INSTITUTO NACIONAL DE PESQUISAS DA AMAZÔNIA – INPA
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIAS BIOLÓGICAS (BOTÂNICA)

RECUPERAÇÃO DE AGROECOSSISTEMAS DE VÁRZEA E PALEOVÁRZEA AMAZÔNICA NO CONTEXTO DAS MUDANÇAS CLIMÁTICAS NA REGIÃO DO MÉDIO SOLIMÕES (AMAZONAS, BRASIL)

JULIA VIEIRA DA CUNHA AVILA

Manaus-Amazonas
Fevereiro 2023

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JULIA VIEIRA DA CUNHA AVILA

Orientador: Dr. Charles Roland Clement
Coorientadoras: Dr. Angela May Steward
Dr. Tamara Ticktin

Tese apresentada ao Instituto Nacional de Pesquisas da Amazônia como requisito para obtenção do título de Doutora em Ciências Biológicas (Botânica).

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INPA – INSTITUTO NACIONAL DE PESQUISAS DA AMAZÔNIA | DIVISÃO DO CURSO DE PÓS-GRADUAÇÃO EM BOTÂNICA

UNIDADE DE PESQUISA DO MINISTÉRIO DA CIÊNCIA, TECNOLOGIA, INOVAÇÕES E COMUNICAÇÕES

ATA DE DEFESA PÚBLICA DE TESE DE DOUTORADO DO PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIAS BIOLÓGICAS (BOTÂNICA) DO INSTITUTO NACIONAL DE PESQUISAS DA AMAZÔNIA

No dia 24-03-2023, às 08:00 horas, discente **Julia Vieira da Cunha Ávila**, sob orientação de **Charles Roland Clement**, defendeu publicamente sua Tese de Doutorado intitulada ***RECUPERAÇÃO DE AGROECOSSISTEMAS DE VÁRZEA E PALEO VÁRZEA AMAZÔNICA NO CONTEXTO DAS MUDANÇAS CLIMÁTICAS NA REGIÃO DO MÉDIO SOLIMÕES (AMAZONAS, BRASIL)***. A defesa foi presidida pelo orientador. Após a exposição pública do trabalho, o discente foi arguido oralmente pelos membros da Comissão Examinadora, que emitiram seus pareceres conforme indicado abaixo:

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Synopsis:
We studied the impacts of extreme floods on Amazon floodplain agroecosystems in the middle Solimões River, Amazonas, Brazil. Aspects such as crop mortality and local adaptive strategies were identified.

Key words: Ethnobotany, Climate Change, Crops

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Resumo

A agrobiodiversidade na Amazônia é resultado do uso e manejo de populações de plantas por povos atuais e pré-colombianos, sendo composta de cultivos domesticados em diferentes graus e de paisagens domesticadas (como agroecossistemas, florestas manejadas, solos antrópicos). Atualmente, os agroecossistemas de produtores tradicionais do médio rio Solimões (Amazonas) vêm sendo fortemente impactados por eventos extremos relacionados às mudanças climáticas, como as grandes enchentes recorrentes. O objetivo geral desta tese é analisar os impactos e a recomposição dos agroecossistemas de ribeirinhos em ecossistemas de várzea amazônica após uma inundação extrema, ocorrida no médio rio Solimões (2015). Nossos objetivos específicos são: a) avaliar quanto a agrobiodiversidade foi impactada e recuperada após uma das maiores inundações extremas já registradas na região (capítulo 1); b) comparar as estratégias adaptativas locais de domesticação da paisagem no contexto das inundações extremas em relação aos anos de inundações normais (capítulo 2); e c) examinar estratégias para o armazenamento da mandioca e a distribuição desse conhecimento entre moradores dos ecossistemas de várzea (capítulo 3). Para isso, entre 2017 e 2019 realizamos entrevistas semiestruturadas, listas-livres, turnês-guiadas, observação participante, construção de calendários sazonais e linhas do tempo. Analisamos a agrobiodiversidade *alpha* e *beta* das etnoespécies e etnovariedades de mandioca manejadas pelos ribeirinhos em três momentos temporais (antes, imediatamente após e dois anos após a enchente extrema de 2015), comparando os impactos e a recomposição dos agroecossistemas na várzea baixa, várzea alta e na paleovárzea. Identificamos que as comunidades locais possuem conhecimento detalhado dos padrões climáticos normais e reconhecem que a imprevisibilidade climática dificulta o planejamento efetivo das atividades necessárias à sua sobrevivência e alimentação, onde seu conhecimento local não é mais confiável. Apontamos que eventos climáticos extremos têm consequências para seus sistemas de cultivo e agrobiodiversidade associada, variando de acordo com o grau de exposição de diferentes ambientes a eventos extremos. Verificamos que os agroecossistemas de várzea baixa são mais afetados pelas enchentes e requerem maior tempo para sua reconstituição, onde mesmo após dois anos de manejo, os agroecossistemas não apresentam a diversidade *alpha* similar ao observado antes da enchente extrema. Além disso, a diversidade das etnoespécies entre os ecossistemas (diversidade *beta*), que antes da enchente extrema era similar, não foi retomada após dois anos de manejo pelos ribeirinhos. No caso da diversidade das etnovariedades de mandioca, impactos maiores também foram observados na várzea baixa imediatamente após a enchente. Durante eventos climáticos extremos os ribeirinhos intensificam estratégias de adaptação como: evitar o estresse nos sistemas radiculares das árvores frutíferas, priorizar o cultivo de plantas que sobrevivem às inundações e cultivar em paisagens menos afetadas. Práticas de adaptação tendem a ocorrer com mais frequência em várzeas, e duas práticas de adaptação foram específicas para várzeas. Além disso, moradores mencionam quatro técnicas de armazenamento de mandioca fresca; dois também citados em estudos arqueológicos ou etnográficos (enterramento e empaneiramento) e dois não citados anteriormente na região (ensacamento e *kanaká*). Na paleovárzea, onde a produção de mandioca é mais importante como fonte de renda, os moradores possuem mais conhecimento das técnicas de armazenamento da mandioca, porém, esse conhecimento também persiste em áreas onde a mandioca tem menor importância para a geração de renda. Nas próximas décadas, espera-se que os impactos de eventos climáticos extremos nas comunidades locais aumentem, principalmente em ambientes mais expostos a inundações. Moradores locais sugerem a documentação e o compartilhamento de estratégias de adaptação como forma de aumentar sua resiliência.

Abstract

Agrobiodiversity in Amazonia is the result of the use and management of plant populations by current and pre-Columbian peoples, being composed of domesticated crops to different degrees and domesticated landscapes, such as agroecosystems, managed forests and anthropic soils. Currently, the agroecosystems of traditional producers on the middle Solimões River (Amazonia) are being heavily impacted by extreme events related to climate change, such as recurrent large floods. The general objective of this thesis is to analyze the impacts and recovery of *ribeirinhos* agroecosystems in Amazonian floodplain ecosystems after one of the most extreme floods in the middle Solimões River (2015). Our specific objectives are: a) to assess how crop agrobiodiversity was impacted and recovered after the extreme flood (chapter 1); b) compare local adaptive landscape domestication strategies to cope with extreme and normal-year floods (chapter 2); and c) examine manioc storage strategies and the distribution of this knowledge among residents of floodplain ecosystems (chapter 3). For this, between 2017 and 2019 we carried out semi-structured interviews, free-lists, guided tours, participant observation, seasonal calendars and timelines. We analyzed the *alpha* and *beta* agrobiodiversity of ethnospecies and manioc ethnovarieties managed by *ribeirinho* communities before, immediately after and two years after the 2015 extreme flood, comparing the impacts and agrobiodiversity in the low *várzea*, high *várzea* and *paleovárzea*. We identified that local communities have detailed knowledge about normal climatic patterns and they recognize that climate unpredictability makes it difficult to effectively realize the activities necessary for their survival and food sovereignty, where their local knowledge is no longer reliable. We point out that extreme climatic events have consequences for their cropping systems and associated agrobiodiversity, varying according to the degree of exposure of different environments to extreme climatic events. We verified that low *várzea* agroecosystems are more affected by the extreme floods and require more time for their reconstitution, whereas even after two years of management, the agroecosystems do not present similar *alpha* agrobiodiversity in comparison with was observed before the extreme flood. In addition, the agrobiodiversity between ecosystems (*beta* agrobiodiversity), which was similar before the extreme flood, was not recovered even after two years of *ribeirinho* management. In the case of the agrobiodiversity of manioc ethnovarieties, greater impacts were also observed in the lower *várzea* immediately after the flood. During extreme climatic events, local communities intensify adaptation strategies such as avoiding stress on the root systems of fruit trees, prioritizing plants that survive to floods and cultivating in less affected landscapes. Adaptation practices tend to occur more frequently in *várzeas*, and two adaptation practices were specific to *várzeas*. In addition, residents mention four techniques for storing fresh manioc; two also mentioned in archaeological or ethnographic studies (burial and basketing) and two not previously mentioned (bagging and *kanaká*). In the *paleovárzea*, where manioc production is more important as a source of income, residents have more knowledge of manioc storage techniques; however, this knowledge also persists in areas where manioc is less important for income generation. In the coming decades, the impacts of extreme climatic events on local communities are expected to increase, especially in environments more exposed to flooding. Residents suggest documenting and sharing adaptation strategies as a way to increase their resilience.

Summary

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General introduction

In Amazonia, local ecological knowledge (LEK) of thousands of *ribeirinhos* rural communities (Adams *et al.* 2009, Costa and Inhetvin 2013) is reproduced, transformed and maintained (Balée 2015), including LEK to adapt to environmental threats (Alves *et al.* 2022). These communities are strongly dependent on the management of local natural resources for their survival, and many of the resources are legacies from previous generations or related groups (Arroyo-Kalin 2016, Levis *et al.* 2018). In the current scenario of global climate change, these communities are being impacted by more frequent and intense floods and droughts (Marengo *et al.* 2013, Cai *et al.* 2014). To deal with changing situations, adaptive strategies are part of LEK, which evolves as societies adapt and includes culturally transmitted understandings, practices and beliefs about the relationships between living beings and the environment (Berkes *et al.* 2000). In this study, we seek to understand the impacts of extreme climatic events on agroecosystems managed by *ribeirinhos* in *várzea* and *paleovárzea* ecosystems, evaluating adaptive strategies that favor local socioecological perpetuation in a scenario with climate change.

In general, to adapt to change and deal with socio-economic or environmental variability, farmers use diversification, modification of crop species and variety portfolios as strategies (Altieri and Nicholls 2017), with ecological knowledge central to the maintenance of agrobiodiversity (Emperaire *et al.* 2016). In a rapidly changing world, understanding changes in farmers' crop portfolios is fundamental to strengthening agrobiodiversity governance (Albuquerque *et al.* 2019), inform agricultural decision-making and design effective strategies for long-term adaptation (Labeyrie *et al.* 2021*a*). However, a global review paper found that studies about climate change and local perceptions on crop impacts are underrepresented in Latin America, which is due either to the lack of studies or few publications in English (Labeyrie *et al.* 2021*a*).

Nowadays, it is recognized that climate change will increase the unpredictability of climate, with more extreme climatic events expected (IPCC 2021). In Amazonia, the best documented change is the increase in the intensity and frequency of extreme floods (Marengo *et al.* 2013, Espinoza *et al.* 2022), which mainly impact low *várzea* ecosystems, while extreme droughts generally have their most intense impacts on *terra-firme* (non-flooded) areas (Pinho *et al.* 2015, Funatsu *et al.* 2019). The occurrence of these extreme events has been associated with phenomena such as El Niño (extreme droughts) and La Niña (extreme floods) (Schöngart and Junk 2007), and affect local socioecological systems (Marengo *et al.* 2011, Barichivich *et* *al.* 2018). To date, one of the most extreme events in the middle Solimões River was in 2015, when the flood was about two meters above the normal maximum and started two months earlier than expected (Ávila *et al.* 2021). This type of extreme event makes land use planning difficult and undermines conservation efforts (Tompkins and Adger 2004), because they increase ecosystem instability and natural rates of diversity loss (Oliveira and Nobre 2008), which can affect traditional means of survival (Lins 2018).

Ribeirinhos are inhabitants of communities located along the banks of rivers and lakes, and organize their life and work routines according to the seasonal variation of water levels (CNPCT 2016). As amazonian communities depend on rivers for numerous aspects of their livelihoods, they are more vulnerable to pronounced variations in rainfall and river level (Dubreuil *et al.* 2017). Locally, the annual flood pulse of large rivers is caused by seasonal variation in precipitation in their drainage basins (Junk 1989, Schöngart and Junk 2007). About 30 % of the Amazon River basin is flooded part of the year (Junk *et al.* 2011*b*) and about 20 % of the Amazonian population lives in flood-prone areas (Junk *et al.* 2011*a*). According to IBGE (2017), the impacts of floods are observed in 90 % of the municipalities in the State of Amazonas, and in 2019 at least 30 municipalities declared states of emergency due to high water levels (Jornal A Crítica 2019a). That flood caused more than R$ 60 million in losses to agricultural producers (Jornal A Crítica 2019b). The losses of crops reduces food supply to local communities and inflates the prices of products in the city, reducing food security and sovereignty of Amazonians in the interior (Tregidgo *et al.* 2020) and in urban centers (Jornal A Crítica 2019b).

