SCIENCE PANEL FOR THE AMAZON

POLICY BRIEF

THE AMAZON WE WANT

Science Panel for the Amazon

DROUGHTS IN THE AMAZON

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KEY MESSAGES

- Strong droughts in the Amazon have been increasing in frequency and intensity, from four in a century to four in less than 25 years, in concert with increasing deforestation and global warming. The synergy of droughts, deforestation, fire, and forest degradation have the potential to drive the Amazon to a tipping point where this globally important ecosystem may significantly reduce its capacity to provide critical services such as water recycling, carbon storage, and provision of goods for human well-being.

- Droughts increase tree mortality, and thus biomass loss, imperiling the functioning of the carbon sink provided by tree growth. Droughts also increase animal mortality, especially when river levels decrease abruptly and when forests are disturbed by fire and forest degradation.

- Droughts increase the risk of fires, with direct impacts such as carbon emissions and the loss of biodiversity and ecosystem services, while also threatening human health and food security and feedbacking to global warming.

- The socioeconomic impacts of droughts are large, and result in social, cultural and economic vulnerability. The impacts include threats to water security and quality, food security, public health, human rights, local-to-large scale economies, mobility, energy production, river bank stability, and human migrations.

- The impacts of droughts vary in nature and intensity across social communities (e.g., Indigenous, afro-descendant, *ribeirinhos, caboclos*, etc.), predominant economic activities (e.g., fishing, farming, extractivism, urban services), gender, age, and the regional differences between countries and the Amazon regions (e.g., lowlands, Amazonian Andes, and foothills).

- There are critical gaps to the knowledge required for planning future and immediate responses to climate crises. These include the lack of comprehensive monitoring of Amazonian forests, climate, and hydrology to inform adaptation programs, and the lack of social, economic, cultural, and demographic data at local and regional scales, especially concerning vulnerable populations.

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RECOMMENDATIONS

- Adopt immediately the UNFCCC Paris Agreement targets for reducing carbon emissions to slow down the increasing frequency of droughts. At the same time, redirect subsidies and public and private investments from carbon-intensive activities to those that conserve nature reserves and restore forests, and increase budget allocations for adaptation and management of catastrophes.

- Stop deforestation and forest degradation, and establish a program to identify priority areas that require immediate conservation, and reinforce the protection of those already formally protected, including Indigenous lands and the buffer-zones around protected areas. All these actions are needed to guarantee the water production of the Amazon forests and to reduce the occurrence of low flows of rivers.

- Promote the creation of new climate-smart jobs in the conservation sector to generate alternative revenue streams. One such alternative is the adoption of diversified agroforestry and agroecological systems as part of restoration processes, improving food security, natural resources management, and alternative livelihoods.

- Implement monitoring programs and early warning systems for droughts, including:

  - Global and regional Earth System models and continental hydrological models from the Andes to the Atlantic oceans

  - Detection of early signs of animal and vegetation stress due to droughts;

  - Policy harmonization on integrated fire management, and real-time fire monitoring and data sharing across jurisdictions.

- Implement the mandates established in 2022 by the UNFCCC regarding the human rights-based and climate justice approach. Assess the vulnerability and exposure of populations through an intersectoral approach for the design of policies; actions should be grounded in a comprehensive understanding of the local realities of different socio-economic groups and regions.

- Implement the Loss and Damage and the Adaptation Funds, and improve funding for actions on drought mitigation and adaptation through international and national funds. Special attention is required for programs focused on:

  - Training, education, fire vigilance, and firefighting;

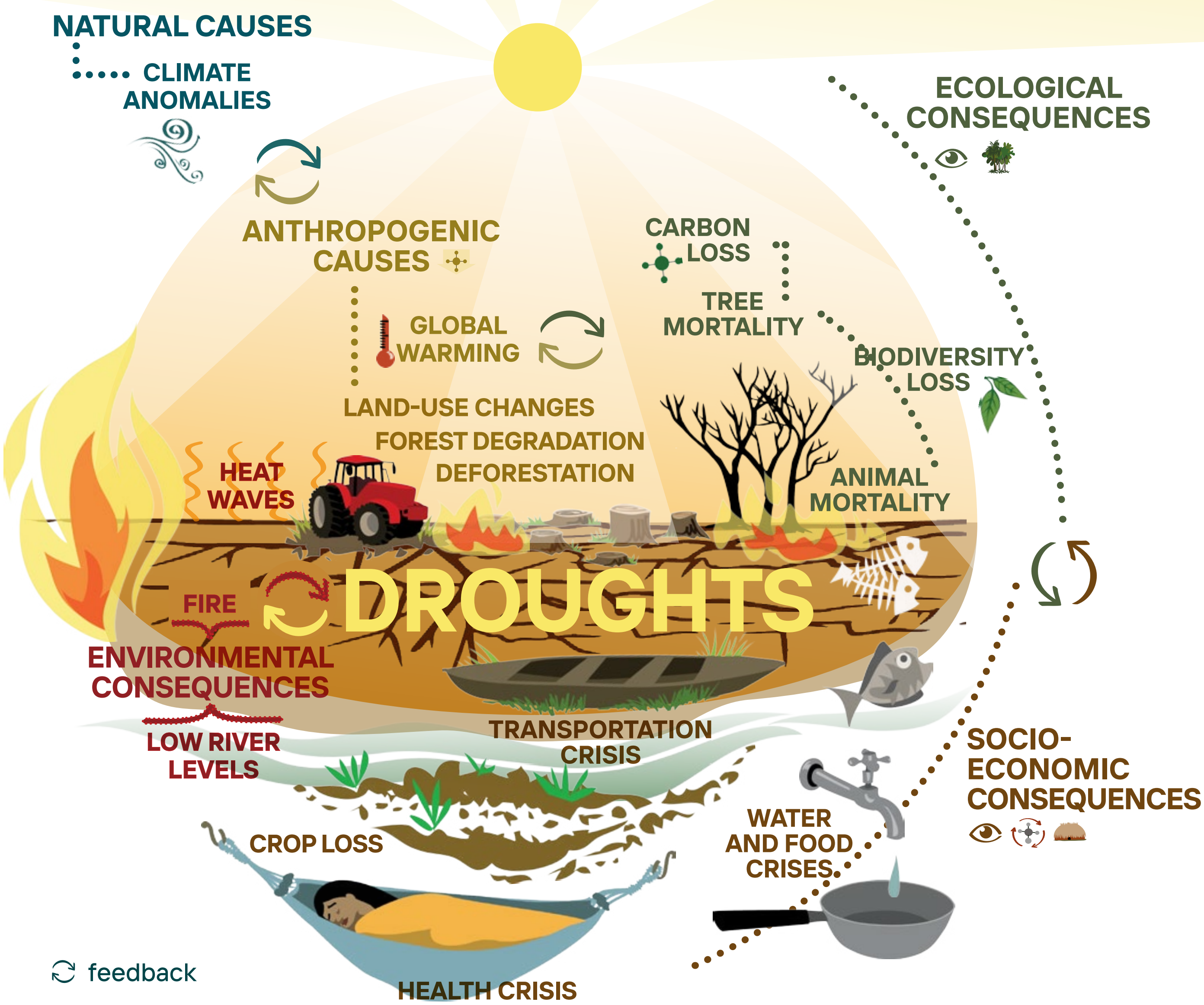
  - Developments on science, technology, and innovation for better water treatment strategies and higher storage capacities;

  - Improving food security at local scales;

  - Science, technology, and monitoring on diseases born or aggravated by droughts.

