Unprecedented Social-Ecological Impacts of the 2023 Extreme Drought in the Central Amazon

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Abstract

While the 2023 record-breaking drought led to widespread social-ecological impacts across Amazonia, local impacts of such extreme events are rarely described in detail. Here we leverage a large interdisciplinary data collection related to social and ecological impacts in the Central Amazon. Compound hazards (reduced river water levels, lack of rainfall, high water/air temperatures, river erosion and fire smoke) led to major impacts, including an unprecedented mortality of 209 river dolphins and blooms of the potentially ichthyotoxic *Euglena sanguinea* phytoplankton. Fish kills in lakes and changes in caiman relative abundance along floodplain channels were observed, as well as lower-than-usual production of flowers and fruits in floodplain trees. Impaired river transportation was the main socio-economic impact, affecting important value chains such as the arapaima fishery and manioc flour production, and also access to healthcare, drinking water and urban markets. Our results also show the contrasting impacts between rural and urban populations, with the latter presenting a higher resilience throughout the event. Continuous records of impacts like those presented here are fundamental to guide future disaster management policies in Amazonia. This is particularly important to help vulnerable remote people and ecosystems during extreme events, which are likely to increase in the near future.

Keywords: Amazonia, climate change, extreme events

Introduction

The rhythm of the waters along the Amazon River Basin has a very tight relationship with the well-being and functioning of the region's social-ecological systems. Amazonian human populations[1], as well as flora and fauna[2], have adapted to one of the greatest seasonal water level fluctuations on the planet, with an average of up to 12 m between dry and flood seasons in some portions the Amazon River[3]. While adaptive strategies have been developed during the millennia that humans have inhabited the basin's rivers, recent extreme seasonal hydrological events (floods and droughts) have been threatening livelihoods and the health of these social-ecological systems.

In 2023-2024, a major drought occurred in the basin[4,5], arguably the most impactful on record - while past droughts usually affected certain portions of the basin, in 2023-2024 the whole system was directly affected. In October 2023, the lowest water levels were observed since records began 122 years ago (at the basin's longest water level record at the port of Manaus), and in October 2024 the historical levels were once again surpassed. This is particularly remarkable given that in July 2021 the highest water level on record was observed at the same station. These extreme floods and droughts in the last decade challenge people and ecosystems, and the complex and interdependent interactions between them, which form the multiple social-ecological systems of the Amazon[6,7].

Amazonian social-ecological systems are particularly vulnerable to climate change[6]. Regionally high poverty[8] and food insecurity[9] levels can be exacerbated by extreme climatic events (such as floods and droughts), which impact the ecological resources on which they depend[10], thereby exceeding the ability of much of the population to cope with these phenomena[1,11]. Particularly during droughts, compound hazards may arise by combining the reduced water levels with other disasters such as forest fires and heatwaves. In 2023, record breaking air temperature measurements were made globally[12]. In the face of climatic change, a holistic understanding of the impacts, vulnerabilities and adaptation strategies developed by various Amazonian populations and ecosystems is required. Given the high likelihood of the intensification of extreme events in the near future, it is essential to record the impacts of such events, and collectively create strategies to encompass both urban infrastructure and management of natural resources in protected areas[8,13–15].

Here, we present a broad description of the multi-sectoral impacts of the 2023 drought in the Central Amazon, in the heavily affected Mid-Solimões region in the Brazilian Amazon, based on an intensive in-situ collection of social and ecological information. We present a comprehensive assessment of the meteorological and hydrological aspects of the drought in the region, and its impacts on ecosystems (forest, phytoplankton, fish, water birds, caimans and dolphins), fisheries management, and rural and urban human populations, including human health impacts, access to water, and food prices.

Results

The physical environment

In the Central Amazon, air temperatures have been on a steady upward trend in the last decade. In the city of Tefé (Figure 1), September of 2023 displayed an average temperature of 29°C, which is 2°C above the monthly mean, with a maximum of 39.1°C on September 28th (Figure 1e), according to the locally observed data made available by the Brazilian National Institute of Meteorology (INMET). This was exacerbated by lower than average monthly rainfall, with 77 mm recorded compared to the climatological average of 131 mm. Forest fires during the period were also higher than normal in the region[16], and the combination of fires and low rainfall favoured the high concentration of air pollutants. Our air quality measurements indicated high pollution levels from fine particles (PM 2.5), which remained above 50 µg/m³ for the entire month of September 2023, and daily means exceeded 100 µg/m³ for 12 non-consecutive days during the same period (Supplementary Figure S1).

The Amazon River at Coari, a river gauge station with a similar hydrological signal in relation to Tefé, faced a major reduction in its water levels. Interestingly, unlike many other parts of Amazonia, the Central Amazon River did not have its minimum water level recorded in 2023, which was slightly higher than that of 2010. However, the compound nature of the event, with other climate change-related hazards such as forest fires and an air and water heatwaves, led to what has been called by most Amazonian populations the worst drought ever recorded. The annual average water level variation from high to low water at Coari is 10.5 m, but in 2023 the variation was 15.18 m. The reduced water levels, in combination with other environmental drivers, led to abnormal heating of lakes[17]. Lake Tefé, a large ria lake formed at the confluence between Tefé and Amazon rivers, was extremely shallow, with up to 10 km extent less than 0.5 m deep (Supplementary Figure S2), also becoming very turbid (Secchi disk depth less than 15 cm)[17]. Together with high incoming solar radiation, this shallowness was the main factor that led to the lake's abnormally extreme heating, which reached maximum daily values as high as 40°C, and diel variation of up to 13.3°C (Figure 1c)[17]. These high temperatures were likely the main cause of major aquatic fauna mortality, as described in the next section.

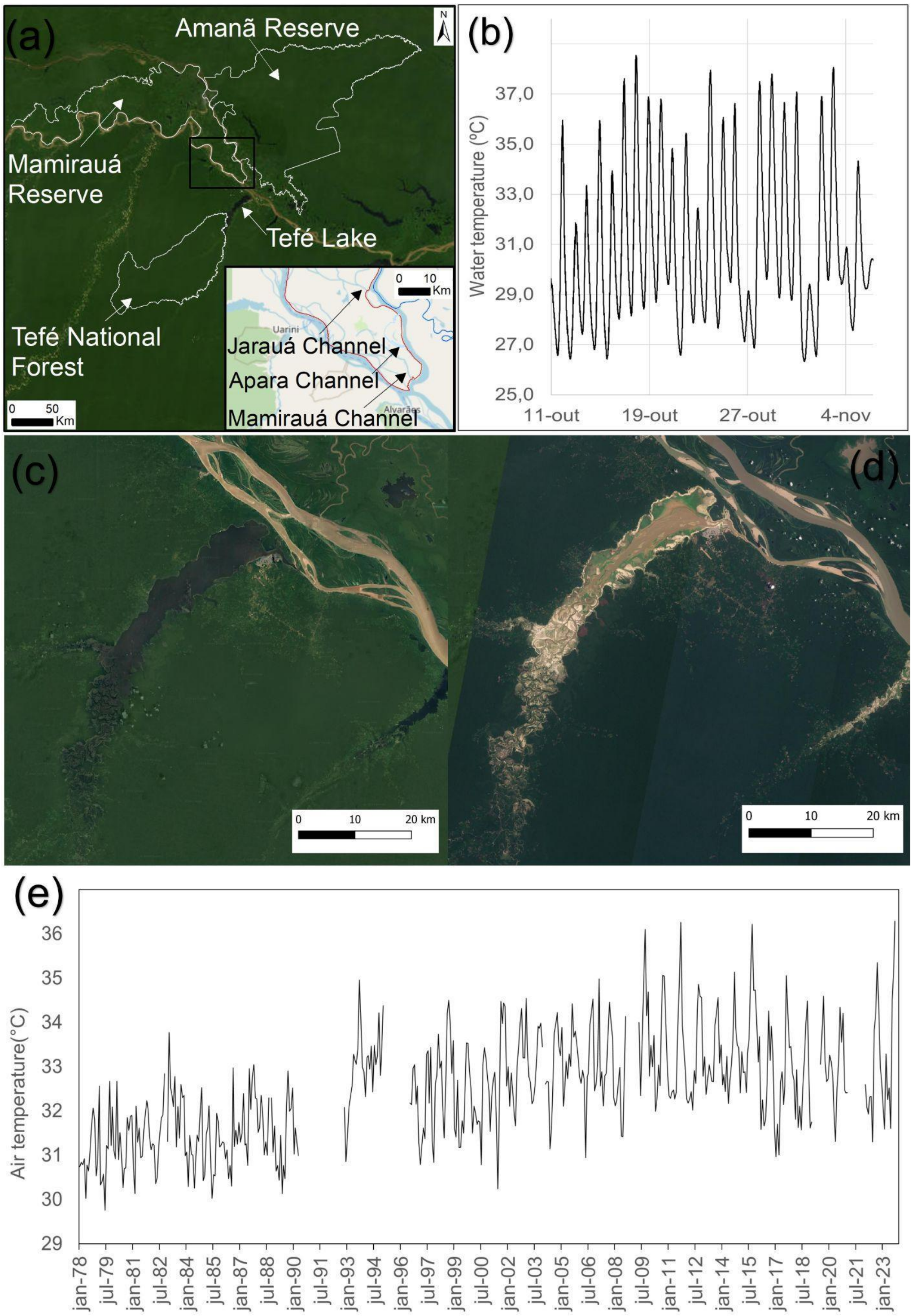

Figure 1. (a) Study area in the Central Amazon, highlighting the protected areas of Mamirauá and Amanã reserves and the Tefé National Forest. (b) Water temperature variation in Lake Tefé during the drought. (c) Lake Tefé under normal and (d) drought (18th Oct 2023) conditions, as revealed by PlanetScope imagery. (e) Long-term in-situ surface air temperature in Tefé (Brazilian INMET station).