Floodplains (*várzeas*) cover 9 % of the Amazon River basin, *paleovárzeas* cover 1 % (Irion *et al.* 2010), and other seasonally flooded areas cover about 20 % of the region (Junk 1993). *Várzeas* are alluvial plains of white water rivers formed from nutrient-rich sediments derived from the Andes and deposited in the Amazonian lowlands during the Holocene (Junk 1989). They are flooded in regular annual cycles, during which some areas may be flooded for up to six months (Junk 1989). In these ecosystems, which are largely flat, subtle changes in elevation can represent large differences in flood timing and duration that create environmental gradients (Denevan 1984, Hiraoka 1985). When floods are extensive, higher *várzea* areas can be covered by 1- 2.5 meters of floodwater for 2- 4 months. In contrast, the lower *várzeas* areas are flooded annually with water by 3-5 meters for about 4-6 months, even during normal flood years (Ayres 2006).

Paleovárzeas are ancient alluvial plains of white-water rivers that originated in the Late Pleistocene during the last interglacial period (125-75 thousand years ago), when the sea level was higher than today (Irion *et al.* 2010). Thus, *paleovárzeas* are higher than *várzeas*, and this difference tends to decrease as one moves away from the current Atlantic coast (Irion *et al.* 2010). The *paleovárzeas* in the study area are only 1.0-3.0 m higher than the *várzeas*, experiencing occasional flooding in years with major flooding, but not annual flooding.

The combination of preconditions that allow individuals or groups to respond to changes are called "adaptive capacity" (Olsson and Folke 2001), and include intentional and unintentional adaptive strategies (Athayde and Silva-Lugo 2018), focused on the local context (Rout *et al.* 2020). The basis for adaptive strategies is LEK, which allows local communities to manage resources in the face of the natural unpredictability of ecosystems (Berkes *et al.* 2000, Gómez-Baggethun and Reyes-García 2013, McMillen *et al.* 2017). The increase in adaptive capacity, manifested by post-disturbance reorganization of socioecological systems, is one of the attributes of resilience (Peterson *et al.* 1998, Rout *et al.* 2020), and represents the ability to learn from disturbances and subsequently adapt and reorganize (Walker 2020). Given the potential of climate change to alter annual flooding patterns, LEK holders may change their decisions about resource use and management, including those about legacy-domesticated landscapes. Hence, assessing how agrobiodiversity and landscape management practices are maintained or adapted can increase understanding of the socio-ecological impacts and consequences of climate change.

Past and current traditional communities practice diversified production systems, using both inter- and intraspecific crop diversity (Carneiro da Cunha 2012, Lima *et al.* 2012, Emperaire 2017). In the study area, the most pronounced intraspecific diversity is for manioc (*Manihot esculenta* Crantz) (Schmidt 2003, Rognant and Steward 2015). Assessing changes in species composition in the agrobiodiversity maintained by producer families (*alpha* diversity) and between communities or ecosystems (*beta* diversity) (Magurran 2004), can contribute to the development of conservation strategies (Swenson *et al.* 2012), including after the occurrence of extreme climatic events.

In this thesis, we investigate the following questions: a) how do extreme floods impact agrobiodiversity?, b) is agroecosystem recovery related to flood exposition? (Chapter 1), c) how are local communities and their management activities affected by extreme climatic events? (Chapter 2), d) what are the techniques known by local communities for manioc root storage that allow further processing and consumption when water recedes?, and e) how is the knowledge about manioc store techniques distributes between ecosystems? (Chapter 3).

Data collected on the low and high *várzeas* showed little discrepancy in chapters 2 and 3 of this thesis, being analyzed jointly. Due to the low and high *várzeas* being discrepant in the first chapter, they were analyzed separately.

General objective

The general objective of this thesis is to analyze the impacts and recovery of *ribeirinho* agroecosystems after an extreme flood event in the middle Solimões River floodplain ecosystems.

Specific objetives

1) Identify extreme flood impacts on *alpha* and *beta* crop agrobiodiversity in Amazonian floodplain ecosystems (chapter 1);
2) Compare agroecosystem recovery according to their exposition to flood (chapter 1);
3) Characterize climate patterns according to local knowledge and identify changes in climate and in livelihood activities (chapter 2);
4) Identify how local communities and their management activities are affected by an extreme flood event (chapter 2);
5) Register adaptive management strategies used for new climatic contexts (chapter 2);
6) Investigate the techniques known and/or used for manioc root storage that allow further processing and consumption when flood waters recede (chapter 3);
7) Compare the distribution of knowledge about manioc root storage techniques between *várzea* and *paleovárzea* communities (chapter 3).

Chapter 1

Ávila, J.V.C., Ticktin, T., Giehl, E.L.H., Cantor, M., Steward, A.M., Clement, C.R. 2023 Recovery of local agrobiodiversity after an extreme flood in the middle Solimões River floodplain, Amazonas, Brazil. To be submitted

Chapter 1: Recovery of local agrobiodiversity after an extreme flood in the middle Solimões River floodplain, Amazonas, Brazil

Abstract

Agrobiodiversity is economically, socially, culturally, and ecologically important for resilience of local communities and their agroecosystems. Extreme climate events are increasing in Amazonia and may even double in frequency in coming years. Here, we identify the impacts of an extreme flood on *alpha* and *beta* crop diversity before, immediately after and two years after the largest flood ever recorded in three different floodplain ecosystems (low and high *várzea*, and *paleovárzea*) along the middle Solimões River in Brazilian Amazonia. We found that palms and trees, and species native to Brazil, had highest survival rates in all three ecosystems. The low *várzea* showed the most expressive losses of ethnospecies and manioc *alpha* diversity among the ecosystems; ethnospecies original diversities were not recovered even two years after the flood, and for manioc had the slowest recovery. Ethnospecies *beta* diversity was relatively homogeneous among ecosystems before the flood; this changed after the extreme flood, represented by an increase in *beta* diversity. These results highlight the vulnerability of local agrobiodiversity in the face of extreme climatic events, which drastically affect local food sovereignty and income sources.

Key words: agrobiodiversity; climate change; *ribeirinhos.*

Introduction

Indigenous Peoples acquired detailed knowledge about how to manage biodiversity and transform ecosystems during the Holocene (Albuquerque and Ferreira-Júnior 2018, Cassino *et al.* 2019, Clement *et al.* 2021). Local communities in Amazonia inherited indigenous agrobiodiversity and associated management practices (Rognant and Steward 2015), producing and conserving considerable specific and genetic diversity in their agroecosystems (Carneiro da Cunha 2012, Emperaire 2017). Local contexts are subject to constant change (Nobre *et al.* 2007), in terms of both socioeconomics and, especially, climate change. In Amazonia, the occurrence of record breaking floods and droughts are increasing in frequency (Marengo *et al.* 2011, Marengo and Espinoza 2016, Barichivich *et al.* 2018). Assessing the impacts of extreme climatic events on local agrobiodiversity can help guide local strategies to deal with changing scenarios.

High levels of agrobiodiversity can contribute to greater productivity, resistance to plant pests and diseases, adaptation to changing contexts, and improves ecosystem functions (Altieri 1999, Santilli 2009, Altieri and Nicholls 2017). With their diverse uses of plants and landscapes, Indigenous Peoples and Local Communities (IPLC) create mosaics that increase the diversity and complexity of their systems (Mijatović *et al.* 2013). This diversity can enhance the resilience of local communities in the context of social, economic and environmental change

(Walker *et al.* 2004, Ticktin *et al.* 2018), buffering against changes in system structure and function (Walker *et al.* 2006). For example, after major disturbances, such as large floods, greater landscape and species diversity has been shown to improve resilience of both local communities and their agroecosystems (Altieri *et al.* 2015). In this study, we investigate some components of resilience to a major disturbance, focusing on agrobiodiversity.

During and after a disturbance, local ecological knowledge (LEK) is central to the maintenance of agrobiodiversity (Emperaire *et al.* 2016). Along the Solimões River (Ávila *et al.* 2021*b*) and in other Amazonian regions (Piedade *et al.* 2013, Guimarães *et al.* 2019, Estevo *et al.* 2022), local producers called *ribeirinhos* have reported impacts or changes in their crop portfolios due to climate change, including the selection of species that are more tolerant to recurrent extreme floods (Ávila *et al.* 2021*b*). Their production systems concentrate on manioc (*Manihot esculenta* Crantz), used to produce flour, combined with various fruits and other products (Rognant and Steward 2015). Numerous manioc varieties are cultivated on the region, to supply this demand (Lima *et al.* 2012). Since manioc has low resistance to flooding, diversity of local varieties allows *ribeirinho*s to manage manioc in different climatic and ecosystem scenarios, where some varieties can be harvested 5-6 months after planting, while others can be harvested after one year or more (Schmidt 2003).

Ribeirinhos are inhabitants of banks of rivers and lakes, and organize their life according to the seasonal variation of water levels (CNPCT 2016). Historically, *ribeirinho* communities manage high levels of inter- and intraspecific agrobiodiversity (Steward 2013). The main drivers for maintaining inter- and intraspecific crop diversity are to expand food options and optimize family income (Pereira 2008), resulting in diverse economies and reflecting the complexity of agricultural systems in different ecosystems (Lima *et al.* 2012). Since Amazonian *ribeirinho* communities depend on rivers for their livelihoods, they are vulnerable to pronounced variations in rainfall and river levels (Dubreuil *et al.* 2017). Planting one or two short-cycle crops per year is an appropriate practice developed by such communities (Ohly 2020), which works well under the predicted annual flood intensity in the State of Amazonas (Schöngart and Junk 2007).

Along the middle Solimões River, normal variation in water levels was historically about 10 meters (Ramalho *et al.* 2010), but now extreme floods and droughts are increasing in frequency and intensity, and changing seasonality, a trend that is likely to intensify (Marengo *et al.* 2013) and even double in the future (Cai *et al.* 2014). Extreme floods impact low-lying *várzea* ecosystems most severely, while extreme droughts generally have their most intense impact on *terra-firme* (non-flooded) areas (Pinho *et al.* 2015, Funatsu *et al.* 2019). Thus, extreme climatic events have wide-ranging effects, including social, ecological, economic and political impacts (Marengo *et al.* 2013). For example, in the extreme climate event of 2019, crop losses were estimated at over R$ 60 million (close to US$ 12 million) along the Solimões River (A Crítica 2019).

Várzeas are floodplains formed during the Holocene and flood in regular annual cycles (Junk 1989). In normal years, low *várzeas* are flooded annually by 3-5 meters of water for about 4-6 months (Ayres 2006), and during extreme floods, higher *várzeas* may be covered by 1-2.5 meters of water for 2-4 months. In contrast, *paleovárzeas* originated during the last interglacial period, in the Late Pleistocene, when sea level was higher than today (Irion *et al.* 2010). Thus, *paleovárzeas* are higher than high *várzeas*, and this difference tends to decrease as one moves away from the current Atlantic coast (Irion *et al.* 2010). The *paleovárzeas* in the study area are 1.5-2.0 m higher than the high *várzeas* and are only affected by major floods (Irion *et al.* 2010). Given this complexity, crop repertoires are constantly decided by *ribeirinhos* according to the duration and intensity of the expected flood (Schmidt 2003).

Extreme floods can affect species differently. In general, extreme climatic events increase the mortality of many trees (Gloor *et al.* 2015), and diminish the floristic richness of species that do not support the new rhythm of flood cycles (Wittmann *et al.* 2004). However, some palms and trees with edible fruits are reported to survive extreme floods (Jardim 2019). Despite the negative effects of many of these events, the Civil Defense Service of the State of Amazonas and the Geological Service of Brazil (CPRM) issue only extreme flood alerts. Due to the low precision of these alerts, intense or even total loss of crops is often the outcome (Ohly 2020). Under these scenarios, adaptive strategies are key for crop management and sociocultural perpetuation (Pereira *et al.* 2017, Ávila *et al.* 2021*a*, Ávila *et al.* 2022).

Evaluating the impacts of climate change on agrobiodiversity and how this varies spatially is therefore critical. One approach is to assess changes in resource availability through ethnobotanical interviews and field surveys (Gaoue *et al.* 2017), as done by Ticktin *et al.* (2018) and McGuigan *et al.* (2022). Agrobiodiversity is generally evaluated in terms of the crop species and variety diversity managed by individual producers or communities (*alpha* agrobiodiversity), and the variation in the composition of crop portfolios among communities (*beta* agrobiodiversity) (Labeyrie *et al.* 2021). Combining these approaches can increase our understanding about how resilient an agroecosystem is in the face of social and environmental changes (McGuire and Sperling 2013, Mwongera *et al.* 2014), and contribute to agrobiodiversity conservation for food sovereignty (Thomas *et al.* 2015).

