– 2nd Draft -

Policy Brief - Droughts in Amazonia

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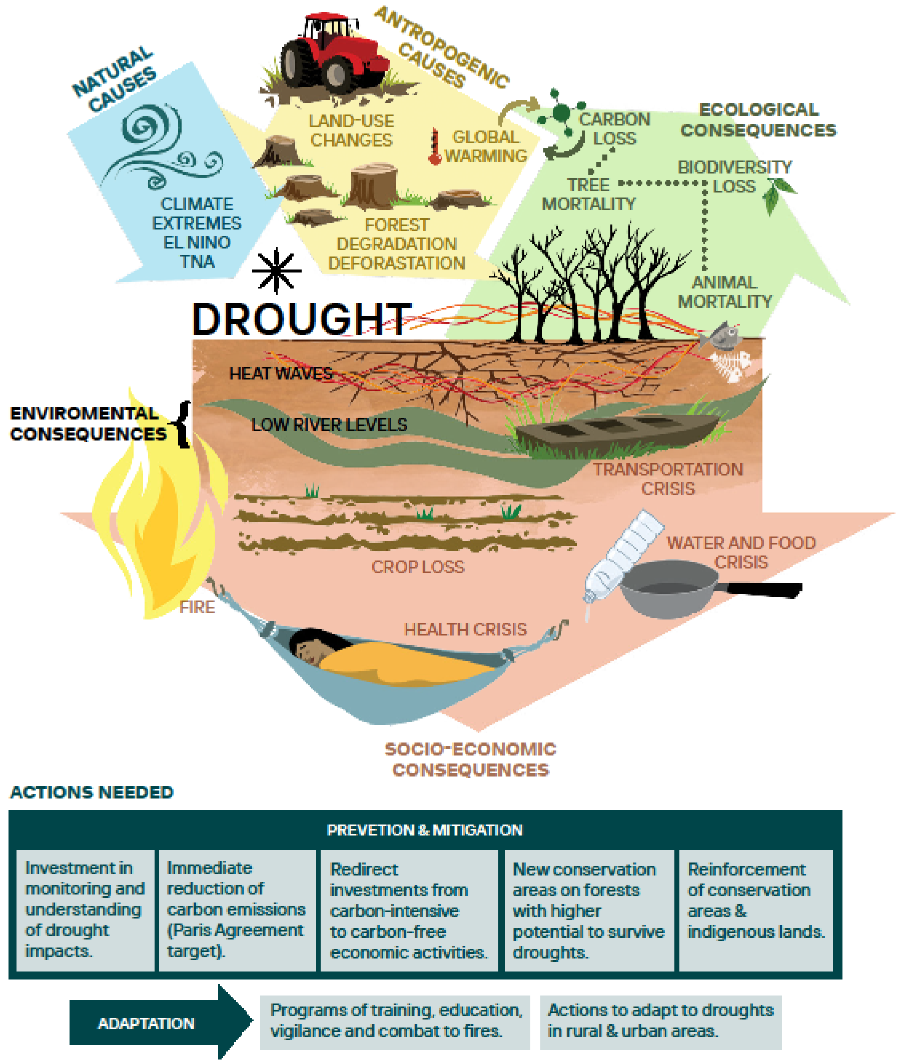
Graphical Abstract



ACTIONS NEEDED

PREVETION & MITIGATION

- Investment in monitoring and understanding of drought impacts.
- Immediate reduction of carbon emissions (Paris Agreement target).
- Redirect investments from carbon-intensive to carbon-free economic activities.
- New conservation areas on forests with higher potential to survive droughts.
- Reinforcement of conservation areas & indigenous lands.

ADAPTATION

- Programs of training, education, vigilance and combat to fires.
- Actions to adapt to droughts in rural & urban areas.

Key Messages & Recommendations

1. Strong droughts in Amazonia 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 degradation have the potential to drive Amazonia 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.

Ø **Immediate reduction of carbon emissions (under Paris Agreement targets), reduction of deforestation and forest degradation are key to slow down or halt the increasing frequency of droughts**

Ø **Redirect subsidies and public investments from carbon-intensive activities to conserving nature reserves and forest restoration to promote the creation of new jobs in the conservation sector and generating alternative revenue streams, while increasing budget allocations for adaptation and management of catastrophes**

2. Droughts increase tree mortality across many forests and thus biomass loss, imperiling the functioning of the carbon sink provided by tree growth. Droughts increase animal mortality, especially when river levels decrease abruptly and when forests are disturbed by fire and forest degradation, with consequences for ecosystem diversity and resources to local communities.

Ø **Start an identification program of priority areas that should be immediately conserved to maintain ecosystem services, and reinforce the protection of already conserved areas and indigenous lands to avoid potentially negative disturbance synergies**

Ø **Monitoring programs to detect early signs of animal stress and take action to develop mitigation plans**

3. Droughts increase the risk of fires with direct impacts, such as carbon emissions, loss of biodiversity and ecosystem services, while also threatening human health and food security, causing social, cultural and economic vulnerability.

Ø **Continued funding for programs of training, education, vigilance and combat to fires, particularly in years of extreme drought. Actions to ensure that buffer zones around Protected Areas are maintained**

4. The socioeconomic impacts of droughts include threats to water security, food sovereignty, public health, human rights, local economies, mobility, energy production, river bank stability, and human migrations.

Ø **Implement the mandates established in 2022 by UNFCCC regarding the human rights-based and climate justice approach.**

Ø **Implement the loss and damage fund, and improvement of funding through international and national funds.**

Ø **Strengthen capacity building of local people and governments to access diverse financial mechanisms for adaptation**

Ø **Promote the adoption of diversified agroforestry and agroecological systems in the restoration and reforestation actions, to improve food sovereignty**

Ø **Invest on science, technology and innovation for better water treatment strategies and higher storage capacities, such as rainwater cisterns, more and deeper wells,**

nanotechnology-based filters, and distribution of emergency water treatment kits to remote communities.

5. The socioeconomic impacts of droughts vary in nature and intensity across different social groups (Indigenous peoples, peasants, fishermen, cattle ranchers to urban populations), gender, age, and also among Amazonian countries and regions (Arcs of Deforestation, lowlands, Andean Amazonia, and foothills).