Ecological impacts

Multiple ecological impacts were observed during the drought. Our in-situ records revealed mass fish and dolphin mortality, and major changes in tree phenology, phytoplankton composition and the relative abundance of water birds and caimans (Figure 2). We found that the production of flower buds, which typically occurs in September-October, shifted earlier to June-July in the floodplain forest surrounding Tefé. Additionally, the production of flower buds and flowers during the 2023 dry season was lower than usual, leading to lower fruit production in the beginning of 2024 (Figure 3). Surprisingly, the production of unripe and ripe fruits before the extreme drought event, during the high-water season (March to May), was also lower than the interannual average (Figure 3).

Phytoplankton composition from Lake Tefé was constituted by five classes: Chlorophyceae (3 taxa), Cyanophyceae (3 taxa), Bacillariophyceae (4 taxa), Zygnemaphyceae (7 taxa) and Euglenophyceae (1 taxon). We detected an *Euglena sanguinea* (Euglenophyceae) bloom, which created a large reddish patch on the lake surface (Figure 2b), and that adhered to the ground when the water level dropped – to our knowledge this is the first record of a bloom of this phytoplankton in Amazonia. We also detected blooms of *Pinullaria gibba* and *Spirogyra* sp. While *E. sanguinea* may be ichthyotoxic[18], we found only a few dead fish individuals surrounding the bloom. These belonged to five fish species, and we did not detect *E. sanguinea* in the gills nor the stomachs of those fish. However, we did find Bacillariophyceae algae on the gills and in the stomachs of *Hypophthalmus edentatus*, *Geophagus proximus* and *Osteoglossum bicirrhosum* fish species, as well as Cyanophyceae algae in the gills of *H. edentatus*.

Fish mortality was high in Lake Tefé, but within what would be expected for extreme drought events in Amazonia[19]. The active search identified 11 species of dead fish floating in the water or on the lake shores. Although mortality by species was not measured, we noted that the greatest mortality was of *Hypophthalmus edentatus*, a catfish that lives close to the water surface and has an important economic value in the Amazon. The trawl net samples captured 31 species alive, belonging to 19 families, of which six species were also found dead during the active search, namely *Prochilodus nigricans*, *Loricaria simillima*, *Pimelodus blochii*, *Geophagus proximus*, *Plagioscion squamosissimus*, *and Colomesus asellus* (Supplementary Table S1).

Total abundance of water birds in the Mamirauá Reserve was correlated with river water level. We found a significant decline in the total abundance after the extreme drought event, in January 2024, in comparison with bird abundance in January 2023 (Figure 4a). In turn, the caiman relative abundance (two species: *Melanosuchus niger* and *Caiman crocodilus*) increased in 2023 in the Jarauá floodplain channel (Figure 4b), close to Tefé. The absolute number of caimans counted (4412 individuals in 2023) was similar to the annual average (4474 individuals on average), but the area covered by population surveys was only 41% of the annual average number of kilometres travelled. Thus, the overall relative abundance was 250 caimans/km, which was much higher than the long-term average (102 caimans/km). The nest monitoring also presented a smaller covered area and a greater number of nests found, with a relative number of caiman nests per lake (10 nests/lake), higher than the usual number of nests (7 nests/lake).

Finally, we registered the death of 209 river dolphins in Lake Tefé in less than two months. All age classes and both species of Amazonian dolphins (Amazon River dolphin *Inia geoffrensis* and the tucuxi *Sotalia*) were affected. Approximately 12% of the population of river dolphins in Lake Tefé perished during the 2023 drought event – and both species are classified as Endangered, nationally and internationally.

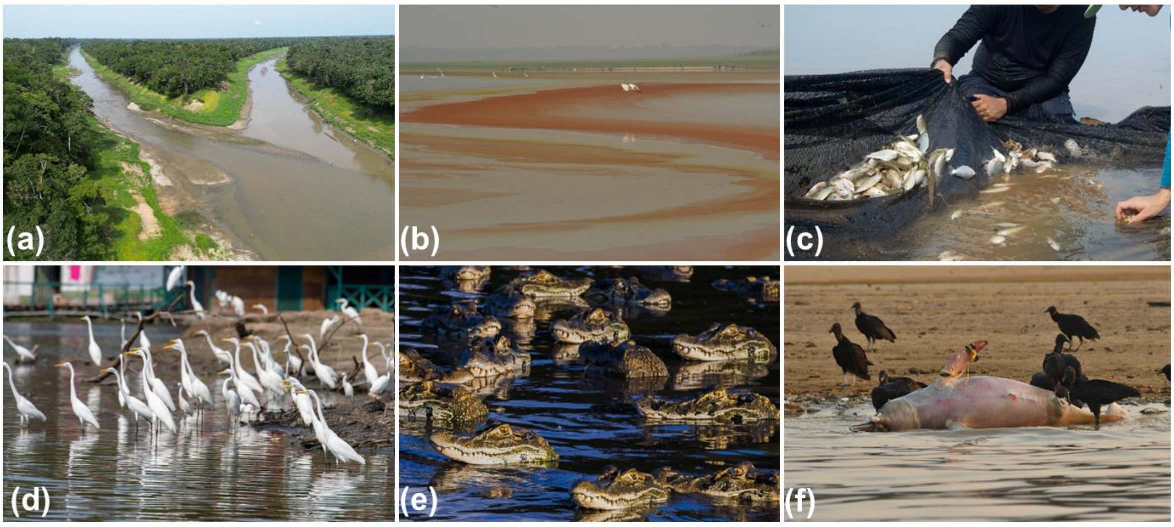

Figure 2. Different biological groups impacted by the 2023 drought in Central Amazon: (a) floodplain forests, (b) phytoplankton, (c) fish, (d) water birds, (e) caiman and (f) Amazon river dolphins. Photos by (a) Débora Hymans, (b,f) André Zumak, (c) Daiana Guedes, (d) Miguel Monteiro, (e) Marcelo Santana.

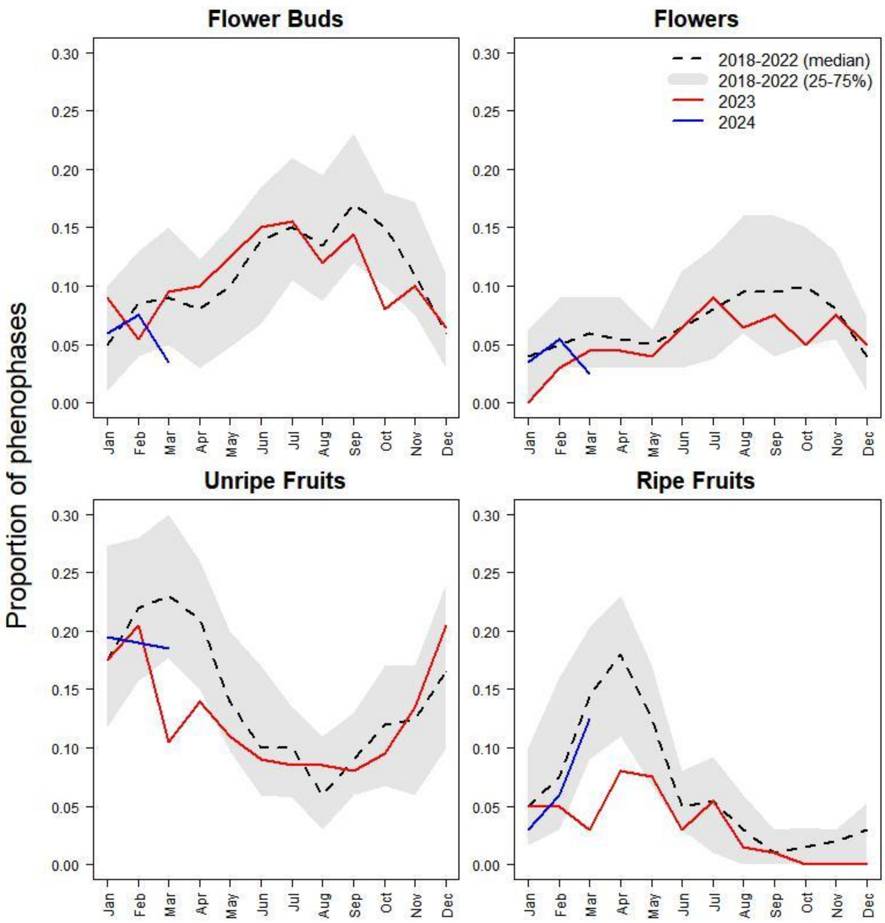

Figure 3. Impacts of the 2023 drought in tree phenology of floodplain forests in the Mamirauá Reserve.