- Invest in capacity building of local people and governments to directly access diverse financial mechanisms for adaptation, and in co-production of solutions with local rural and urban populations to manage drought-caused disasters. Prioritize research and monitoring efforts to fill environmental, ecological, and socioeconomic data gaps.

GRAPHICAL ABSTRACT



ACTIONS NEEDED:

PREVENTION & MITIGATION

- Immediate reduction of greenhouse gas emissions (Paris Agreement targets).
- Redirect investments from carbon-intensive to carbon-free economic activities.
- New conservation areas on forests with higher potential to survive droughts and forest restoration in degraded lands.
- Reinforcement of conservation areas & indigenous territories
- Investiments in monitoring and understanding of drought impacts and causes.

ADAPTATION

- Implement the Loss and Damage and the Adaptation Funds
- Programs on fire control, water storage and treatment, food security and drought-borne disease monitoring and control
- Capacity building and co-production of solutions with local rural and urban populations to manage drought-caused disasters

1. CLIMATIC AND HYDROLOGICAL DYNAMICS

Natural causes of droughts. Since the beginning of the 21st century four extreme droughts have occurred in the Amazon. These droughts were each classified as a "one-in-a-100-year event" at the time of occurrence, and yet, each was surpassed by the next one [1–4]. Most of the severe droughts in the Amazonian region are associated with anomalous sea surface temperatures (SST) in the Equatorial Pacific, known as the El Niño event. However, droughts in 2005 and 2010 were largely induced by high SST anomalies in the Tropical North Atlantic (TNA). Both El Niño and warm TNA inhibit rainfall over the Amazon [5,6]. Another contributor to droughts is the warm phase of the Atlantic Multidecadal Oscillation (AMO) [6,7], characterized by a cyclical variation of the large-scale oceanic and atmospheric conditions in the TNA. The majority (80%) of the historical severe hydrological droughts in the Amazon basin coincide with warm phases of AMO (1925-1970 and since 1995), weakening in the moisture transport into and inside the Amazon east of the Andes by means of atmospheric rivers ("flying rivers")[8,9] **(BOX 1).** The atmospheric rivers transport a tremendous amount of water in the form of vapor, greater even than the flow of 19 Gt of water out of the Amazon River itself.

Natural climatic variability vs human induced droughts. Although droughts have a natural climatological component and have always happened in the Amazon, the frequency and intensity of droughts are increasing, mostly due to human-induced global warming, deforestation, and forest degradation [10]. Modeling and observational studies suggest that the Amazonian droughts occur via a decline in precipitation and late onset of the rainy season (longer dry season) during El Niño and/or TNA years. On the other hand, increasing global mean surface temperature (i.e. global warming) reduces precipitation and strongly elevates local temperatures, thus increasing water loss through increasing evapotranspiration, leading to the large water deficits in terrestrial and aquatic systems [11]. Climate change has increased the likelihood of hydrological droughts (which impact river flow) by a factor of 10, while agricultural droughts (which impact agricultural activities) have become about 30 times more likely [11]. Moreover, multiple years of deforestation in the Amazon have produced extensive dry land surfaces, where extensive pastures and croplands significantly reduce water return to the atmosphere when vegetation senesces in the dry season. These contribute ~4% to the atmospheric drying trend, with deforestation-drought feedback increasing as deforestation accumulates [12,13].

In 2023, the Amazon experienced an extreme drought and warmth situation. The integrated drought index (combining meteorological, hydrological, and agricultural droughts) of 2023 was classified as severe-extreme in the Western Amazon region of Brazil, over the Bolivian and Peruvian Amazon regions, and extending to most of the Amazon south of 5°S (**Figure 1 a, b**) [2]. A recent study shows that the transition from La Niña in 2022 to El Niño in 2023 is related to this historical event [2]. In addition, an exceptionally warm TNA [2] and the background global warming signal [12] exacerbated the El Niño impacts over the region during the austral winter and Spring of 2023, such that El Niño and climate change were each responsible for 50% of the precipitation reduction.

