SCIENCE PANEL FOR THE AMAZON

POLICY BRIEF

NINE WAYS TO AVOID THE AMAZON TIPPING POINT

Bernardo M. Flores, Adriane Esquivel-Muelbert*, Marco Ehrlich*, Emilio Vilanova, Raquel Chaves, Marina Hirota, Michelle Kalamandeen* | ***Co-lead authors**

KEY MESSAGES

(i) Global greenhouse gas emissions, combined with local deforestation and forest degradation, are pushing the Amazonian system closer to a tipping point. Climatic and land-use disturbances are already weakening moisture flow across the Amazon, reducing forest resilience downwind and increasing the risk of forest collapse in peripheral and central parts of the biome. This increases the risk of crossing a large-scale tipping point.

(ii) A large-scale Amazon tipping point may trigger the collapse of most forests and consequently: (1) accelerate global warming, hindering efforts to achieve the goals of the Paris Agreement; (2) reduce moisture flow across South America, threatening water security for basic socioeconomic activities, such as agriculture; (3) increase temperatures across the Amazon region that may become unbearable for humans living in urban and rural areas; (4) cause mass species extinctions; and (5) compromise the biological and cultural assets that represent key solutions to the current and future challenges of humanity.

(iii) Synergies between disturbances may cause unexpected tipping behaviour, even in forest regions previously considered as resilient to climate change, such as the central or western Amazon. Current climate models of the IPCC AR6 agree that a large-scale tipping point of the Amazon system is unlikely to be crossed within this or the next century, but these models ignore the multiple interactions and synergies between climate and land-use disturbances (e.g., simultaneous heat waves, prolonged and extreme droughts, and forest fires).

RECOMMENDATIONS

To reduce the likelihood of reaching a large-scale tipping of the Amazon forest system, actions that strengthen forest resilience are urgently needed (for detail list see section D):

(i) Act at global, regional, and local scales to drastically reduce greenhouse gas emissions, to stop deforestation, forest degradation, and wildfires.

(ii) Implement large scale restoration (natural regeneration and reforestation) along an 'Arc of Restoration' will strengthen forest-rainfall feedback across the Amazon, reducing the risk of tipping events and improving forest connectivity across the Andes-Amazonian frontier.

(iii) Recognize and strengthen the leadership role of Indigenous peoples and local communities in Amazonian governance, given their diverse ecological knowledge, practices, and biocultural connections that increase forest resilience to global changes. This involves expanding Indigenous territories and sustainable-use protected areas, strengthening Indigenous and environmental agencies, and including the effective participation of Indigenous peoples and local communities in decision-making processes.

(iv) Monitor Amazonian forest dynamics and responses to environmental stress (e.g., thermal and water stress) and disturbances (e.g., deforestation and degradation due to illegal logging and forest fires), to provide timely information that can help strengthen local governance. This requires investing in research focusing on the impacts of compounding, synergistic disturbances on forest resilience.

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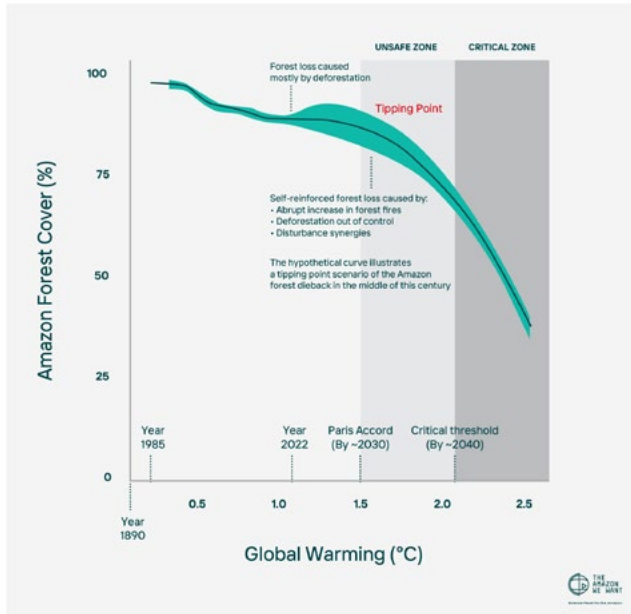
GRAPHICAL ABSTRACT. Nine ways to avoid the Amazon tipping point.

