Adaptation to drought in the Amazon: participatory approaches for strengthening the perspective of riverside communities

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ABSTRACT

The Amazon has experienced, in recent decades, extreme drought events (e.g., 2005, 2010 and 2015/16) with severe impacts to local populations: isolation of communities due to restrictions on river transportation, scarcity of food, medicine, and fuel in rural areas, increase in prices of crucial supplies, loss of agricultural crops, forest fires with consequences for human health, among others. While the dry season constitutes a natural part of seasonal variability in water availability, reflected in river levels and soil moisture, severe droughts, on the other hand, are periods during which water deficit occurs in an exacerbated manner in intensity and/or duration, leading to negative and serious consequences for ecosystems and human populations. Historical data shows an increasing trend in the number of dry days in the southern region of the Amazon basin and an opposite trend in the northern region, demonstrating that the changes the basin is undergoing are spatially heterogeneous. Climatological projections for the Amazon basin indicate a significant increase in the area exposed to moderate and severe droughts over the next eighty years, alongside an increase in the frequency of extreme events such as droughts and floods. In this regard, how can we address adaptation at the local level? Participatory experiences with local communities in the Amazon region have shown that communities have developed strategies by themselves based on traditional knowledge that can help in coping with the impacts of severe droughts. In the present work, we bring forth some experiences reported in the literature, including: housing and transportation adaptations, agricultural activity adjustments, development of an ecological calendar, and hybrid governance systems involving various social actors (e.g., community leaders, scientists, and government representatives) to address climate extremes. Finally, we provide some recommendations on technical and public policy aspects. The target audience for this document includes socio-environmental leaders, public servants, elected political representatives at local, regional, and national levels, researchers, educators, as well as individuals interested in learning more about the significance of local populations' perspectives in the process of adapting to extreme droughts.

Keywords: climate extremes, impact, adaptation, traditional knowledge, climate change, Amazonian populations.

Cobra-grande tanta seca estorvou
O prenúncio da Amazônia é savana
Uirapuru, amiúde não cantou
Chora, chora Amazônia

Lyrics from the song "Amazônia Eterna", Munduruku tribes

Definitions of drought and its local and regional perceptions in the Amazon

1. What is drought?

The word "drought," in a general sense, corresponds to a lack of water. The concepts and notions about drought are complex and vary across literature. Drought can be categorized as: *meteorological*, when there is a low rainfall rate, meaning significantly less rain than expected; *agricultural*, when drought affects, in the short term, the soil during crop growth periods; *hydrological*, when there's a reduction in river flow and water levels of lakes, reservoirs, and other surface water bodies, as well as affecting groundwater levels; *socioeconomic*, due to its impact on living conditions, economic assets, and human well-being; and *environmental*, when it leads to fire, land degradation, and sandstorms (Tonna *et al.* 2009, UNISDR 2009, Stanke *et al.* 2013). In this sense, drought can be defined as a phenomenon that, although recurrent and natural, can become severe (extreme drought), entailing negative consequences for the socioeconomic activities of local populations and ecosystems (Alpino *et al.* 2014).

It is common for the dry season to be defined by the rainfall regime. The dry season varies widely across the Amazon basin. If we define the dry season as the consecutive months with precipitation below the evapotranspiration rate, it is possible to identify 74 regions with distinct dry seasons in the Amazon territory (Carvalho *et al.* 2021). This definition takes into account the water stress imposed on the forest, which means that if the amount of rainfall is less than the water evaporated into the atmosphere from the forest, water bodies, and the soil, the forest loses more water than it replenishes, and therefore, would be under water stress. This is a technical definition, which may delimit a seasonality that is different from the local perception of drought. However, it is a useful definition for the identification of extreme events, that is events in which the expected dry season is more intense and/or longer than normal.

The Amazon basin has been undergoing changes in its rainfall regime. There is no clear consensus regarding a single trend concerning historical precipitation in the Amazon (Marengo *et al.* 2018), however, some studies indicate an increase in the number of wet days in the northern region of the Amazon in recent decades and an increase in the number of dry days in the southern region (e.g., Espinoza *et al.* 2019). Li *et al.* (2008) found evidence of a precipitation reduction across the entire basin, equivalent to 0.32% per year. In addition to these observed changes in recent decades, there are also natural events like the El Niño Southern Oscillation (ENSO) and other phenomena related to changes in sea surface temperature (e.g., Atlantic Ocean) that cause extreme droughts in some parts of the Amazon (Aragão *et al.* 2007; Yoon & Zeng 2010). It is possible to identify at least four regions that have experienced extreme droughts in the Amazon in recent decades:

1. Southwestern Amazon: the region that includes parts of Bolivia, Brazil and Peru has experienced one of the most severe droughts in the Amazon in recent years. The combination of climate change and deforestation has made this area particularly vulnerable to water scarcity and forest fires (Panisset *et al.* 2018);
2. Eastern Amazon: in 2015-2016, an El Niño-related drought caused widespread damage to forests and plantations in the eastern Amazon (Panisset *et al.* 2018);
3. Transition zone between the Amazon and the Cerrado: area located in central Brazil, in which deforestation is concentrated. The conversion of forest to to agricultural fields and pasture has reduced the area's capacity to retain moisture, making it more susceptible to droughts; and,
4. Peruvian Amazon: a region that has experienced many severe droughts in recent years, including one in 2010 that caused widespread damage to forests and crops (Marengo & Espinoza 2016). Deforestation, mining, and other human activities have contributed to the vulnerability of this area to droughts.

Climate change is expected to have a significant impact on these phenomena, increasing the intensity, extent and frequency of extreme droughts (Anderson *et al.* 2018). As temperatures rise and rainfall patterns change, Amazonian ecosystems become increasingly water-stressed and more susceptible to the deleterious effects of droughts, such as forest degradation, biodiversity losses and higher carbon emissions (Marengo *et al.* 2011; Duffy *et al.* 2015). In addition to the changes mentioned above, some areas of the basin, currently less vulnerable to droughts, may become more susceptible. The implications of these changes are potentially significant, as Amazonian ecosystems and human communities are adapted to historical patterns of rainfall, temperature and river regime. Changes in the spatial distribution of droughts can change species distribution, lead to changes in vegetation types (Esquivel-Muelbert *et al.* 2017), and affect the regional hydrological cycle, among other impacts that will be discussed in more detail in this document. Droughts could also exacerbate existing social and economic inequalities in the Amazon, as some regions may have more resources and adaptive capacity in relation to droughts than others (Marengo & Espinoza 2016). In this sense, the local perception of changes in drought regimes is fundamental for the elaboration of adaptation plans and mitigation of their impacts in a contextualized and useful way.