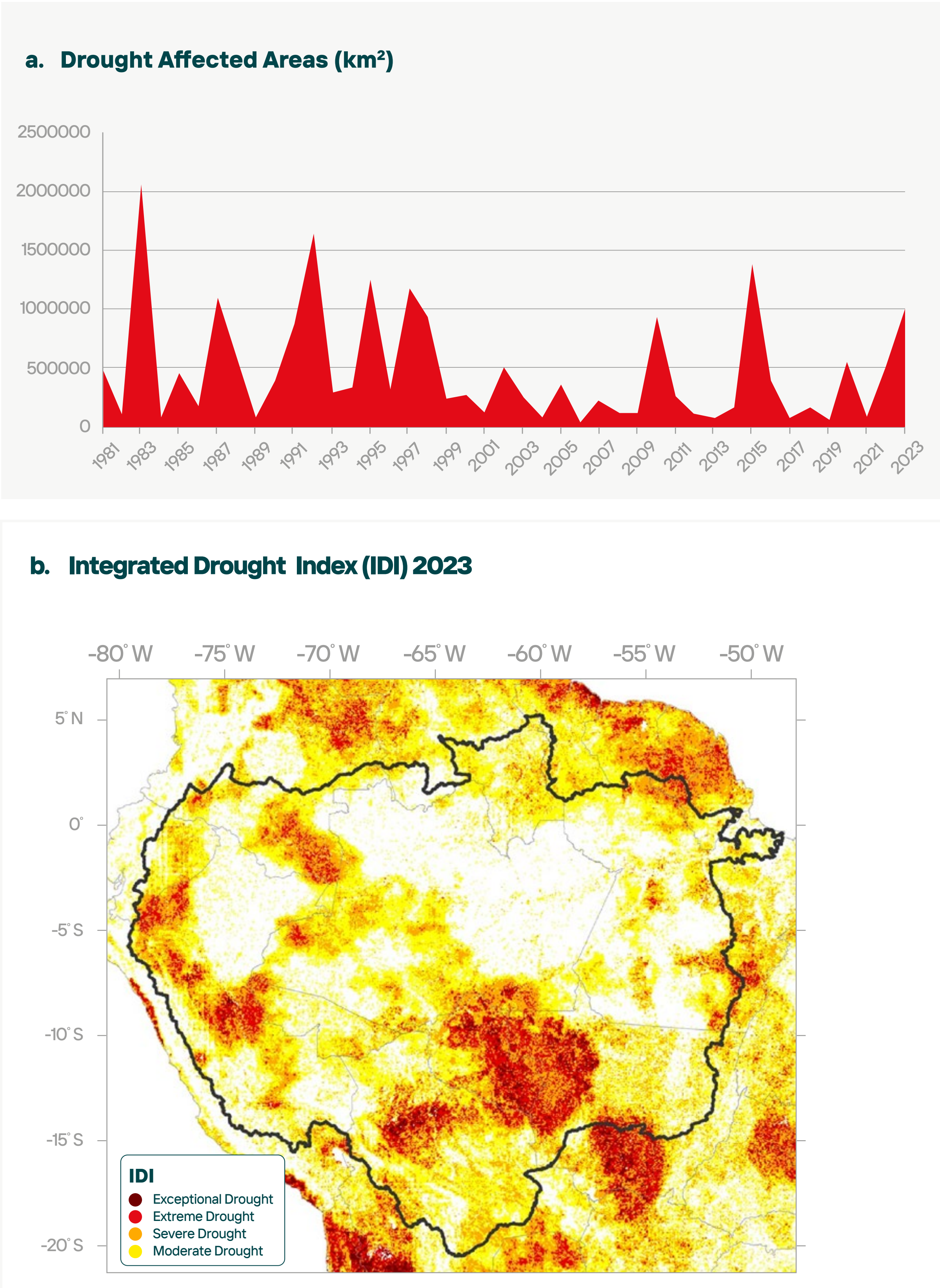


FIGURE 1. a) Area affected by droughts in the Amazonian region since 1981; b) areas affected by hydrological drought as represented by the Integrated Drought Index (IDI [99]), using SPI-12. The IDI combines the Standardized Precipitation Index (SPI), and Available Soil Water (ASW) together with the Vegetation Water Supply Index (VSWI) and thus represents the response of meteorological, hydrological, and agricultural droughts.

BOX 1. DEFINITIONS

Agricultural drought: conditions that result in adverse crop responses, usually because of limited soil moisture and high transpiration demand to plants.

Atlantic Multidecadal Oscillation (AMO): the AMO is an ongoing series of long-duration changes in the sea surface temperature of the North Atlantic Ocean, with cool and warm phases that may last for 20-40 years at a time and a difference of about 1°F between extremes. These changes are natural and have been occurring for at least the last 1,000 years (https://www.aoml.noaa.gov/phod/amo_faq.php)

Atmospheric rivers ("flying rivers"): relatively long, narrow regions in the atmosphere – like rivers in the sky – that transport most of the water vapor outside of the tropics. (https://www.noaa.gov/stories/what-are-atmospheric-rivers)

Drought: a period of abnormally dry weather sufficiently long to cause a serious hydrological imbalance. From a climatic point of view, a drought results from a shortfall in precipitation over an extended period of time, from the inadequate timing of precipitation relative to the needs of the vegetation cover, or from a negative water balance due to an increased potential evapotranspiration caused by high temperatures [97].

El Niño: refers to a above-average warming of the sea surface temperatures, in the central and eastern tropical Pacific Ocean. This leads to the low-level surface winds, which normally blow from east to west along the equator ("easterly winds"), to instead weaken or, in some cases, start blowing the other direction. El Niño recurs irregularly, from two years to a decade, and no two events are exactly alike. El Niño events can disrupt normal weather patterns globally. (https://www.usgs.gov/faqs/what-el-nino-and-what-are-its-effects)

Hydrological drought: prolonged period of below-normal precipitation, causing deficiencies in water supply, as measured by below-normal stream flow, lake and reservoir levels, groundwater levels, and depleted soil moisture content.

Hydraulic failure: the loss of the capacity to conduct water through the plant vessels beyond a threshold for survival, that occurs during drought-induced water stress.

Igapó: vegetation that is seasonally flooded by river waters poor in sediments and nutrients, descending from the Guiana and Brazilian Shields.

La Niña: refers to the periodic cooling of ocean surface temperatures in the central and east-central equatorial Pacific. Typically, La Niña events occur every 3 to 5 years or so, but on occasion can occur over successive years. La Niña represents the cool phase of the El Niño cycle (https://www.weather.gov/iwx/la_nina)

Mega-wildfires: fires spreading over 10,000 ha or more, arising from single or multiple related ignition events [98].

Sea Surface Temperatures (SST): sea surface temperature (SST) is defined as the temperature of the top few millimeters of the ocean. (https://ecowatch.noaa.gov/thematic/sea-surface-temperature)

Tipping-point: for a system that has been disturbed, this is the point of no-return to the original conditions. Here, it applies to the point beyond which large areas of the Amazon no longer have sufficient rainfall to support broadleaf evergreen forests.

Várzea: Vegetation that is seasonally flooded by river waters rich in sediments and nutrients, descending from the Andes.

However, the strong water deficits in land and aquatic systems were almost entirely due to increased global temperature [11]. The intensity of the 2015-16 drought has also been linked to anthropogenic causes [14].

Impacts on river levels and air temperature. Over the last 120 years, 18 severe floods and 12 extreme hydrological droughts have been recorded at the port of Manaus, the only available series of Amazonian water levels that spans more than 100 years [1–3]. Analysis of this dataset indicates a significant trend of increasing frequency and magnitude of extreme floods over the last 120 years, including the largest water level ever measured in Manaus in 2021 [3]. On the other hand, no long-term trend is identified regarding increasing hydrological droughts, although the number of extreme droughts has increased since 1995: six extreme droughts occurred between 1995 and 2023, compared to seven in the whole period of 1903-1994 [2]. Considering the critical level of emergency at the Manaus port for floods (>29 m) and hydrological droughts (<15.8 m), there is a significant increase of the annual amplitude of about 150 cm during the last 30 years, compared to the period before (**Figure 2a**). Regarding the duration of emergency of both extremes, until the 1990s, hydrological droughts had more impacts on riverine populations than floods, while floods have been stronger in the 21st century. The mean duration of flood emergencies is in general longer (53 ± 24 days) compared to droughts (36 ± 19 days).

