natural regeneration of tropical dry forests for restoration. *Restor. Ecol.* 14(1):11–20
155. Jakovac CC, Junqueira AB, Crouzeilles R, Peña-Claros M, Mesquita RCG, Bongers F. 2021. The role of land-use history in driving successional pathways and its implications for the restoration of tropical forests. *Biol. Rev.* 96(4):1114–34
156. Chazdon RL, Brancalion PHS, Laestadius L, Bennett-Curry A, Buckingham K, et al. 2016. When is a forest a forest? Forest concepts and definitions in the era of forest and landscape restoration. *Ambio* 45(5):538–50
157. Heinrich VHA, Vancutsem C, Dalagnol R, Rosan TM, Fawcett D, et al. 2023. The carbon sink of secondary and degraded humid tropical forests. *Nature* 615(7952):436–42
158. Lyra A, Imbach P, Rodriguez D, Chou SC, Georgiou S, Garofolo L. 2017. Projections of climate change impacts on central America tropical rainforest. *Clim. Change* 141(1):93–105
159. Ritchie PDL, Parry I, Clarke JJ, Huntingford C, Cox PM. 2022. Increases in the temperature seasonal cycle indicate long-term drying trends in Amazonia. *Commun. Earth Environ.* 3(1):199
160. Berenguer E, Gardner TA, Ferreira J, Aragão LEOC, Mac Nally R, et al. 2018. Seeing the woods through the saplings: using wood density to assess the recovery of human-modified Amazonian forests. *J. Ecol.* 106(6):2190–203
161. Berenguer E, Ferreira J, Gardner TA, Aragão LEOC, De Camargo PB, et al. 2014. A large-scale field assessment of carbon stocks in human-modified tropical forests. *Glob. Change Biol.* 20(12):3713–26
162. Elias F, Marimon BH Jr., De Oliveira FJM, De Oliveira JCA, Marimon BS. 2019. Soil and topographic variation as a key factor driving the distribution of tree flora in the Amazonia/Cerrado transition. *Acta Oecol.* 100:103467

163. Paolucci LN, Pereira RL, Rattis L, Silvério DV, Marques NCS, et al. 2019. Lowland tapirs facilitate seed dispersal in degraded Amazonian forests. *Biotropica* 51(2):245–52
164. Wotton DM, Kelly D. 2011. Frugivore loss limits recruitment of large-seeded trees. *Proc. R. Soc. B* 278(1723):3345–54
165. Lemos MC, Agrawal A. 2006. Environmental governance. *Annu. Rev. Environ. Resour.* 31:297–325
166. Nepstad D, McGrath D, Stickler C, Alencar A, Azevedo A, et al. 2014. Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *Science* 344(6188):1118–23
167. Lambin EF, Furumo PR. 2023. Deforestation-free commodity supply chains: myth or reality? *Annu. Rev. Environ. Resour.* 48:237–61
168. Furumo PR, Lambin EF. 2021. Policy sequencing to reduce tropical deforestation. *Glob. Sustain.* 4:e24
169. Duchelle AE, Seymour F, Brockhaus M, Angelsen A, Larson AM, et al. 2019. *Forest-Based Climate Mitigation: Lessons from REDD+ Implementation*. World Resources Institute
170. Sze JS, Childs DZ, Carrasco LR, Edwards DP. 2022. Indigenous lands in protected areas have high forest integrity across the tropics. *Curr. Biol.* 32(22):4949–56.e3
171. Walker WS, Gorelik SR, Baccini A, Aragon-Osejo JL, Josse C, et al. 2020. The role of forest conversion, degradation, and disturbance in the carbon dynamics of Amazon indigenous territories and protected areas. *PNAS* 117(6):3015–25
172. Barretto Filho HT, Ramos A, Sobral Barra C, Barroso M, Caron P, et al. 2021. Strengthening land and natural resource governance and management: protected areas, Indigenous lands, and local communities' territories. In *Amazon Assessment Report 2021*, ed. C Nobre, A Encalada, E Anderson, FH Roca Alcazar, M Bustamante, et al., Chapter 31. UN Sustainable Development Solutions Network (SDSN). 1st ed.
