



## Research Letters

## Amazon climate extremes: Increasing droughts and floods in Brazil's state of Acre



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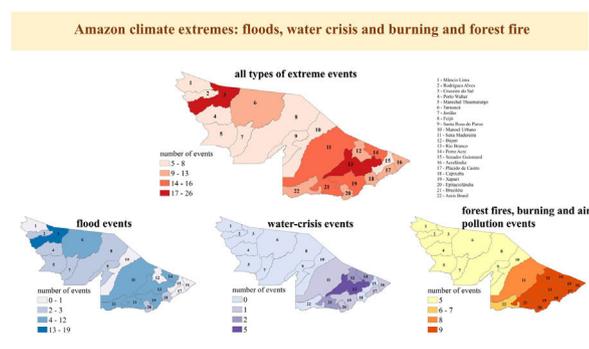
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## HIGHLIGHTS

- The intensification of extreme climate events is already a reality throughout the world.
- The state of Acre recorded 202 extreme events between 1987 and 2022.
- The year 2010 marked a breaking point in the trend of extreme events.
- We may be experiencing the tipping point for climate disasters.
- These data show the urgency of implementing actions to adapt to climate extremes.

## GRAPHICAL ABSTRACT



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## ABSTRACT

The intensification of extreme climate events is already a reality throughout the world. In the Brazilian Amazon, the most frequent extreme events are linked to droughts and floods. This study expanded the documentation on extreme events of floods, water crisis, fires and forest fires in the state of Acre, in the southwestern Brazilian Amazon. We analyzed extreme weather events in state and municipal state-of-emergency and public-calamity decrees, reports of people who faced the impacts of these events, scientific articles, and press reports. The results show that the state of Acre recorded 202 extreme events between 1987 and 2023, with an increasing trend in the number and occurrence of various types of extreme events in the same year since 2010. Twenty-one state-of-emergency and public-calamity decrees were issued, with flood events being the most frequent. The cities of Rio Branco and Cruzeiro do Sul recorded 14 and 21 extreme events, respectively, or approximately one event every two years. These data show the urgency of implementing actions to adapt to climate extremes. Starting in 2005, the annual results indicate an increase in municipalities (counties) experiencing more than one type of extreme event, pointing to the need for effective public policies for adaptation and mitigation in the state of Acre.

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## Introduction

Extreme weather events such as droughts, heat waves and floods have occurred more frequently in various parts of the world and can affect people's food security, economy, culture and physical and mental health (IPCC, 2022). In addition, global warming can interact with social factors, such as population growth and disorderly urbanization, accentuating social inequalities, soil and water degradation, loss of biodiversity and the emergence of pandemics, thus compromising future human well-being (Thornton et al., 2014; IPCC, 2022).

Climate change is a reality in all terrestrial ecosystems, with effects in urban and rural areas (including natural areas), with strong impacts observed in terrestrial and aquatic systems, but also agricultural ones, increasing malnutrition, collective worsening of mental health and climate refugees (IPCC, 2022). The impacts of climate change are different in different regions of the planet, but in Brazil drought and flood events have become more frequent, triggering effects with impacts on agriculture, an increase in diseases, forest fires and burning in deforested areas, in addition to increased frequency of flooding in cities (Marengo et al., 2016). Costa et al. (2022) have projected that these extreme events, including longer sequences of drier days and more concentrated precipitation events, should become more frequent throughout this century even in more moderate emission scenarios such as RCP4.5 and SSP2-4.5.

In Brazil, many instruments have been implemented with the intention of directing adaptation and mitigation actions against the impacts of climate change. These are laws and other devices that seek constant adaptation to the dynamics involved in these processes (Brasil, 2009, 2016). However, the results are still incipient, especially with regard to the effectiveness of actions, as extreme events have become increasingly frequent, affecting a greater number of territories and enhancing environmental, economic and social damage. Freitas et al. (2020) point out that the occurrence of natural disasters in Brazil between the years 2000 and 2015 resulted in economic losses of 4 billion reais (US\$ 800 million) in health facilities alone, with the largest cost per event being concentrated in the northern region of the country.