This scenario was changed by the 2023-24 drought. Most of the main rivers in the Amazon, including the Solimões, Purus, Acre, and Branco rivers all suffered from extreme drops in their levels, or just simply dried up. In October 2023, the Rio Negro level in Manaus recorded its lowest level since measurements began in September 1902, 12.70m (the average annual minimum water level was 17.64 m for the 1902-2022 period). In the Peruvian Amazon, the Huallaga River at Tingo María showed an anomaly of -45% in the discharge in October 2023. The Mamoré-Guaporé and Madeira rivers in Bolivian territory remained very low due to deficient rainfall from July 2022 to June 2023. Generally, droughts related to El Niño events have a greater effect on rivers with headwaters in the northern hemisphere, as the period of reduced rainfall coincides with the natural low water period. However, the 2023 drought started much earlier due to the many synergetic effects reviewed above, and thus affected a broader range of rivers across the Amazon.

All the study regions in the Amazon have evidence of statistically significant warming trends during the last four decades (**Figure 2b**). Warming trends are higher for the Sep-Oct-Nov season than for the Jun-Jul-Aug season, and higher for the Southern and Eastern than the Northern and Western Amazon. Although the time series shows peaks of increased temperatures related to different drought episodes, it was in 2023 when the highest values of positive air temperature anomalies were observed [2]. Six heat waves during the 6-month period between June and November of 2023 in the western and northern regions exacerbated the effects of the lack of precipitation. The southwestern Amazon had a warmer austral winter and spring due to heat domes of hot and dry air. Maximum temperatures were between +2°C to +5°C above average over the affected Brazilian states of Amazonas, Rondônia, Roraima, and Acre in Sep-Oct-Nov

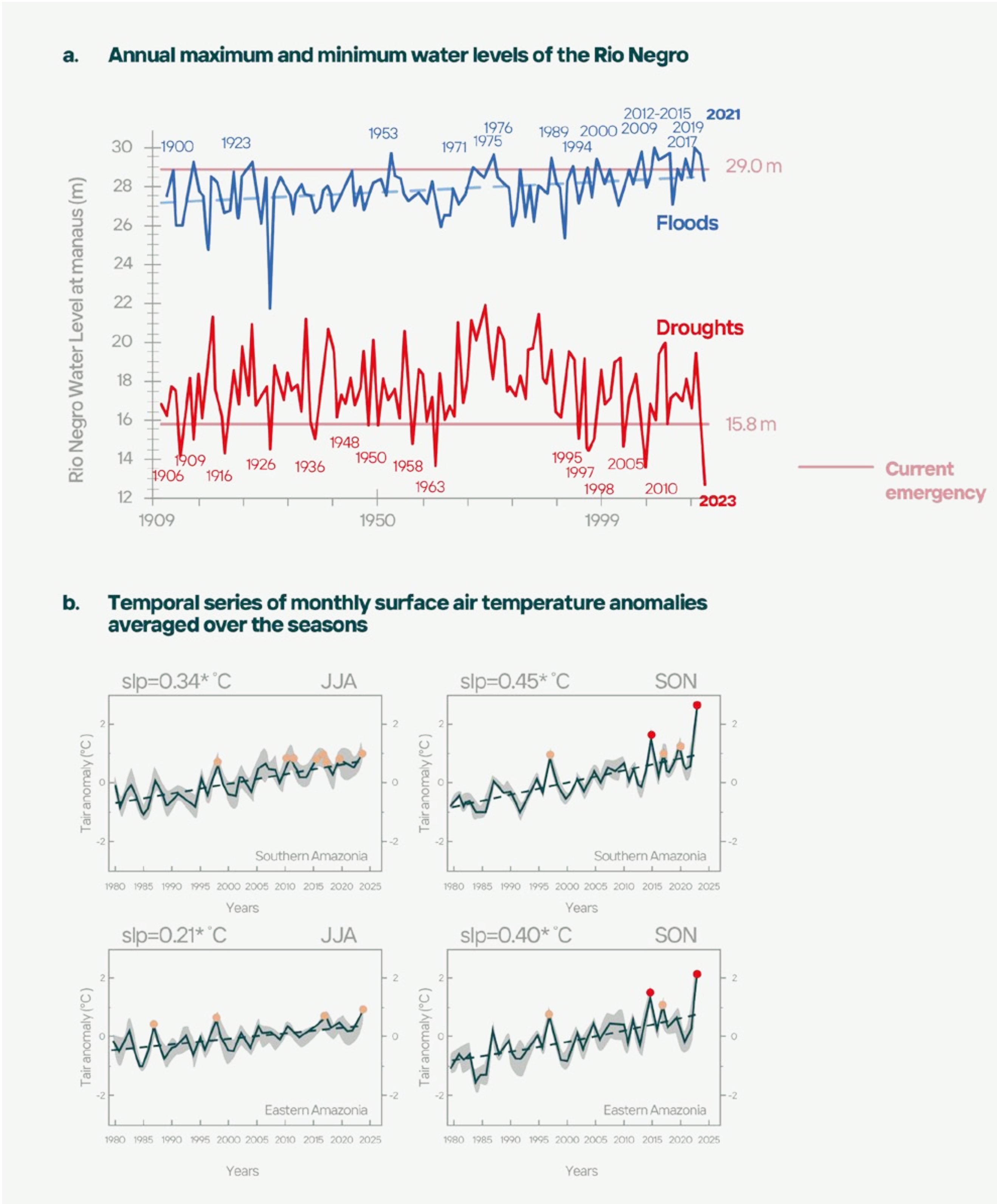


FIGURE 2 a) Annual maximum (floods, blue lines) and minimum (hydrological droughts, red) water levels of the Rio Negro monitored at the port of Manaus from 1902 to 2023 (central Amazon). Calendar years indicate extreme flood (>=29 m) and drought (<15.8 m) events (Source: J. Schöngart, INPA). b) Temporal series of monthly surface air temperature anomalies averaged over the seasons, JJA (June, July, and August) and SON (September, October, November) from 1980 to 2023. The dashed line refers to the linear trend, with the slope value (slp) in °C per decade. The slope's statistically significant values ($p<0.05$) are marked with an asterisk. Data points of anomalies are statistically different from zero at 1s and 2s levels and are colored yellow and red, respectively. Values of temperature anomalies were extracted from ERA5-Land reanalysis.

2023 trimester. Extreme low water levels and high incoming radiation caused water temperature in lakes (e.g. Lake Tefé, the central Amazon) to reach more than 40°C.