How drought phenomena are perceived and defined based on Amazon's local and regional perspectives?

In the Amazon, populations have a strong connection with water, and therefore, their lives are linked to the pulses of rising and falling river levels. Water constitutes a transformative agent of the region's way of life (Tocantins 2000). At the same time, the rainfall regime guides sociocultural activities in the Amazon, as the waters alter spaces and landscape, a movement referred to as seasonality (Pereira & Oliveira 2012). The seasonality of the rivers is described in four phases: rising water, high water, falling water, and dry season. Each phase of seasonality imposes, in its own way, strategies of use and exchange between humans and nature, sometimes limiting, sometimes providing their resources (Figure 1).

When assessing how Amazon populations use the term "drought," we can identify that it is not related to disasters, but rather as one of the phases of seasonality, as mentioned earlier. The dry season of the rivers is associated with a period of reduced rainfall in the region. In most of the Amazon basin, populations traditionally define two climatic seasons, marked by the period of higher or lower occurrence of rain: they name them "winter" and "summer". The intensity and distribution of the rainy season, as well as the seasonality of the rivers, are not homogeneous throughout the basin, due to its extension (Alves 2013). However, with the latest occurrences of extreme climatic events, populations have noticed an increase in the intensity and frequency of droughts after the 2000s and have called the events: extreme droughts, major droughts, severe droughts, intense dropping water level, and/or extreme low-water period (Nascimento 2017; Vasconcelos 2020; Silva 2022).

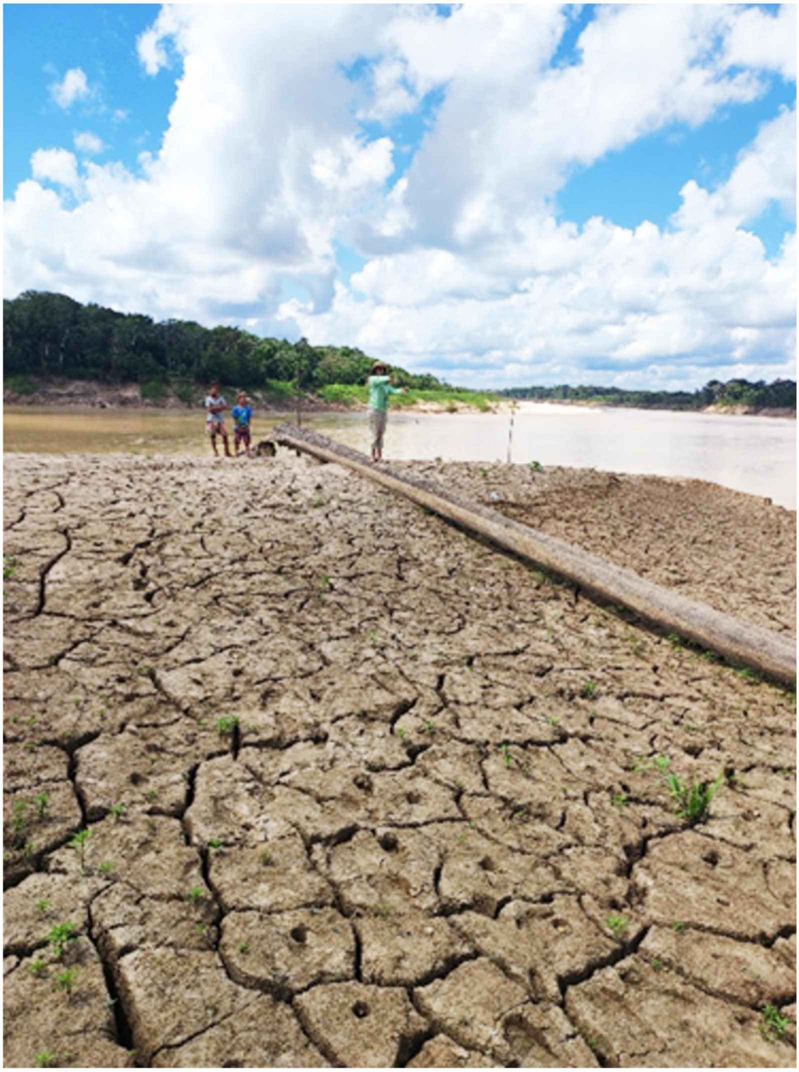

Figure 1 Drought in the Nova União community, in the Extractive Reserve of Médio Juruá, in the municipality of Carauari, Amazonas, Brazil (August 2022). *Photo:* Mônica Vasconcelos (2022).

Amazon populations engage in a range of socioeconomic activities based on the natural resources of rivers and forests, forming a connection with their environment. They organize their annual agricultural calendars according to the cycles of rainfall and river levels, and for this reason, they have noticed changes in recent years (Vasconcelos 2020). In a study conducted in the lower Negro River, women perceived the occurrence of drought events as:

> There is a change in the regular rainfall calendar, and this contributes to the occurrence of forest fires. Furthermore, they state that major droughts make it challenging to carry out fishing, farming, and wood extraction activities. During significant droughts, the difficulty of access requires the use of smaller canoes. The major droughts are associated with periods of reduced rainfall and increased heat, according to community members of the Rio Negro Sustainable Development Reserve (Vasconcelos 2020).

Due to this dynamic exchange with the environmental system, traditional populations adjust their ways of life to a certain predictability of the seasonality of rivers. For Fraxe (2004, p. 330), "the river is a dominant factor in the physiographic and human structure, an ethos and a rhythm to regional life". However, in the year 2005, for example, the residents of the riverside community of Terra Nova, located in the Careiro da Várzea District, Amazonas (Amazon River), were taken by surprise with an extreme decrease in water levels that made it difficult to obtain water for household use and irrigation, also causing disruptions in the transportation of goods and people, particularly that of children transportation to school (Nascimento 2017). Furthermore, in years of severe droughts, the floating houses cluster in smaller spaces, which can damage their structures.