Climate extremes in the Amazon are usually major floods and/or droughts (Marengo et al., 2011; Marengo and Espinoza, 2016). These events have become more frequent and intense in the last two decades, affecting urban and rural regions, and their causes may be related to anomalous heating or cooling of part of the tropical oceans, with emphasis on the El Niño and La Niña phenomena and changes in the South Atlantic Convergence Zone (SACZ). These phenomena can act simultaneously or separately (Brown et al., 2006; Aragão et al., 2007; Zeng et al., 2008; Gloor et al., 2013; Marengo and Espinoza, 2016).

A major challenge in tackling climate change and the resulting extreme events lies in denialism on the part of society (Ferrante and Fearnside, 2021). Not only denial about science, the existence of climate change and human influence, there is also a process of disseminating misinformation throughout society (Diele-Viegas et al., 2021; Bustamante et al., 2023). This situation makes it difficult to build mitigation and adaptation strategies to extreme climate events, which have become more intense and more frequent (Nobre and Borma, 2009; IPCC, 2022).

In the state of Acre, in the southwestern Brazilian Amazon, drought and flood events have been recorded more frequently in recent decades. In 2005, Acre was the epicenter of a severe drought (Zeng et al., 2008; Lewis et al., 2011). In 2015, the state capital (Rio Branco) had the worst flooding that had ever been recorded, with damage estimated between 60–200 million US dollars (Dolman et al., 2018).

Oliveira et al. (2022) identified an intensification in extreme precipitation events and changes in hydrological patterns for the city of Rio Branco and found that the government actions were spotty and limited to the resolution of damage in the short term through declarations of state of emergency or public calamity (see also: Nina and Szlafstein, 2014; Rocha, 2016). Other extreme events have occurred in the state of Acre over time, but the record of these events is scattered, not showing spatial and/or temporal patterns. The objective of this study is to quantify the frequency of extreme drought and flood events in the state of Acre, in addition to analyzing their causes and impacts.

## Material and methods

### Study area

The state of Acre (Fig. 1) has an area of 164,173 km<sup>2</sup>, distributed among 22 municipalities (counties) (Acre, 2010; IBGE, 2022). The state is located in two climatic zones according to the Köppen classification: Af, which covers about 70% of its territory, with annual precipitation between 2200 mm and 2500 mm and annual temperature in the range of 22–24 °C, and Am, which comprises around 30% of the state's area, with lower values for annual rainfall (1900–2200 mm) and higher temperatures (24 °C–26 °C) (Alvares et al., 2013).

Acre had an estimated population of 906,876 inhabitants in 2021 (IBGE, 2022), with about 72% residing in urban areas. Ranching and agriculture are concentrated in the eastern region, where the Am climate zone predominates. Until 2021, deforestation in Acre was 24,058 km<sup>2</sup> (15% of the total area) but eight municipalities have more than 30% of their territory deforested, including extreme cases such as Senador Guiomard and Plácido de Castro where more than 73% of the territory is without native forest cover (INPE, 2022). The eastern region of the State of Acre is part of an agribusiness expansion project, especially livestock farming, known as AMACRO (acronym in Portuguese with the acronym for the states of Amazonas, Acre and Rondônia), which has driven alarming deforestation rates in the last ten years, expanding the arc of deforestation (MAPBIOMAS, 2023; Vilani et al., 2023).

### Definition of extreme climate events

This study used as a basis the publication of Normative Instruction No. 1, of 24 August 2012, which is the Codification of Disasters, Threats and Risks (COBRAE, acronym in Portuguese) defined by the National Civil Defense. The extremes selected were: flooding, drought causing water crisis, and forest fires (Table 1).

### Documentation of extreme climate event

Extreme events were identified by number of occurrences per municipality. Identification based on state and municipal decrees declaring a state of environmental alert, emergency or public calamity (Acre, 2022), scientific papers, technical reports and on press releases available in digital format. The number of occurrences of extreme events was calculated for each municipality in the state of Acre.

The study covered the period from 1987 to 2023, however, for the years before 2005, the records of extreme events were carried out only by articles from print vehicles available in digital format (Senado Federal, 1997; Folha de São Paulo, 1999), state and municipal decrees declaring a state of emergency or public calamity (1997–2023), long-term scientific research, such as the mapping of forest fires carried out by Silva et al. (2018), mapping of fires



Fig. 1. Location of the study area, state of Acre and municipal divisions in the context of South America and the Amazon.