In this study, we investigate the consequences of an extreme flood on agroecosystems in three floodplain ecosystems (low and high *várzea*, and *paleovárzea*) before (T1), immediately after (T2), and two years after (T3) the extreme flood event of 2015. Our objectives were to: a) identify impacts of extreme flooding on *alpha* and *beta* agrobiodiversity, b) compare agroecosystem recovery over time across ecosystems, and c) identify which types of crops were most and least tolerant. Given the expectation of higher impacts of extreme floods in low *várzea*, our first hypothesis was that in low *várzea alpha* and *beta* agrobiodiversity would decline immediately (T2), especially manioc varieties, and might not recover to pre-extreme flood levels after two years (T3). Our second hypothesis was that the effects of extreme flooding on *alpha* and *beta* agrobiodiversity would be much lower in the high *várzea* and *paleovárzea*, including for manioc, and that recovery would be faster. Our third hypothesis is that trees and palms used for food will have a better resistance to extreme flood events in comparison to other grow forms.

Methodology

Study area

We investigated communities in three floodplain ecosystems in Central Amazonia: the low *várzea*, high *várzea* and *paleovárzea*. The low and high *várzea* communities studied are in the *Mamirauá* Sustainable Development Reserve (RDSM) and the *paleovárzea* is in the *Amanã* Sustainable Development Reserve (RDSA) (Figure 1), both included in the Central Amazon Biosphere Reserve. The low and high *várzea* communities of this study are in areas of white water, rich in sediments from the Andes (Junk 1989, Ayres 2006), including calcium, magnesium, and the pH is only slightly acidic (Souza 2012). The *paleovárzea* communities are surrounded by black water, which has few dissolved minerals and the pH is comparatively more acidic (Souza 2012).

In the Köppen system, the climate in the region is tropical rainforest (Af), with one dry and one rainy season during the year (Ramalho *et al.* 2010). The highest extreme flood event yet recorded was in 2015, when flooding was about two meters above the normal maximum and started two months before the expected period (Ávila *et al.* 2021*a*).

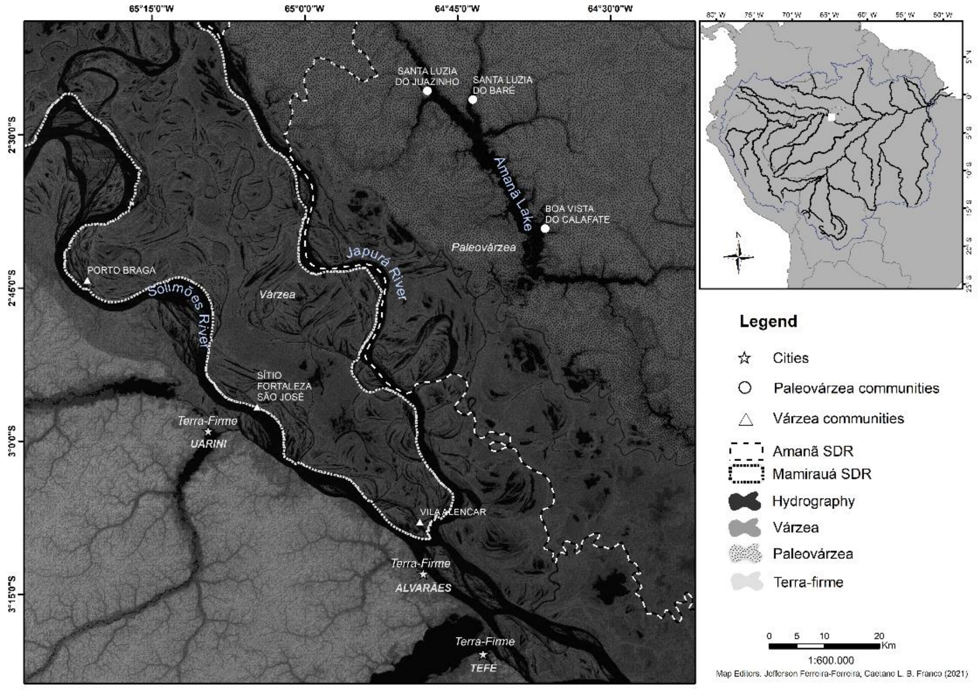

Figure 1. Map of the study area along the middle Solimões River basin in the State of Amazonas, Brazil, showing the *várzea* and *paleovárzea* communities where this study was conducted. Tefé, Alvarães and Uarini are municipal seats.

In low and high *várzea*, farming activities are guided by the seasonal flood cycle of rivers, where productive areas can flood for many months (Ohly 2020, Ávila *et al.* 2021 *a*, Junk *et al.* 2023), and crops are managed in areas where sediment deposition is higher (Noda 2009, Ávila *et al.* 2021*a*). During the year, communities who live in all floodplain ecosystems are important seasonal sellers at local markets, prioritizing the management of short-cycle species on beaches and lower areas (Ohly 2020, Junk *et al.* 2023), and managing a wide diversity of fruits, vegetables, maniocs, medicinal and ornamental plants in higher areas (Lima and Alencar 2000).

Data collection

Between August 2017 and May 2019, we conducted semi-structured interviews with one member per family who was more than 18 years old. We talked to people in two low *várzea* communities (Vila Alencar, Sítio Fortaleza; 27 interviews), one high *várzea* community (Porto Braga; 32 interviews) and three *paleovárzea* communities (Santa Luzia do Juazinho, Santa Luzia do Baré, Boa Vista do Calafate; 42 interviews). General socio-economic information can be found in Ávila *et al.* (2021a). We asked interviewees about their a) socio-economic data, b) perceptions of climate change, and c) free lists of edible ethnospecies and manioc ethnovarieties managed before the 2015 flood (T1), the plants managed immediately after the extreme flood

(T2) and the plants managed two years after the extreme flood (T3). Here, we use "ethnospecies" and "ethnovarieties" as a synonym for "common name". Given the large number of ethnovarieties of many crops, we recorded only one common name of each ethnospecies, and the impacts of and recovery after the extreme flood. As manioc intraspecific diversity is high (Schmidt 2003, Lima *et al.* 2012), each manioc ethnovariety was fully investigated; we asked the name, the impact of the 2015 flood and if the *ribeirinho* planted it again after the flood.

After gathering free lists, we also created a checklist of plants that are commonly managed in the region, based on previous studies by the Amazonian Agriculture, Biodiversity and Sustainable Management Group of the Mamirauá Institute and asked participants about the plants they did not mention in the free listing exercise. Guided tours (Alexiades 1996, Albuquerque *et al.* 2014) were also carried out in the agroecosystems with all the interviewees, where specimens of food plants were collected following conventional methods used in plant taxonomy (Fidalgo and Bononi 1989), for later botanical identification with support of a parataxonomist.

We then checked specialist information on each species listed. Information about each ethnospecies' resistance or fragility to extreme floods was obtained from meetings with community leaders and at least one key informant in each community. Subsequently, this information was also checked in collective meetings[1]. During the collective meetings (two per community), we also shared and validated the results of this study processed before COVID-19. We used the Flora do Brasil (2021)[2] website to verify if the cited species are native to Brazil, to check or update botanical names (see Supplementary Materials Table 1 for a full list of common names in Portuguese and English whenever possible, their associated Latin name, and authorship), and the grow form of the species managed.

Data analysis

We used descriptive statistics to evaluate the percentage of Brazilian native and non-native ethnospecies managed, those affected by the 2015 flood and those replanted, as well as to evaluate the grow form of the plants managed in the region. To evaluate the effect of the extreme flooding on crop persistence, we considered richness to be the number of ethnospecies

[1] Due to COVID-19, we could not organize meetings on the high *várzea* community Porto Braga.

[2] https://floradobrasil.jbrj.gov.br/reflora/listaBrasil/ConsultaPublicaUC/ConsultaPublicaUC.do#CondicaoTaxonCP (Date access: 13 April 2022)

cited by producers and relative abundance to be the number of producers who cited each ethnospecies (Gaoue *et al.* 2017). We used a binomial generalized linear model to test the effects of extreme flooding on richness of ethnospecies and manioc ethnovarieties and if this differed across the low *várzea*, high *várzea* and *paleovárzea* ecosystems.

We investigated *alpha* agrobiodiversity focusing on differences of food species managed in each ecosystem (Labeyrie *et al.* 2021). To compare the richness of ethnospecies in each ecosystem at each time and with different sample sizes (Peet 1974, Begossi 1996), we interpolated diversity values based on the incidence of ethnospecies (presence or absence) (Gotelli and Colwell 2001). We then estimated 95 % confidence intervals for interpolated values (Hsieh *et al.* 2016) and checked separation of intervals as evidence of relevant differences (Colwell *et al.* 2004). Manioc ethnovarieties were evaluated separately from other ethnospecies. *Alpha* agrobiodiversity values and confidence intervals were calculated with the iNEXT package (Hsieh *et al.* 2016) for R (R Core Team 2020).

We assessed *beta* agrobiodiversity by contrasting ethnospecies composition using binary–Jaccard dissimilarities and represented composition dissimilarities in multivariate graphic space with a Principal Coordinate Analysis. To identify differences in composition of ethnospecies and ethnovarieties managed before (T1), immediately after (T2), and two years after the 2015 flood (T3), we tested multivariate dispersion among groups (Anderson *et al.* 2006), usingpermutation tests in the 'vegan' (Oksanen *et al.* 2018) and 'betapart' packages (Baselga *et al.* 2018) for R (R Core Team 2020) to assess statistical significance. In these analyses, individual *ribeirinhos* were considered replicates, with ecosystems compared independently. As for *alpha* agrobiodiversity, manioc ethnovarieties were evaluated separately from other local crops.

Results

Differential vulnerability of crops to extreme flooding

Prior to the 2015 extreme flood, we collected 607 citations of plants managed for food in the low *várzea*, corresponding to 66 ethnospecies, and 100 citations of manioc, related to 24 manioc ethnovarieties. In the high *várzea*, were made 1012 citations, corresponding to 80 ethnospecies, and 158 citations of manioc, for 38 manioc ethnovarieties. In the *paleovárzea*, we obtained 1014 citations referred to 75 ethnospecies, and 187 citations of manioc, about 36 manioc ethnovarieties.

The extreme flood of 2015 had severe impacts on the agroecosystems managed by *ribeirinhos* in the middle Solimões River basin. In the low *várzea*, 61.4 % of the managed ethnospecies (excluding manioc) were affected, while in the high *várzea* this percentage was 42.4 % and in the *paleovárzea* 41.1 %. When considering manioc ethnovarieties, 70.3 % of manioc ethnovarieties were affected (those not harvested before the flood) in the high *várzea*, followed by 65.1 % in the *paleovárzea*, and 54 % in the low *várzea*, where fewer ethnovarieties are planted (Figure 2).

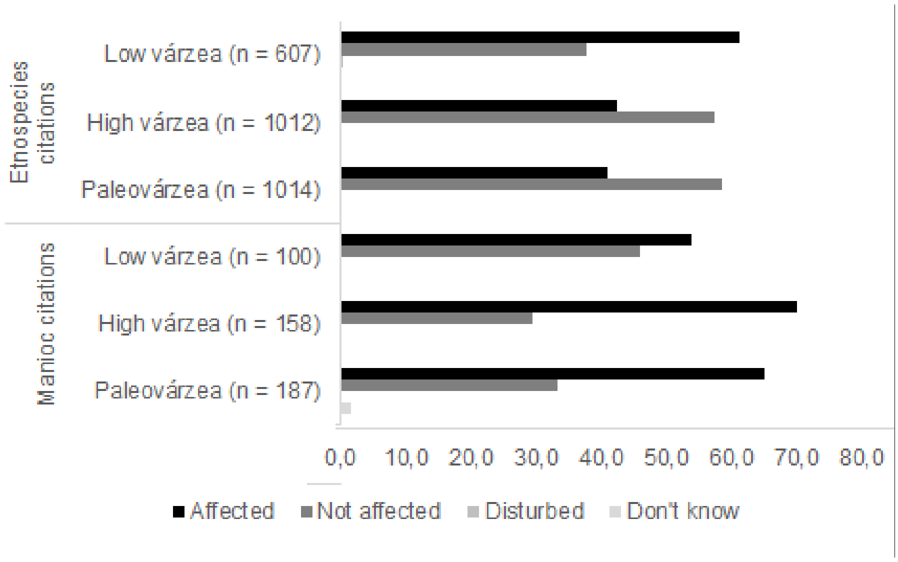

Figure 2. Percent of ethnospecies and manioc ethnovarieties citations as affected, not affected, disturbed (e.g. impacted on phenology), and do not know by the 2015 extreme flood in the middle Solimões River basin agroecosystems, Amazonas, Brazil.