In a study that sought to evaluate the perception of riverside populations along the Madeira River, Silva (2022) pointed out that, in episodes of abnormal receding water levels, residents report: isolation of riverside communities, leaving them without access to clean water or fish in lakes and rivers, increased vulnerability to fires due to the potential for it to reach the communities, as well as an increase in the cost of fuel, cooking gas, and basic necessities. According to the Wapichana indigenous people, who occupy the valleys of the Uraricoera River and the Tacutu River in the state of Roraima, the warming of river water has caused fish to migrate, reducing their food availability. They believe that this is a consequence of climate change (Alcantara 2019). Although the problems caused by major droughts in the Amazon are notorious, the perceptions of local populations indicate that, depending on the case, it can also have positive impacts on their livelihoods, such as increasing the availability of fish for consumption due to their confinement in restricted spaces like lakes.

Finally, the perceptions of the drought phenomenon are quite plural in the Amazon. Traditional populations have evolved their practices in the context of the seasonality of rain, of the rivers, and of the different crops, recognizing the connection between these dynamics. The rain plays a leading role in this seasonality, marking the seasons of the year. The onset of rainfall is greeted with prepared fields and a sociocultural dynamic that anticipates the rise of the rivers, and it is evident that, beyond the sociocultural context influenced by the river's seasonality, there is a change in the local landscape due to the dynamics of water covering the land (Figure 2). However, climate change affects this seasonality and what was once known and predictable becomes an additional factor of vulnerability for populations living in close relationship with the rivers.

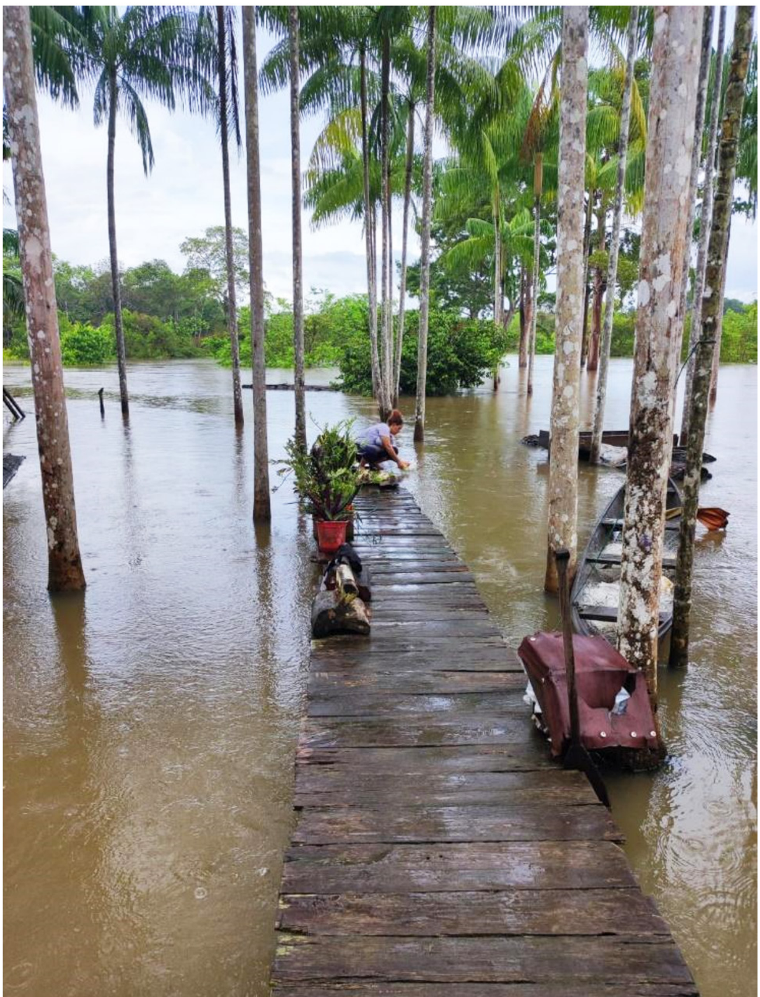

Figure 2 Rainy season in the São Raimundo community, in the Extractive Reserve of Médio Juruá, in the municipality of Carauari, Amazonas, Brazil. *Photo:* Mônica Vasconcelos (2022).

It should be noted that the phenomenon of drought in the Amazon is related to a change observed in the climatic cycles of the ecological calendar, which, in some cases, includes the prolongation of dry season. These changes have led local populations to reduce their ability to maintain their traditional socioecological adaptation systems, change the dynamics of fishing, hunting, planting, and collecting forest products. They have had to address these needs by adopting lifestyles that are more dependent on markets and the state. According to Moraes and Schor (2010), in certain items of the regionally adjusted basic food basket, there is a cost variation depending on the river's seasonality, with this cost being higher during periods of extreme droughts. This is due to the difficulty of boats reaching more distant cities and, especially, riverside communities, which increases the freight cost.

Future perspectives of droughts in the Amazon

Scenarios that take into account the phenomena associated with drought in the Amazon play a role in demonstrating how this type of event can negatively impact the future of the forest and local populations (e.g., riverside, urban and indigenous). Climate models projections can assist decision-makers in developing actions to reduce the impacts of droughts in the Amazon and contribute to strengthening adaptation strategies of local populations to drought events, particularly those associated with severe droughts (Duffy *et al.* 2015). Through a diagnosis of the climatic conditions observed in a historical period, it is possible to understand the mechanisms that drive drought events in the Amazon (Nobre *et al.* 2007; Philips *et al.* 2009; Mu *et al.* 2023). This understanding is essential to project the occurrence of future severe drought events and their potential negative impacts on the forest and local populations.