173. Bergamo D, Zerbini O, Pinho P, Moutinho P. 2022. The Amazon bioeconomy: beyond the use of forest products. *Ecol. Econ.* 199:107448
174. Ferreira J, Coudel E, Abramovay R, Barlow J, Garrett R, et al. 2024. A lack of clarity on the bioeconomy concept might be harmful for Amazonian ecosystems and its people. *Ecol. Econ.* 224:108299
175. Vieira ICG, Fernandes DA, Araújo R, Freitas MAB, Brandão F. 2024. Scaling up sociobioeconomy in the Amazon: opportunities and risks. *One Earth* 7(11):1908–12
176. Garrett R, Ferreira J, Abramovay R, Brandão J, Brondizio E, et al. 2024. Transformative changes are needed to support socio-bioeconomies for people and ecosystems in the Amazon. *Nat. Ecol. Evol.* 8(10):1815–25
177. Stabile MCC, Guimarães AL, Silva DS, Ribeiro V, Macedo MN, et al. 2020. Solving Brazil's land use puzzle: increasing production and slowing Amazon deforestation. *Land Use Policy* 91:104362
178. Nasi R, Frost PGH. 2009. Sustainable forest management in the tropics: Is everything in order but the patient still dying? *Ecol. Soc.* 14(2):40
179. Putz FE, Romero C, Sist P, Schwartz G, Thompson I, et al. 2022. Sustained timber yield claims, considerations, and tradeoffs for selectively logged forests. *PNAS Nexus* 1(3):pgac102
180. Assis TO, De Aguiar APD, Von Randow C, Melo de Paula Gomes D, Kury JN, et al. 2020. CO₂ emissions from forest degradation in Brazilian Amazon. *Environ. Res. Lett.* 15(10):104035
181. Carmenta R, Vermeylen S, Parry L, Barlow J. 2013. Shifting cultivation and fire policy: insights from the Brazilian Amazon. *Hum. Ecol.* 41(4):603–14
182. Barlow J, Parry L, Gardner TA, Ferreira J, Aragão LEOC, et al. 2012. The critical importance of considering fire in REDD+ programs. *Biol. Conserv.* 154:1–8
183. Nóbrega Spínola J, Soares Da Silva MJ, Assis Da Silva JR, Barlow J, Ferreira J. 2020. A shared perspective on managing Amazonian sustainable-use reserves in an era of megafires. *J. Appl. Ecol.* 57(11):2132–38
184. Crouzeilles R, Beyer HL, Monteiro LM, Feltran-Barbieri R, Pessôa ACM, et al. 2020. Achieving cost-effective landscape-scale forest restoration through targeted natural regeneration. *Conserv. Lett.* 13(3):e12709
185. Miranda LDS, Awade M, Jaffé R, Costa WF, Trevelin LC, et al. 2021. Combining connectivity and species distribution modeling to define conservation and restoration priorities for multiple species: a case study in the eastern Amazon. *Biol. Conserv.* 257:109148

186. Urzedo D, Piña-Rodrigues F, Feltran-Barbieri R, Junqueira R, Fisher R. 2020. Seed networks for upscaling forest landscape restoration: Is it possible to expand native plant sources in Brazil? *Forests* 11(3):259
187. Barlow J, Sist P, Almeida R, Arantes C, Berenguer E, et al. 2021. Restoration priorities and benefits within landscapes and catchments and across the Amazon Basin. In *Amazon Assessment Report 2021*, ed. C Nobre, A Encalada, E Anderson, FH Roca Alcazar, M Bustamante, et al., Chapter 29. UN SDSN. 1st ed.
188. Smith CC, Healey JR, Berenguer E, Young PJ, Taylor B, et al. 2021. Old-growth forest loss and secondary forest recovery across Amazonian countries. *Environ. Res. Lett.* 16(8):085009
189. Elias F, Ferreira J, Resende AF, Berenguer E, França F, et al. 2022. Comparing contemporary and life-time rates of carbon accumulation from secondary forests in the eastern Amazon. *Forest Ecol. Manag.* 508:120053
190. Alves-Pinto HN, Cordeiro CLO, Geldmann J, Jonas HD, Gaiarsa MP, et al. 2022. The role of different governance regimes in reducing native vegetation conversion and promoting regrowth in the Brazilian Amazon. *Biol. Conserv.* 267:109473
191. MapBiomias. 2023. *Annual land cover and land use maps of Brazil: Collection 8*. MapBiomias. https://brasil.mapbiomas.org/wp-content/uploads/sites/4/2023/09/Fact_ing_versao-final.pdf
192. Garrett RD, Gardner TA, Morello TF, Marchand S, Barlow J, et al. 2017. Explaining the persistence of low income and environmentally degrading land uses in the Brazilian Amazon. *Ecol. Soc.* 22(3):27
193. Garrett RD, Ryschawy J, Bell LW, Cortner O, Ferreira J, et al. 2020. Drivers of decoupling and recoupling of crop and livestock systems at farm and territorial scales. *Ecol. Soc.* 25(1):24
194. Paquette A, Hawryshyn J, Senikas AV, Potvin C. 2009. Enrichment planting in secondary forests: a promising clean development mechanism to increase terrestrial carbon sinks. *Ecol. Soc.* 14(1):31
195. Loch VDC, Celentano D, Carvalho Saraiva RV, Alvarado ST, de Freitas Berto F, et al. 2023. Forest species for biocultural restoration in eastern Amazon, Brazil. *Ethnobiol. Conserv.* 12. <https://doi.org/10.15451/ec2023-02-12.03-1-15>
196. Pereira CA, Tabarelli M, Barros MF, Vieira ICG. 2023. Restoring fire-degraded social forests via biocultural approaches: a key strategy to safeguard the Amazon legacy. *Restor. Ecol.* 31(8):e13976
197. Levis C, Rezende JS, Barreto JPL, Barreto SS, Baniwa F, et al. 2024. Indigenizing conservation science for a sustainable Amazon. *Science* 386(6727):1229–32
198. Kopp RE, Gilmore EA, Shwom RL, Adams H, Adler C, et al. 2025. “Tipping points” confuse and can distract from urgent climate action. *Nat. Clim. Change* 15:29–36
199. Nabi RL, Gustafson A, Jensen R. 2018. Framing climate change: exploring the role of emotion in generating advocacy behavior. *Sci. Commun.* 40(4):442–68