As we had expected, agrobiodiversity in the low *várzea* was more impacted after the major flood, than in the high *várzea* and *paleovárzea* (GLMM, $\beta = 0.82593$, SE = 0.10177, $z = 8.116$, $p < 0.001$). For the diversity of manioc ethnovarieties, however, we found no differences among ecosystems ($\beta = -0.4458$, SE = 0.2523, $z = -1.767$, $p = 0.0773$). This is probably because the *ribeirinhos* historically store manioc cuttings during the flood season, sometimes being able to replant the manioc immediately when the river water recedes. In addition, some ethnovarieties were harvested before the flood. Detailed information about the flood impacts on each ethnospecies in each ecosystem is presented in supplementary materials Table 1 and for each manioc ethnovariety in supplementary materials Table 2. The quantity of citations of ethnospecies and manioc ethnovarieties managed before the extreme flood was higher than immediately after the extreme flood and two years after the extreme flood (Figure 3).

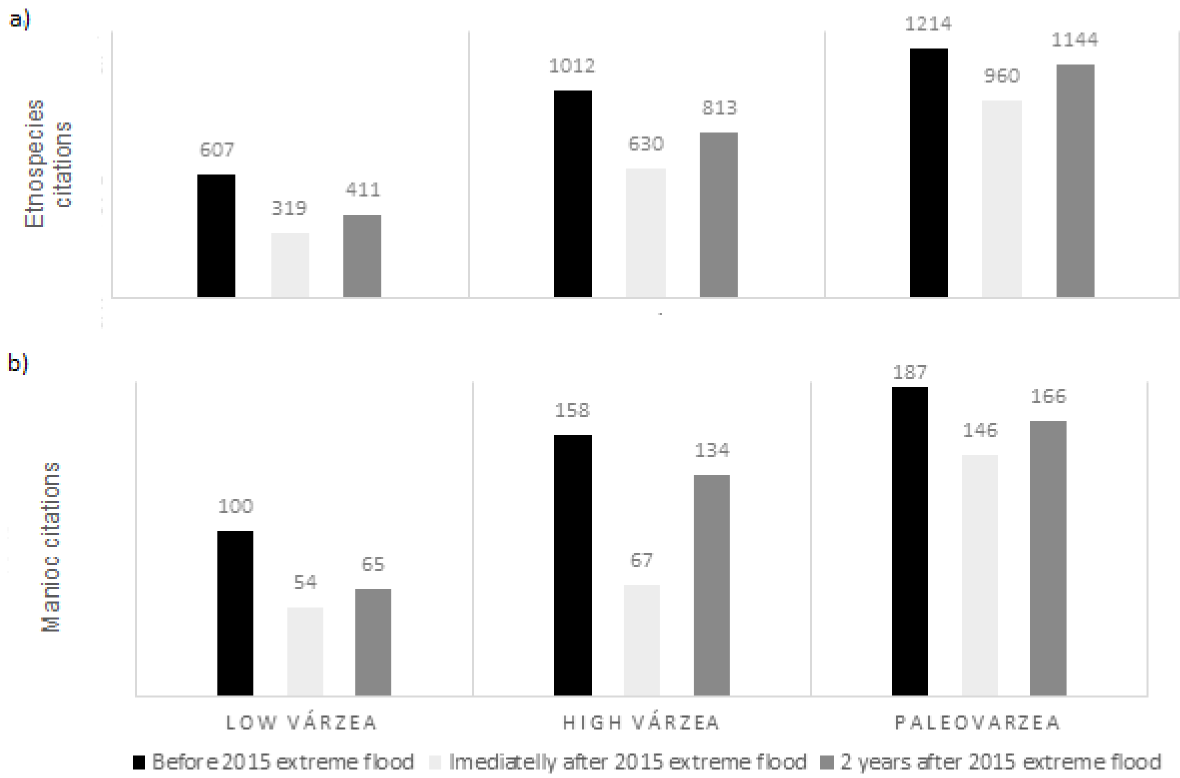

Figure 3. Total citations of ethnospecies and manioc ethnovarieties managed before the extreme flood, immediately after the extreme flood and two years after the extreme flood in the middle Solimões River basin agroecosystems, Amazonas, Brazil.

Based on the collective perception of *ribeirinhos* in the low *várzea*, 16 % of the ethnospecies managed for food resist the most intense floods (they survive even if the plant is covered by water for many months), 44 % have intermediate resistance (e.g., the plants survive if there was no movement or heating of the roots, and if the plant was not deeply or completely covered by water) and 40 % of the ethnospecies are very fragile (e.g., the plant dies a few days after the roots are submerged on the water). In the *paleovárzea,* they affirmed that 17 % of the ethnospecies resist major floods, 30 % have intermediate resistance and 53 % are very susceptible to flooding. The perceptions of *ribeirinhos* in low *várzea* and *paleovárzea* environments about the resistance or fragility of each ethnospecie to extreme flooding, obtained in collective meetings, are presented in supplementary materials (Table 3 and 4, respectively)[3].

Characteristics of the plants affected

In *várzeas* and *paleovárzeas* ecosystems, native ethnospecies had greater tolerance to the major flood than non-native ethnospecies (Figure 4). Although short-cycle crops were severely affected (Supplementary Material Table 5), *ribeirinhos* who managed those as sources

[3] Due to COVID-19 we could not collect general information related to ethnospecies survivor/mortality face to extreme flood events on the high *várzea* ecosystem.

of income (e.g., pumpkin/squash and watermelon; see scientific names in Supplementary Material Table 1) affirm that they can still harvest under the extreme flood context. This is possible if short-cycle crops are planted as soon as the water recedes and if they can harvest the plants before the flood. Among perennial ethnospecies, however, 39.5 % of *ribeirinhos* highlighted the loss of avocado (Supplementary Material Table 1), which is an important source of income on the *paleovárzea*. Considering all ethnospecies, 30 were lost by the majority (80-100 %) of *ribeirinhos* in the várzea, contrasting with 18 ethnospecies on the high *várzea* and 7 ethnospecies on *paleovárzea* (Table 6 supplementary materials).

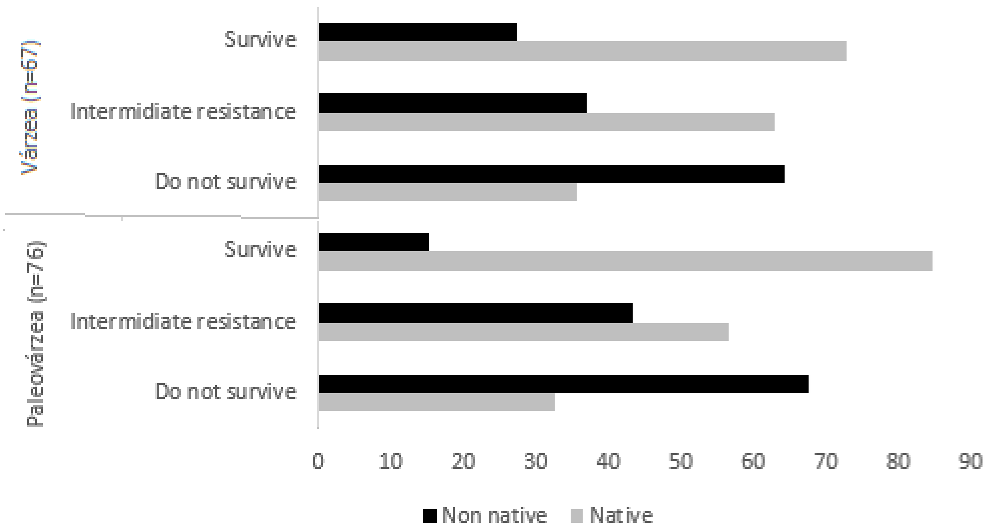

Figure 4. Percent survival of native and non-native ethnospecies (including manioc) managed in the middle Solimões River basin agroecosystems, Amazonas, Brazil.

Palms and trees or shrubs tended to survive better than vines and herbs in all ecosystems (Figure 5, complete information on the grow forms of the species is presented in Table 1 of the supplementary material.). The trees most mentioned as having greater resistance to extreme floods were strawberry guava (*Psidium cf. striatulum*, *Eugenia stipitata*, *Psidium acutangulum*), *bacuri* (*Garcinia brasiliensis*, *Garcinia madruno*), cacao (*Theobroma bicolor*, *Theobroma cacao and Theobroma obovatum*), *camu-camu* (*Myrciaria dubia*), and genipap (*Genipa americana*). Among the palms, the mention survival was highest for *açaí-do-mato* (*Euterpe precatoria*), *bacaba* (*Oenocarpus bacaba*), and *buriti* (*Mauritia flexuosa).*

The trees with the highest mortality were avocado (*Persea americana*), cashew (*Anacardium occidentale*), *cupuaçu* (*Theobroma grandiflorum*), *ingá (Inga cf. cinnamomea, Inga edulis, Inga macrophylla*), lemon (*Citrus aurantiifolia*), papaya (*Carica papaya*), mango (*Mangifera indica*), and the palms mentioned with high mortality were *açaí-do-Pará (Euterpe oleracea*), coconut (*Cocos nucifera*) and peach palm (*Bactris gasipaes*) (Supplementary

Material Table 1). Moreover, herbs survived better in the high *várzea* than in other ecosystems, which is due to floating houses being common in the community and where herbs are managed in planters in front of windows and balconies.

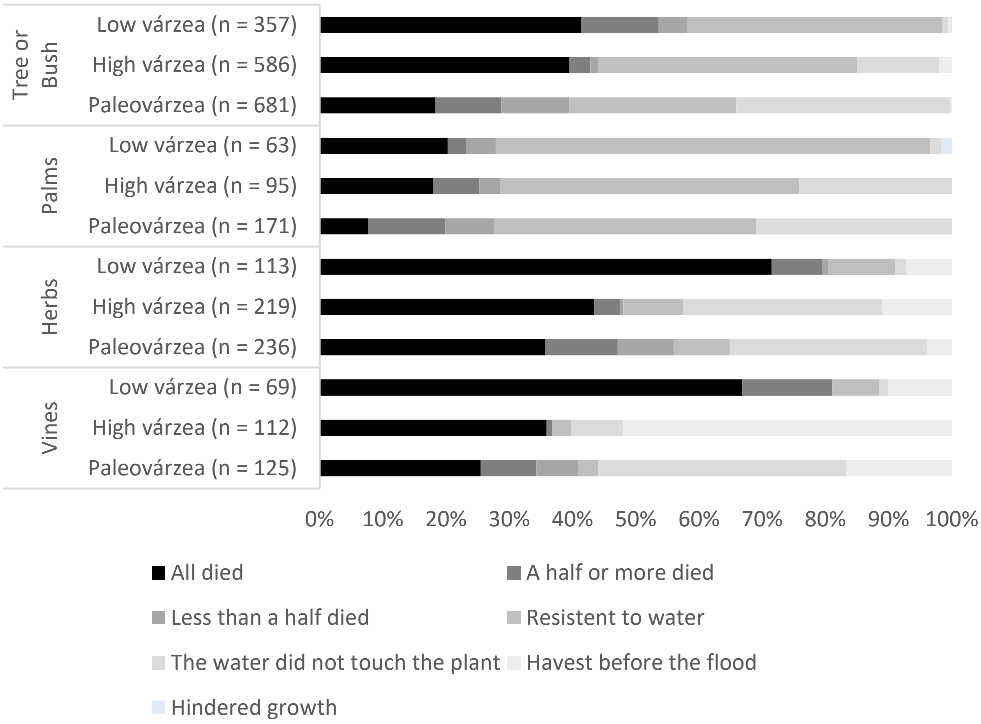

Figure 5. Percentage of citation survival and impacts of the 2015 flood on different ethnospecies grow forms according to *ribeirinho* reports in different ecosystems in the middle Solimões River basin agroecosystems, Amazonas, Brazil (citation as "do not know" if the plant survived was not included).

In the low *várzea*, 15 % of the ethnospecies were not replanted during the two years after the extreme flood, 70 % of which were herbs. In the high várzea, 5 % were not replanted during that time (75 % of them were trees) and in the paleovárzea only 1.4 % ethnospecies was not replanted (a shrub) (Supplementary Table 7).

Effects of extreme flooding on *alpha* and *beta* agrobiodiversity

To identify where and how the extreme flooding event impacted agrobiodiversity in the different ecosystems of the region and over time, we compared changes in *alpha* and *beta* agrobiodiversity. As expected, the low *várzea* suffered greater loss of ethnospecies (*alpha* diversity) than the high *várzea* (Figure 6a, comparison of T1 and T2), while the *paleovárzea* suffered least. Two years after the flood (T3), *alpha* agrobiodiversity had recovered less in the low *várzea* than in the high *várzea*, while the *paleovárzea* had almost recovered to pre-flood levels.

In terms of the manioc ethnovarieties, there was a statistically significant decline in *alpha* diversity in the low *várzea* right after the flood (T2), but there was no difference in the high *várzea* and the *paleovárzea* (Figure 6b, compare T1 and T2). In all ecosystems, recovery of *alpha* diversity was slow, with the *ribeirinhos* on the high *várzea* adding more manioc ethnovarieties to their plantings than *ribeirinhos* in the low *várzea* and *paleovárzea* (Figure 6b, compare T3 and T2).