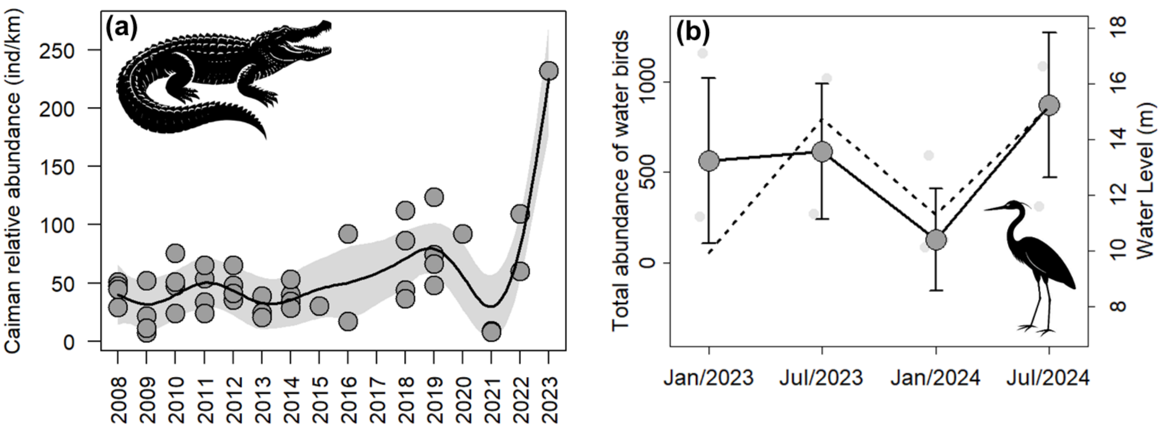

Figure 4. (a) Pronounced increase in Black caiman (*Melanosuchus niger*) relative abundance during the 2023 drought. (b) Variation in the total abundance of aquatic bird species (continuous line) before and after the 2023 drought. The dashed line represents the water level variation (observed at the Mamirauá floodplain channel gauge).

Socio-economic impacts

Impaired river navigability due to reduced water levels

Hydrological droughts are associated with rainfall deficit in the whole upstream drainage area, which corresponds to 1.7 million km^2 in the Amazon River near Tefé. The 2023 hydrological drought led to impaired navigability across the region (Figure 5), where most people depend on water bodies for transportation of people and goods and access to services. To elucidate the socio-economic impacts, we conducted interviews with urban and rural people (in riverine communities) across the region. The impaired navigability led to a lack of medicines and medical assistance in the region's health centres. For example, the entire Lake Amanã Sector of the Amanã Reserve is served by a single health centre, normally staffed by a doctor or nurse for 15 days each month. However, during the drought, the sector was left without a healthcare professional, as they were unable to return due to the navigability difficulties. In Tefé municipality, three out of 19 indigenous villages remained without health care (no visits from government health professionals) during the most critical period of the drought (impacting about 200 villagers), and in five others (impacting about 800 villagers) there was major difficulty of access by health professionals.

The large beaches that formed between communities and adjacent water bodies further impaired access to domestic water supplies, as there lacked water pipes long enough to reach the water bodies. Additionally, these conditions contributed to poor water quality, as stagnant water tended to accumulate, becoming more turbid. The communities' isolation also led to lack of power supply for pumps (usually diesel-powered), further affecting domestic water supply.

Education and culture were also highly impacted, with many pupils unable to commute to schools in neighbouring communities (especially for secondary education, which is available in fewer, more centralised locations) due to isolation of the communities - in some cases, students had to walk long distances along exposed beaches to access boats. Furthermore, school schedules had to be adapted, concentrating classes in the morning and significantly reducing the overall class hours to minimise students' exposure to the challenging conditions (especially high air temperatures). The relationship between communities, which is a fundamental basis of social organisation development in the region[20], was reported to be directly impacted through the impediment of holding festivities between communities. Periodic meetings of local organisations and leisure activities, like community football tournaments, were affected or interrupted, limiting social interaction and weakening the traditional ties that sustain the socio-spatial relations of communities[21].

The logistic challenges during the drought affected food production. Isolation of communities led to loss of crops (e.g. manioc and banana) because producers could not access nearby urban centres to sell their production. The Amanã Reserve Residents Association (CAMURA) reported an 80% loss in manioc flour sales, since farmers were approximately three months without being able to access the market, while the Tefé National Forest Association (APAFE) stated that some families suffered losses of more than ten thousand Brazilian reais (BRL R$; around two thousand USD)[22].

Commercial fisheries were affected due to the difficulty in accessing lakes and transporting fish to consumer centres (Figure 6d). Sustainable arapaima fishing is one of the most important economic activities in the Central Amazon[23], providing an important income once a year during the dry season, when the fishing occurs. For the first time in 25 years of management activities, two fishing licence extensions were provided by federal authorities, changing the final fishing day from 30 November 2023 to 10th Jan 2024. In the absence of these extensions, by 30 November only 23% of the authorised fish quota would have been captured, for the 12 arapaima management groups assisted by the Mamirauá Institute. By January, after the waters started rising again, only one management group could not accomplish the fishing because of the impaired river navigability. The Association of Pirarucu Fish Managers in the Mamirauá Region (FEMAPAM) reported a reduction in fish catch of approximately 40% during the drought.

Impaired navigation also impacted urban areas. In Tefé, the large boats that bring most goods from the Amazonas state capital of Manaus had to land more than 8 km downstream from the city's port for 52 days, from September 28th to November 18th. While shallower boats such as canoes were brought in to ensure that most goods still arrived in the city, increased food prices were observed (Figure 6). An overall 8% (BRL R$ 124 to R$ 135) increase in the basic food basket was observed during the drought, affecting both the urban population and adjacent rural communities. Particularly high price increases were witnessed for certain items, such as a 20% increase in the price of manioc flour (from R$ 8 to R$ 10 per litre), a fivefold increase in some vegetables, such as *cheiro verde* fresh herbs (from R$ 1 to R$ 5 a bunch), a doubling for some fish, such as *Pseudoplatystoma punctifer* (from R$ 20 to R$ 40 per kg), and an increase of over a third for frozen chicken (from R$ 8 to R$ 13 per kg). However, even with the increase of water levels from mid-October onward, the prices continued to rise until the end of the year because of other market processes, including the proximity to Christmas and New Year periods.

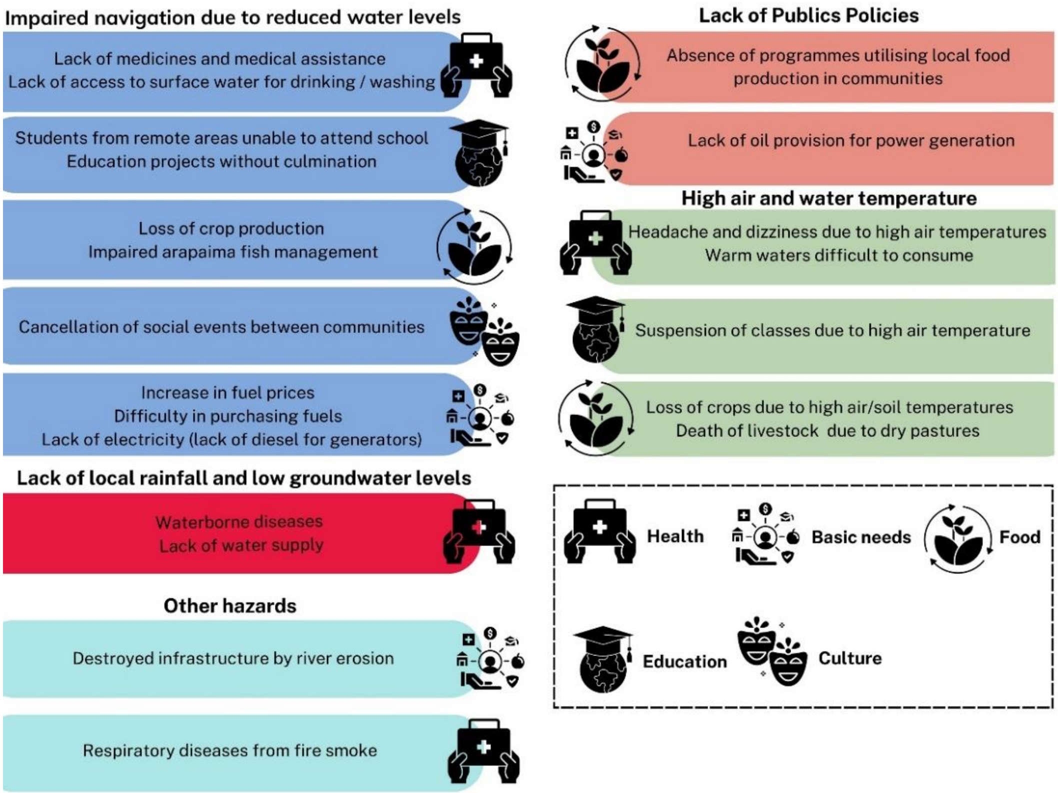

Figure 5. Main socio-economic impacts observed in the communities of Tefé's region during the 2023 drought.