Table 1

Description of extreme events based on the Codification of Disasters, Threats and Risks (COBRAE, acronym in Portuguese) defined by the National Civil Defense.

Type of event	COBRAE	Description
Flooding	1.2.1.0.0	Submergence of areas outside the normal limits of a watercourse in areas that are not normally submerged. The overflow occurs gradually, usually caused by prolonged rains in lowland areas.
Drought causing water crisis	1.4.1.2.0	A prolonged drought, lasting long enough for the lack of precipitation to cause serious hydrological imbalance.
Forest fire, burnings and degrading air quality	1.4.1.3.2	Uncontrolled fire propagation in any type of vegetation that is or is not in an area under legal protection, causing degraded air quality.
	1.4.1.3.1	

by [Mapbiomas \(2021\)](#), scientific articles such as [Setzer and Pereira \(1991\)](#) and [Brown et al. \(2006\)](#), as well as reports from local people who experienced extreme weather events before 2005.

For trend analysis of the time series of extreme weather events in Acre we used the non-parametric Mann-Kendall test ([Mann, 1945; Kendall, 1975](#)). We used the Pettitt test to identify when there was a sudden change in the mean of the time series.

## Results

A total of 254 extreme events were identified between 1987 and 2023, 60% being forest fire and burning in deforested areas, 33% being floods and 6% water crises. On average, six municipalities were affected per year by water crisis, fires or floods ([Fig. 2](#)). Up to 2004, an average of one extreme event was recorded per year. After this period, two or more events were recorded in the same year ([Fig. 2b](#)). A statistically significant breaking point in the trend was identified by the Pettitt test ( $p\text{-value} = 0.0025$ ) in 2010, and from then on the extremes intensified.

Twenty-four municipal or state decrees were identified declaring a state of environmental alert, emergency or public calamity in the analyzed period ([Table 2](#)). State government decrees are issued when more than one municipality was affected by an event, and these represent 54% of the decrees issued. Of the decrees issued by municipalities, 54% were made by the municipal government of the state capital - Rio Branco ( $n = 6$ ), followed by Sena Madureira ( $n = 3$ )