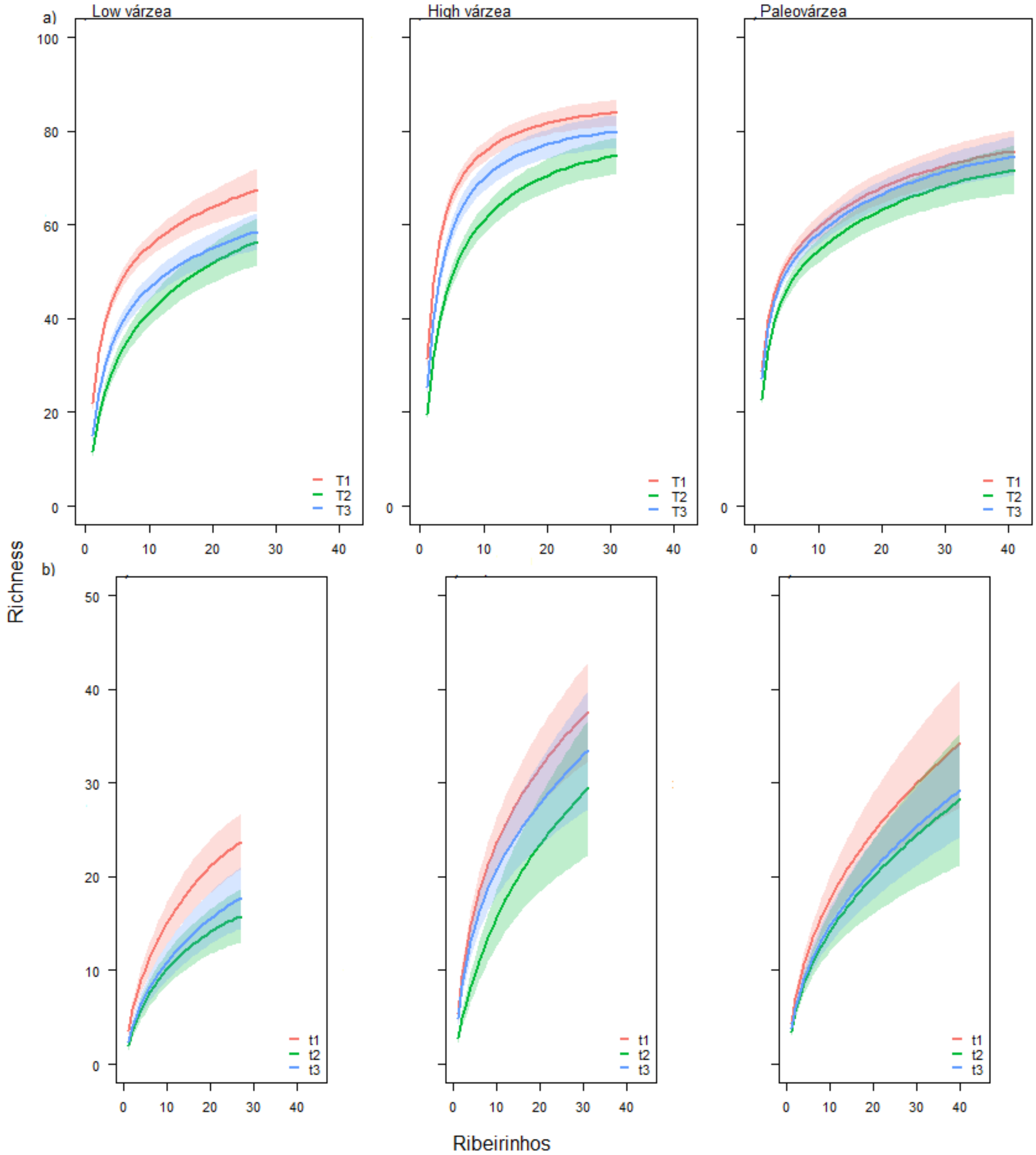

Figure 6. Interpolation of *alpha* agrobiodiversity ("a" richness of ethnospecies and "b" richness of manioc ethnovarieties) in each ecosystem in the middle Solimões River basin, Amazonas, Brazil. T1 represents the period before the flood, T2 immediately after the flood and T3 two years after the flood.

There was an increase in ethnospecies beta agrobiodiversity over time, ranging from no difference in ethnospecies composition before the flood (F = 2.278; p = 0.107) to increasing differences from T2 (F = 3.762; p = 0.026) to T3 (F = 7.822; p = 0.002) (Figure 7a). This means that *beta* agrobiodiversity among ecosystems was similar before the extreme flood (T1). However, right after the extreme flood (T2) and two years after the extreme flood (T3), composition of ethnospecies became distinct (Figure 7a). With respect to *beta* diversity of manioc ethnovarieties, there was no difference among ecosystems before the flood (F = 1.751; p = 0.191), immediately after the flood (F = 2.117; p = 0.15), or two years after the flood (F = 2.405; p = 0.109) (Figure 7b).

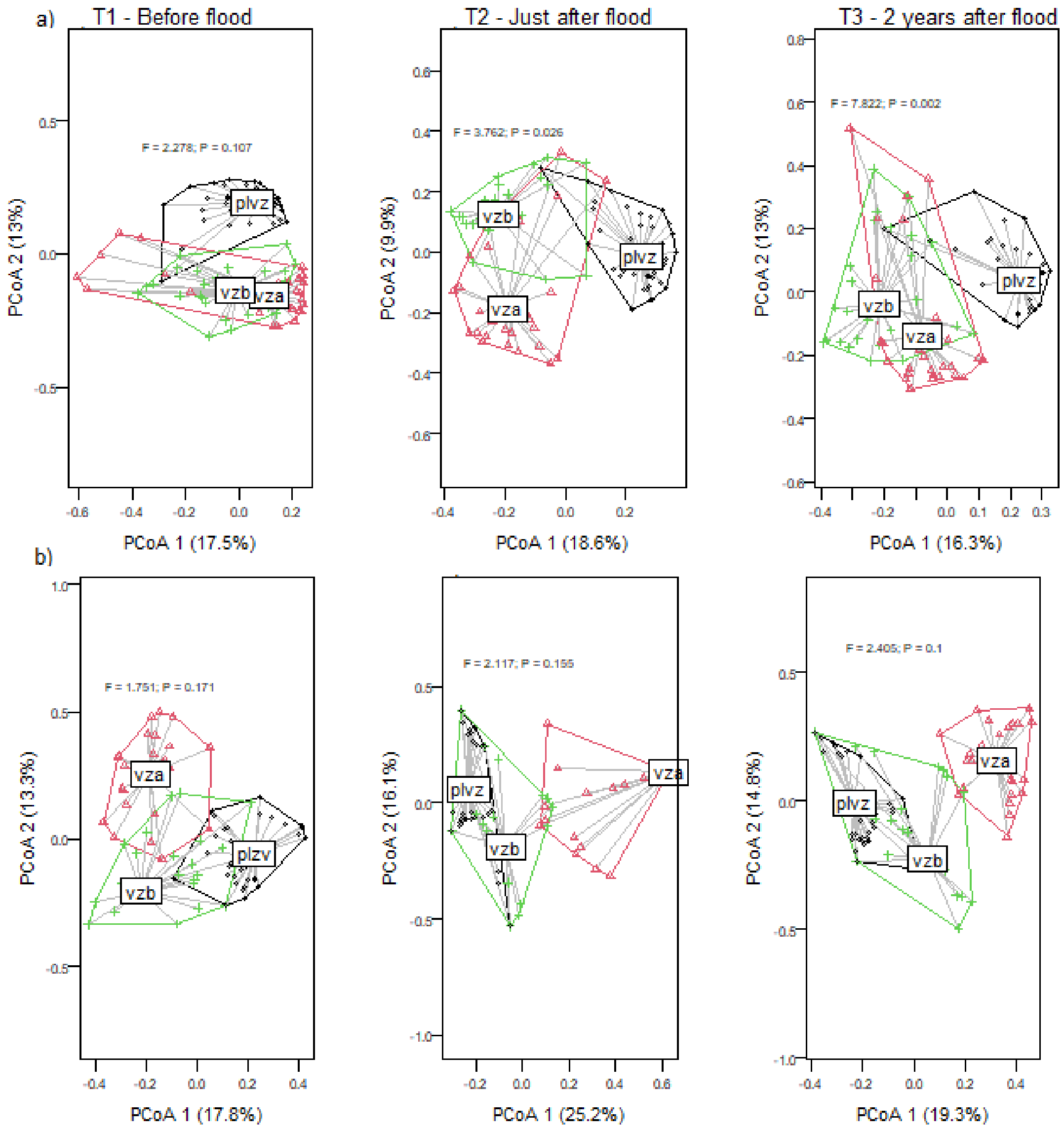

Figure 7. *Beta* agrobiodiversity ("a" composition of ethnospecies and "b" composition of manioc ethnovarieties), managed by ribeirinhos on the low *várzea* (vzb), the high *várzea* (vza) and the *paleovárzea* (plvz) in the middle Solimões River basin, Amazonas, Brazil, before, immediately after and two years after the extreme flood of 2015, where difference in agrobiodiversity among ecosystems is evaluated through multivariate tests of group homogeneity.

Discussion

Across the three studied ecosystems, palms and trees, and species native to Brazil had the highest survival during extreme floods. We found that more ethnospecies were lost in the low *várzea* after the extreme flooding event than in the other two ecosystems, and that the level of *alpha* agrobiodiversity did not recover two years after the extreme flood. *Alpha* diversity of manioc ethnovarieties was also reduced on the low *várzea* immediately after the flood, but it recovered after two years. The extreme flood also led to increases in *beta* diversity of ethnospecies across the communities.

Differential vulnerability of crops to extreme flooding

Our results are consistent with other studies. A previous study carried out in the *várzeas* and *paleovárzeas* of the Mamirauá and Amanã Sustainable Development Reserves also demonstrated the impact of the extreme floods of 1999 on agroecosystems, highlighting the mortality of avocado, banana, *cupuaçu*, lemon, orange, mango, guava, peach palm and *bacaba* (Schmidt 2003). Other studies in Amazonia reported that extreme floods destroyed several perennial crops and prevented a second harvest of short-cycle plants (Ohly 2020), strongly impacting crops in floodplain ecosystems (Louzada 2019). Extreme hydrological events have also contributed to the decrease in floristic diversity in other Amazonian agroecosystems (Jardim 2019, Silva and Noda 2016), with the low *várzea* being the most critically affected ecosystem (Rios and Matos 2017). In terms of crop agrobiodiversity, the high *várzea* contrasts with the low *várzea*. The shorter duration of the flood in the high *várzea* or even the fact that some areas are not flooded in normal years, allows native and exotic perennial plants intolerant to the floods to be managed, containing a diversity comparable to the *terra firme* (Schmidt 2003) or *paleovárzeas*.

We found that producers stopped managing some species and varieties relevant to food sovereignty, due to the greater recurrence of extreme floods, similar to *ribeirinhos* in regions such as Careiro da Várzea, close to Manaus (Amazonas, Brazil) (Abadias 2019, Pereira 2020). Our findings of the impacts of extreme flooding on manioc was like reported in other regions of Amazonia, where higher mortality and reduced productivity was found (Almeida *et al.* 2017, Abadias 2019). Reductions in banana, mango, and cocoa cultivation were also reported (Jardim 2019), with cocoa high mortality in the Madeira River (Simão 2017).

For Careiro da Várzea, the flood of 2009 was also severe, impacting more than 30 species, especially trees such as guava, *cupuaçú*, cashew, cocoa, and chiefly mango

(Nascimento 2017, Guimarães *et al.* 2019). In addition, in the same municipality coconut, avocado and papaya were affected (Jardim 2019) and the survival of palms and trees was perceived to be greater than that of other grow forms, where *buriti*, cashew, soursop, among others, were still present in the agroforestry homegardens (Jardim 2019). Our study in the middle Solimões River is consistent with these findings in the reduction of food species, especially trees for which the productive cycle is three or more years, such as avocado, since the trees take this period of time to start producing fruits and the *ribeirinhos* have no guarantees of harvest, consumption or sales (Ávila *et al.* 2021*a*).

Similar to what we observed in the middle Solimões River, other studies in Amazonia also describe variation in perceptions of the survival of ethnospecies to extreme climatic events (Lima, 1994, Schmidt 2003, Parolin *et al.* 2004, Delgado *et al.*, 2016, Jardim 2019). Near Manaus, local producers consider avocados, *ata*, and bananas to be “highly sensitive” to extreme flooding; guava, peach palm, papaya, *sapota*, *abiu*, and citrus are considered “sensitive”; *açaí-do-mato*, soursop, *cupuaçu*, and coconut have “intermediate” resistance, while *inga*, cocoa, cashew, *açaí-do-Pará*, and genipap have “good” resistance (Bahri 1993). However, trees that support only short periods of submersion can sometimes be considered of intermediate resistance, such as guava, *açaí*, genipap, and *ingá* (Bahri 1993).