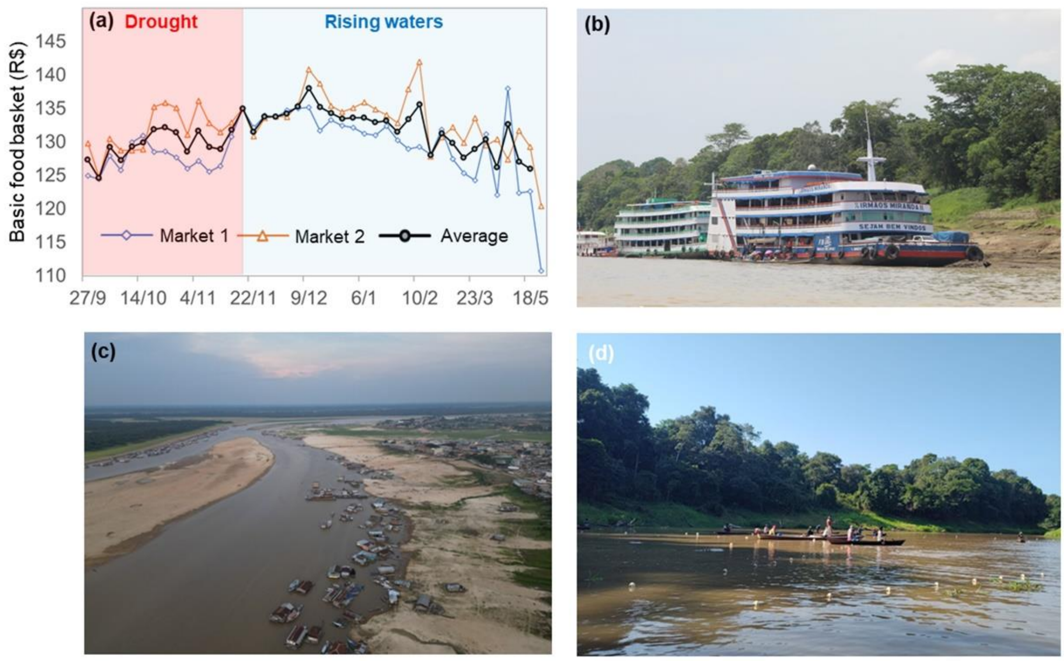

Figure 6. River navigation difficulties and its impacts on product transportation and prices. (a) Price variation of the basic food basket in Tefé, based on the average of the two main supermarkets in the city. The red rectangle shows the drought period (from the beginning of data collection to Nov 18th, when the first ferry boats could not dock in Tefé). The photos depict (b) a line of boats more than 8 km downstream of Tefé's urban area due to difficulties in navigation; (c) the drought-created large sandy beaches along the Lake Tefé shorelines;

(d) Most arapaima fishery management areas reached the target fishing quota after two official fishing extensions were granted due to impaired river navigation.

Lack of local rainfall and low groundwater levels

Besides reduced river water levels, local rainfall deficit led to meteorological and agricultural droughts. Access to drinking water was one of the most cited impacts by local communities. Many that depend on rainwater were left without, having to directly use river water without any proper treatment. Floodplain communities rely mainly on rainwater for drinking, but a combination of low rainfall and small water storage tanks (Figure 5; Gomes et al.[24]) led many communities to run out of water during the drought. This could be overcome to some extent by investing in larger rainwater storage facilities. For instance, with a total of 48.6 mm of rainfall, August 2023 was the driest month in the year. If an average house roof (60 m^2 on average, according to PlanetScope satellite imagery for three surveyed communities in Mamirauá, Amanã and Flona-Tefé reserves) harvested rainwater, considering a loss coefficient of 0.8, this amount could produce 2333 L of drinkable water for the household. Yet, only 2% of the community houses in the region (as revealed by a census in the Mamirauá Reserve) have sufficient water storage facilities (more than 2333 L; Gomes et al.[24]).

Groundwater is a major water source for local upland communities and urban areas in the Central Amazon, although generally with low water quality[25]. Most community wells were less than 50 metres deep, and several dried up during the drought. Lack of adequate pumping equipment also led to infrastructure damage, leaving many communities without a water supply. In the Tefé municipality, almost 2000 indigenous people were directly affected by unsuitable groundwater supply.

Waterborne diseases were reported by communities to have increased during the drought. According to Tefé's Health Secretary, diarrhoea cases increased during the period in 2023, but reached values similar to the 2022 dry season (Supplementary Figure S3). This may have occurred due to underestimation of the cases associated with the difficulties of transporting ill rural people to urban areas.

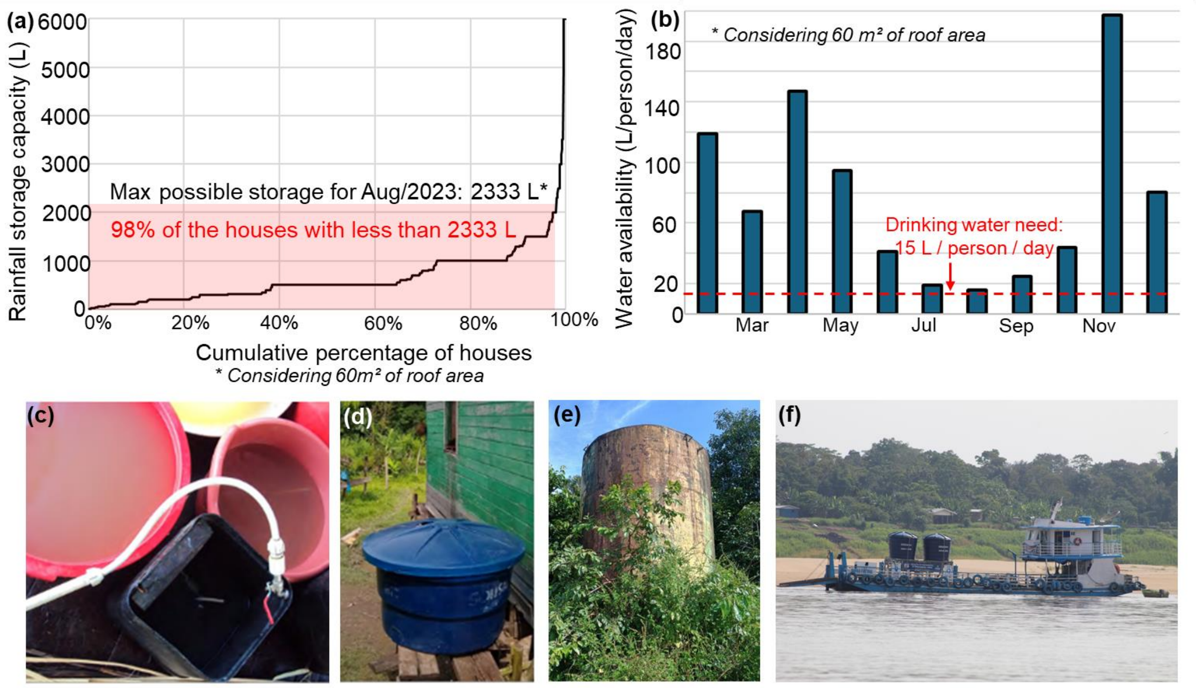

Figure 7.(a) Comparison between the current household water storage in the Mamirauá Sustainable Development Reserve and the potential rainfall harvesting volume during the 2023 drought, considering an average roof area of 60 m² and (b) all the rainfall water availability throughout the year of 2023. The photos depict different sources of water during the drought: (c) small buckets, (d) 310 L cisterns, (e) a community well, and (f) emergency water provision by the Government of Amazonas State.

High air and water temperatures

High air and water temperatures impacted human health: communities reported headaches, dizziness, and challenges in accessing water due to superheated lakes and streams. To deal with the latter, they reported adapting the time of surface water collection to early morning or evening, in order to collect cooler water. Working hours had to change due to the intense heatwave (avoiding working outside in the afternoon), and a common measure adopted by schools in the region was the suspension of afternoon classes.

In the mid-Solimões region, agricultural losses were estimated at 155 hectares[26], at an economic cost of around R$ 1.3 million (USD 230,000). Communities attributed most losses to high air and soil temperatures (likely associated with water stress). Lack of water for irrigation also led to losses of crops such as watermelon, melon and vegetables. CAMURA also reported that manioc production dropped to a level whereby not just agricultural incomes but even local consumption was impacted. Death of livestock due to the absence and drying of pastures was also mentioned.

Other hazards and lack of public policies

Besides reduced water levels and rainfall, and high temperatures, other disasters also occurred. River erosion, a naturally occurring phenomenon along Amazonian white-water rivers[27], destroyed a community's groundwater well. There was anecdotal evidence from local health professionals of increased respiratory diseases and related hospital admissions as a result of the smoke from forest fires, largely associated with the opening/maintenance of crop areas. The synergy of hazards was further compounded by the lack of public policies for disaster risk reduction in the region, which was also evident as a major source of social vulnerability in the Central Amazon. Lack of permanent health professionals (doctor or nurse) in the communities, school calendars that are not adapted to the dry season, difficulties to absorb local food production (e.g. fish and crops) in the community (e.g. for the school feeding program), and even lack of power supply (usually diesel, which was also scarce during the drought) decreased the communities' ability to cope with the drought and was highlighted by the communities' interviewees.

Discussion

Ecological implications

Here we presented a range of ecological impacts of the drought, including unprecedented mortality of 209 Amazonian river dolphins (only in Lake Tefé), a new record of a phytoplankton bloom (*Euglena sanguinea*), fish kills, an increase in caiman relative abundance, reduced forest fruit production, and a likely impact on water birds in the post-drought period. Extreme events are becoming more frequent in the Amazon, and understanding how aquatic biodiversity will be able to adapt to ongoing environmental changes becomes a great challenge for science. In this section we discuss the main ecological implications of our findings.

Water levels trigger tree phenological events in the Amazon floodplain forests[28,29]. While flowers are commonly produced during low water, fruits are mainly produced during high water[30,31]. We found the production of flowers was anticipated and lower than usual, leading to the lower fruit production in early 2024. Reduced soil water availability may have hampered the trees' ability to obtain nutrients for flower production. Unexpected lower fruit production was also found before the hydrological drought which may be related to the lower rainfall rates. Falls in Amazonian floodplain fruit production have been previously associated with drought conditions, with local people citing low initial production and failure of developing fruit[32].

The unprecedented bloom of phytoplankton (*Euglena sanguinea*) was likely favoured by the reduced water levels, high solar radiation (stimulating the production of hematochromes), and high water temperatures. The occurrence of harmful algal blooms has been linked to rising temperatures globally[33], and our finding poses a warning for Amazonian freshwater ecosystems. *E. sanguinea* is potentially ichthyotoxic, and its impacts on Amazonian fish should be further studied, especially considering the high dependence of riverine human communities on the lake's water and natural resources.