Global warming, combined with the AMO warm phase and increasing sea surface temperatures of the TNA are directly related to the increase in air temperature and the length and intensity of the dry season (in the order of 1-2 weeks), especially over Amazonian regions undergoing large-scale deforestation and fire [15]. Combined, these processes are likely to reduce the return period of severe drought events in the upcoming years.

2. ECOLOGICAL IMPACTS OF DROUGHTS

Impacts on terra-firme ecosystems. Continuous long-term (~50 y) monitoring of non-flooded Amazonian forests and artificially-imposed droughts have shown the sensitivity of Amazonian forest' trees to low water supply, with increased tree mortality being the most consistent response across studies [16–18]. Remote sensing studies also suggest that droughts decrease the photosynthetic capacity of trees, and the magnitude of this effect has been increasing through time [19]. The most sensitive plants are those with low resistance to hydraulic failure, the largest trees more exposed to drier atmospheres and short-lived trees (as they both tend to have lower hydraulic resistance), and the smallest trees situated in forests within the driest Amazon regions, because of shallow roots [18–23].These differential mortality patterns have been increasing the number of drought-tolerant species while decreasing the number of drought-intolerant species [24], which face the risk of disappearing. Repeated droughts will likely lead Amazonian forests to be dominated by a lower number of tree species, shorter in stature, and with higher hydraulic resistance.

Forests that naturally have longer dry seasons (dominant in the southern half of the Amazon) have been the most affected by strong droughts (**Figure 3**), with increased tree mortality and consequently biomass loss [25,26]. The negative effects of droughts are exacerbated by deforestation in the eastern and southern Amazon [12,27,28]. At the same time, forests with constant access to groundwater supply (in valleys and lowlands) or forests that are able to exploit deep soil water reserves have shown more resilience to droughts, with no significant loss of biomass [29,30]. The carbon sink provided by tree growth across the Amazon (estimated in 0.42 to 0.65 tons of C per hectare per year between 1990-2007, around 25% of the terrestrial sink) has been decreasing in the past two decades [30], but was especially affected by droughts, dropping to near zero shortly after the 2009-2010 and 2015-2016 droughts, due to lower tree growth and higher tree mortality [24,25]. This means that droughts can offset the carbon sink of forests, accelerating global warming. Moreover, the negative impacts of low water supply interact with those of increased temperature [31], such that droughts with multiple heatwaves, as in 2023, have the potential to accelerate forest biomass loss. Around 21% of the Amazon has been estimated to be degraded by the extreme droughts of this century [32], without considering the impacts of the 2023-24 event.

Changes of forest structure caused by droughts – e.g. decreased canopy cover, disruption of understory regeneration – lead to a decline of terrestrial and aquatic fauna that depend on intact forests, which can in turn lead to empty forests [33–35]. Drought-induced changes in tree phenology may decrease fruit availability, leading to higher mortality rates of frugivore animals. Droughts also lead to physiological stress of arboreal fauna, decreasing the time dedicated to feeding with the ultimate effect of increasing mortality rates [35]. Frequent sequential extreme events (droughts and floods) increase the mortality rates of several terrestrial mammals [35](white-lipped peccary, collared peccary, red brocket deer, black agouti, paca, giant anteaters, and nine-banded armadillo)