In addition, plants subject to extreme flooding can be affected by higher environmental or water temperatures, intense sunlight, and the movement of root systems when trees are pushed by canoes, floating logs (Parolin *et al.* 2004, Delgado *et al.*, 2016, Jardim 2019, Ávila *et al.* 2021*b*), or by large boats creating waves close to the agroecosystems (Ávila *et al.* 2021*a*). In this sense, extreme floods have the potential to cause catastrophic tree mortality (Guimarães *et al.* 2019), including species that tend to survive common floods, such as cocoa (Simão 2017), coconut, and mango (Jardim 2019).

Characteristics of the plants affected

In order to restore their agroecosystems, *ribeirinhos* select plants that were easy to replant and manage in home gardens, raised beds, floating house planters or higher areas, until they could be transferred to the swidden, agroforest, or secondary forest (*capoeiras*) (Schmidt 2003, Nascimento 2017, Ávila *et al.* 2021*b*). In low *várzea* ecosystems, soil fertility contributes to faster plant development, favoring the recovery of *alpha* agrobiodiversity. For example, banana fruits within 8 months in *várzeas*, but it can take up to 12 months to fruit in the *paleovárzea* and on the *terra firme* (Schmidt 2003). In the case of manioc, although some ethnovarieties can be harvested by 6 months in the *várzea*, higher production is generally obtained when the roots remain in the soil for more months (Schmidt 2003).

Comparing our findings to other studies suggests that levels of species mortality due to extreme flooding depends on the locality. For example, *açaí-do-mato* (Bahri 1993, Abadias 2019) and cocoa (Simão 2017) were identified to have critical or intermediate survival in the face of extreme floods close to Manaus, but we found that in the middle Solimões River, these species had high resistance to extreme floods. Previous studies in the middle Solimões River region (Lima 1994, Schmidt 2003, Ávila *et al.* 2021*a*) and in Careiro da Várzea (Jardim 2019) emphasized that the survival of food plant species in the context of climate change is not solely determined by plant physiological or anatomical adaptations to floods. Indeed, some plants are unable to resist being completely covered by floods, especially seeds and young seedlings, as is the case with *açaí* and *ingá* (Schmidt 2003). In these cases, the exchange of gases in the leaves becomes unfeasible (Visser *et al.* 2003, Parolin *et al.* 2004), because flooding induces the closing of the stomata, thus reducing the rate of photosynthesis and carbon assimilation (Gonçalves *et al.* 2012), leading to death (Lopes and Piedade 2015) or total defoliation of plants (Maurenza *et al.* 2012).

We found that native species were more resistant to extreme flooding than introduced species. In other studies in Amazonia, the impacts of extreme floods on perennial plants were also more intense for non-native species, such as jambolans, lemons, and blackberry (Abadias 2019). It has been suggested that in Amazonia, climate change will lead to a replacement of species unable to adapt to hypoxic conditions, gradually altering the patterns of floristic composition and distribution of floodplain environments, which also affects crop production and human life that are dependent on these environments (Abadias 2019). In other regions of the world, the replacement of local species and varieties by non-native and improved varieties are reported (Brush 1980, Negri 2003, McGuigan *et al.* 2022). However, as many Brazilian native crops are resistant to extreme flooding, the species portfolio in the study area continues to be based on local ethnovarieties.

Only a small percentage of the *ribeirinhos* in this study cited the mortality of *camu-camu* in extreme floods. Mortality of this species was noted as unexpected in the Manaus region (Guimarães *et al.* 2019), since this is a wild species which occurs at low elevations and is known to have a high resistance to common floods. This finding highlights that the long period and intensity of extreme flooding can start to affect native species, including those locally recognized as showing high resistance to annual floods.

Effects of extreme flooding on *alpha* and *beta* agrobiodiversity

Ribeirinhos located in low-lying areas can feel less motivated to replant and recover their crops (Schmidt 2003). This is especially important in the context of climate change, as studies indicate that extreme flooding impacts intensify the vulnerability of people and agroecosystems to deal with the next disturbances (Thaman 2008, Krishnamurthy and Reddiar 2011, McGuigan *et al.* 2022).

Previous research has pointed out that *alpha* and *beta* diversity are reduced when there is a standardization of cultures (Labeyrie *et al.* 2021). We found that extreme flooding reduced *alpha* diversity, particularly for ethnospecies on the low *várzea*, which persisted for two years after the flood, as well as for ethnospecies on the high *várzea* and manioc ethnovarieties in the low *várzea,* which were immediately impacted. As consequence of the impacts on *alpha* diversity, the diversity between ecosystems (*beta* diversity) is also affected and does not recover immediately or two years after the flood. Research in Pacific Island agroecosystems showed that after an extreme cyclone, that also generated large floods, ethnospecies diversity was not affected, but the diversity of staple crop varieties was reduced and had not recovered two years post-cyclone (McGuigan *et al.* 2022). Our results suggest that major floods have a critical impact on the recovery of agroecosystems.

Conclusion

We evaluated local impacts of the 2015 extreme flooding event in the middle Solimões River basin, comparing the agrobiodiversity of crops and cultivars in three Amazonian ecosystems before, immediately after, and two years after the extreme flood of 2015. While agroecosystems managed by *ribeirinhos* in all three ecosystems were negatively affected, the greatest impacts were observed on the low *várzea,* and this was also the slowest to recover.

We found that *ribeirinhos* have deep knowledge of the plants that are adapted to the regular flood context, where 60 % of the ethnospecies managed on low *várzeas* and 47 % of the ethnospecies managed on *paleovárzeas* are at least somewhat resistant to floods. *Ribeirinho* knowledge also confirms that plants native to Brazil are able to better survive extreme flood scenarios. Nevertheless, extreme flooding due to climate change resulted in the loss of local ethnospecies and ethnovarieties, especially in low *várzeas*, and in all floodplain ecosystems, local communities emphasized the loss of food sovereignty and income from crop losses.

The intense consequences of extreme floods on local agrobiodiversity highlights the importance of recognizing and sharing local and governmental strategies that favor adaptive capacity to mitigate the effects of climate change in Amazonia. In view of the great impacts on *ribeirinho* agroecosystems, it also points to the importance of emergency plans and greater public governance to support *ribeirinhos* before, during and after local extreme events.

Appendix - Supplemental material Chapter 1

Table 1. Ethnospecies managed in the floodplain ecosystems of the middle Solimões River basin, with information about survival, post-flood management, grow form and origin in relation to Brazil. Plants in low *várzea* with asterisk (*) are exclusively managed on *terra-firme* (non-flood areas). The hyphen (-), according to the column, represent no English name, or absence of ethnospecie citations on the specific ecosystem.

Local name	English name	Scientific name	Botanical Family	Growth form	Survival (%) as reported in interviews			% of people that have the ethnospecies after flood			Origin in relation to Brazil
					Low *várzea*	High *várzea*	*Paleo várzea*	Low *várzea*	High *várzea*	*Paleo várzea*	
abacate	avocado	*Persea americana* Mill.	Lauraceae	tree	0,0	18,2	39,5	7,4	9,4	90,5	naturalized
abacaxi	pineapple	*Ananas comosus* (L.) Merril	Bromeliaceae	herb	42,9	100,0	50,0	14,8	31,3	78,6	native
abiu	-	*Pouteria caimito* (Ruiz & Pav.) Radlk.	Sapotaceae	shrub, tree	21,4	57,1	73,9	14,8	15,6	52,4	native
açaí	-	*Euterpe oleracea* Mart., *Euterpe precatoria* Mart.	Arecaceae	palm	69,6	55,0	66,7	74,1	59,4	92,9	native
acerola	-	*Malpighia emarginata* DC.	Malpighiaceae	tree	-	20,0	0,0	-	9,4	2,4	cultivated
apuruí	-	*Alibertia stipularis* (Ducke) W. Schultze-Motel	Rubiaceae	tree	100,0	80,0	87.5	7,4	56,3	14.3	native
araçá	strawberry guava	*Psidium acutangulum* DC, *Psidium* cf. *striatulum* Mart. ex DC, *Eugenia stipitata* McVaugh	Myrtaceae	shrub, tree	72,2	81,8	73,3	63,0	59,4	35,7	native
araçapéu	-	NI	-	tree	0,0	66,7	-	3,7	25,0	-	
arati	-	*Eugenia inundata* DC.	Myrtaceae	shrub, tree	-	87,5	100,0	-	25,0	2,4	native
araticum	-	*Annona montana* Macfad.	Annonaceae	tree	0,0	50,0	100,0	3,7	3,1	4,8	native
ariá	-	*Goeppertia allouia* (Aubl.) Borchs. & S. Suárez	Marantaceae	herb	0,0	100,0	81,8	0,0	6,3	26,2	native

Local name	English name	Scientific name	Botanical Family	Growth form	Survival (%) as reported in interviews			% of people that have the ethnospecies after flood			Origin in relation to Brazil
					Low *várzea*	High *várzea*	*Paleo várzea*	Low *várzea*	High *várzea*	*Paleo várzea*	
arroz	rice	*Oryza* sp.	Poaceae	herb	0,0	0,0	-	0,0	0,0	-	native
azeitona	jambolan	*Syzygium cumini* (L.) Skeels	Myrtaceae	tree	66,7	80,0	76,0	25,9	56,3	57,1	naturalized
bacaba	-	*Oenocarpus bacaba* Mart.	Arecaceae	palm	62,5	84,2	92,9	22,2	53,1	66,7	native
bacuri	-	*Garcinia brasiliensis* Mart., *Garcinia madruno* (Kunth) Hammel	Clusiaceae	shrub, tree	94,7	93,8	88,2	70,4	46,9	40,5	native
banana	banana	*Musa* spp.	Musaceae	herb	12,5	3,8	37,5	63,0	65,6	95,2	naturalized
batata-doce	sweet potato	*Ipomoea batatas* (L.) Lam.	Convolvulaceae	herb, vine	0,0	33,3	100,0	3,7	15,6	14,3	naturalized
biribá	-	*Rollinia* aff. *neoinsignis* H.Rainer, *Annona mucosa* Jacq.	Annonaceae	tree	42,9	100,0	60,0	11,1	9,4	40,5	native
buriti	-	*Mauritia flexuosa* L. f.	Arecaceae	palm	100,0	90,0	90,0	55,6	62,5	42,9	native
cacau	cacao	*Theobroma bicolor* Humb. & Bonpl., *Theobroma cacao* L. and *Theobroma obovatum* Klotzsch ex Bernoulli	Malvaceae	tree	60,0	81,8	64,7	74,1	62,5	35,7	native
cacauí	-	*Herrania mariae* (Mart.) Decne ex Goudot	Malvaceae	tree	-	83,3	-	-	34,4	-	native
café	coffee	*Coffea arabica* L.	Rubiaceae	shrub	0,0	-	0,0	0,0	-	0,0	naturalized
caju	cashew	*Anacardium occidentale* L.	Anacardiaceae	tree	16,7	27,8	73,0	18,5	31,3	88,1	native
camu-camu	-	*Myrciaria dubia* (Kunth) McVaugh	Myrtaceae	shrub, tree	100,0	95,0	100,0	14,8	59,4	4,8	native
cana	sugar cane	*Saccharum officinarum* L.	Poaceae	herb	0,0	4,8	50,0	14,8	56,3	71,4	cultivated