Ø Evaluate the vulnerability of populations through an intersectional approach for the design of policies; actions should be grounded in a comprehensive understanding of local realities.

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

Ø Prioritize research and monitoring efforts to fill environmental, ecological and socioeconomic data gaps.

Ø Implement monitoring programs and early warning systems of droughts, including modelling of the global and regional atmospheric circulation and continental hydrology from the Andes to the Atlantic Ocean

Ø Invest in capacity building and co-production of solutions with local -rural and urban- populations to manage disasters.

Final recommendation: Mitigation of droughts require serious effort to control global warming, deforestation and forest degradation. Adaptation to droughts requires multisectoral approaches, including interventions in infrastructure, agriculture, sanitation, potable water access and health. These require climate financing through *adaptation, loss & damage budgets*, national and local budgets, green initiatives, capacity building of local populations, and bioeconomy-based initiatives to tackle current and future challenges posed by droughts in Amazonia. It is necessary to foster collaboration between scientific and traditional knowledge systems to maximize effectiveness. This holistic approach will help addressing identified issues and bolster our capacity to mitigate the impacts of droughts in Amazonian region.

MAIN TEXT

1. **Climatic and Hydrological Dynamics**

Natural causes of droughts. Since the beginning of the 21st century four “megadroughts" have occurred in Amazonia. These droughts were classified as “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 increase atmospheric subsidence over Amazonia, i.e. downward air movements, which bring dry air and inhibit cloud formation [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).

Natural climatic variability vs human induced droughts. Although droughts have a natural climatological component and have cyclically happened in Amazonia[8], the frequency and intensity of droughts are increasing, mostly due to human-induced global warming, deforestation, and forest degradation. Modelling studies suggest that the Amazonian droughts occur via a decline in precipitation during El-Niño years. On the other hand, increasing global mean surface temperature (i.e. global warming) reduces precipitation, but also strongly elevates local temperatures, thus increasing water loss through increasing evapotranspiration leading to the large water deficits in terrestrial and aquatic systems [9]. Climate change has increased the likelihood of hydrological droughts (that impacts river flow) by a factor of 10, while agricultural droughts (that impacts agricultural activities) have become about 30 times more likely [9]. Moreover, multiple years of deforestation in Amazonia 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 feedbacks increasing as deforestation accumulates [10,11].

In 2023, Amazonia experienced an extreme drought and warmth situation. 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 [10] 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. However, the strong water deficits in land and aquatic systems were almost entirely due to increased global temperatures [9]. The intensity of the 2015-16 drought has also been linked to anthropogenic causes [12].

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). The mean duration of flood emergencies is in general longer (53 ± 24 days) compared to droughts (36 ± 19 days). Regarding the duration of emergency of both extremes, until the 1990s hydrological droughts had more impacts than floods, while floods have been stronger in the 21st century.

This scenario was changed by the 2023-24 drought. Most of the main rivers in Amazonia, including the Solimões, Purus, Acre, and Branco rivers all suffered from extreme drops in their levels, or just dried up. In October 2023, the Rio Negro level in Manaus recorded its lowest level since measurements began in September 1902, 12.70 m (the average annual minimum water level was 17.64 m for the 1902-2022 period). In the Peruvian Amazonia, the Huallaga River at Tingo María showed an anomaly of -45% in the discharge in October 2023. In Bolivia, the Mamoré-Guaporé and Madeira rivers in Bolivian territory remained very low due to deficient rainfall from July 2022 to June

2023. The hydrological drought of 2023 was classified as severe-extreme in the Western Amazonia region of Brazil and over the Bolivian and Peruvian Amazonia regions and extended to most of Amazonia south of 5ºS (Figure 1b) [2,13]. 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 Amazonia.

All the study regions in Amazonia have evidence of statistically significant warming trends during the last four decades (Figure 1b). Warming trends are higher for the Sep-Oct-Nov season than for the Jun-Jul-Aug season, and higher for Southern and Eastern than Northern and Western Amazonia. Although the time series shows peaks of increased temperatures related to different drought episodes, it is 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 Nov of 2023 in the western and northern regions exacerbated the effects of the lack of precipitation. Southwestern Amazonia had warmer winter and spring due to heat domes of hot and dry air. Maximum temperatures were between +2ºC to +5ºC above average over the affected states of Amazonas, Rondônia, Roraima, and Acre in Sep-Oct-Nov 2023 trimester. Extreme low water levels and high incoming radiation caused water temperature in lakes (e.g. Lake Tefé, central Amazonia) 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 [14]. Combined, these processes are likely to reduce the return period of severe drought events in the next years.

2. Ecological impacts of Droughts

Impacts on terra-firme ecosystems. Continuous long-term (~50 y) monitoring of non-flooded Amazonian forests [15] and artificially-imposed droughts [16–18] have shown the sensitivity of Amazonian forest' trees to low water supply, with increased tree mortality being the most consistent response across studies. Remote sensing studies also suggest that droughts decrease the photosynthetic capacity of trees, and the magnitude of this effect has been increasing along 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 [15], which face the risk of disappearing. Repeated droughts will likely lead Amazonian forests to be dominated by lower number of tree species, of shorter stature, and higher hydraulic resistance.

Forests that already have longer dry seasons (dominant in the southern half of Amazonia) have been the most affected by strong droughts (Figure 3), with increased tree mortality and consequently biomass loss [24,25]. At the same time, forests with constant access to groundwater supply (in valleys and lowlands) or able to exploit deep soil water reserves have shown more resilience to droughts, with no significant loss of biomass [26,27]. The carbon sink provided by tree growth across Amazonia (estimated in 0.42 to 0.65 tons of C per ha/y between 1990-2007, around 25% of the terrestrial sink) has been decreasing in the past two decades [28], 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 [15,24]. This means that droughts can offset the carbon sink and thus accelerate global warming. Moreover, the negative impacts of low water supply interact with those of increased temperature [29], such that droughts with multiple heatwaves, as in 2023, have the potential to accelerate forest biomass loss. Around 21% of Amazonia has been estimated to be degraded by the extreme droughts of this century [30], still not 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 [31–33]. 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 [33]. Frequent sequential extreme events (droughts and floods) increase the mortality rates of several terrestrial mammals [32] (white-lipped peccary, collared peccary, red brocket deer, black agouti, paca, giant anteaters and nine-banded armadillo) that are key for the regulation of forest diversity[34,35]. Terrestrial and aquatic species are affected differently, as long periods of flooding have higher impacts on terrestrial species, decreasing their population by 95%, while long periods of drought decrease aquatic animals populations by 61% [26].