Climatic prediction models can indicate, with some advance notice, where, how, and when possible severe drought events may occur. For instance, the model developed by the Center for Weather Forecast and Climate Studies at the National Institute for Space Research (CPTEC/INPE) managed to provide indications and drought conditions for the events that took place in 1998, 2005, and 2010 with one month of anticipation (Borma & Nobre 2013). Despite the relatively short time, with this information, public institutions can issue alerts and propose emergency measures to mitigate the impacts associated with these phenomena, especially in areas that may be highly affected by these events. With an effective governance and alert system in place, the local population can, with government support, prepare in advance, thereby reducing economic, social, and environmental damages (Borma & Nobre 2013).

Factors such as deforestation, forest degradation through logging, forest fires, edge effects in the forest, extreme droughts, and urban area expansion have accelerated climate change and/or intensified its local effects (Foley *et al.* 2007; Lawrence & Vandecar 2015). It is estimated that approximately 2.5×10^6 km^2 (38%) of the remaining forest in the Amazon is degraded, which can reduce evapotranspiration by up to 34% during the dry season, causing significant disruptions in the forest's functioning, loss of biodiversity, and impacts on the way of life of local populations (Lapola *et al.* 2023).

1. What do the climate projections indicate?

Studies based on climate observations have already shown evidence of variations in precipitation in regions of strong anthropogenic pressure in the Amazon, especially in the dry season, in the coming decades. In the future, the dry season may become longer and more intense. In addition, severe drought events drought events, such as those that occurred in 2005 and 2010, may occur more frequently (Gatti *et al.* 2021; Marengo *et al.* 2011; Mu *et al.* 2023; Soares & Marengo 2013). Climate projections in the Amazon region have also shown that the trend is for the climate to become drier and warmer in the future (Marengo *et al.* 2010). According to a probability model for the occurrence of drought events like that of 2005, the frequency of such events was one every twenty years in the past but may increase, reaching nine every ten years by 2060 (Cox *et al.* 2008). On the other hand, some regions of the Amazon may face major floods more frequently in the near future (Duffy *et al.* 2015).

Studies based on deforestation scenarios indicate that the increase in deforested area in the Amazon may contribute to an increase in the number of days with water deficit in the southwest region, particularly in the Juruá and Purus River basins, due to changes in precipitation (Lima *et al.* 2014). These and other hydroclimatological changes projected from studies with models and scenarios are summarized in Table 1.

Table 1 Expected hydroclimatological changes for the Amazon basin according to some studies based on scenarios and simulation of climate change models.

Study area	Changes projected by the models	Reference
Amazon River basin	The size of the area currently affected by moderate droughts will double by the year 2100. Furthermore, the area affected by severe droughts will triple, and there will be a tendency for an increase in the annual average precipitation in the western part of the basin.	Duffy *et al.* (2015)
Amazon River basin	Extreme drought events like the one in 2005 could occur 9 times every 10 years by 2060.	Cox *et al.* (2008)
Western Amazon	Extreme flood events will occur more frequently after 2040.	Duffy et al. (2015)
Western Amazon	An increase in the annual average temperature of approximately 6°C in western Amazonia, with potential increases of up to 8°C during the dry season.	Marengo *et al.* (2010)
Amazon basin	By the end of the 21st century, the annual average flows will decrease in the southern tributaries of the Amazon basin. Seasonal flow rates are projected to increase during the wet season and decrease even further during the dry season, thus increasing the amplitude of flow rates throughout the annual cycle.	Nakaegawa *et al.* (2013)
Eastern Amazon	Water stress during the dry season is likely to increase in eastern Amazonia over the 21st century. Several factors contribute to this, including increasing temperature and evapotranspiration rates, increased deforestation and forest degradation.	Malhi *et al.* (2009)
Madeira River basin	Scenarios projected through hydrological modeling using climate change projections indicate a reduction in the minimum flow rate regime in the Madeira River basin. In the presence of combined climate change and deforestation, projections suggest a reduction in minimum flow rates in the upper part of the basin, and changes in flow rates overall throughout the hydrological year in the lower part of the basin.	Siqueira Júnior *et al.* (2015)

Therefore, the vulnerability of the Amazon and its inhabitants to climate change is related to the climatic variability observed in recent decades and the impact caused by the increase in greenhouse gases in the atmosphere, for which anthropogenic activities related to the degradation and deforestation of the remaining forest are important vectors. Studies indicate that increased deforestation in recent years and the intensification of the dry season cause an increase in fire occurrence and carbon emissions, especially where the ecosystem is already under water stress, such as the eastern part of the Amazon (Gatti *et al.* 2021). Consequently, projection models that relate the effect of deforestation to the temporal and spatial variability of the dry season at different intensities throughout the Amazon region can represent the future impacts associated with land use and land cover changes in the Amazon more accurately (Staal *et al.* 2020). It is important to emphasize that models are simplifications of reality, therefore, all climate projections have uncertainties and limitations, since it is not possible to represent all the complexity of the climate system and the changes in land use and land cover associated with forest loss in a model (Soares & Marengo 2013).

The Amazon rainforest plays a key role in maintaining the global climate, however, with increasing greenhouse gas emissions, deforestation and forest fires, Amazonian ecosystems are more susceptible to global climate change (Albert *et al.* 2023; Marengo & Souza Jr. 2018). This has a major effect on Amazonian populations that depend on forest resources. The risk of climate change for these populations is enormous. Thus, it is fundamental to strengthen local perception about the best ways to adapt to climate change. This can be done by associating the knowledge and experience that Amazonian residents already have about drought events, as well as the strategies used by them over the years in which they have experienced extreme events, with studies of climate change projections that show the possible trajectories of changes in the Amazon basin.

Impacts of droughts on local populations

Rivers are the main transportation routes for a significant portion of the Amazonian population, being essential throughout most of the basin and playing a fundamental role in the local economy through the transportation of various consumer goods. Inland water transport is particularly important in regions where road access is not available or where roads are not in good condition, especially during rainy season when many roads become unsuitable for traffic. Thus, traveling along the rivers is part of the routine, the means of life and the culture of many Amazonian populations, especially the riverine (David 2019).