Local name	English name	Scientific name	Botanical Family	Growth form	Survival (%) as reported in interviews			% of people that have the ethnospecies after flood			Origin in relation to Brazil
					Low *várzea*	High *várzea*	*Paleo várzea*	Low *várzea*	High *várzea*	*Paleo várzea*	
cará	yam	*Dioscorea* aff. *bulbifera* L., *Dioscorea trifida* L.f.	Dioscoreaceae	vine	25,0	50,0	58,3	18,5	46,9	85,7	native, naturalized
carambola	star fruit	*Averrhoa carambola* L.	Oxalidaceae	tree	33,3	0,0	100,0	7,4	0,0	2,4	cultivated
cariru	-	*Talinum fruticosum* (L.) Juss	Talinaceae	herb	0,0	55,0	16,7	0,0	46,9	11,9	native
castanha-do-Brasil	Brazil nut	*Bertholletia excelsa* Bonpl.	Lecythidaceae	herb	100,0*	100,0	75,8	11,1	21,9	78,6	native
cebola-de-palha	chive	*Allium fistulosum* L.	Amaryllidaceae	herb	9,1	69,6	64,3	25,9	68,8	64,3	cultivated
chicória	chicory	*Eryngium foetidum* L.	Apiaceae	herb	11,8	33,3	17,9	44,4	18,8	57,1	native
coco	coconut	*Cocos nucifera* L.	Arecaceae	palm	81,8	28,6	31,8	37,0	31,3	45,2	naturalized
coentro	cilantro	*Coriandrum sativum* L.	Apiaceae	herb	0,0	100,0	50,0	0,0	6,3	9,5	cultivated
cominho	cumin	*Pectis elongata* Kunth	Asteraceae	herb, subshrub	-	66,7	-	-	18,8	-	native
couve	collard greens	*Brassica oleracea* L.	Brassicaceae	herb, subshrub	0,0	64,7	33,3	0,0	40,6	11,9	cultivated
cubiu	Orinoco apple	*Solanum sessiliflorum* Dunal	Solanaceae	shrub, subshrub	-	11,8	100,0	-	40,6	4,8	native
cupuaçú	-	*Theobroma grandiflorum* (Willd. ex Spreng) K. Schum. in Mart.	Malvaceae	tree	25,0	25,0	54,1	29,6	37,5	88,1	native
cupuí	-	*Theobroma subincanum* Mart.	Malvaceae	tree	-	85,7	80,0	-	18,8	11,9	native
feijão	beans	*Phaseolus vulgaris* L.	Fabaceae	subshrub	50,0	77,8	100,0	3,7	21,9	2,4	cultivated
fruta-pão	breadfruit	*Artocarpus* sp.	Moraceae	tree	61,5	78,9	100,0	44,4	53,1	4,8	naturalized
genipapo	genipap	*Genipa americana* L.	Rubiaceae	shrub, tree	100,0	95,0	75,0	59,3	59,4	9,5	native
gergelim	sesame	*Sesamum indicum* L.	Pedaliaceae	shrub, subshrub	-	0,0	100,0	-	6,3	2,4	naturalized
goiaba	guava	*Psidium guajava* L.	Myrtaceae	tree	9,5	73,9	77,1	51,9	68,8	83,3	naturalized

Local name	English name	Scientific name	Botanical Family	Growth form	Survival (%) as reported in interviews			% of people that have the ethnospecies after flood			Origin in relation to Brazil
					Low *várzea*	High *várzea*	*Paleo várzea*	Low *várzea*	High *várzea*	*Paleo várzea*	
graviola	soursop	*Annona muricata* L.	Annonaceae	shrub, tree	25,0	30,8	39,1	11,1	25,0	50,0	cultivated
ingá	-	*Inga* cf. *cinnamomea* Spruce ex Benth., *Inga edulis* Mart., *Inga macrophylla* Humb. & Bonpl. ex Willd.	Fabaceae	tree	47,4	33,3	39,3	59,3	43,8	64,3	native
jaca	jackfruit	*Artocarpus heterophyllus* Lam.	Moraceae	tree	0,0	22,2	100,0	0,0	12,5	4,8	naturalized
jambo	rose apple	*Syzygium malaccense* (L.) Merr. & L.M. Perry	Myrtaceae	tree	29,4	36,4	47,4	40,7	50,0	35,7	cultivated
jambu	-	*Acmella oleracea* (L.) R.K. Jansen	Asteraceae	herb	7,7	8,3	4,3	33,3	28,1	45,2	naturalized
jerimum	pumpkin	*Cucurbita* spp.	Cucurbitaceae	herb, vine	9,1	76,2	62,5	48,1	53,1	52,4	cultivated
laranja	orange	*Citrus sinensis* (L.) Osbeck	Rutaceae	shrub, tree	28,6	0,0	47,1	18,5	0,0	35,7	cultivated
lima	lime	*Citrus* spp.	Rutaceae	shrub, tree	33,3	0,0	-	3,7	0,0	-	naturalized
limão	lemon	*Citrus aurantiifolia (*Christm.) Swingle	Rutaceae	tree	14,3	0,0	50,0	37,0	6,3	66,7	cultivated
mamão	papaya	*Carica papaya* L.	Caricaceae	shrub, tree	0,0	4,5	43,3	22,2	59,4	64,3	naturalized
manga	mango	*Mangifera indica* L.	Anacardiaceae	tree	46,7	4,5	68,6	48,1	59,4	81,0	cultivated
mangarataia	ginger	*Zingiber officinale* Roscoe	Zingiberaceae	herb	-	50,0	100,0	-	6,3	2,4	cultivated
maracujá	passion fruit	*Passiflora edulis* Sims, *Passiflora nitida* Kunth, *Passiflora coccinea* Aubl.	Passifloraceae	vine	20,0	0,0	47,1	7,4	12,5	28,6	native
mari	-	*Poraqueiba sericea* Tul.	Metteniusaceae	tree	25,0	81,8	57,1	7,4	31,3	66,7	native
mari-mari	-	*Cassia leiandra* Benth.	Fabaceae	tree	100,0	62,5	66,7	3,7	15,6	7,1	native

Local name	English name	Scientific name	Botanical Family	Growth form	Survival (%) as reported in interviews			% of people that have the ethnospecies after flood			Origin in relation to Brazil
					Low *várzea*	High *várzea*	*Paleo várzea*	Low *várzea*	High *várzea*	*Paleo várzea*	
marirana	-	*Couepia* aff. *subcordata* Benth. ex hook.f.	Chrysobalanaceae	tree	78,6	70,6	100,0	48,1	40,6	2,4	native
maxixe	maroon cucumber	*Cucumis anguria* L.	Cucurbitaceae	vine	10,0	63,2	44,4	18,5	46,9	61,9	native
melancia	watermelon	*Citrullus lanatus* (Thunb.) Matsum. & Nakai	Cucurbitaceae	vine	30,4	95,0	83,3	51,9	62,5	28,6	cultivated
melão	melon	*Cucumis melo* L.	Cucurbitaceae	vine	0,0	94,7	-	0,0	59,4	-	cultivated
milho	maize	*Zea mays* L.	Poaceae	herb	50,0	95,2	87,5	51,9	62,5	38,1	cultivated
nones	noni	*Morinda citrifolia* L.	Rubiaceae	tree	-	100,0	42,9	-	3,1	9,5	cultivated
patauá	-	*Oenocarpus bataua* Mart.	Arecaceae	palm	-	100,0*	100,0	-	12,5	2,4	native
pepino	cucumber	*Cucumis sativus* L.	Cucurbitaceae	vine	-	54,5	66,7	-	21,9	4,8	cultivated
pimenta	pepper	*Capsicum* spp.	Solanaceae	shrub, subshrub	20,0	61,9	40,0	40,7	53,1	61,9	cultivated
pimentão	bell pepper	*Capsicum annuum* L.	Solanaceae	shrub	25,0	46,7	22,2	25,9	31,3	14,3	cultivated
piquiá	-	*Caryocar villosum* (Aubl.) Pers.	Caryocaraceae	tree	100,0*	87,5	93,1	3,7	21,9	69,0	native
pupunha	peach palm	*Bactris gasipaes* Kunth	Arecaceae	palm	0,0	80,0	54,5	3,7	25,0	76,2	native
quiabo	okra	*Abelmoschus esculentus* (L.) Moench	Malvaceae	shrub, subshrub	-	18,2	0,0	-	21,9	2,4	cultivated
rambutamo	rambutan	*Nephelium lappaceum* L.	Sapindaceae	tree	-	-	25,0	-	-	7,1	naturalized
salsinha	parsley	*Petroselinum crispum* (Mill.) Fuss	Apiaceae	herb	0,0	44,4	50,0	0,0	18,8	2,4	cultivated
sorva	-	*Couma utilis* (Mart.) Müll. Arg.	Apocynaceae	tree	-	100,0	81,0	-	21,9	47,6	native
taioba	-	*Xanthosoma* sp.	Araceae	herb	-	33,3	33,3	-	9,4	7,1	native
tangerina	tangerine	*Citrus* spp.	Rutaceae	shrub, tree	100,0*	0,0	33,3	3,7	6,3	14,3	naturalized
taperebá	hog plum	*Spondias mombin* L.	Anacardiaceae	herb	66,7	100,0	-	11,1	50,0	-	native

Local name	**English name**	**Scientific name**	**Botanical Family**	**Growth form**	**Survival (%) as reported in interviews**			**% of people that have the ethnospecies after flood**			**Origin in relation to Brazil**
					Low *várzea*	High *várzea*	*Paleo várzea*	Low *várzea*	High *várzea*	*Paleo várzea*	
tomate	tomato	*Solanum lycopersicum* L.	Solanaceae	shrub	0,0	62,5	0,0	3,7	37,5	4,8	cultivated
tucumã	-	*Astrocaryum aculeatum* G. Mey.	Arecaceae	palm	50,0	87,5	100,0	3,7	21,9	66,7	native
uixi	-	*Endopleura uchi* (Huber) Cuatrec.	Humiriaceae	tree	0,0	80,0	60,0	3,7	12,5	11,9	native
uixirana	-	*Vantanea parviflora* Lam.	Humiriaceae	tree	-	100,0	100,0	-	9,4	4,8	native
urucu	achiote	*Bixa orellana* L.	Bixaceae	shrub, tree	42,9	11,1	50,0	14,8	15,6	50,0	native

Table 2. Information about survival and post-flood management for each manioc ethnovariety managed in the ecosystems studied. The hyphen (-) represent absence of ethnovariety citations on a specific ecosystem.

Common name	**Survival (%), as reported in interviews**			**% of people that have the ethnovariety after flood**		
	Low *várzea*	High *várzea*	*Paleovárzea*	Low *várzea*	High *várzea*	*Paleovárzea*
macaxeira	33,3	-	100,0	3,7	-	2,4
macaxeira 4-meses	-	-	0,0	-	-	0,0
macaxeira açaí	-	36,4	-	-	28,1	-
macaxeira amarela (or macaixerão)	-	0,0	-	-	3,1	-
macaxeira aruanã	0,0	-	-	0,0		-
macaxeira branquinha	-	0,0	-	-	6,3	-
macaxeira Brasil (or gaivotinha)	-	100,0	-	-	3,1	-
macaxeira caboquinha	-	-	0,0	-	-	4,9
macaxeira cabral	-	28,6	-	-	18,8	-
macaxeira casca-branca	-	-	0,0	-	-	2,4
macaxeira casca-roxa	-	-	40,0	-	-	11,9
macaxeira geralda	-	0,0	-	-	0,0	-
macaxeira jurití	-	0,0	-	-	3,1	-
macaxeira macaxeirão	0,0	-	-	0,0	-	-
macaxeira manteiguinha	100,0	-	9,8	40,0	-	23,8
macaxeira marreção	-	0,0	-	-	3,1	-
macaxeira marrequinha	0,0	-	-	0,0	-	-
macaxeira mudumbi	0,0	-	75,0	0,0	-	9,5
macaxeira negão	-	-	100,0	-	-	2,4
macaxeira pagoa	-	-	50,0	-	-	4,8
macaxeira pão	30,4	38,9	44,4	63,0	50,0	64,3
macaxeira pão-do-chile	-	-	100,0	-	-	2,4
macaxeira pãozinha-nova	-	0,0	-	-	3,1	-
macaxeira peixe-boi	0,0	-	100,0	3,7	-	2,4
macaxeira peruana	-	-	50,0	-	-	4,9

Common name	Survival (%), as reported in interviews			% of people that have the ethnovariety after flood		
	Low *várzea*	High *várzea*	*Paleovárzea*	Low *várzea*	High *várzea*	*Paleovárzea*
macaxeira preta	0,0	22,2	0,0	3,7	21,9	2,4
macaxeira rio-de-janeiro	0,0	-	-	0,0	-	-
macaxeira roxa	-	-	30,0	-	-	23,8
macaxeira tambaqui	-	-	66,7	-	-	4,9
macaxeira vinagre	-	100,0	-	-	3,1	-
mandioca	33,3	100,0	-	7,4	3,1	-
mandioca 4-meses	-	40,0	100,0	-	15,6	2,4
mandioca 6-meses	100,0	100,0	-	3,7	3,1	-
mandioca 7-anos	-	-	26,7	-	-	35,7
mandioca açaizinha	-	-	0,0	-	-	0,0
mandioca amarela	-	40,0	-	-	15,6	-
mandioca angelina	-	-	66,7	-	-	7,1
mandioca antinha	50,0	0,0	-	7,4	0,0	-
mandioca ará	100,0	-	-	7,4	-	-
mandioca baiana	71,4	100,0	-	22,2	3,1	-
mandioca baixotinha	71,4	0,0	22,2	18,5	9,4	33,3
mandioca caboquinha	-	-	0,0	-	-	2,4
mandioca calaí	-	-	33,3	-	-	2,4
mandioca capura	-	0,0	-	-	0,0	-
mandioca catombo	33,3	36,4	23,1	37,0	28,1	92,9
mandioca coco	-	-	0,0	-	-	2,4
mandioca erninha	-	0,0	-	-	3,1	-
mandioca eva	-	-	0,0	-	-	2,4
mandioca geralda	-	11,1	50,0	-	25,0	2,4
mandioca hástia	-	50,0	-	-	3,1	-
mandioca joão-gonçalo	66,7	50,0	20,0	7,4	6,3	2,4
mandioca leoncio	-	-	57,1	-	-	11,9

Common name	**Survival (%), as reported in interviews**			**% of people that have the ethnovariety after flood**		
	Low *várzea*	High *várzea*	*Paleovárzea*	Low *várzea*	High *várzea*	*Paleovárzea*
mandioca lisa	100,0	-	-	7,4	-	-
mandioca manivão	50,0	37,5	-	3,7	25,0	-
mandioca marrecão	-	0,0	-	-	3,1	-
mandioca negão	-	-	100,0	-	-	2,4
mandioca ourinho	-	21,4	-	-	37,5	-
mandioca pacú	-	0,0	-	-	9,4	-
mandioca pacuzinha	-	0,0	-	-	0,0	-
mandioca pagoa	0,0	0,0	0,0	0,0	3,1	0,0
mandioca peixe-boi	0,0	-	-	3,7	-	-
mandioca pele	-	0,0	-	-	9,4	-
mandioca peruana	-	0,0	-	-	0,0	-
mandioca piramiri	-	-	100,0	-	-	2,4
mandioca pretona	-	16,7	0,0	-	34,4	0,0
mandioca sacaí	100,0	25,0	37,5	3,7	6,3	16,7
mandioca semente	-	50,0	-	-	3,1	-
mandioca tapaiona	-	-	0,0	-	-	2,4
mandioca tartaruga	-	-	50,0	-	-	7,1
mandioca uiraninha	-	50,0	-	-	3,1	-
mandioca valdivina	31,3	57,1	-	29,6	21,9	-
mandioca vila-nova	-	100,0	-	-	3,1	-

Table 3. Perception of how ethnospecies are affected by extreme floods in *várzeas*. Scientific names in Table 1.