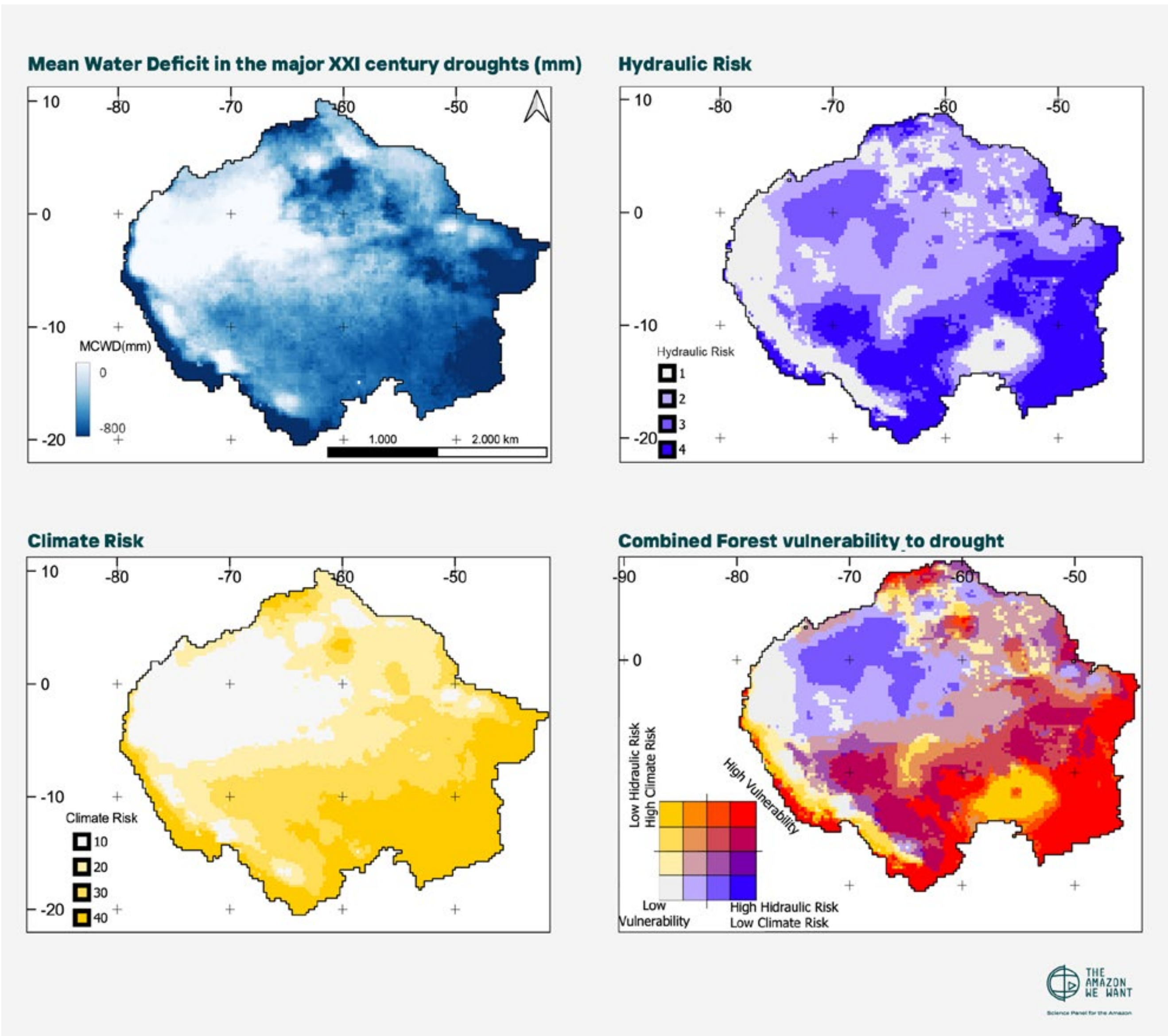


FIGURE 3 Ecological vulnerability of Amazonian regions based on the impacts of the 2015-16 drought and the intrinsic vulnerability of trees. The maps show that **higher water deficit during droughts, climatic and hydraulic risks, and the combined risk of tree death increase towards the south and eastern Amazonian regions, with some patches of high risk in the central-eastern region**. Water deficit was calculated as the Maximum Cumulative Water Deficit (MCWD) for the major droughts: 2005, 2009 and 2015. Climate risk was projected based on carbon-loss due to tree mortality from the 2015-16 drought, as a function of the historical annual water deficit [26]. Hydraulic risk represents the risk that trees will lose the capacity to conduct water [100]. The combined forest vulnerability to drought is the overlap of the Climatic and Hydraulic Risks, warmer colors indicate higher combined vulnerability to both factors.

that are key for the regulation of forest diversity [36,37]. Terrestrial and aquatic species are affected differently, as long periods of flooding have higher impacts on terrestrial species, decreasing population of terrestrial species such as white-lipped peccary and collared peccary, while long periods of drought can decrease aquatic animals populations of species such as manatees, river dolphins and several fishes [35,38].

Impacts on seasonally flooded ecosystems. Hydrological drought conditions in the Amazonian floodplains vary considerably as these areas experience low water levels in different periods of the year, depending on their geographic location, which has strong implications for plant-water availability and fire vulnerability. Droughts induced by severe El Niño events (December–March) coincide with low-water periods in the middle-upper Negro River, Branco River, and other Guyana Shield tributaries dominated by igapós [27]. In contrast, várzea floodplains are mainly located in the southern hemisphere and tend to be less vulnerable to El Niño-induced drought and fire hazards due to already increasing water levels during this period [39]. In regions where low-water stages coincide with the dry season, drought can increase floodplain tree mortality, especially of shallow-rooted seedlings and young trees of igapós. Igapós are also more vulnerable to droughts due to the mostly sandy or silty soils [40] which drain faster than the clay soils of várzeas – and the generally very shallow (≤ 40 cm) [41] rooting systems.

The forest canopy in the igapó is generally less stratified and lower, resulting in lower relative air humidity at the forest floor [42,43]. This can cause these ecosystems to be highly vulnerable to fires [44,45], as documented in the severe droughts of 1925-1926, 1982-1983, 1997-1998 and 2015-2016 [44,46,47]. The dry hydro-meteorological conditions generated by El Niño favors the spreading of understory fires along the soil surface, leading to massive tree mortality [43]. Further insights into the vulnerability of igapó trees to severe drought are provided by dams, such as Balbina, which induced a prolonged severe artificial drought in the downstream igapó floodplain causing widespread tree mortality [48]. Secondary forests extending for several dozen kilometers along the Uatumã River downstream of the Balbina dam probably established and developed after the mass mortality of the former igapó forests [49,50]. In contrast, increased tree growth has been observed in the central Amazonian várzea during El Niño events, as the growing season of tree species during the non-flooded period is extended [51,52]. Based on these observations, we can assume that the ecological impacts for floodplain vegetation caused by the historical drought event of 2023 might be more intense in the igapó forests compared to the várzea forests.

Although occupying a smaller fraction of the Amazon (about 6-10% [53,54]), floodplains are capable of supporting a high abundance of animals and are essential for some stages of their life cycles, since many Amazonian aquatic species (e.g. manatees and many fishes, including arapaima) migrate to more permanent water bodies in the dry season [55–58]. However, extreme droughts cause the rapid isolation of water bodies from previously connected environments, and these migratory animals can become trapped in isolated and shallow water bodies [53], which could lead to over-harvesting of animals trapped in shallow lakes. During the 2023 drought, however, hundreds of mammals (e.g., river dolphins) [59] were killed due to increased water temperature and decreased oxygen concentration. Droughts also have long lasting effects on the aquatic fauna, such as the changes in the fish species' composition and functional types caused by the 2005 event that were still present nearly 10 years later [60]. In addition, the reduction of rivers' water volume may increase the risk of fire in the surrounding areas. There is evidence that forest cover is essential for maintaining fish diversity and productivity [58,60], so the loss of vegetation may increase the rate of siltation, making water bodies shallower and interrupting the connections between water bodies.

Droughts and fire. Droughts greatly increase fire incidence in the Amazon, as reported in 2005, 2010 and 2015 [61], and 2023 [62], leading to a positive feedback loop between fires and droughts. High water deficits, widespread tree mortality, and litterfall generated by droughts increase fuel availability that turns once humid forests into more flammable systems. During 2005 (14,584 km^2) and 2010 (32,815 km^2), the total forest area burned was two to four times the mean for the 2001–2018 period [32]. In the 2015 extreme drought, fire extended beyond the Arc of Deforestation, hitting areas in the central Amazon not previously impacted [62]. The lower Tapajós region in the Eastern Amazon – the epicenter of that drought – experienced unprecedented mega-wildfires, which burned around 10,000 km^2 of forests [61].

Carbon emissions are among the main impacts of forest fires during extreme Amazonian droughts. Forest fires have been estimated to be responsible for around a third of the carbon emissions attributed to deforestation during the 2003–2015 period and are more than half as great as those from old-growth deforestation during drought years [62]. A single understory forest fire can reduce aboveground carbon stocks by up to 50% [63]. In the lower Tapajós region, the 2015–16 El Niño and associated fires resulted in the estimated death of >2.5 billion woody stems, leading to the emission of 495 ± 94 Tg CO_2, with globally relevant impacts [64]. Such an area corresponds to only 1.2% of the Brazilian Amazon, but the emissions were larger than the mean annual CO_2 emissions from deforestation across the whole Brazilian Amazon between 2009 and 2018 [64]. In addition, wildfires can turn a forest into a net source of carbon for many years following the fire [64], resulting in ~25% less stored carbon even after 30 years. Recurrent fires, which become more likely across time as more of the region is affected by droughts and fires, can lead to carbon losses of over 80% of aboveground carbon [63].