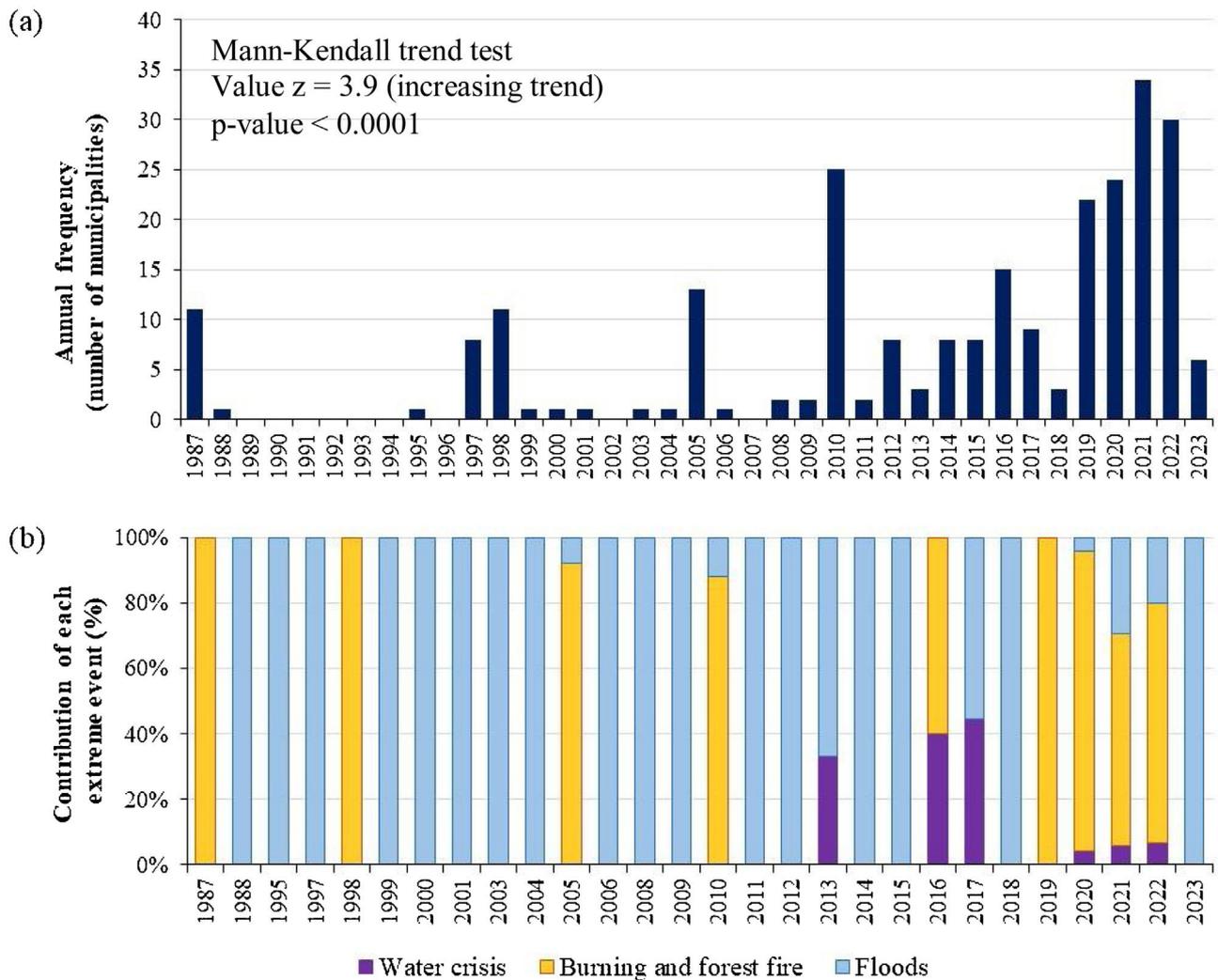
and Tarauacá and Bujari (both with  $n = 1$ ). Based only on the publication of the decrees, the most frequent extreme event was flooding ( $n = 10$ ), followed by water crisis ( $n = 6$ ) and forest fire ( $n = 5$ ).

Extreme events in the state of Acre are concentrated in the most populous regions, especially the two most populous: Rio Branco and Cruzeiro do Sul ([Fig. 3](#)). In the analyzed period, all municipalities in Acre recorded at least three extreme events. However, the municipalities of Rio Branco and Cruzeiro do Sul recorded 17–26 extreme events, corresponding to one event every two years ([Fig. 3a](#)). Flood events were more concentrated in Cruzeiro do Sul, in the western part of the state, registering 19 events ([Fig. 3b](#)), while water-crisis events, forest fires and burning in deforested areas are concentrated in the eastern part of the state ([Fig. 3c and 3d](#)).

## Discussion

### Implications for risk management

For decades, IPCC reports have shown evidence of the effects of global warming and how they could intensify extreme weather events on a regional scale ([IPCC, 2022](#)). The state of Acre has stood out as a region where extreme events have intensified in recent decades, with impacts on a regional scale that are evident, especially for the most exposed population. Remarkable events, such as the fires in 2005 that burned more than 500,000 ha in agricultural and ranching areas and 350,000 ha in native forest and burned



**Fig. 2.** Interannual variation of extreme events registered in the state of Acre from 1987 to 2023. (a) Sum of the occurrences of extreme events by municipalities per year and (b) proportional contribution of the occurrence of extreme events.

**Table 2**  
 Municipal and state decrees of public calamity or emergency issued in the state of Acre between 1997 and 2023.