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 [36]. In contrast, varzea floodplains are mainly located in the southern hemisphere and tend to be less vulnerable to El Niño-induced drought and fire hazard due to already increasing water levels during this period [37]. 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 [38] which drain faster than the clay soils of várzeas - and the generally very shallow (≤ 40 cm) [39] rooting systems.

The forest canopy in the igapó is generally less stratified and lower, resulting in lower relative air humidity at the forest floor [40,41]. This can cause these ecosystems to be highly vulnerable to fires [42,43], as documented in the severe droughts of 1925-1926, 1982-1983, 1997-1998 and 2015-2016 [42,44,45]. The dry hydrometeorological conditions generated by El Niño favors the spreading of understory fires along the soil surface, leading to massive tree mortality [41]. 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 [46]. 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 [47,48]. 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 [49,50]. 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 Amazonia (about 6-10% [51,52]), 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 [53–56]. 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 [51], which could lead to over-harvesting of animals trapped in shallow lakes. During the 2023 drought, however, hundreds of mammals (e.g. dolphins) [57] 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. 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 [56,58], 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 increases fire incidence in the Amazon, as reported in 2005, 2010 and 2015 [53], and 2023 [59]. 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 [30]. In the 2015 extreme drought, fire extended beyond the Arc of Deforestation, hitting areas in central Amazonia not previously impacted [60]. The lower Tapajós region on Eastern Amazonia - 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, with increasing contributions in comparison to deforestation. Forest fires have been estimated to be responsible for around a third of the carbon emissions attributed to deforestation during the 2003–2015 period (mean annual committed gross emission of 454 ± 496 Tg CO_2 year^{-1})[60]. A single understory forest fire can reduce aboveground carbon stocks by up to 50% [62]. 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 [63]. Such an area corresponds to only 1.2% of the Brazilian Amazonia, but the emissions were larger than the mean annual CO_2 emissions from deforestation across the whole Brazilian Amazon between 2009 and 2018 [63]. Wildfires can turn a forest into a net source of carbon for many years following the fire [63], resulting in ~25% less 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% [62].

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 [63,64]. Recurrent fires profoundly change the forest structure and species composition, with larger changes for birds, beetles, trees, and frugivore and granivore mammals [65–67], potentially leading to the loss of ecological services and lower food security for the traditional people who feed on several of those animals [32]. The high frequency of extreme droughts can turn Amazonian forests into fire-prone ecosystems making fires a relevant driver of a possible tipping-point and collapse of the Amazon [68].

3. Socioeconomic Impacts of Droughts

Droughts pose great challenges to Amazonian people and can lead to short-term and long-lasting socioeconomic impacts, particularly to the most vulnerable Indigenous Peoples and Local Communities (IPLCs). Droughts affect the livelihoods of the ~ 47 million people that live in the pan-Amazonia region in many ways: threats to water security (especially access to drinkable water) in rural and urban areas, food insecurity, uncertain production of extractive' resources, impacts in local economies, public health issues, interruption of mobility and transportation, decline in energy production, affections to human rights, and changes in cultural habits. Within the Brazilian Amazon, approximately 8.5 million people, including IPLCs, inhabit areas with limited infrastructure and insufficient services to cope with the impacts of climate extremes [65]. 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 [68], as occurred in 2005 [69], especially those living in more remote tributaries. In 2023, around 150,000 families and more than 600,000 people [70], 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. In fact, in the State of Amazonas, Brazil, all 62 municipalities remained in a state of emergency for many months. This phenomenon is not new, in Brazilian Amazonia 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 [71]. 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. Low river levels are also linked to disastrous landslides of the river banks, destroying houses and killing people [72].

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 third most indigenous city in Brazil - had a cascading effect on the functioning of other basic services such as healthcare and school operations[i].

Operation of hydroelectric dams is affected by low river levels. Ecuador introduced power cuts of several hours a day for two months[ii], due to the severe drought of 2023-2024 that hit the production of some hydroelectric plants. Manaus also experienced 6h of energy cuts daily due to the low level of the Balbina dam during the 1997 drought [73].

From uplands to lowlands, the Amazon food production and sovereignty is largely impacted by droughts and accompanying heat waves. High air temperatures harm staple crops such as cacao, cassava and extractive products such as açaí [74,75], but also the large soy monocultures in deforested regions [76]. Fishing is affected due to

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[i] https://radaramazonico.com.br/sao-gabriel-da-cachoeira-enfrenta-falta-de-energia-e-encarecimento-da-cesta-basica-por-conta-da-seca-historica/#:~:text=A%20seca%20hist%C3%B3rica%20que%20atinge,de%20itens%20da%20cesta%20b%C3%A1sica

[ii] https://www.reuters.com/world/americas/ecuador-impose-power-cuts-el-nino-hits-hydroelectric-plants-2023-10-26/

challenges in accessing fishing lakes, transportation to the main markets and the high mortality of fish during these events [71,77–79]. In general, the lack of access to markets hamper commercialization of communities' production [74].

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 [80]. 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 [81]. Waterborne diseases such as diarrhea are common during extreme droughts because of poor water quality. 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 [82], depending on the adjacent water bodies - usually polluted - during droughts [83]. In 2023, even communities with groundwater wells remained without access to water and dependent on supply by local civil defenses [iii]. Several Amazon urban areas also present high levels of water insecurity [iv].

As extreme droughts and floods become increasingly frequent, climate-related migration has been reported from floodplains to uplands, and from rural to urban areas [69,84]. 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 Amazonia due to different factors, including search for better access to education and other basic services [85], hindering individuals' capacity to adapt to extreme climatic events and threatening the proper functioning of the already crowded Amazonian capitals [69].