A. THE LARGEST AND MOST DIVERSE TROPICAL FOREST ON THE PLANET AT RISK

The Amazon forest system has a key role in regulating the global climate system[1,2], but there is a growing concern that it may cross a tipping point within this century (see Box 1), potentially leading to drastic and irreversible ecosystem shifts. An Amazon forest collapse, even if partial, would have severe consequences to biodiversity, the livelihoods of Indigenous peoples and local communities, and the persistence of Earth's current climatic conditions. It would disrupt the hydrological cycle of large parts of South America, threatening water supplies for millions of people within and outside the Amazon, in regions such as the Andes, the La Plata Basin, and the Pantanal wetlands. It would exacerbate extreme hydrological events, such as floods and droughts[3.] Forest loss across the Amazon would also increase regional temperatures, making it unbearable for humans in both urban and rural areas[4,5].

The region is home to over 47 million people, including 410 Indigenous groups with diverse cultures and knowledge systems. These groups are deeply interconnected with Amazonian ecosystems, which allows them to quickly identify changes and become early warning voices against deforestation, degradation, climate change, biodiversity loss, and ecological transitions. Indigenous peoples are therefore key for developing mitigation and adaptation strategies in the face of global changes[6,7].

BOX 1: Tipping point is a threshold value of a stressing condition at which a given system is unstable, and a small change in conditions could cause the whole system to shift abruptly into an alternative stable state[8]. As a system approaches a tipping point, it gradually loses resilience while still persisting in a certain state, until suddenly collapsing into a contrasting state. Such tipping behaviour depends on the existence of positive feedback mechanisms, which are self-reinforcing interactions that cause small changes to intensify, spread, or accelerate[9]. **An Amazonian tipping point** is a value of a stressor (e.g., thermal or water stress) beyond which the forest would irreversibly collapse, locally or at larger scale (i.e., systemically), shifting into an open vegetation (non-forested) state.



BOX FIGURE. **Potential irreversible collapse of the Amazon forest triggered by a tipping point in global warming.** Increased temperatures are already changing the Amazon's regional climate, exposing forests to increasing water stress. In addition, synergies between the impacts of global warming and deforestation, and associated disturbances, such as extreme droughts and forest fires, may anticipate the collapse of the system. The hypothetical curve illustrates a tipping point scenario for Amazon forest dieback in the middle of this century.

B. DRIVERS OF STRESS AND THE POTENTIAL OF REACHING CRITICAL THRESHOLDS

Greenhouse gas emissions and **deforestation** are the two main drivers of stresses on the Amazonian system. Independently or combined, these drivers can lead to drastic changes in three key mechanisms that shape Amazonian resilience:

1. Global warming: Some models indicate a potential large-scale tipping point of the Amazon forest at a critical threshold, somewhere between 2°C and 6°C of global warming[10]. Increasing mean global temperature causes climatic conditions to change in the Amazon region, which is projected to become warmer and drier (with the exception of the north-western Amazon), causing widespread water stress.

2. Rainfall conditions: Three potential critical thresholds in rainfall conditions can result in a tipping point related to water stress: (1) annual rainfall below 1,000 mm; (2) annual maximum cumulative water deficit (MCWD, a proxy for seasonality intensity) greater than 450 mm; (3) dry season length above 6-8 months[11-13].

3. Forest cover and landscape connectivity: At the Amazon biome scale, forest cover loss beyond 20% (20-50%) may weaken basin-wide forest-rainfall feedback, likely accelerating regional climatic changes and potentially causing more forest loss due to water stress[13,14]. At landscape scales, empirical evidence suggests that forest loss beyond 70% could be a critical threshold for the collapse of ecological integrity in tropical forests, with most vertebrate species disappearing[15]. Parts of the Amazon forest within deforestation frontiers are close to or may have already crossed this critical threshold[5]. Andes-Amazon connectivity is particularly critical for animal mobility and enabling species to migrate to climatic refuges[16,17].

BOX 2: Feedbacks that can accelerate a large-scale tipping point

Global-warming and carbon emissions feedback: Global warming is projected to increase drought regimes and temperatures across the Amazon[2], which is confirmed by current satellite observations of climatic conditions[18]. These changes are already increasing tree mortality rates[19] and fire incidence[20], causing south-eastern Amazonian forests to shift from a carbon sink to a carbon source[21,22]. Greenhouse gas emissions increase from both above- and below-ground sources, particularly from wetlands[23]. For example, with increasing droughts, at least 5 Pg of carbon stored in peatlands and wetlands of the Peruvian Amazon could be released to the atmosphere, further accelerating global warming[24].