Decree Number	Type of Decree
State Decree No. 6118 of 27 March 1997	State of public calamity due to flooding
State Decree No. 12849 of 21 September 2005	Emergency situation for burning and forest fires
State Decree No. 5571 of 9 August 2010	Emergency situation for burning and forest fires
Municipal Decree of Sena Madureira nº 007 of 19 February 2012	Emergency situation due to flooding
State Decree No. 3286 of 15 February 2012	Emergency situation for burning and forest fires
Municipal Decree of Sena Madureira nº 7 of 19 February 2012	Emergency situation due to flooding
State Decree No. 7308 of 7 April 2014	State of public calamity due to flooding
Municipal Decree of Rio Branco No. 193 of 23 February 2015	Situação de emergência por ocorrência de inundações
Municipal Decree of Rio Branco No. 217 of 4 March 2015	State of public calamity due to flooding
Municipal Decree of Rio Branco No. 511 of 27 May 2015	State of public calamity due to flooding
State Decree No. 5052, of July 7, 2016 – Portaria No. 161, of 2 August 2016	Emergency situation due to drought - water crisis and burning and forest fires
State Decree No. 7,485 of 24 August 2017	Emergency situation due to drought - water crisis
State Decree No. 3,869, of 22 August 2019	Emergency situation due to burning and forest fires
Municipal Decree of Rio Branco No. 744 of 7 October 2020	Emergency situation due to drought - water crisis
State Decree No. 6698, of 31 August 2020	Emergency situation due to burning and forest fires
Municipal Decree of Rio Branco No. 741 of 26 March 2021	Emergency situation due to flooding
Municipal Decree of Tarauacá No. 39, of 18 February 2021	State of public calamity due to flooding
Municipal Decree of Sena Madureira No. 38 of 17 February 2021	Emergency situation due to flooding
State Decree No. 8.441 of 24 March 2021	State of public calamity due to flooding
Municipal Decree of Rio Branco No. 1.257 of 30 August 2021	Emergency situation due to drought - water crisis
State Decree No. 11.023, of 24 March 2022	Emergency situation due to flooding
State Decree No. 11.117, of 13 September 2022	Emergency situation due to burning and forest fires
Bujari Municipal Decree No. 136 of 20 October 2022	Emergency situation due to drought - water crisis
State Decree No. 11.209, of 24 March 2023	Emergency situation due to flooding

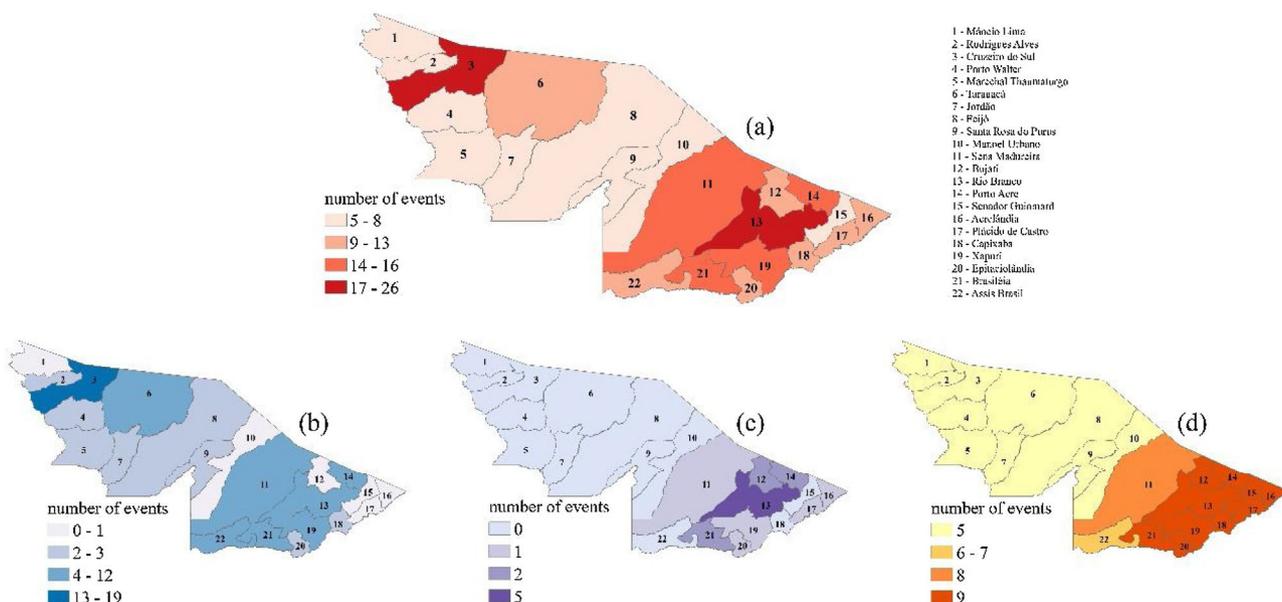


Fig. 3. Cumulative number of occurrences of extreme events by municipality in the state of Acre from 1987 to 2022. (a) All types of extreme events, (b) flood events, (c) water-crisis events and (d) forest fires, burning in deforested areas and air pollution.