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 (Indigenous peoples, peasants, fishermen, cattle ranchers, urban, upland vs floodplain caboclos, etc.), gender and age, and the regional differences between countries and Amazonia regions (e.g. Arc of Deforestation, 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 increase rainfall and floods in the coast and Western Andes of Ecuador, droughts reach the northern and eastern parts of the country [v]. Populations in urban areas are differently impacted than rural communities.

Remote communities are often ignored by climate policies and also have limited access to information and participation in the climate debate [84], as well as their right of consent on the adopted strategies [86]. This calls attention to the need of improving our understanding of the vulnerability of these people at regional scales [83,87], and co-producing adaptation measures [83,87]. While Amazonian people generally agree on the

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[iii] https://reporterbrasil.org.br/2023/11/indigenas-cavam-poco-em-rio-seco-para-achar-agua-no-amazonas/

[iv] https://g1.globo.com/ac/acre/noticia/2023/10/22/devido-a-seca-de-igarape-saneacre-inicia-racionamento-de-agua-em-cidade-do-interior.ghtml

[v]

perception of ongoing environmental and climate changes, such as increasing summer air temperatures, the perception about climate extremes differs among cultures [84]. Many communities report a higher unpredictability of climate and river regimes [74] which hamper a proper adaptation to ongoing changes.

National and local government responses to drought events have historically prioritized emergency relief assistance [69,88]. Between 1997 and 2023, the state of Acre, Brazil, experienced five instances where municipal or state declared state of emergency due to drought-induced water crises [89]. Climate mitigation plans that exist in some Amazonian countries are still not fully implemented. There is a need thus to establish risk prevention and long-term adaptation strategies [85].

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 USD $287,829,541 on disaster management, significantly less than the USD $14,188,053,010 invested in carbon-intensive activities such as fossil fuel production [90]. 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 will be higher with time.

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 UNFCCC regarding the climate justice approach, including "losses and damages", and the rights of children and future generations to development.

Box 1. Definitions

Drought. A period of abnormally dry weather sufficiently long enough 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. https://drmkc.jrc.ec.europa.eu/portals/0/Knowledge/ScienceforDRM/ch03_s03/ch03_s03_subch0309.pdf)

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

Hydrological drought. Prolonged period of below-normal precipitation, causing deficiencies in water supply, as measured by below-normal streamflow, 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.

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

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

Mega-wildfires[91]. Fires spreading over 10,000 ha or more, arising from single or multiple related ignition events.

References

1.Barichivich, J. et al. Recent intensification of Amazon flooding extremes driven by strengthened Walker circulation. Sci Adv 4, eaat8785–eaat8785 (2018).
2.Espinoza J. et al. The new record of drought and warmth in the Amazon in 2023: Regional and global climatic features. Preprint at (2024).
3.Espinoza, J.-C., Marengo, J. A., Schongart, J. & Jimenez, J. C. The new historical flood of 2021 in the Amazon River compared to major floods of the 21st century: Atmospheric features in the context of the intensification of floods. Weather and Climate Extremes 35, 100406 (2022).
4. Papastefanou, P. et al. Recent extreme drought events in the Amazon rainforest: assessment of different precipitation and evapotranspiration datasets and drought indicators. Biogeosciences 19, 3843–3861 (2022).
5...Cai, W. et al. Climate impacts of the El Niño–Southern Oscillation on South America. Nature Reviews Earth & Environment 1, 215–231 (2020).
6.Yoon, J.-H. & Zeng, N. An Atlantic influence on Amazon rainfall. Clim Dyn 34, 249–264 (2010).
7.Espinoza, J. C., Ronchail, J., Marengo, J. A. & Segura, H. Contrasting North–South changes in Amazon wet-day and dry-day frequency and related atmospheric features (1981–2017). Clim Dyn 52, 5413–5430 (2019).
8. Coelho, C. A. S. et al. Climate diagnostics of three major drought events in the Amazon and illustrations of their seasonal precipitation predictions. Meteorological Applications 19, 237–255 (2012).
9. Clarke, B. et al. Climate Change, Not El Niño, Main Driver of Exceptional Drought in Highly Vulnerable Amazon River Basin. https://www.worldweatherattribution.org/climate-change-not-el-nino-main-driver-of-exceptional-drought-in-highly-vulnerable-amazon-river-basin/ (2024).
10. Staal, A. et al. Feedback between drought and deforestation in the Amazon. Environ. Res. Lett. 15, 044024 (2020).
11.Leite-Filho, A. T., Soares-Filho, B. S., Davis, J. L., Abrahão, G. M. & Börner, J. Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. Nat Commun 12, 2591 (2021).
12. Ribeiro Neto, G. G. et al. Attributing the 2015/2016 Amazon basin drought to anthropogenic influence. Climate Resilience and Sustainability 1, e25 (2022).
13. Marengo J A, Cunha AP, & Espinoza JC. Extremes of hydrometeorology and dry season length in Amazonia associated with the drought of 2023,. (2024).
14. Marengo, J. A., Jimenez, J. C., Espinoza, J.-C., Cunha, A. P. & Aragão, L. E. O. Increased climate pressure on the agricultural frontier in the Eastern Amazonia–Cerrado transition zone. Sci Rep 12, 457 (2022).
15... Feldpausch, T. R. et al. Amazon forest response to repeated droughts. Global Biogeochemical Cycles 30, 964–982 (2016).
16. da Costa, A. C. L. et al. Stand dynamics modulate water cycling and mortality risk in droughted tropical forest. Global Change Biology 24, 249–258 (2018).
17. Nepstad, D. C., Tohver, I. M., Ray, D., Moutinho, P. & Cardinot, G. MORTALITY OF LARGE TREES AND LIANAS FOLLOWING EXPERIMENTAL DROUGHT IN AN AMAZON FOREST. Ecology 88, 2259–2269 (2007).
18. Rowland, L. et al. Death from drought in tropical forests is triggered by hydraulics not carbon starvation. Nature 528, 119–122 (2015).
19. Aleixo, I. et al. Amazonian rainforest tree mortality driven by climate and functional traits. Nature Climate Change 9, 384–388 (2019).
20. Barros, M. I. A. D. Caracterização da visitação, dos visitantes e avaliação dos impactos ecológicos e recreativos do planalto do Parque Nacional do Itatiaia. Piracicaba, SP 121 (2003).
21. Brum, M. et al. Hydrological niche segregation defines forest structure and drought tolerance strategies in a seasonal Amazon forest. Journal of Ecology 107, 318–333 (2019).
22. Esquivel-Muelbert, A. et al. Compositional response of Amazon forests to climate change. Global Change Biology 25, 39–56 (2019).
23.....Powers, J. S. et al. A catastrophic tropical drought kills hydraulically vulnerable tree species. Global Change Biology 26, 3122–3133 (2020).
24. Bennett, A. C. et al. Sensitivity of South American tropical forests to an extreme climate anomaly. Nat. Clim. Chang. 13, 967–974 (2023).
25. Phillips, O. L. et al. Drought–mortality relationships for tropical forests. New Phytologist 187, 631–646 (2010).
26. Esteban, E. J. L., Castilho, C. V., Melgaço, K. L. & Costa, F. R. C. The other side of droughts: wet extremes and topography as buffers of negative drought effects in an Amazonian forest. New Phytologist 229, 1995–2006 (2021).