Rapid environmental changes have been a major challenge for Amazonian fish species, which often lack sufficient plasticity to cope with such accelerated changes[34]. During the drought, Lake Tefé's water temperature reached up to 40.9°C, a value beyond the thermal tolerance of most Amazonian fish species[35,36]. Amazonian fish species with a balanced life strategy tend to be more resilient to environmental changes in comparison with opportunistic species[37], which corroborates our results: we found a greater richness of species of the Cichlidae family (which tend to have balanced life strategies). *Hypophthalmus edentatus*, for instance, is an opportunistic species that lives near the surface, where water temperature becomes higher, so it has become more susceptible to increased water temperature.

A high caiman population density was found in a 43-km reach of a floodplain channel in the Mamirauá Reserve, where the only caiman management program authorised in the Amazonas state is conducted by a local community[38,39]. This higher density may favour intra-specific conflicts: scientific captures of black caimans (*Melanosuchus niger*) conducted in 2023 identified recent wounds and bite marks in 40% (4 out of 10) of the individuals. Caimans' nesting period coincides with the dry season[40,41], as females need dry land to build their nests and deposit their eggs, and the increase in the number of nests may have been influenced by the drought and consequent increase in the areas available for nesting. Drastic droughts can also influence the movement and feeding behaviour of caimans when there are fewer viable options of water bodies[42]. The observed heatwave may directly impact the reproduction of caimans and the recruitment of new individuals, as the species exhibits thermal tolerance in the hatching success of their eggs and thermal dependence in the sex ratio of the offspring produced[43].

An unprecedented mortality event occurred in Lake Tefé, resulting in the deaths of 209 river dolphins, which has been directly associated with hyperthermia[44] – the lake waters reached up to 40.9°C. While the final diagnosis analyses are still being conducted, if confirmed this may be the first reported case of aquatic mammals mortality by hyperthermia. High water temperature diel variation and air pollution may also have affected the animals.

Towards an integrated understanding of social-ecological impacts and its solutions

The unprecedented 2023 drought brought multi-sectoral impacts to the ecosystems and rural and urban human populations of the Central Amazon (Figure 8). Communities reported negative impacts on access to potable water, food production, education, transport, economy, and health. This was further impacted by the lack of appropriate public policies and the compounding nature of the event, with simultaneous occurrence of reduced water levels and local rainfall, river erosion, fire smoke, and heat waves in both the air and water. Social-ecological systems and the multiple bioeconomy chains were directly affected, such as manioc, fruit and vegetable production, and arapaima fish management. Lack of drinking water was reported as one of the major problems. While upland communities tend to principally use groundwater wells, those in floodplains rely more on rainwater and surface water[24]. All three of these water sources were significantly impacted during the drought, particularly due to the compounded effects of inadequate infrastructure (i.e. insufficiently deep wells, low rainwater storage capacity, and lack of long tubes to reach river/lake surface water), and led to several health issues, including diarrhoea surges. The lack of sanitation in rural Amazonia is a long-term debated issue[45], and was exacerbated considerably during the drought. It is paramount that public authorities, from local to state and national level, urgently improve sanitation and provide this human right to local Amazonians; investing, for instance, in the distribution of larger rainfall cisterns for communities, as occurred recently in the Brazilian semiarid[46], is certainly a way forward.

The extreme drought of 2023 affected both rural and urban residents, but in different ways. For 55% of the urban interviewees, the most striking impact of the drought was the death of dolphins and fish near the city, while this fact was much less relevant for rural communities. For them, their livelihoods as a whole were disrupted by the drought, being affected by all the impacts mentioned in the previous paragraph. Urban people in Tefé felt more affected by the price of food and goods, and the impacts of reduced navigation on access to nearby communities and the state capital of Manaus, for example to seek medical care. There is an established association between social vulnerability to climatic shocks and the remoteness of Amazonian urban areas disconnected from the road network, and in the Brazilian Amazon there are nearly one million people that live in such roadless urban centres[47], including those in our study region. There are, however, important differences among these roadless urban centres, for example with the lakeside city of Tefé becoming isolated from the fluvial network for a shorter time period than the nearby city of Uarini (Supplementary Figure S4), and with more remote urban areas in Amazon River tributaries likely suffering even more.

It is clear that existing solutions and adaptations were insufficient for local communities to cope with the drought impacts, even though the riverine people are generally well-adapted to the riverscape and hydrological dynamics imposed by the Amazon River environment, including a 10.5 m annual variation of water levels in the region. This context is even more worrying considering that the 2024 drought event surpassed the 2023 drought in many portions of the basin, likely triggering cascade social and ecological effects. There is a huge need for long-term, continuous monitoring of hydrological-ecological-social impacts of extreme events in the Amazon, considering the species most vulnerable to extreme events (e.g. turtles, dolphins, fish[19,48]) as well as the most impacted human communities[11] and their dynamic vulnerabilities[49]. This monitoring strategy should also consider the nature of compound hazards that are taking place and that lead to major synergistic impacts. Such an integrated monitoring approach should help overcome ongoing public faults in the region such as lack of a disaster prevention culture in the Amazon[50], moving away from the current focus on emergency response (e.g. distribution of basic food baskets and bottles of drinking water). This should also move the disaster reduction agenda in Amazonia beyond monitoring and response to single events[15], but instead considering the long-lasting impacts of hydrological extremes in the Amazon's complex adaptive social-ecological systems. It is also important to note that even ongoing research projects in Amazonia were affected by the drought: at the Mamirauá Institute, for instance, dozens of projects had to stop their activities because of logistical challenges, many experienced raised operating costs due to significantly increased navigation distances, and in some cases field infrastructure (such as boats) were damaged.

The intensification of hydrological extremes in the Amazon requires new adaptive solutions; and many possible concrete solutions exist. A recent publication lists 23 solutions co-created with more than 50 local community leaders from the Amanã Reserve in Central Amazon[51]. This local knowledge evidences the need of increasing cisterns, installing more and deeper wells, distributing emergency river water treatment kits, adapting health and education systems (including changes in school calendars), and creating new ways of absorbing local food production in the communities, avoiding the complex fluvial transportation during droughts. Local, regional private (e.g., social organisations) and public institutions, as well as research institutions, should be strengthened to work together with local communities in implementing effective public policies to address the ongoing challenges of the climate emergency[52]. This collaborative effort should be guided by appropriate risk communication and co-creation approaches[14], ensuring that solutions are tailored to the specific needs of the region. By doing so, these institutions can play a crucial role in developing strategies that not only respond to immediate threats but also build long-term adaptation strategies, safeguarding the health, the food security, and well-being of Amazonian populations and the ecosystems that sustain them.

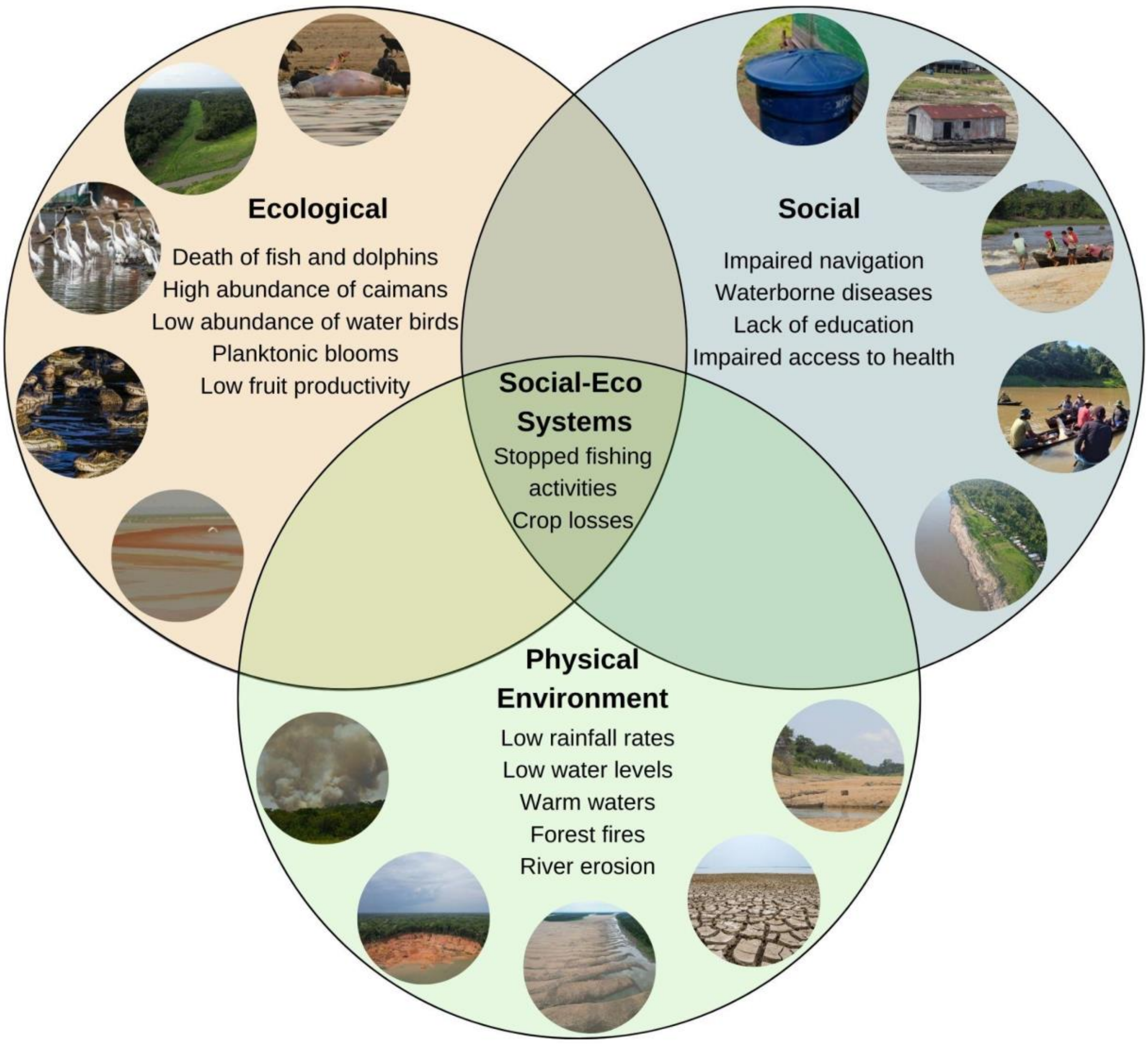

Figure 8. Integrated understanding of the physical environment and social-ecological impacts of the 2023 extreme drought in the Central Amazon.