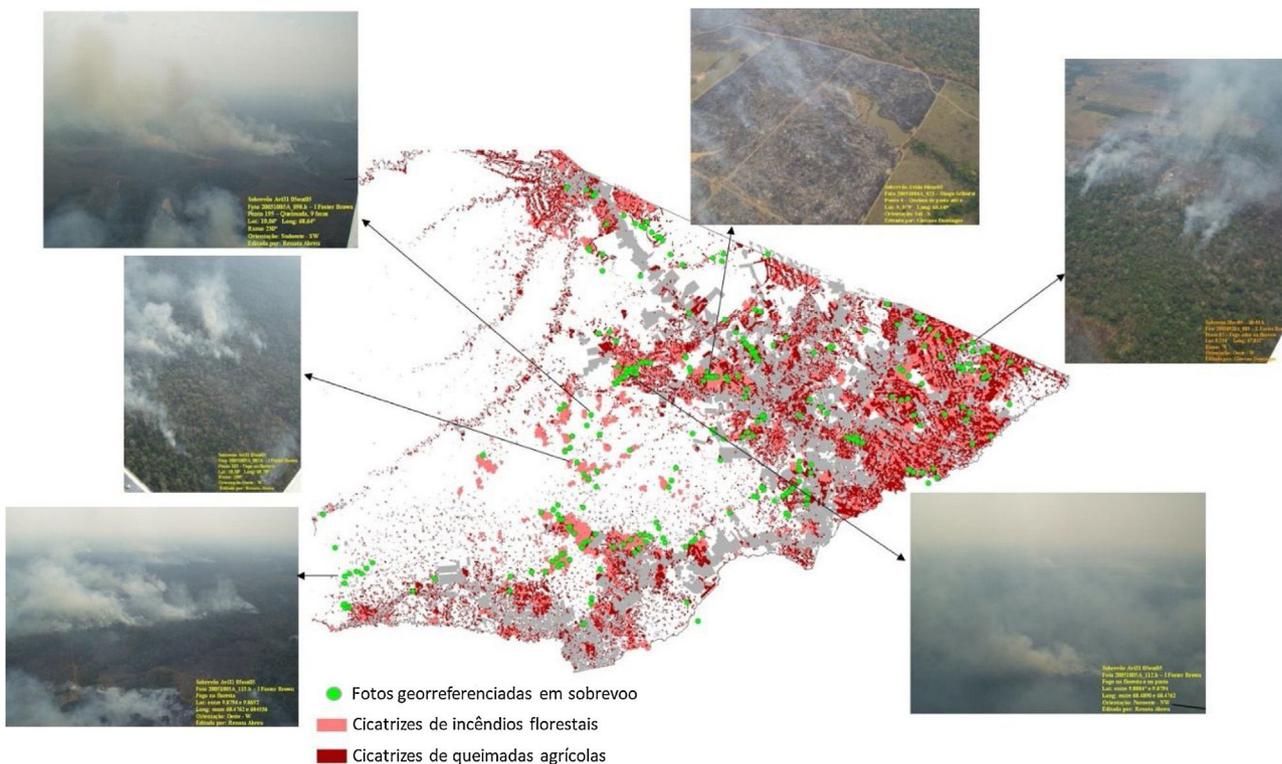


Fig. 4. Mapping of wildfires and forest fires in the eastern part of Acre in 2005 with visualization of checkpoints and assessment of the situation through overflights. Photos and points of the overflights provided by Foster Brown SETEM/PZ/UFAC.

uncontrollably for about two months (Fig. 4), closing airports and schools (Brown et al., 2006; Silva et al., 2018; Anderson et al., 2023). In 2015, the municipalities along the Acre river experienced the worst flooding ever recorded, where the Rio Branco spent 32 days under the effect of the event, affecting more than 71 thousand people, with economic damage estimated at 60–200 million US dollars (Dolman et al., 2018; Tamwing et al., 2021).