27. Costa, F. R. C., Schietti, J., Stark, S. C. & Smith, M. N. The other side of tropical forest drought: do shallow water table regions of Amazonia act as large-scale hydrological refugia from drought? New Phytologist 237, 714–733 (2023).
28..... Brienen, R. J. W. et al. Long-term decline of the Amazon carbon sink. Nature 519, 344–348 (2015).
29. Sullivan, M. J. P. et al. Long-term thermal sensitivity of Earth's tropical forests. Science 368, 869–874 (2020).
30. Lapola, D. M. et al. The drivers and impacts of Amazon forest degradation. Science 379, (2023).
31....Wilkie, D. S., Bennett, E. L., Peres, C. a. & Cunningham, A. a. The empty forest revisited. Annals of the New York Academy of Sciences 1223, 120–128 (2011).
32.Bodmer, R. et al. Major shifts in Amazon wildlife populations from recent intensification of floods and drought. Conservation Biology 32, 333–344 (2018).
33....Young, C. et al. Climate induced stress and mortality in vervet monkeys. R. Soc. open sci. 6, 191078 (2019).
34..Lacher, T. E. et al. The functional roles of mammals in ecosystems. Journal of Mammalogy 100, 942–964 (2019).
35. Bogoni, J. A., Peres, C. A. & Ferraz, K. M. P. M. B. Effects of mammal defaunation on natural ecosystem services and human well being throughout the entire Neotropical realm. Ecosystem Services 45, 101173 (2020).
36. Fassoni-Andrade, A. C. et al. Amazon hydrology from space: scientific advances and future challenges. (2021) doi:10.1002/essoar.10506527.1.
37... Schöngart, J., Wittmann, F., Junk, W. J. & Piedade, M. T. F. Vulnerability of Amazonian floodplains to wildfires differs according to their typologies impeding generalizations. Proc Natl Acad Sci U S A 114, E8550–E8551 (2017).
38. Wittmann, F. et al. A Review of the Ecological and Biogeographic Differences of Amazonian Floodplain Forests. Water 14, 3360 (2022).
39....dos Santos, A. R. & Nelson, B. W. Leaf decomposition and fine fuels in floodplain forests of the Rio Negro in the Brazilian Amazon. Journal of Tropical Ecology 29, 455–458 (2013).
40..Almeida, D. R. A. de et al. Contrasting fire damage and fire susceptibility between seasonally flooded forest and upland forest in the Central Amazon using portable profiling LiDAR. Remote Sensing of Environment 184, 153–160 (2016).
41. de Resende, A. F., Nelson, B. W., Flores, B. M. & de Almeida, D. R. Fire Damage in Seasonally Flooded and Upland Forests of the Central Amazon. Biotropica 46, 643–646 (2014).
42.. Carvalho, T. C. et al. Fires in Amazonian Blackwater Floodplain Forests: Causes, Human Dimension, and Implications for Conservation. Frontiers in Forests and Global Change 4, (2021).
43...Flores, B. M. & Holmgren, M. White-Sand Savannas Expand at the Core of the Amazon After Forest Wildfires. Ecosystems 24, 1624–1637 (2021).
44. Flores, B. M., Piedade, M.-T. F. & Nelson, B. W. Fire disturbance in Amazonian blackwater floodplain forests. Plant Ecology & Diversity 7, 319–327 (2014).
45. Williams, E. et al. The drought of the century in the Amazon Basin: an analysis of the regional variation of rainfall in South America in 1926. Acta Amazonica 35, 231–238 (2005).
46. Resende, A. F. et al. Flood-pulse disturbances as a threat for long-living Amazonian trees. New Phytologist 227, 1790–1803 (2020).
47.Neves, J. R. D., Piedade, M. T. F., Resende, A. F. de, Feitosa, Y. O. & Schöngart, J. Impact of climatic and hydrological disturbances on blackwater floodplain forests in Central Amazonia. Biotropica 51, 484–489 (2019).
48. Salerno, L. et al. Satellite Analyses Unravel the Multi-Decadal Impact of Dam Management on Tropical Floodplain Vegetation. Frontiers in Environmental Science 10, (2022).
49. Schöngart, J. et al. Teleconnection between tree growth in the Amazonian floodplains and the El Niño–Southern Oscillation effect. Global Change Biology 10, 683–692 (2004).
50. Schöngart, J., Piedade, M. T. F., Wittmann, F., Junk, W. J. & Worbes, M. Wood growth patterns of Macrolobium acaciifolium (Benth.) Benth. (Fabaceae) in Amazonian black-water and white-water floodplain forests. Oecologia 145, 454–461 (2005).
51. Melack, J. M. & Hess, L. L. Remote Sensing of the Distribution and Extent of Wetlands in the Amazon Basin. in Amazonian Floodplain Forests (eds. Junk, W. J., Piedade, M. T. F., Wittmann, F., Schöngart, J. & Parolin, P.) vol. 210 43–59 (Springer Netherlands, Dordrecht, 2010).
52. Junk, W. J., Piedade, M.T.F., Wittmann, F., & Schöngart, J. Várzeas Amazônicas: desafios para um manejo sustentável. (Editora INPA, Manaus, 2020).
53. Arraut, E. M., Arraut, J. L., Marmontel, M., Mantovani, J. E. & Novo, E. M. L. D. M. Bottlenecks in the migration routes of Amazonian manatees and the threat of hydroelectric dams. Acta Amaz. 47, 7–18 (2017).