Conclusion

The climate emergency is imposing unparalleled challenges to the Amazon’s people and nature. The unprecedented 2023 drought occurred only two years after the largest flood since records began at the Manaus river gauge, over 120 years ago. Here we leverage in-situ datasets to reveal the impacts of the drought for diverse biological groups and both urban and rural human populations in the Central Amazon, in the region of Tefé. Compound hazards (reduced water levels, air and water heat waves, river erosion, forest fires) led to multi-sectoral impacts. We show an unprecedented mortality of 209 dolphins in Lake Tefé, a first record of an *Euglena sanguinea* algal bloom, changes in abundance of caiman and water birds, and fish kills. Rural riverine communities were more affected than urban populations, although both areas felt the impacts of impaired navigation in the provision of goods and services. Rural communities, however, were directly impacted by the lack of access to water, food insecurity, education and health, as well as to impaired navigation to nearby urban areas to access markets and general services. The lack of long-term public policies to reduce disaster risk in the region is evident, and it is time to urgently change this scenario, from local to regional and national levels. A new strategy for disaster risk reduction in Amazonia should be delineated, acknowledging the compound nature of ongoing hazards and the dynamic vulnerability of its people and ecosystems. The co-creation of adaptation measures with local traditional populations is a necessary step further, to develop effective solutions for the climate crisis that threatens the largest river system on Earth.

Methods

Study area

This study focuses on the Central Amazon region, especially in the area of the municipality of Tefé and surrounding protected areas (Figure 1). These include the Mamirauá and Amanã Sustainable Development Reserves and the National Forest of Tefé. Tefé plays a major role in the region, being a hub of services for the whole Mid-Solimões region exerting direct influence on eight municipalities (Uarini, Alvarães, Fonte Boa, Maraã, Japurá, Juruá, Jutaí, and Tonantins; IBGE, 2008)[53]. For instance, its health system receives patients from all these areas[54]. This direct influence region covers an area of 220,000 km² that is sparsely occupied, with around 188,000 people[55]. Tefé has 73.669 people (56,366 in the urban area and 17,303 in the rural), with 142 riverine communities and 3,357 families[55]. Tefé's urban area is located by the shore of Lake Tefé, a major ria lake formed at the downstream confluence of Tefé and Amazon rivers. This is a black water lake that provides major natural resources and services for local and regional populations, including fish and water for human consumption and navigation.

The region faces major social vulnerability. For instance, national (Brazil) and regional (North region) social indices dramatically understate the poverty experienced in the study area (e.g., Tefé, Alvarães, Maraã, and Uarini municipalities). Human development indices in these municipalities (0.639, 0.527, 0.498, and 0.527 respectively[56]) are considerably lower than Brazil's (0.722), and instead comparable with Sub-Saharan African Nations' (e.g. 0.516 in Sudan). Food insecurity follows a similar pattern, with the country's poorest indices occurring in the Amazon[55], and the severe levels experienced by rural riverine communities[57] reflected by startling levels of malnutrition, for example with childhood anaemia over five times higher than nationally[58].

Data collection and analysis

Hydrometeorological variables

<u>Meteorology</u>

Climatological data for air temperature cited in this paper was collected by a conventional weather station located in Tefé and operated by the Brazilian National Institute of Meteorology (INMET; available at < https://bdmep.inmet.gov.br/#>; last access 22th Oct 2024). Air quality data was collected by a PurpleAir Classic Air Quality Monitor device (PurpleAir, Draper, UT, USA; online data available at: <https://map.purpleair.com/1/mAQI/a10/p604800/cC0#7.63/-2.984/-64.784>) at the Mamirauá Institute campus.

<u>Hydrology and water temperature</u>

Bathymetry of Lake Tefé was obtained with a hull-mounted Garmin Echosounder Echomap Plus 42 cv. Transversal water depth cross sections were obtained and later interpolated using the kriging method with ArcGIS software. The sections were obtained in different campaigns between October 2023 and June 2024, and all data were homogenised considering altitude values, estimated with a GNSS receiver (Spectra SP60 RTK), and considering the local water level differences between the dates.

Two Hobo Pendant MX2201 water temperature probes were installed in Lake Tefé in front of Tefé's urban area and continuously measured this variable (10 min time resolution). Water levels were measured in Lake Tefé using both a pressure transducer (Solinst Levelogger 5) and a conventional gauge, deployed at the Mamirauá Institute's floating station with rulers being measured twice a day (7h and 17h local time) by the institute's team. Data from an additional gauge at the Mamirauá floodplain channel in the Mamirauá Reserve (Figure 1a) was used for the water bird analysis (Figure 4b). Long-term water level data, used to investigate the water level anomaly in 2023, were obtained from the Brazilian Water Agency for the Amazon River gauge station at Coari (code 13150000, available at <https://www.snirh.gov.br/hidroweb/serieshistoricas>). This station is located around 200 km downstream from Tefé, but the difference in drainage area between the Amazon River at Tefé and Coari is small (around 5%, from 1,700,000 to 1,780,000 km^2), in a way that the hydrological signal is very similar between both (Pearson linear correlation of 0.986 between the Tefé and Coari time series). However, given the longer availability of data and the higher data quality of the Coari station, this one was used for the study's analysis.

Ecological indicators

<u>Tree phenology</u>: From February 2018 to March 2024, we collected phenological data from 1,450 to 1,496 individual trees (DBH ≥ 10 cm) of 205 species, distributed in 48 plots of 25 x 25 m in the Mamirauá Reserve. Difference in the number of monitored trees is due to tree mortality, new recruitments, and seasonal submersion of some individuals. During the monitoring period, we monthly registered the presence/absence of phenophases (flower buds, flowers, unripe fruits and ripe fruits) for each monitored tree. Phenological monitoring

covered the three main habitats of the várzea forests (*chavascal*, low várzea, and high várzea)[59]. For each month, we estimated the overall production of each phenophase by dividing the number of trees with the presence of a given phenophase by the total number of monitored trees. We then summarised data from 2018 to 2022 to monthly median, 1st and 3rd quartiles, in order to compare with the monthly production of each phenophase in 2023 and 2024.

<u>Phytoplankton</u>: We conducted phytoplankton collections from 5th to 20th October (16 days), at four sampling points in Lake Tefé. Samples were collected with a 20 mesh net through horizontal trawls. Opportunistic samples were also obtained from gills and stomach contents from dead fish found in the lake. All samples were taken to the laboratory for analysis under an optical stereomicroscope.

<u>Fish</u>: Sampling of fish assemblages was conducted with two methods. The first method consisted of an active search on beaches formed during the drought, in which we travelled along the beaches identifying the number of dead fish species. In the second method, we used trawl nets of 35m x 6m, with a mesh of 5 mm between opposite nodes, to collect fish. Dragging was carried out in three sampling points in front of the city of Tefé. During the survey, two people went into the water from the beach taking the net as deep as possible, or until one reached the length of the net, then one person walked with one of the ends of the net parallel to the beach until the net was fully open. Then each person walked towards the beach with one of the ends of the net, when arriving at the beach the lead of the net was pulled, forming a bag where the fish were caught. The caught fish were identified and released immediately after capture. At each point, three runs were performed.

<u>Water birds</u>: Water birds were surveyed in January and July of 2023 and 2024, in the Mamirauá Reserve (Apara and Mamirauá floodplain channels; Figure 1a), as part of a Neotropical Survey of Water Birds aiming to monitor the richness and abundance of water bird species. The Mamirauá, Apara and Jarauá floodplain channels were surveyed. Surveys consisted of 60-hp boat travels on water bodies transects at a constant pace (10-20 km/h), in which researchers registered the number of individuals per species in each transect. Surveys occurred in the morning, from 06:30-10:00h. We calculated the number of water bird species and the total abundance of birds in each survey transect for each survey occasion. We then compared the mean number of species and mean total abundance among survey occasions (i.e., in January and July of 2023 and 2024).

<u>Caimans</u>: Caiman population surveys were carried out in the Mamirauá Reserve, from 2008 to 2023, focusing on the Jarauá sector (Figure 1a), where sustainable harvesting activities are carried out[38,39]. Survey occasions occurred during the dry season, at night by boats at a constant pace (15 km/h), using flashlights to spot, count, and record the number of sighted caimans[60]. The relative abundance of caimans is calculated by dividing the number of caimans counted per kilometre travelled. Caiman nesting sites are also monitored, by searching for nests along lake margins[40], from 2010 to 2023. The relative number of nests per lake found in 2023 was compared with the historical average from the caiman nesting monitoring.