Forest-rainfall feedback: Through the process of evapotranspiration, trees cool the lower atmosphere and transfer moisture from the ground to the atmosphere, increasing humidity. Consequently, this increases rainfall amount and stability, at the local and regional scale, via atmospheric circulation[25,26]. This is the mechanism by which the forest itself generates much of its own rain, and that of other regions. Accumulated deforestation may weaken this positive feedback and reduce rainfall in the southern and south-western parts of the Amazon forest, which are the most vulnerable to the cascading effects of deforestation on moisture flow[25,26]. Tree mortality as a result of water stress would further accentuate regional climatic changes, weakening forest-rainfall feedback and reducing moisture flow to other regions, such as the Andes, La Plata Basin, and Pantanal wetlands.

Tree cover and fire feedback: Disturbances that open the forest canopy (e.g., logging) and allow grasses to expand can increase forest flammability. As grasses are more flammable, fires can spread more frequently, which in turn prevents tree recruitment, maintaining the ecosystem in an open vegetation state[27,28].

C. OBSERVED EVIDENCE OF AN APPROACHING TIPPING POINT

1. Compounding disturbances may accelerate change. Forests may become increasingly overwhelmed with compounding disturbances related to climate and land-use changes. When compounding disturbances interact, powerful synergistic effects may emerge (e.g., by simultaneous heatwaves, extreme droughts, and forest fires) and cause unexpected tipping behaviour[29], even in regions previously considered resilient. Dry-season mean temperature is already 2°C higher today than 40 years ago in most of the Amazon18. Currently, 16% of the Amazon has been deforested and 17% of remaining forests have been degraded by compounding human disturbances[30,31], a statistic that reaches 38% if we consider degradation by repeated extreme drought events (e.g., in 2005, 2010, 2014-16, and 2023)[32]. Even remote parts of the central Amazon are now exposed to warming temperatures, repeated extreme drought events, and wildfires, making them vulnerable to ecosystem transition in the coming decades[8,18,30]. The current 2023 El Niño is demonstrating how these synergies can be destructive for the forest, its fauna, and local human societies.

2. Forests are going through ecological transitions. Tree mortality rates are increasing in most parts of the Amazon[33], and drought-affiliated tree species are becoming more abundant, changing forest composition and functioning[34]. Trees in the southern fringes of the Amazon are operating beyond their physiological thresholds (hydraulic-safety margin) in terms of water availability[35]. In floodplain forests, wildfires are facilitating the expansion of white-sand savanna ecosystems, with major shifts in the species of trees, birds, and fish[36-38].

FIGURE 1. **Causes, drivers, and solutions that affect the risk of reaching Amazon tipping points.** The causes - greenhouse gas emissions and land-use changes - weaken the forest-rainfall feedback; i.e., forest loss contributes to climatic changes that further increase forest loss (Box 2), thus reducing forest resilience. The solutions - increased governance for reduced emissions and land-use changes - strengthen the forest-rainfall feedback, thus increasing forest resilience.

3. Amazonian forests are losing resilience. Forest resilience is declining in three-quarters of the Amazon biome, as indicated by observations of satellite data revealing a phenomenon known as 'critical slowing down', suggesting that the system might be approaching a tipping point[39].

4. Disturbed forests struggle to recover. Approximately 4% of Amazonian forests are in a secondary forest state[40], but the recovery of these forests is uncertain, as some areas may persist in a degraded state for decades or even centuries[41-43] as a consequence of positive feedbacks[9] (Box 2). Some examples are forests dominated by Vismia trees, bamboos, and lianas, which are expanding as a result of forest fires and other disturbances4[4-46]. Within agricultural frontiers, flammable alien grasses contribute to the spread of repeated fires, with at least 5% of landscapes in the southern Amazon maintaining an open-canopy degraded state[47,48].