54. Ribeiro, M. C. L. de B. & Junior, M. P. Fisheries ecololgy and management of the Jaraqui (Semaprochilodus Taeniurus, S. Insignis) in central Amazonia. Regulated Rivers: Research & Management 5, 195–215 (1990).
55. Fernandes, C. C. Lateral migration of fishes in Amazon floodplains. Ecology of Freshwater Fish 6, 36–44 (1997).
56. Castello, L. et al. Fishery yields vary with land cover on the Amazon River floodplain. Fish and Fisheries 19, 431–440 (2017).
57.....Marmontel, M., Fleischmann, A., Val, A. & Forsberg, B. Safeguard Amazon's aquatic fauna against climate change. Nature 625, 450–450 (2024).
58. Arantes, C. C. et al. Relationships between forest cover and fish diversity in the Amazon River floodplain. Journal of Applied Ecology 55, 386–395 (2018).
59. Mataveli, G. et al. Deforestation falls but rise of wildfires continues degrading Brazilian Amazon forests. Global Change Biology 30, e17202 (2024).
60. Aragão, L. E. O. C. et al. 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. Nat Commun 9, 536–536 (2018).
61... Withey, K. et al. Quantifying immediate carbon emissions from El Niño-mediated wildfires in humid tropical forests. Philos Trans R Soc Lond B Biol Sci 373, 20170312 (2018).
62. Barlow, J. et al. The critical importance of considering fire in REDD+ programs. Biological Conservation 154, 1–8 (2012).
63....Berenguer, E. et al. Tracking the impacts of El Niño drought and fire in human-modified Amazonian forests. Proc Natl Acad Sci U S A 118, e2019377118 (2021).
64. Barlow, J. et al. Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation. Nature 535, 144–147 (2016).
65. França, F. M. et al. El Niño impacts on human-modified tropical forests: Consequences for dung beetle diversity and associated ecological processes. Biotropica 52, 252–262 (2020).
66. Silveira, J. M. et al. A Multi-Taxa Assessment of Biodiversity Change After Single and Recurrent Wildfires in a Brazilian Amazon Forest. Biotropica 48, 170–180 (2015).
67. Barlow, J. & Peres, C. A. Ecological responses to El Niño–induced surface fires in central Brazilian Amazonia: management implications for flammable tropical forests. Phil. Trans. R. Soc. Lond. B 359, 367–380 (2004).
68. Flores, B. M. et al. Critical transitions in the Amazon forest system. Nature 626, 555–564 (2024).
69.... Lapola, D. M. et al. Limiting the high impacts of Amazon forest dieback with no-regrets science and policy action. Proc Natl Acad Sci U S A 115, 11671–11679 (2018).
70. UNICEF. Brazil Humanitarian Situation Report No. 2 (Amazon Drought). https://www.unicef.org/mali/media/1561/file/ParisPrinciples.pdf (2023).
71. Marengo, J. A. et al. Recent Extremes of Drought and Flooding in Amazonia: Vulnerabilities and Human Adaptation. American Journal of Climate Change 02, 87–96 (2013).
72. Bandeira, I. C. N., Adamy, A., Andretta, E. R., Costa da Conceição, R. A. & de Andrade, M. M. N. Terras caídas: Fluvial erosion or distinct phenomenon in the Amazon? Environmental Earth Sciences 77, (2018).
73. Parry, L. et al. Social Vulnerability to Climatic Shocks Is Shaped by Urban Accessibility. Annals of the American Association of Geographers 108, 125–143 (2018).
74. Ávila, J. V. da C., Clement, C. R., Junqueira, A. B., Ticktin, T. & Steward, A. M. Adaptive management strategies of local communities in two Amazonian floodplain ecosystems in the face of extreme climate events. J Ethnobiol 41, 409–426 (2021).
75.....Tregidgo, D., Campbell, A. J., Rivero, S., Freitas, M. A. B. & Almeida, O. Vulnerability of the Açaí Palm to Climate Change. Human Ecology 48, 505–514 (2020).
76... Gusso, A., Ducati, J. R., Veronez, M. R., Arvor, D. & Da Silveira, L. G. Monitoring the vulnerability of soybean to heat waves and their impacts in Mato Grosso state, Brazil. in 2014 IEEE Geoscience and Remote Sensing Symposium 859–862 (IEEE, Quebec City, QC, 2014). doi:10.1109/IGARSS.2014.6946560.
77. Anderson, L. O. & Pinheiro, R. L. G. Impacto das cheias na estrutura física das escolas da várzea de Santarém. Revista Ibero-Americana de Ciências Ambientais 13, 294–313 (2022).
78. Marengo, J. A. & Espinoza, J. C. Extreme seasonal droughts and floods in Amazonia: causes, trends and impacts. International Journal of Climatology 36, 1033–1050 (2016).
79. Pinheiro, J. A. C. et al. Perception of Amazonian fishers regarding environmental changes as causes of drastic events of fish mortality. Brazilian Journal of Biology 82, (2022).
80. Smith, L. T., Aragão, L. E. O. C., Sabel, C. E. & Nakaya, T. Drought impacts on children's respiratory health in the Brazilian Amazon. Sci Rep 4, 3726–3726 (2014).