Extreme droughts can cause major mobility and accessibility problems, as the water levels of rivers are considerably reduced (Pereira *et al.* 2021; Lima *et al.* 2023). Vessels require a minimum depth for traffic on rivers and streams. If the water level is too low, boats can run aground on sandbanks or be damaged by colliding with rocks and gravel from the exposed riverbed. When the drought is very intense, boats can be stranded in the port itself, with no way out (Kolanski *et al.* 2021). Furthermore, even when boats are still accessible, drought can force passengers to walk across sandbanks that form between the port and the boat anchorage point. All of this poses significant challenges to the water transport sector (Lima *et al. in prep*.).

When the boats manage to make the journeys during intense droughts, they still encounter many difficulties until they reach their destination. Heavy and large boats need to be replaced by lighter vessels that can navigate in shallower waters. However, these boats also tend to have a reduced capacity for transporting passengers and cargo. Therefore, several trips are necessary to transport the same amount of goods or passengers, and this can increase the cost of transport. To further complicate the situation, due to the risk of accidents, journeys need to be made more slowly and often involve zigzag routes to avoid obstacles. With the increased risk of accidents, it is common for authorities that control transportation via rivers to establish navigation restrictions, either regarding the maximum draft of the vessel or regarding the permitted transit hours (Lima *et al. in prep*.).

Transportation via rivers is crucial for numerous Amazonian communities in terms of access to consumer goods such as food, clothing, electronics, medicines, as well as household appliances and construction materials. For this reason, during severe droughts, the supply of consumer goods can be severely compromised and can lead to an increase in prices, causing, as well, temporary shortages in entire communities (Pinho *et al.* 2015; Pereira *et al.* 2021; Silva 2022). This is particularly alarming when it comes to essential immediate consumer goods, such as food and medicines (Marengo *et al.* 2013). Severe drought not only leads to shortages, but also hinders the transportation of agricultural production from rural communities. In some situations, communities may lose their entire crop yield due to the difficulty in transporting it to regional consumer centers or intermediary markets that trade the products (Lima *et al.* 2023).

Severe droughts also impact fishing, hunting, farming, and forest products extraction activities. When intense droughts occur, species that are typically fished or hunted may have their behavior altered or become less abundant due to food scarcity in the environment or ecological changes resulting from the drought (Pinho *et al.* 2015). In lakes and streams, the heat and reduced water levels can lead to fish mortality due to their impact on water quality. However, depending on the severity of the drought event, in some Amazonian regions, the opposite can occur; that is, fishing can be facilitated because the reduced water levels concentrate fish schools in smaller spaces. In contrast, with low water levels, the displacement of individuals engaged in fishing, hunting, or extraction can be compromised, making it difficult to access resources. Depending on the severity of the drought event, farming activities can also be affected. This is because, during severe droughts, the amount of water stored in the soil can be significantly reduced, leading to crop loss. Drought can also hinder plant germination and delay harvesting schedules.

Fuel is another important product whose access is reduced during severe droughts (Pinho *et al.* 2015). Several sectors of the local economy can be impacted by this shortage, given that fuel is not only strategic for local and regional transport, but also for power generation. Many communities in remote regions of the Amazon are not connected to the electrical grid and, therefore, rely on diesel-powered generators to operate household appliances, local businesses, schools and healthcare facilities. Refrigerators and freezers are essential for storing perishable foods, such as meat and fish, as well as some medications, such as vaccines and insulin. Therefore, during fuel shortages due to a severe drought, many communities may lose perishable items due to a lack of electrical power (Lima *et al. in prep*.).

Severe drought can also lead to a significant restriction of access to services that are of great importance to the population, such as healthcare and education. Complex situations involving various accidents, pregnancy and childbirth, chronic illnesses, care for newborns and the elderly can be tremendously worsened due to transportation difficulties (Garnelo *et al.* 2020). Reduced and slower travel impacts the arrival of patients at healthcare facilities, as well as the arrival of healthcare workers, nurses, and doctors at the homes of affected families (Lima *et al.* in prep.). Similarly, access to schools is impaired during periods of intense drought due to disruptions and delays in the school calendar. All the materials that students depend on also become scarce, compromising the progress of classes.

Finally, another major challenge posed by severe droughts is the increase in forest fires due to low air and soil humidity and the increase in tree mortality. Forest fires can occur due to illegal activity in the forest or uncontrolled use of fire in agricultural fields and pastures and can rarely be of natural origin. These events cause major problems for Amazonian populations, increasing the incidence of respiratory problems, which mainly affect the health of children, the elderly, and individuals with chronic problems (Marengo *et al.* 2013). Forest fires also hinder transportation via aircrafts and vessels, as the smoke reduces visibility during journeys, and they cause economic losses by damaging infrastructure (fences, houses, and cultivation areas).

Adaptive strategies based on local knowledge and participatory approaches to cope with droughts

Adapting to climate change refers to "the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities" (IPCC 2018). Here, we refer to adjustments related to extreme drought events in the Amazon. Adaptation can be classified, in terms of intentionality, as planned or spontaneous (Lindoso & Rodrigues Filho 2016). According to Smit *et al.* (2000), "planned adaptations" are those carried out by governments, typically through public policies, while "spontaneous adaptations," as the name suggests, are autonomous and reactive; for example, those carried out by rural populations in the Amazon. Many of these adaptations occur in the absence of government actions, primarily due to the initiative and resilience of these populations in the face of climate change scenarios.

Some proposals for adapting to drought phenomena are based on innovations that integrate the knowledge of local populations with scientific knowledge. Many of these proposals originate from participatory experiences in which practices were implemented, with relative success, approached the resolution of technical adaptation challenges and anticipated measures to mitigate severe droughts in the Amazon. In this regard, many non-governmental organizations (NGOs), government agencies, social movements, universities, and research institutes are leading initiatives with significant outcomes for the adaptation and mitigation of the effects that drought can have on the food, health, and well-being of indigenous peoples (Abdenur *et al.* 2019). We illustrate some experiences in this present work, including: housing and transportation adaptations, agricultural activity adaptations, the development of an ecological calendar, and hybrid governance systems involving different social actors to address climate extremes (i.e., community leaders, scientists, and government representatives).