Even with such impactful events registered in Acre, 13 other extreme events occurred after 2015 but effective actions under

public policies aimed at adapting and/or mitigating the impacts associated with these phenomena were not perceptible. What has occurred is a greater number of decrees declaring a state of emergency or public calamity, these decrees being instruments for the immediate resolution of damage. Between 2020 and 2022 eight decrees were issued (38% of the total since 1997). From a survey of natural disasters recorded in the Integrated Disaster Information System of Brazil between 2000 and 2015, of all 27 Brazilian states, Acre had the highest cost per event: more than 15 million reais

(US\$ 3 million) per event per state (Freitas et al., 2020). Brazilian regions, such as the Northeast, have a greater number of emergency and public calamity decrees (Moura et al., 2016); however, no systematic study has been carried out for the states of the Amazon. The data collected in this study suggest that Acre may be approaching or have passed a tipping point for extreme weather events, and that forest collapse may be either immanent or already underway.

#### Social impacts of extreme weather events

A variety of damages to society can result from extreme weather events, including loss of human life, mental health impacts, economic losses, and other forms of damage. The Flood Contingency Plan of the city of Rio Branco estimates values for damages and economic losses between 21 and 212 million reais per year, considering the years 1988, 1997, 2006, 2012, 2013 and 2014 (Rio Branco, 2016). Despite this, there are no estimates associated with damage for different types of extreme events.

Campanharo et al. (2019) estimated economic impacts of 53 million US dollars related to the fires in Acre, considering carbon dioxide (CO<sub>2</sub>) emission, in addition to losses in agricultural production and pasture, reestablishment of crops and increased respiratory diseases. Mendonça et al. (2004) evaluated the extreme events of wildfires and forest fires from 1996 to 1999 in the Amazon, estimating that the loss of pasture, agriculture and rural infrastructure between 87 and 168 million US dollars.

These studies allow us to have a dimension of the problem, but more research is needed on the subject, especially regarding the social implications of these events. Little is known about the damage and consequences of extreme events, such as damage to people's mental health, psychosocial condition and well-being, in addition to the loss of biodiversity (fauna and flora), impacts on food security and malnutrition, the appearance and/or emergence of infectious diseases, increased government infrastructure for care (Pereira and Barata, 2014; Carvalho and Oliveira, 2020; IPCC, 2022).

Another factor that should be discussed is the socio-environmental vulnerability of some social groups and locations, which lack the capacity to prevent or respond to extreme events and to rebuild. An example is the municipality of Tarauacá, where in 2021 almost 90% of the urban area was affected by an extreme flood event. Even with a state of public calamity decree, a national campaign was established to collect urgent donations for the population (G1, 2021).

Impacts of extreme drought events that cause water crises jeopardizing the supply and distribution of drinking water are poorly measured. The reported impacts are linked to the improvement of water collection and treatment infrastructure (Pontes, 2021, 2022; G1, 2022). However, the damage to public health and many of the economic impacts on the population still remain unknown.

#### Conclusions

Climate extremes, floods, droughts and water crises, have intensified, as has been warned by the Intergovernmental Panel on Climate Change (IPCC) reports. Acre may be among the most critical Brazilian states impacted by extreme weather events, however more studies like this must be carried out for all states in the Amazon and Brazil.

Extreme events have been recorded since the 1980s; there was a break point in 2010, after which the number of events increased. The occurrence since 2010 of more than one type of event in the same year in a given municipality may mean the crossing of a tipping point for climate disasters. The large and growing number of extreme weather events in Acre documented here serves as a wake-up call for the Amazon as a whole.

Adaptation and mitigation processes must be considered urgent, not only in the municipalities of Rio Branco and Cruzeiro do Sul, but throughout the state of Acre, especially in the municipalities with greatest social and economic vulnerability.

#### Declaration of interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Sonaira Souza da Silva reports financial support and article publishing charges were provided by Federal University of Acre.

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