81. Campanharo, W., Lopes, A., Anderson, L., da Silva, T. & Aragão, L. Translating Fire Impacts in Southwestern Amazonia into Economic Costs. Remote Sensing 11, 764 (2019).
82. Gomes, M. C. R. L., Andrade, L. C. de, Nascimento, A. C. S. do, Pedro, J. P. B. & Filho, C. R. M. Conditions of use and levels of household access to water in rural communities in the Amazon. Ambiente & Sociedade 25, (2022).
83. Sena, J. A., Beser de Deus, L. A., Freitas, M. A. V. & Costa, L. Extreme Events of Droughts and Floods in Amazonia: 2005 and 2009. Water Resources Management 26, 1665–1676 (2012).
84.....Funatsu, B. M. et al. Perceptions of climate and climate change by Amazonian communities. Global Environmental Change 57, 101923 (2019).
85. Pereira, H. C., Nascimento, A. C. S. do, Moura, E. A. F., Corrêa, D. S. S. & Chagas, H. C. das. Migração rural-urbana por demanda educacional no Médio Solimões, Amazonas. Revista Brasileira de Educação 27, (2022).
86. Lago, M. C. do, Rebelo, G. H., Bruno, A. C. & Henriques, L. M. P. Tikuna Perceptions of Extreme Weather Events: A Case Study on an Indigenous Lands in the Upper Solimões River, Brazil. Ethnobiology and Conservation 13, (2024).
87. Langill, J. C., Abizaid, C., Takasaki, Y. & Coomes, O. T. Integrated multi-scalar analysis of vulnerability to environmental hazards: Assessing extreme flooding in western Amazonia. Global Environmental Change 76, 102585 (2022).
88. Pinho, P. F., Marengo, J. A. & Smith, M. S. Complex socio-ecological dynamics driven by extreme events in the Amazon. Regional Environmental Change 15, 643–655 (2015).
89. Silva, S. S. da et al. Amazon climate extremes: Increasing droughts and floods in Brazil's state of Acre. Perspectives in Ecology and Conservation 21, 311–317 (2023).
90. GFLAC, Grupo de Financiamento Climático LAC, Índice de Finanzas Sostenibles 2023 (datos de 2022), Panorama de las Finanzas Sostenibles em América Latina y el Caribe. (https://www.sustainablefinance4future.org/_files/ugd/32948d_bc5467d51e2e4a83b19ff82875dd452f.pdf). (2023)
91. Linley, G. D., Jolly, C. J., Doherty, T. S., Geary, W. L., Armenteras, D., Belcher, C. M., ... & Nimmo, D. G. (2022). What do you mean,'megafire'?. Global Ecology and Biogeography, 31(10), 1906-1922.

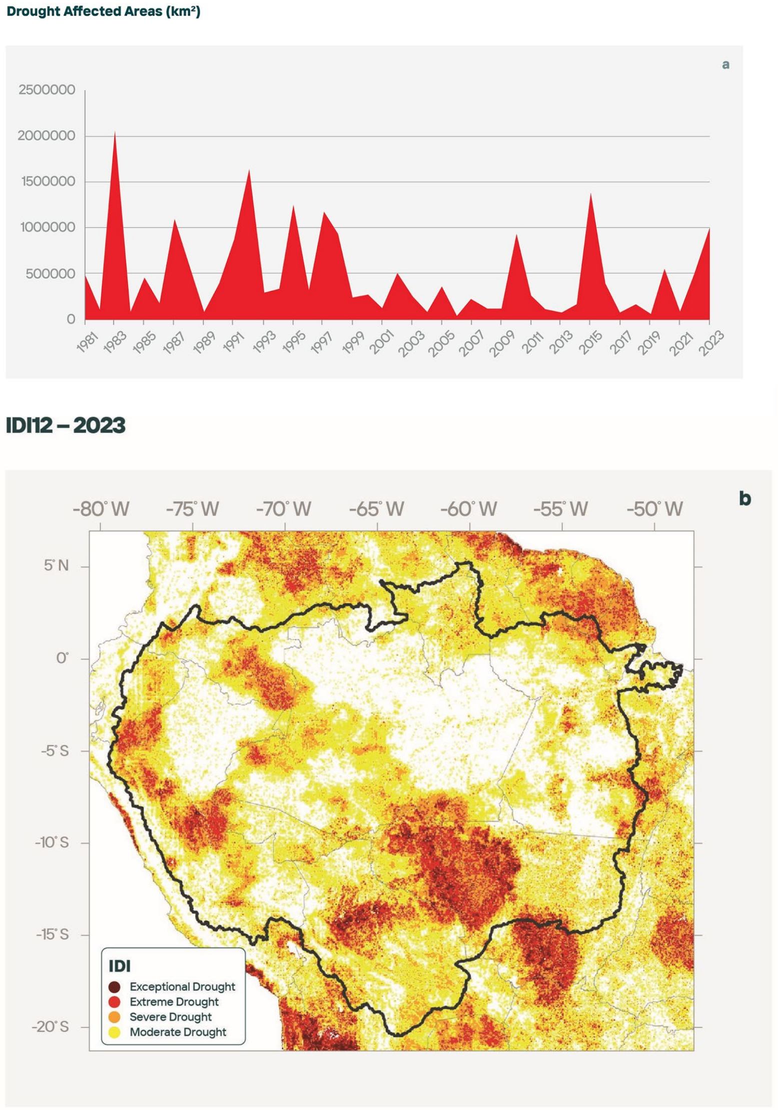

Figure 1. a) Area affected by droughts in the Amazonian region since 1981; b) areas affected by hydrological drought as represented by the IDI-12 (using SPI-12).