1. Housing and transport adaptations

We begin with the case of the Lago do Catalão Community, located in the municipality of Iranduba, at the confluence of the Negro River and the Solimões River. In this community, due to the phenomenon of "landfall" (*terras caídas*), which is the riverine erosive process caused by the action of rivers and significantly intensified by hydrological extremes (Guimarães *et al.* 2019), all houses, as well as the local school, are constructed on top of tree trunks that serve as floating structures for support, in such a way that the buildings are adapted to the seasonality of water levels (Menin 2021). Due to the increased erosion of the community's shoreline, starting in 2007, residents began relocating to the upland area, so the floating constructions themselves became an adaptive strategy (Guimarães *et al.* 2019; Menin 2021). However, life on floating houses has its challenges as well: during years of severe river droughts, the foundations and beams of these houses are often damaged and require replacement.

During severe droughts, the main watercourse becomes quite distant from the houses, and hydraulic pumps are used to access water. Additionally, a temporary dam made of sandbags is built in Lago do Catalão to prevent the water from completely flowing out in the direction of the river course (Menin 2021). An important adaptation to highlight in this community is the one made to recreational structures, particularly for soccer, a popular sport in rural areas of the Amazon. In the Lago do Catalão Community, soccer is played on a field created on top of the floating tree trunks (Vasconcelos 2020).

In the lower Negro River, adaptations made during years of severe droughts are primarily associated with transportation along the rivers, using smaller canoes. These canoes are used for various productive activities such as the extraction of forest products, agriculture, fishing, gathering, and hunting. They are also essential for accessing schools, healthcare services, and recreational activities. Additionally, artesian wells have been constructed over the years due to the difficulty of accessing water (Vasconcelos 2020). The use of smaller boats during severe droughts is a common adaptation in many parts of the Amazon because it allows for navigation on rivers and streams with very low water levels, which would not be feasible using larger boats. However, since these smaller vessels have limited capacity, more trips are required to transport the same amount of load or individuals.

Similar responses were identified in Nascimento 2017, however, in the Lago do Rei Community, the mais adaptation is related to housing: during severe droughts, traditional floating houses need to be moved to areas that still have water, and this is not always possible. Moreover, the restricted space poses a risk of collision with other houses or boats. Nascimento (2017) describes an alternative of floating houses on plastic drum floats, which do not need to be relocated in extreme droughts and are more affordable when compared to traditional floating houses built on açacu logs (*Hura crepitans* L.). In the Madeira River basin, an interesting adaptation involves the logistics of boat transportation: local populations changed their timing for transporting goods during years of extreme drought. The event occurs during the same period as the Amazon summer, with high temperatures, and due to the formation of long sandbars, community members find it challenging to reach the boats due to thermal discomfort. Therefore, transportation is carried out in the late afternoon (Silva 2022).

2. Agricultural strategies

Among the various strategies for adapting to climate change in the Amazon region, there are those aimed at addressing the impacts on agriculture. Here, we report on some participatory experiences that illustrate the efforts of different social groups to promote soil conservation and adjust harvest times to climate variability, as well as other actions to protect traditional agricultural practices with the support of science.

We begin with the collaboration between scientists and indigenous peoples in efforts to enrich soils in chagra systems. Chagra is an ancestral agroforestry system practiced by traditional communities in the Amazon and Andean regions, originating from indigenous knowledge (Marentes *et al.* 2022). A close synonym would be “slash-and-burn agriculture” or “traditional swidden agriculture.” This rotational farming system is mainly practiced in countries such as Ecuador, Colombia, and Peru and involves a series of activities that promote both food production and biodiversity. It’s important to emphasize that when carried out by traditional populations, its impact on the forest is minimal compared to modern agriculture, where extensive cutting and burning occur, making it a driver of deforestation and an unsustainable practice.

Soil enrichment in chagras is an important issue in some regions of the Amazon due to adverse climatic conditions. Drought is one of the major challenges faced by farmers in the Amazon, as it can severely impact crop productivity (UN Periodico 2022). Changes in droughts and rainfall periods have resulted in alterations to the slash-and-burn activities in the chagra system (UN Periodico 2022). In the case of communities near the city of Leticia in the Colombian Amazon, soil enrichment through agroecological practices has proven effective in enhancing crop productivity in chagras and increasing their resilience to drought events. These practices include crop rotation, diversification, the use of organic fertilizers, and soil conservation.

In addition, continuous monitoring and evaluation of soil conditions and crop yields are essential to ensure the long-term success of soil enrichment in the Amazon. The active participation of traditional communities in this process is important to ensure the effective and sustainable implementation of agro-ecological practices (UN Periodico 2022). For example, indigenous groups in the south and east of the Colombian Amazon, in the Caquetá-Putumayo interfluve (Uitoto, Muinane, Nonuya) and in the Colombian Amazon trapeze (Ticuna and Cocama) have implemented soil fertilization and enrichment practices for horticulture.

Traditional chagras have a limited lifespan, lasting only a few years before being temporarily abandoned and converted into fallow areas for local conditions to recover. While the shifting cultivation forest system benefits from the ecological succession process to replenish soil nutrients during the fallow period, traditional populations are not accustomed to soil enrichment practices adopted in other regions. To promote soil enrichment in chagras, the idea of composting and soil maintenance practices has been promoted by the Sinchi Institute, a government institution in Colombia, in the Amazonian trapezoid and the Igaraparana River region (Caqueta-Putumayo). The institution recommends avoiding forest burning and, instead planting in existing fields, maintaining productivity and adding natural fertilizers (ashes, decaying wood, etc.). This system is still in its early stages, and its results still genarate expectations. It requires much more intense dedication to horticulture, which competes with the available time for other subsistence activities (UN Periodico 2022).

An example of how soils are treated for the cultivation of aromatic and culinary medicinal plants in agroforestry backyards and swidden fields in floodplain areas is described by Chagas (2011) in two communities, São Francisco and Santa Luzia do Baixio, located on the left bank of the Solimões River, specifically in the Careiro da Várzea District, a microregion of Manaus, in the state of Amazonas. In these communities, cultivation is done directly on the ground during the dry season and on raised beds during the river's high-water season. Therefore, as the flood season approaches, the soil enriched on the ground is transferred to the raised beds for planting (Chagas 2011). To aid in soil fertilization, both chemical and organic fertilizers are used, such as poultry and cattle manure, ashes from burned organic materials (e.g., wood, branches, and leaves), and residue from cultural practices (Chagas 2011).