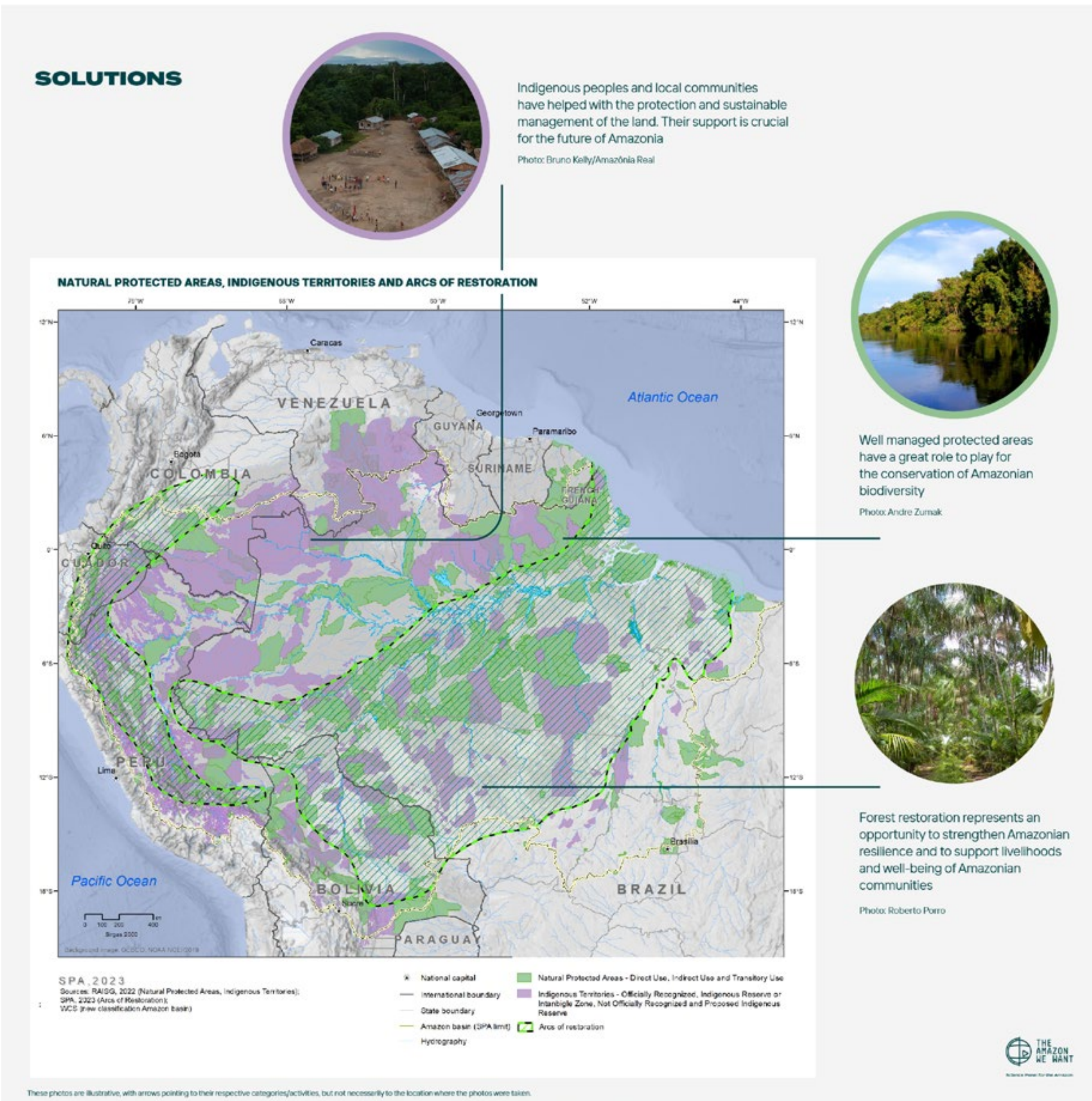


FIGURE 2. Solutions to avoid the Amazon tipping point include creating and maintaining Protected Areas and Indigenous Territories, as well as supporting large-scale restoration.

5. Landscapes have lost critical connectivity. Deforestation in the Colombian portion of the Andes-Amazon frontier is disrupting animal mobility[49], threatening climate-sensitive species' survival in the coming decades, including plant species that depend on animals for dispersal and pollination[9]. Hydroelectric dam construction along the Andes-Amazon frontier also threatens the mobility of migratory fish, as well as sediment and nutrient flow, causing food insecurity for local people and affecting floodplain ecosystems[50], for instance, by causing mass tree mortality[51].