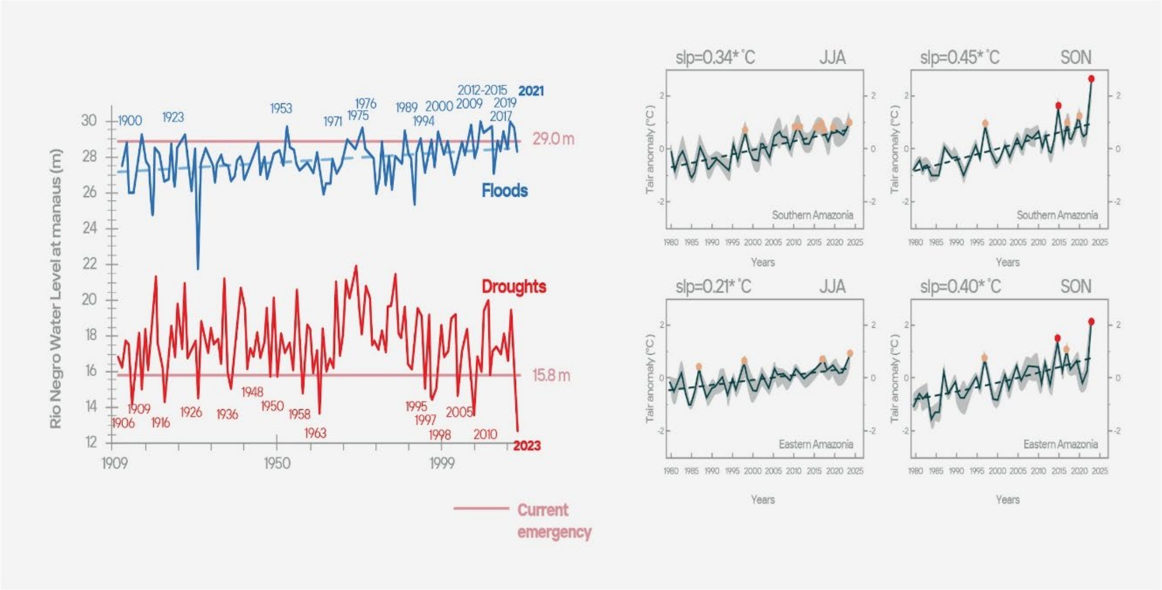

Figure 2. a) Annual maximum (floods, blue lines) and minimum (hydrological droughts, red) water levels of the Rio Negro monitored at the Port of Manaus from 1902 to 2023 (central Amazonia). Calendar years indicate extreme flood (>=29 m) and drought (<15.8 m) events (Source: J. Schöngart, INPA). b) Temporal series of monthly surface air temperature anomalies averaged over the seasons, JJA) and SON) from 1980 to 2023. The dashed line refers to the linear trend, with the slope value (slp) in ºC 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.

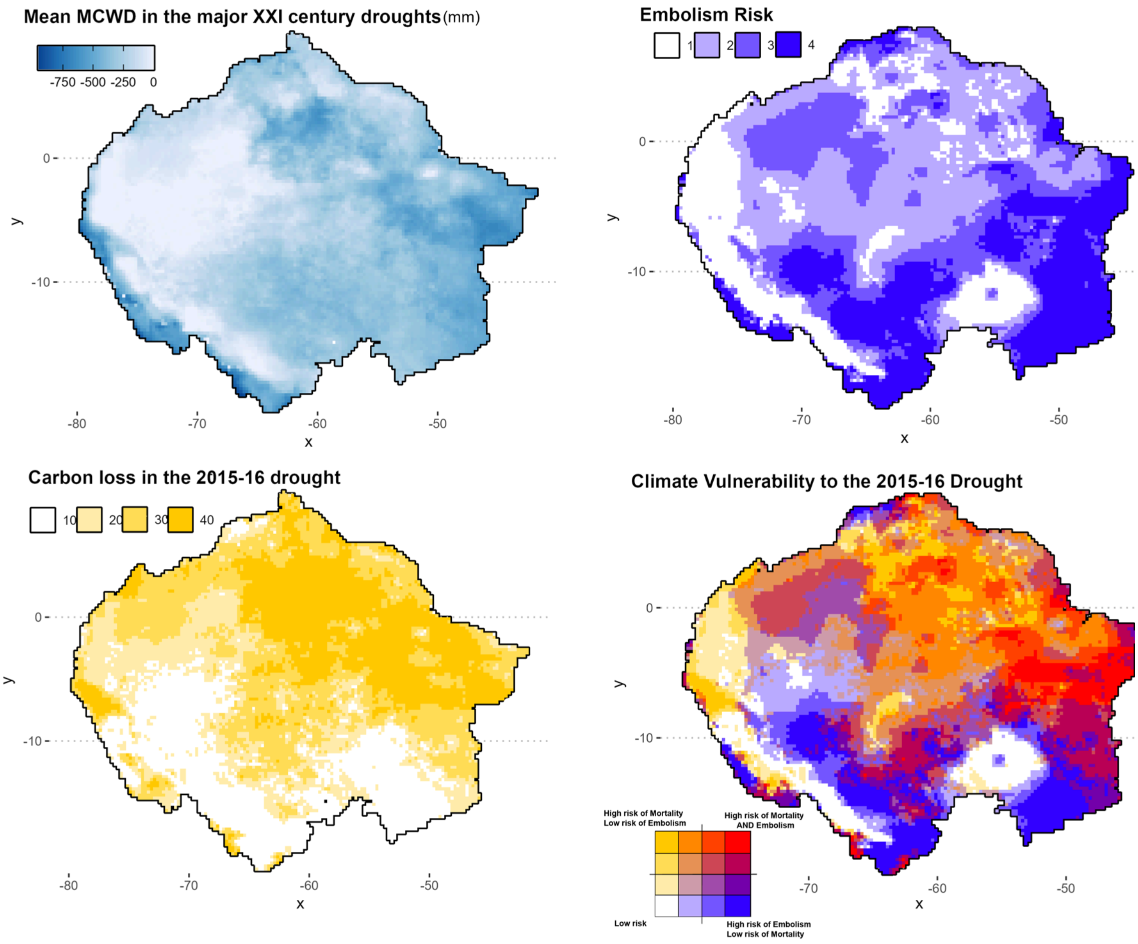

Figure 3. Map of ecological vulnerability of Amazonian regions based on the impacts of the 2015 – 16 drought events. Mean MCWD was calculated as the mean of the MCWD in the hydrological year (from May to April) for the drought events of the 21 century: 2005, 2009 and 2015. Embolism Risk (from Garcia et al. 2023) is given by 4 percentiles, higher values indicate higher chances of loss of hydraulic function, i.e. the capacity to transport water. Carbon loss (from Bennet et al. 2023) represent loss by tree mortality in the drought event of 2015-2016, also given in percentiles. The forest Climatic Vulnerability to the 2015-16 drought is the overlap of Embolism Risk and Carbon Losses: red regions indicate where high tree mortality was associated to high embolism risk; yellow regions indicate where carbon loss was high despite a high embolism resistance; and blue regions indicate where vulnerability is high because of high embolism risk, but where not much affected in 2015-16 because the water deficit was smaller.