A recent study by Silva (2022) describes adaptation strategies in cultivation systems implemented by residents of four riverside communities in the Rio Madeira Sustainable Development Reserve, located in the municipality of Novo Aripuanã, Amazonas. These strategies became necessary due to the high mortality rate observed in fruit trees, arboreal, and short-cycle crops (Silva 2022). The first strategy involves cultivating in upland areas, as they are generally not affected by sediment and sandy soil deposition. The second strategy is related to the way manioc (cassava) is planted and an increase in the depth of the planting pit. Residents started planting manioc vertically and increased the depth of the pit by 20 cm for banana cultivation (Silva 2022).

3. Ecological calendar

For thirty years, indigenous organizations, with the support of NGOs and state organizations, have been promoting the systematization of agricultural, climatic, and cultural knowledge through what has been called an "ecological calendar" in the Colombian and Peruvian Amazon. These initiatives aim to strengthen community research and the self-government of local, indigenous and community organizations. Through the "dialogue of knowledge" approach, knowledge of ecosystem changes in biocultural, climatic, and seasonal cycles is represented in the ecological calendar (Echeverri 2009).

The ecological calendar is a concept adopted to describe the knowledge about the use and management of nature and the productive systems of indigenous communities. It is considered a participatory, community-driven process, led by the efforts of indigenous leaders, researchers, government officials, and activists interested in generating learning experiences in which indigenous ecological knowledge and scientific understanding of animals, plants, soils, and landscapes are collected and organized.

In academia and institutions, the ecological calendar is named as such because it has been represented in this way through contributions from Western knowledge, both graphically and in written form. This tool is also used in Indigenous Education programs, particularly in the Natural Sciences, where curricula have been structured under the management criteria of indigenous groups (a process that the Indigenous Major Council of Tarapacá - CIMTAR - has been implementing in the Colombian Amazon). These programs aim to place scientific and traditional knowledge on an equal footing, without one superseding the other (De La Cruz 2013).

Ecological calendars have also been implemented in the Amazon as a local strategy for adapting to climate change. In the southern Colombian Amazon, the outcomes of these reflections have established two dimensions for addressing the topic: firstly, how phenomena associated with climate change are understood or interpreted based on cultural traditions, and secondly, assessments of the impact of these changes on the daily activities of the communities (Lasprilla 2015).

The ecological calendar (Figure 3) is based on traditional knowledge of indigenous communities and scientific research and is used to anticipate the expected availability of natural resources in the region according to local seasonality. For example, it is used to predict the best moment for hunting, fishing, fruit gathering and planting. The calendar is also used to promote the sustainable management of natural resources, encouraging conservation and long-term sustainability. By utilizing local knowledge and science, the ecological calendar becomes a valuable tool to help communities make informed decisions and protect the region's biodiversity and natural resources.

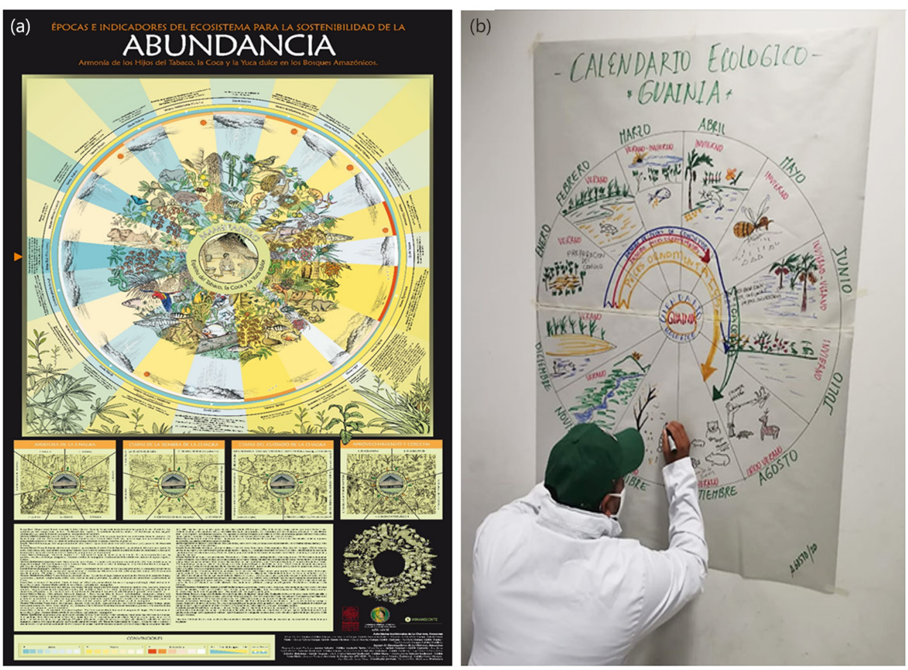

Figure 3 (a) Abundance calendar of ethnic groups in the central region of the Colombian Amazon. *Source:* Sinchi Institute (2012). (b) Development of the ecological calendar at the OPIAC training school. *Source:* OPIAC (2018).

4. Hybrid governance

Current environmental governance models are increasingly adopting community-based proposals, grounded in local knowledge and traditional practice. In the southwestern Amazon, specifically in the MAP region, an experiment – the MAP[1] Initiative – has been ongoing for over a decade. It employs a hybrid approach to environmental governance that combines the perspectives of local communities, scientific knowledge, and state participation, with the state providing public resources to support local governance (Perz *et al.* 2008).

The MAP Initiative is a trinational network that emerged from the interaction among scientists, community leaders, and government representatives, recognizing that solutions to cross-border challenges, such as environmental threats and climate change, require integrated environmental planning (Rioja 2005). The initiative comprises various organizations in each member country, serving as nodes in a larger network of governmental and non-governmental organizations and communities, with the primary focus on collectively identifying and advocating for strategies to mitigate environmental impacts (Brown *et al.* 2002). The success of the initiative in its initial actions gave rise to working groups, referred to as mini-MAP, with specific objectives.