Wildfires have significant effects on biodiversity, leading to high levels of community turnover, with the loss of sensitive species of high conservation value and functional importance, such as birds with smaller range sizes and plants with higher wood densities [64,65]. Recurrent fires profoundly change the forest structure and species composition, with larger changes for birds, beetles, trees, and frugivore and granivore mammals [66–68], potentially leading to the loss of ecological services and lower food security for the traditional people who depend on forest products [34]. The high frequency of extreme droughts can turn Amazon forests into fire-prone ecosystems making fires a relevant driver of a possible tipping-point of the Amazon [69].

3. SOCIOECONOMIC IMPACTS OF DROUGHTS

Droughts pose great challenges to Amazonian people and can lead to both short-term and long-lasting socioeconomic impacts, particularly to the most vulnerable Indigenous Peoples and Local Communities (**Figure 4**). Droughts affect the livelihoods of the ~47 million people that live in the Amazon region in many ways: threats to water security and water quality (especially access to drinkable water) in rural and urban areas, food insecurity, uncertainties around the harvest of some natural products, impacts in local to regional economies, public health issues, interruption of transportation, decline in energy production, access to human rights, changes in cultural habits, and even compounding effects with other hazards such as river bank collapse. Within the Brazilian Amazon, approximately 8.5 million people, including Indigenous Peoples and Local Communities, inhabit areas with limited infrastructure and insufficient services to cope with the impacts of climate extremes [66].

With rivers being the main transportation route in the region, thousands of people in both urban and rural areas are directly affected by isolation when droughts decrease river levels [69], as occurred in 2005 [70], especially those living in more remote tributaries. In 2023, around 150,000 families and more than 600,000 people [71], including Indigenous Peoples and the rural and river dwellers who depend on river transport to access food, water, medical assistance, and markets to sell products, were impacted by drought, becoming isolated for several months. For instance, in the State of Amazonas, Brazil, all 62 municipalities remained in a state of emergency for many months. Another transport-related externality is the increase in the prices of goods, including food – the greater the distance of sales locations from distribution centers, generally located in large cities such as Manaus and Iquitos, the higher the price of goods will be during droughts. This phenomenon is not new: in the Brazilian Amazon in 2010 for example, 62,000 families felt the impact of drought, demanding government investment in the order of US $13.5 million in emergency aid [72]. Between 1997 and 2023, the state of Acre, Brazil experienced five instances where municipalities or states declared a state of emergency due to drought-induced water crises [73]. Furthermore, low river levels are also linked to disastrous landslides of the riverbanks, destroying houses and killing people [74].

Impacts of water shortage in transportation also affect household energy availability, which generally depends on fuel delivered by boat. For example, the energy shortage during the 2023 drought in São Gabriel da Cachoeira, upper Rio Negro – the city with the third largest Indigenous population in Brazil – had a cascading effect on the functioning of other basic services such as healthcare and education. Operation of hydroelectric dams is also affected by low river levels. Ecuador introduced power cuts of several hours a day for two months due to the severe drought of 2023-2024 that hit the production of some hydroelectric plants . Manaus also experienced 6 hours of energy cuts daily due to the low level of the Balbina dam during the 1997 drought [75].

From uplands to lowlands, the Amazon food production and security are largely impacted by droughts and accompanying heatwaves. High air temperatures harm staple crops such as cacao,

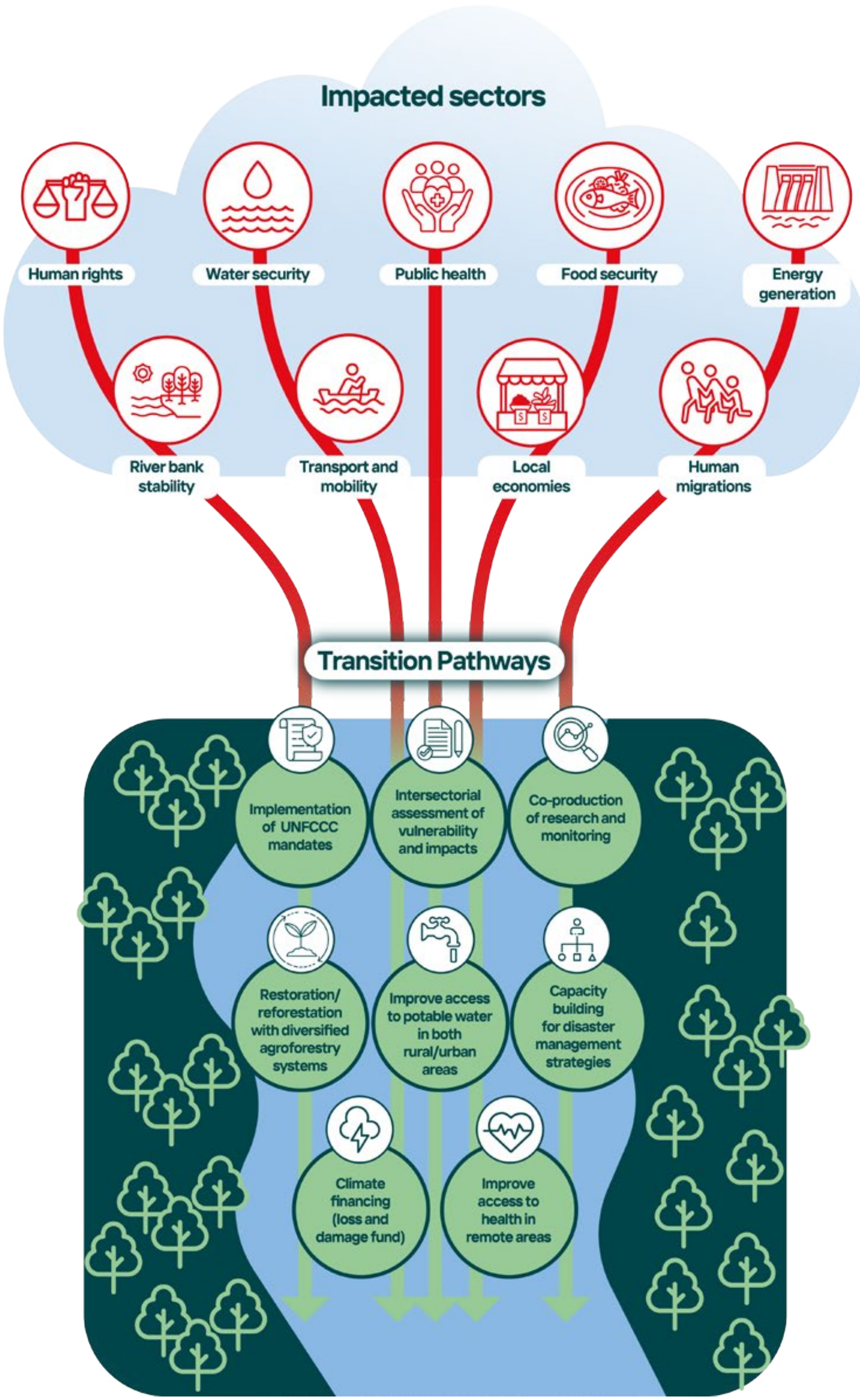


FIGURE 4. Impacted sectors and transition pathways towards reduced socioeconomic impacts and better solutions for future droughts in the Amazon.

cassava, and extractive products such as açaí [76,77], but also the large soy monocultures in deforested regions [78]. Fishing is affected due to challenges in accessing fishing lakes, transportation to the main markets, and the high mortality of fish during these events [72,79–82]. The lack of access to markets hampers the commercialization of the communities' production [76].