D. SOLUTIONS FOR MITIGATION AND ADAPTATION

Actions that strengthen forest resilience are urgently needed if we are to follow a precautionary approach, mitigate the main drivers of stress, and increase the adaptability of the forest and local societies to avoid Amazonian tipping-points.

1. Drastically reducing global greenhouse gas emissions is a key first step to mitigate global climate change and its impacts on Amazonian climatic conditions.

2. Ending large-scale deforestation, degradation, and forest fires in the Amazon is equally important to mitigate changes in Amazonian climatic conditions. This requires novel policies to address the main drivers of deforestation, degradation, and forest fires in each Amazonian country, and coordination among Amazonian countries to prevent the internationalization of illegal land markets[52].

3. Restoring abandoned and degraded forests at large scales is crucial to maintain Amazonian climatic conditions[53]. This requires facilitating passive restoration by avoiding deforestation of secondary forests, and active reforestation to promote the recovery of degraded forests by planting diverse combinations of native tree species with economic potential[54].

4. Creating and maintaining protected areas and Indigenous territories is an effective and low-cost action that contributes significantly to reducing deforestation and fires[55-57]. Constitutional demarcation and the provision of legal rights to Indigenous and local communities' lands is a key step to strengthening the resilience of both the biological and cultural assets of Amazonian ecosystems.

5. Investing in science, technology and innovation can strengthen Amazonian resilience. A better understanding of the complexity of the Amazon through long-term monitoring and data-enabled models will help predict how the system will respond to global changes and to synergistic effects of climatic and land-use disturbances. Ultimately, protecting the Amazon requires transdisciplinary research, produced through ethical and fair approaches, across multiple knowledge systems, and including perspectives from Indigenous and local communities[58]. This requires improving the scientific capacity of research institutions in the Amazon.

6. Strengthening the participation of civil society organizations in environmental decision making is necessary to maintain a resilient governance system. When public policies from government institutions fail, civil society organizations can act to maintain and/or strengthen Amazonian governance.

7. Developing a sustainable socio-bioeconomy of healthy standing forests and flowing rivers can contribute to empower Indigenous peoples and local communities that retain the ancient ecological knowledge about Amazonian socio-biodiversity[59]. This requires developing supply and value chains with sustainable infrastructure logistics[60], connecting remote communities and markets, as well as sustainable harvesting initiatives[61].

8. Maintaining forest connectivity across the Andes-Amazonian frontier is vital to ensure species' resilience; past climactic change events have demonstrated that animal mobility is key for guaranteeing access to climate refuges, with the Andes acting as the cradle of Amazonian biodiversity[16].

9. Including the fundamental rights of the Amazon in the constitution of Amazonian countries. Countries should follow the example of Ecuador, which enshrined the rights of nature in its constitution, and Bolivia and Colombia, which have created legal and jurisprudential support for the rights of nature. Such practices can be effective legal instruments to protect landscapes, ecosystems, rivers, mountains, species, and other elements of the social-ecological system from destructive human activities, while also adopting a systemic perspective that understands all beings are interconnected.

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AUTHORS AFFILIATIONS

Bernardo Flores: Federal University of Santa Catarina, Graduate Program in Ecology, Florianópolis, Brazil, mflores.bernardo@gmail.com

Adriane Esquivel-Muelbert: School of Geography, Earth and Environmental Sciences, University of Birmingham, UK and Birmingham Institute of Forest Research (BIFoR), University of Birmingham, UK. a.esquivelmuelbert@bham.ac.uk

Marco Ehrlich: Universidad El Bosque, Av. Cra. 9 No. 131 A – 02, Bogotá, Colombia, marcoehrlich58@gmail.com

Emilio Vilanova: Wildlife Conservation Society (WCS). 2300 Southern Boulevard. Bronx, New York 10460.

Raquel Sousa Chaves: Universidade de Brasília, Department of Anthropology, Brasilia – DF, Brazil ; leadership of the Tupinambá people of Tapajós

Marina Hirota: Federal University of Santa Catarina, Department of Physics. Florianópolis, SC, Brazil

Michelle Kalamandeen: School of Earth and Environment, McMaster University, 1280 Main St W, Hamilton, ON L8S 4L8, Canada