The drought in 2005 and the floods in 2006 in the southwestern Amazon primarily affected the state of Acre (Brazil) and the Department of Madre de Dios (Peru), resulting in significant material damage and serious health issues due to the smoke resulting from increased slash-and-burn activities and forest fires (Perz *et al.* 2022). The prolonged drought led to over 300,000 hectares of forest burned in the southwestern Amazon and at least $50 million in direct economic losses (Brown *et al.* 2006). Due to these events, the MAP Initiative took measures to improve governance in response to natural disasters and adaptation to climate change. One of these measures was the creation of the risk management working group called "Mini-MAP Risk Management" (MMGR), with the aim of enhancing planning for extreme weather events (Perz *et al.* 2022).

Through this working group, regular public forums were established to discuss participatory regional environmental planning actions involving members of regional universities, NGOs, local governments, and some national ministries, as well as civil defense authorities, including firefighters and the military (Perz *et al.* 2022). The public forums provided spaces for participatory dialogues, enabling the sharing of experiences with the goal of co-producing knowledge on future risk management to be used as a foundation for drought response preparedness. In addition to the forums, this co-production of knowledge and response preparation also included regular visits to communities in high-risk areas to discuss experiences and coordinate emergency plans (Perz *et al.* 2022). The continuity of the MMGR working group was based on the development of regional capacities to, alongside initiative partners, coordinate emergency responses during extreme events using real-time data on rainfall and hydrological conditions from the early warning system (Perz *et al.* 2022).

Another initiative that has contributed to the early warning system in the MAP region and the capacity building for climate change mitigation and adaptation in the southwestern Amazon in recent years is the MAP-Fire project (Multi-Actor Plan to Address the Increasing Risk of Forest Fires[1]). This project quantifies the risk of forest fires in the MAP region and studies the interaction between potential impacts and risk management (Anderson *et al.* 2020). Two key outcomes of this project are: (i) a platform for managing the risk and impacts of forest fires, providing real-time monitoring and access to geospatial data to support the activities of technicians and decision-makers, and (ii) the book "É Fogo!" (It's fire!)[2], written for the school community with the aim of incorporating the topic of fire into the curriculum (Anderson *et al.* 2020). Both products were co-produced with stakeholders through workshops and training, allowing the content to be adapted to local needs and specificities. The MAP-Fire project serves as an example of dialogue between science and society, an essential action for disaster risk governance that transcends boundaries, whether political, environmental or disciplinary (Anderson *et al.* 2020).

Final considerations

This work sheds light on the relevance of severe droughts in the Amazon, exploring both scientific definitions and local perceptions of this phenomenon. The impact of extreme droughts on the livelihoods and well-being of local communities in the Amazon is already evident, as reported in the literature regarding recent extreme events. Climate projections indicate that the scenario may become even more challenging if nothing is done to curb deforestation and forest degradation in the Amazon. The projections also underscore the importance of urgently adopting measures to reduce the negative impacts of climate change on local populations and the forest.

1. The acronym MAP-Fire in the original English means: Multi-Actor Adaptation Plan to cope with Forests under Increasing Risk of Extensive fires.

2. The book can be accessed for free at https://efogo.weebly.com/

In this context, scientific knowledge and the experience of local communities must be combined to strengthen climate change adaptation strategies in the Amazon region. The participatory experiences explored in this work suggest possible ways to adapt and mitigate the drought in the Amazon through the integration of indigenous, local, and scientific knowledge. By involving local populations, particularly traditional peoples, these approaches facilitate the development of context-specific strategies, enhancing resilience and reducing the vulnerability of these populations. Ultimately, a holistic and inclusive approach is essential to address the complex dynamics of droughts in the Amazon and ensure the sustainable future of the region and its inhabitants. Some recommendations are provided below, both in terms of research conducted in the Amazon and the implementation of adaptive strategies and participatory approaches:

- Promote the adoption of adaptation and mitigation measures for extreme events, such as droughts and floods, based on the traditional knowledge of affected populations, while also facilitating access to information systems and alerts generated through remote sensing applied to monitoring for meteorological phenomena, in a combined strategy of scientific and traditional knowledge.
- Implement mechanisms to bring communities and local governments closer to participatory experiences through integrated, long-term approaches that promote the full participation of civil society in defining and planning more effective measures to address extreme events.
- Permanently halt deforestation in the Amazon biome, primarily by containing the expansion of agricultural and cattle ranching frontiers, considering its effects on precipitation patterns in the Amazon, as well as carbon emissions resulting from deforestation and forest degradation. Additionally, strengthen the protection of conservation units and indigenous lands, especially those located in areas under high deforestation pressure. As previously illustrated, deforestation greatly contributes to the lengthening of dry periods in the Amazon and is also linked to forest fires.
- Increase the adoption of drought mitigation and adaptation measures in the Amazon by promoting sustainable practices in the agricultural, forestry, and energy sectors. Encourage collaboration among government organizations, non-governmental entities, universities, and research institutes to develop drought adaptation and mitigation strategies, integrating scientific, indigenous and local knowledge. Promote active participation of local communities in decision-making and policy implementation related to droughts, recognizing and valuing

their knowledge and experiences. Strengthen the capacity of indigenous and local communities to cope with droughts by providing technical support, resources, and access to relevant information.

- Strengthen existing drought monitoring and early warning systems (e.g., Cemaden/MCTI - National Center for Monitoring and Early Warning of Natural Disasters), providing them with budgetary resources and advanced technology for comprehensive and detailed coverage of the Amazon basin, facilitating timely planning and response to extreme weather events. Additionally, invest in data transparency policies, funding and enhancing open data platforms, as well as encouraging open scientific publications, to facilitate access to scientific knowledge about climate extremes.
- Regional and national governments should invest in transdisciplinary studies on vulnerability to extreme drought events, identifying regions and communities in critical exposure situations to these events (or those that will face critical situations in the future), as well as investigating local conditions that increase risk or support adaptive capacity in the face of these events. Strengthen the National System for Civil Protection and Defense, particularly local civil defense agencies, by providing financial resources, technical training, and logistical support for the development of strategic actions that involve the participation of local populations. The goal is to anticipate mitigation actions for the impacts of extreme droughts on society.

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