Health impacts caused by lack of access to medical services, increase of disease vectors, malnutrition, and fire smoke are a major concern during extreme droughts. Additionally, high air temperatures are very impactful to Amazonian people's health. Rural communities have been changing working hours to avoid the warmest afternoon hours, while classes have been canceled in schools due to excessive heat. Child hospitalization due to respiratory diseases caused by high fire incidence peaked in drought-affected municipalities in 2005 [83]. The amplification of fire occurrences during severe droughts poses significant economic repercussions; for example, the Brazilian state of Acre alone had an estimated total economic loss of approximately US$ 243.36 ± 85.05 million (7.03 ± 2.45% of Acre's GDP) during the 2010 drought [84]. Waterborne diseases such as diarrhea are common during extreme droughts because of poor water quality. Compound drought-heatwave events can also lead to increased incidence of vector-borne diseases such as dengue [85]. Indeed, water insecurity is high during these dry periods because of inadequate infrastructure to access potable water and lack of public policies to solve this issue. Communities often have only small rainwater storage facilities [86], depending on the adjacent water bodies – usually polluted – during droughts [87]. In 2023, even communities with groundwater wells remained without access to water and dependent on supply by local civil defenses. Furthermore, in general, several Amazon urban areas also present high levels of water insecurity.

As extreme droughts and floods become increasingly more frequent, climate-related migration has been reported from floodplains to uplands, and from rural to urban areas [70,88]. Seasonal and permanent migratory movements, from sub-regional (e.g., from communities to urban areas) to regional scales (e.g., from smaller to larger urban areas), occur in the Amazon due to different factors, including search for better access to education and other basic services [89], posing additional challenges for the individuals' capacity to adapt to extreme climatic events.

The large social and cultural diversity across the Amazon means a very heterogeneous pattern of drought-related socioeconomic impacts, including the transfer of traditional knowledge. The differences in social groups (e.g., Indigenous, afro-descendant, riverine (*ribeirinhos, caboclos*, etc.), predominant economic activities (e.g., fishing, farming, extractivism, urban services), gender and age, and the regional differences between countries and the Amazon regions (e.g. lowlands, Amazonian Andes, and foothills) require site-specific understanding and adaptation strategies to reduce the impacts of socio-climatic disasters. For instance, while climate extremes have increased rainfall and floods in the coast and Western Andes of Ecuador, droughts have reached the northern and eastern parts of the country. Populations in urban areas are impacted differently than rural communities.

Remote communities are often ignored by climate policies and have limited access to information and participation in the climate debate [88,90], as well as their right of consent on the adopted strategies [91]. This calls attention to the need of improving our understanding of the vulnerability of these people at regional and local scales [87,92], and co-producing adaptation measures [87,92]. While Amazonian people generally agree on the perception of ongoing environmental and climate changes, such as increasing summer air temperatures, the perception about climate extremes differs among cultures [88]. Many communities report a higher unpredictability of climate and river regimes [77] which hampers a proper adaptation to ongoing changes.

The socio-economic impacts of droughts in the Amazon region demand large and varied investments. At the national level, there is a notable disparity in budget allocation to address climate-related disasters. In 2022, Amazon countries like Bolivia, Brazil, Colombia, Ecuador, and Peru collectively spent only US$ 287,829,541 on disaster management, significantly less than the US$ 14,188,053,010 invested in carbon-intensive activities such as fossil fuel production – it is important to note, however, that these expenses are related to the whole countries, going beyond the Amazon region itself [94]. Colombia allocated the highest proportion of its budget, at US$ 142 million (0.19% of its total budget), followed by Ecuador with US$ 14 million (0.03%), Peru with US$10 million (0.02%), Brazil with US$ 121 million (0.01%), and Bolivia with US$ 28,000 (0.0001%). This discrepancy shows that while the allocation of resources is limited, according to the Sustainable Finance Index, the cost for loss and damages may be higher with time. At the same time, as the Amazon gets closer to a tipping point, the cost associated to the increasing frequency and intensity of droughts is estimated to result in a loss of 45 billion dollars in the Gross Domestic Product up to 2050 across the largest countries of the basin (Brazil, Peru, Colombia, Bolivia, and Ecuador), mostly due to the loss of crops and the consequences of fires [93].

All the socioeconomic impacts explained, and others not detailed, not addressed in the literature, or even unknown, can be addressed and understood under a broad umbrella of a human-rights approach. It is important, for example, to consider the mandates established in 2022 by the UNFCCC regarding the climate justice approach, including "losses and damages", and the rights of children and future generations to development. To date, national and local government responses to drought events have historically prioritized emergency relief assistance [71,94]. The current situation, however, requires that climate mitigation and adaptation plans are developed and fully implemented, and that these plans incorporate coping strategies in advance, considering future events, and establishing long-term adaptation strategies through co-production approaches with local populations [89].

CONCLUSIONS

Mitigation of droughts requires serious effort to control global warming, deforestation, and forest degradation, as well as wide efforts on forest restoration [95,96]. Adaptation to droughts requires multisectoral approaches and strong governance, including interventions in infrastructure, agriculture, sanitation, potable water access (such as rainwater cisterns, more and deeper wells, nanotechnology-based filters, and distribution of emergency water treatment kits to remote communities), and health, and the establishment of early warning systems of droughts to minimize socio-economic and environmental impacts and losses. These require climate financing through adaptation, loss & damage budgets, national and local budgets, and green initiatives, as well as capacity building of local populations, and the development of socio-bioeconomy-based initiatives and forest restoration to tackle current and future challenges posed by droughts in the Amazon. It is necessary to foster collaboration between scientific and traditional knowledge systems, government, civil society, and the private sector to maximize effectiveness. This holistic approach will help to address identified issues and bolster our capacity to mitigate the impacts of droughts in the Amazonian region.

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