<u>River dolphins</u>: We closely monitored Lake Tefé starting 23 September 2024, when the first carcasses were reported by locals, from 2 km upriver from the city to 8 km downriver, close to the mouth with the Amazon River. We conducted twice daily outings to search for dead

dolphins or dolphins presenting unusual behaviour indicative of stress. All carcasses encountered were recorded and most of the 209 dead dolphins were recovered. Dolphins code 2 (fresh) were given a full necropsy with multiple sampling; carcasses in code 3 and 4 (moderate and heavy decomposition, respectively) were sampled according to their condition. After the last death attributed to the unusual mortality event we remained monitoring Lake Tefé for another 30 days. We conducted similar procedures in Lake Coari, 200 km south of Tefé, but these results are not presented in this study which focuses on the Tefé's region.

Socio-economic impacts

Information about arapaima management was obtained through interviews with community associations (see below) as well as the Mamirauá Institute's fish management program, which assisted 12 fishery agreements in the Mamirauá and Amanã reserves during the 2023 drought. Information about agriculture impacts was collected directly from family farmers advised by the Mamirauá Institute through direct contact with farmers affected by drought using social networks during the dry season. In addition, data from IDAM[26] and information obtained through the Report of the Meeting of Protagonist Women of the National Forest of Tefé and surroundings were used[22].

Price of the basic food basket was collected twice a week in two supermarkets in Tefé, following the guidelines for the regional staple foods basket, slightly adapted to the context of the city. The price of the following items was collected: rice, beans, sugar, salt, cassava flour, powdered milk, coffee powder, noodles, soya oil, alcohol vinegar, margarine, black pepper, frozen chicken, meat, and fish. The final value of the food basket was calculated by summing the prices of all the products. When a particular item was unavailable, the average price from the previous data collection was used to fill the gap.

Semi-structured interviews were conducted from Dec/2023 to Jun/2024 with Tefé's urban population (40 interviewees) and the surrounding riverine communities of Juruamã, Ingá, São Francisco do Aiucá, and Nova Colômbia, in the Mamirauá Reserve (10 people per community, totaling 40 interviewees). The interviews addressed questions related to the main perceived impacts and mitigation measures that were adopted. This was conducted within the project "From urban to rural: perceptions about the floods and droughts impacts in Middle Solimões", which was approved by the Mamirauá Institute's Ethics Committee (project number 75302223.3.0000.8117). Additional semi-structured interviews with similar questions were conducted in the communities of Caburini, Assunção, Canariá, and Coadi, also in the Mamirauá Reserve through the project "Adaptation and vulnerability of riverine communities to climate change in the Middle Solimões", approved by the Mamirauá Institute's Ethics Committee (project number 69907623.9.0000.8117).

Open dialogues were performed with representatives of the following regional community associations, regarding the main drought impacts perceived: the Amanã Reserve Residents Association (CAMURA), Federation of Managers and Managers of Pirarucu of the region of Mamirauá (FEMAPAM), Nova Esperança Indigenous Agricultural Cooperative (COOINE) and Association of Agro-extractivist Producers of the National Forest of Tefé and

Surroundings (APAFE). Reports were collected without the involvement of sensitive information.
Finally, information about impacts in Indigenous territories was obtained from the Indigenous Special Health Districts[61], and the number of diarrhoea cases in Tefé between 2021 and 2023 was obtained from Tefé's epidemiologic surveillance office.

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Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Supplementary Materials for

Unprecedented Social-Ecological Impacts of the 2023 Extreme Drought in the Central Amazon

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Supplementary Table S1
Figs. S1 to S4

Supplementary Table S1. Fish species found during the fish kill events through active search and capture with nets along Lake Tefé margins. Active search was conducted to find only dead animals, and capture with nets collected both dead and alive individuals.

Order **Family**	**Species**	**Active Search**	**Capture**
OSTEOGLOSSIFORMES: Osteoglossidae	*Osteoglossum bicirrhosum (*Cuvier, 1829)	X	
CLUPEIFORMES: Engraulidae	*Lycengraulis batesii* (Günther, 1868)		X
CHARACIFORMES: Erythrinidae	*Hoplias malabaricus* (Bloch, 1794)		X
Serrasalmidae	*Metynnis luna* Cope, 1878		X
	Pygocentrus nattereri Kner, 1858	X	
	Serrasalmus elongatus Kner, 1858		X
	Serrasalmus rhombeus (Linnaeus, 1766)		X
Hemiodontidae	*Hemiodus gracilis* Günther, 1864		X
Anostomidae	*Laemolyta taeniata* (Kner, 1859)		X
	Schizodon fasciatus Spix & Agassiz, 1829		X

Curimatidae	*Curimata vittata* (Kner, 1858)		X
Prochilodontidae	*Prochilodus nigricans* Spix & Agassiz, 1829	X	X
	Semaprochilodus insignis (Jardine, 1841)		X
Ctenoluciidae	*Boulengerella maculata* (Valenciennes, 1850)		X
Chalceidae	*Chalceus erythrurus* (Cope, 1870)		X
Triportheidae	*Triportheus auritus* (Valenciennes, 1864)		X
Acestrorhynchidae	*Acestrorhynchus falcatus* (Bloch, 1794)		X
Characidae	*Moenkhausia intermedia* Eigenmann, 1908		X
	Moenkhausia lepidura (Kner, 1858)		X
GYMNOTIFORMES: Rhamphichthyidae	*Rhamphichthys marmoratus* Castelnau, 1855	X	
SILURIFORMES: Loricariidae	*Loricaria simillima* Regan, 1904	X	X
	Pterygoplichthys pardalis (Castelnau, 1855)	X	

Pimelodidae	*Pimelodus blochii* Valenciennes, 1840	X	X
	Hypophthalmus edentatus Spix & Agassiz, 1829	X	
	Sorubim lima (Bloch & Schneider, 1801)		X
CICHLIFORMES: Cichlidae	*Biotodoma cupido* (Heckel, 1840)		X
	Cichla monoculus Spix & Agassiz, 1831		X
	Geophagus proximus (Castelnau, 1855)	X	X
	Satanoperca acuticeps (Heckel, 1840)		X
	Satanoperca jurupari (Heckel, 1840)		X
	Symphysodon tarzoo, Lyons 1959		X
	Uaru amphiacanthoides Heckel, 1840		X
PERCIFORMES: Scianidae	*Plagioscion squamosissimus* (Heckel, 1840)	X	X
BELONIFORMES: Belonidae	*Potamorrhaphis guianensis (Jardine, 1843)*		X

TETRAODONTIFORMES: Tetradontidae	*Colomesus asellus* (Müller & Troschel, 1849)	X	X
PLEURONECTIFORMES: Achiridae	*Hypoclinemus mentalis* (Günther, 1862)		X

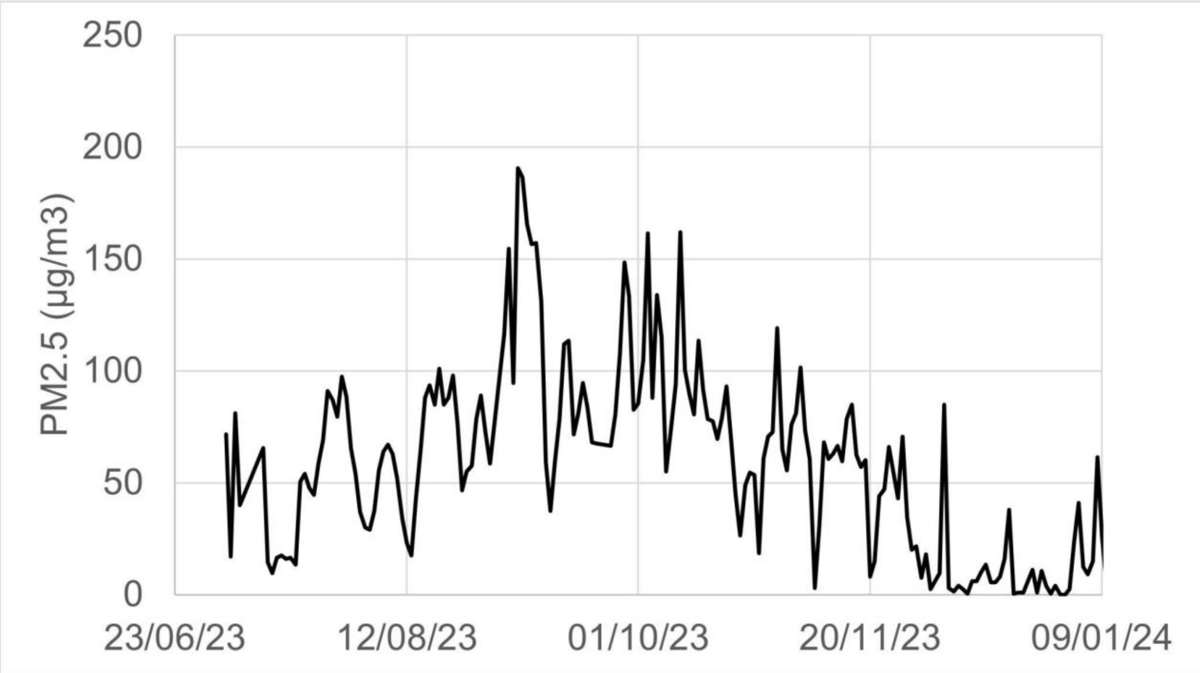

Figure S1. Air quality during the 2023 drought in Tefé, based on particulate matter 2.5 µm measurements.

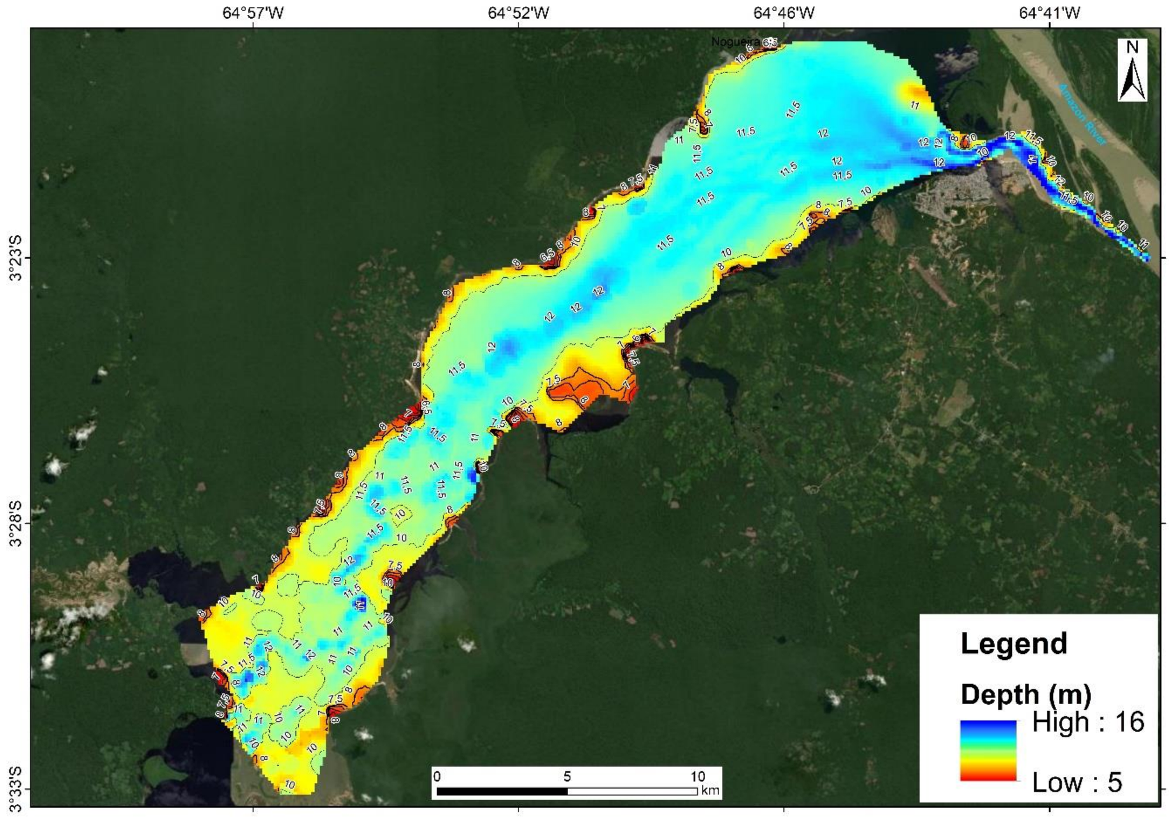

Figure S2. Lake Tefé bathymetry, based on the local reference level of 5th July 2024 (flood season).

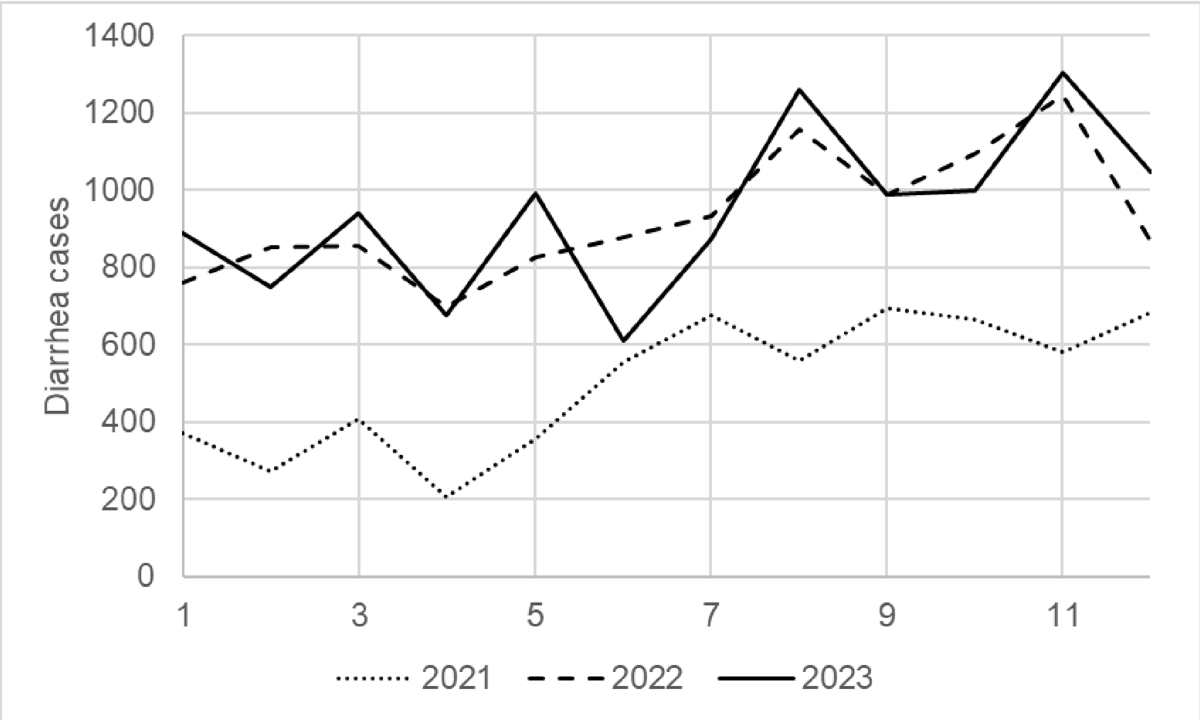

Figure S3. Diarrhea cases in Tefé between 2021 and 2023.

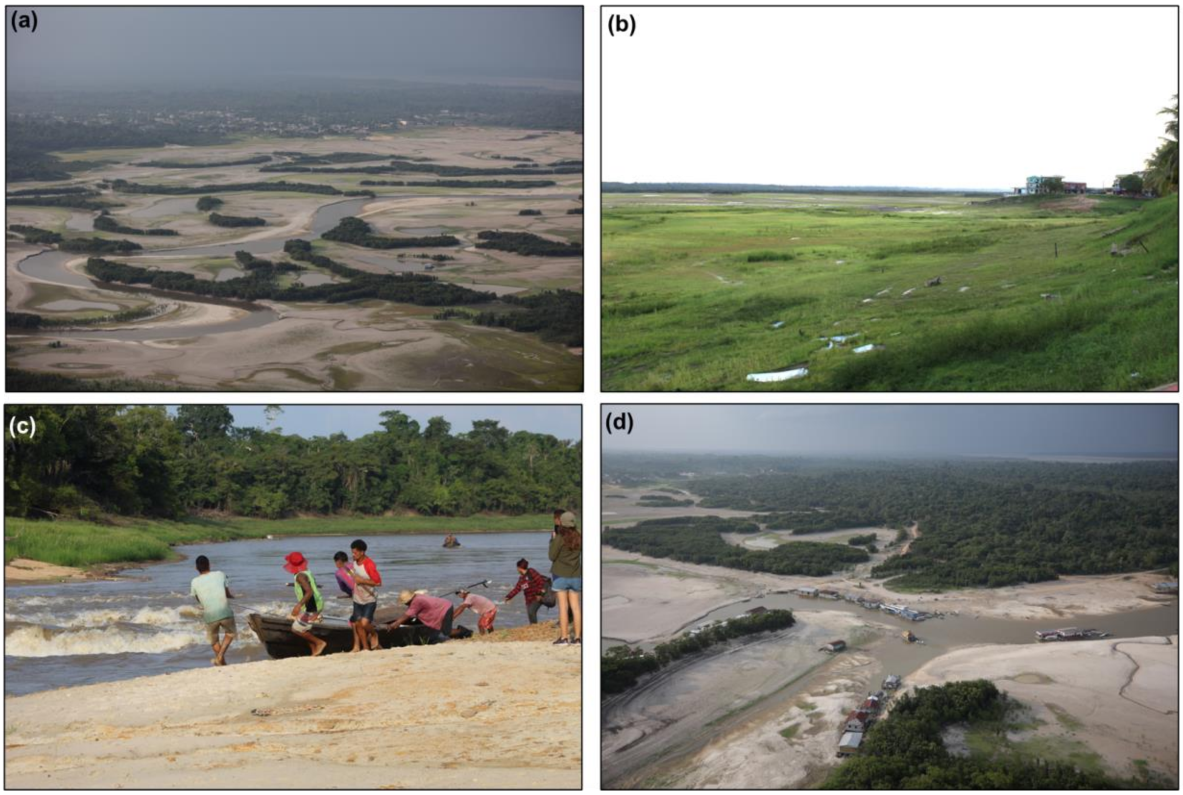

Figure S4. (a, b) Lake Uarini in front of the city of Uarini in the Amazonas State dried dramatically, isolating the whole urban area. The photo in (b) was taken from the urban area, located on the upper part of photo (a). (c) Local fishermen struggled to cross the rapids that formed in the lake's main outlet channel. (d) The lake's channel width was largely reduced. A small road was built in 2022 along the channel to improve the urban area's connection to the Amazon River.