Common name	Dies with a simple wetting	Dies if it moves roots	Dies if it heats up root	Dies if it gets wet too deep	Dies if it gets wet for too long	Dies if the plant drowns (completely cover the plant)	Flood resistant
abacate	x						
abacaxi	x						
abiu		x	x			x	
açaí		x	x				
apuruí							x
araçá		x	x				
araçapéu		x	x				
araticum		x	x	x			
ariá						x	
arroz							x
azeitona							x
bacaba							x
bacuri							x
banana	x						
batata	x						
biribá		x	x				
buriti							x
cacau			x				
café	x						
caju			x	x	x		
camu-camu					x		
cana				x	x		
cará	x						
carambola							x
cariru	x						
castanha-do-Brasil						x	
cebola-de-palha	x						

Common name	Dies with a simple wetting	Dies if it moves roots	Dies if it heats up root	Dies if it gets wet too deep	Dies if it gets wet for too long	Dies if the plant drowns (completely cover the plant)	Flood resistant
chicória	x						
coco		x					
coentro	x						
couve	x						
cupuaçú		x					
feijão	x						
fruta-pão							x
goiaba		x					
graviola	x						
ingá							x
jaca		x	x			x	
jambo						x	
jambú	x						
jenipapo							x
jerimum	x						
laranja		x					
lima				x	x		
limão				x	x		
macaxeira	x						
mamão	x						
mandioca	x						
manga		x				x	
maracujá	x						
mari							
mari-mari						x	
marirana					x	x	
maxixe	x						
melancia	x						
melão	x						
milho	x						
pimenta	x						

Common name	Dies with a simple wetting	Dies if it moves roots	Dies if it heats up root	Dies if it gets wet too deep	Dies if it gets wet for too long	Dies if the plant drowns (completely cover the plant)	Flood resistant
pimentão	x						
piquiá							
pupunha			x			x	
salsinha	x						
tangerina				x	x		
taperebá							x
tomate	x						
tucumã							
uixi							
urucu	x						

Table 4. Perception of how ethnospecies are affected by extreme floods in *paleovárzea*. Scientific names in Table 1.

Common name	Dies with a simple wetting	Dies if it gets deep wet	Dies if you cover the plant	Flood resistant
abacate	x			
abacaxi	x			
abiu		x	x	
açaí			x	
acerola	x			
araçá				x
arati				x
apuruí			x	
azeitona			x	
bacaba				x
bacuri				x
banana	x			
batata	x			
biribá	x			
buriti				x
cacau			x	
café				x
caju			x	
camu-camu				x
cana	x			
cará	x			
carambola	x			
cariru	x			
castanha-do-Brasil		x		
cebola-de-palha	x			
chicória	x			
coco			x	
coentro	x			
couve	x			
cubiu	x			
cupuaçú		x		
cupuí		x		
feijão	x			
Fruta-pão			x	
gergelim	x			

Common name	Dies with a simple wetting	Dies if it gets deep wet	Dies if you cover the plant	Flood resistant
goiaba				x
graviola			x	
ingá	x			
jaca	x			
jambo	x			
jambú	x			
jenipapo				x
jerimum	x			
laranja		x		
lima		x		
limão		x		
mamão	x			
mandioca	x			
manga			x	
maracujá	x			
mari	x			
mari-mari				x
marirana				x
maxixe	x			
melancia	x			
melão	x			
milho	x			
nones			x	
patauá			x	
pepino	x			
pimenta	x			
pimentão	x			
piquiá			x	
pupunha	x			
quiabo	x			
rambutamo	x			
salsinha	x			
sorva			x	
taioba	x			
tangerina		x		
taperebá				x
tomate	x			

Common name	Dies with a simple wetting	Dies if it gets deep wet	Dies if you cover the plant	Flood resistant
tucumã			x	
uixi		x		
uixirana				x
urucu	x			

Table 5. Ethnospecies with greater perceived susceptibility (all or most plants died) or resistant to extreme flooding according to *ribeirinhos* of three different floodplain ecosystems in the middle Solimões River basin, Amazonas, Brazil. Scientific names in Table 1.

	Susceptible	**Resistant**	**Largest reduction in the cultivation/management after flood**
Low *várzea*	banana, chicory, *cupuaçu*, guava, *jambu*, lemon, manioc, papaya, pumpkin/squash, rose apple and watermelon	*açaí-do-mato*, *bacuri*, *buriti*, cocoa, coconut, genipap, *ingá*, *marirana* and strawberry guava	*abiu*, banana, *cupuaçu*, guava, lemon, orange, papaya, pumpkin/squash, sugarcane and watermelon
High *várzea*	banana, cashew, *cubiu*, *cupuaçu*, *ingá*, *jambu*, mango, manioc, papaya, passion fruit and sugarcane	*buriti*, *camu-camu*, cocoa, genipap, guava, strawberry guava and *taperebá*	*acerola*, banana, bell pepper, cashew, *cariru*, jackfruit, passion fruit, rose apple and soursop
Paleovárzea	banana, chicory, coconut, *cupuaçu*, *ingá*, *jambu*, manioc, papaya, pepper, pineapple and sugarcane	*açaí-do-mato*, *bacaba*, cashew, guava, mango and *tucumã*	*biribá*, chicory, coconut, coffee, *jambu*, passion fruit, papaya, pepper, rose apple and sugarcane

Table 6. Ethnospecies that were perceived to be most affected by the extreme flood in 2015 (80-100 % of the ribeirinhos reported losses during semi-structured interviews) in low *várzea*, high *várzea* and *paleovárzea* agroecosystems in the middle Solimões River basin, Amazonas, Brazil.

% loss	**100%**	**99-90%**	**89-80%**
Low *várzea*	avocado, *araça-péu*, *araticum*, *ariá*, coffee, *cariru*, chive, cilantro, collard greens, jackfruit, melon, papaya, parsley, peach palm, rice, sugar cane, sweet potato, tomato, uixi	guava, *jambu*, maize, maroon cucumber, pumpkin	banana, *caju*, chicory, lemon, passion fruit, pepper
High *várzea*	lemon, lime, orange passion fruit, star fruit, sesame, rice, tangerine	banana, *jambu*, mango, papaya, sugar cane	*acerola*, achiote, avocado, *cubiu*, okra
Paleovárzea	*acerola*, coffee, okra, tomato	*jambu*	*cariru*, chicory

Table 7. Species not replanted during the two years after the extreme flood of 2015 in each of the ecosystems studied in the Solimões River basin, Amazonas, Brazil. The grow forms were classified according to the *Flora do Brasil* (2021).

Low *várzea*		High *várzea*		*Paleovárzea*	
Common name	Growth form	Common name	Growth form	Common name	Growth form
ariá	herb	lime	tree	coffee	shrub
carirú	herb	orange	tree		
cilantro	herb	rice	herb		
coffee	shrub	star fruit	tree		
collard greens	herb				
jackfruit	tree				
melon	vine				
parsley	herb				
rice	herb				

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Chapter 2

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Chapter 2: Adaptive management strategies of local communities in two Amazonian floodplain ecosystems in the face of extreme climate events

Abstract

In Amazonia, changes in the frequency and intensity of extreme climate events are occurring and expected to intensify, affecting food security with subsequent social and political problems. We conducted semi-structured interviews in *ribeirinhos* communities of the mid-Solimões River basin (Amazonas, Brazil). Our questions were designed to construct seasonal calendars with residents to understand climatic patterns and changes in livelihood activities, how traditional management is affected by extreme floods and droughts, and to identify their adaptation strategies in new climatic contexts. We studied three floodplain (*várzea*, n = 59 households) and three paleo-floodplain communities, situated 1-3 m higher than the floodplain (*paleovárzea*, n = 42 households). We show that these communities have detailed knowledge of climate patterns and changes, and that they recognize that climatic unpredictability hinders effective planning of subsistence activities, because their local knowledge is no longer fully reliable. Extreme climate events have consequences for their farming systems and associated agrobiodiversity, varying according to the degree of exposure of different environments to extreme events. During extreme events *ribeirinhos* intensify adaptation strategies, such as avoiding stress to fruit-tree root systems, prioritizing plants that survive flooding and working in less affected landscapes. Adaptation practices with long histories tend to occur more often in floodplains, and two adaptation practices were specific to floodplains. The impacts of extreme events on local communities are expected to increase, especially in environments more exposed to floods. Local residents suggest the documentation and sharing of adaptation strategies as a way to increase their resilience.

Keywords: Amazonian floodplains, extreme flood events, paleo-floodplains, riverine communities.

Introduction

Throughout human history, adaptive strategies have provided resilience for local communities in the face of changes (Berkes 2007; Folke *et al.* 2010), including those related to climate (Janssen and Ostrom 2006; Smit and Wandel 2006). Such strategies are based on local ecological knowledge (LEK), which includes culturally transmitted understandings, practices and beliefs concerning the relationships between living beings and the environment, and which evolves as societies adapt (Berkes *et al.* 2000). In Amazonia, where thousands of local communities are rural riverine-dwellers (*ribeirinhos*) (Adams *et al.* 2009; Costa and Inhetvin 2013), LEK is maintained, reproduced and transformed (Balée 2015). *Ribeirinho* communities depend mostly on the management of local natural resources for their survival, including legacy resources left by past communities (Arroyo-Kalin 2016; Levis *et al.* 2018). In the current climate change scenario, these communities are being impacted in different ways, particularly by more frequent and intense river floods and droughts (Cai *et al.* 2014; Marengo *et al.* 2013). In this study, we seek to identify new or reframed adaptive strategies practiced by the *ribeirinhos* that contribute to the maintenance of their livelihoods.

In Amazonia, non-flooded (and much better known) *terra firme* forests cover about 70 % of the region, but 30 % of the basin is flooded during part of the year (Junk *et al.* 2011b). Around 20 % of the population of Amazonia live in these seasonally-flooded areas (Junk *et al.* 2011a). The *várzea* (recently-formed whitewater river floodplains) covers 9 % of the region, the *paleovárzea* (ancient whitewater river floodplains) covers 1 % (Irion *et al.* 2010), and other seasonally-flooded areas cover 20 % of the region (Junk 1993). *Várzeas* are floodplains formed from nutrient-rich sediments derived from the Andes and deposited in Amazonian lowlands during the Holocene (Junk 1989). They are flooded in regular annual cycles, and some areas can be inundated for up to six months (Junk 1989).

In these ecosystems, which are largely flat, subtle changes in elevation may represent large differences in flood duration that create environmental gradients (Denevan 1984; Hiraoka 1985). When floods are extensive, higher *várzea* areas may be covered by 1-2.5 m of floodwaters for 2-4 months. In contrast, lower-lying *várzea* areas are inundated annually with waters 3-5 m deep for about 4-6 months, even during normal flood years (Ayres 2006). *Paleovárzeas* originated in the Late Pleistocene, formed during the last interglacial period (125-75 thousand years ago), when sea levels were 15-20 m higher than today (Irion *et al.* 2010). Thus, *paleovárzeas* have higher elevation than *várzeas,* although this difference tends to diminish with increasing distance from the current coastline (Irion *et al.* 2010). Lower-lying *paleovárzeas*, such as those in our study site, are usually only 1-3 m higher than the current high *várzeas*. Consequently, they suffer occasional flooding in years with large floods, but are not flooded annually, like *várzeas* are.

The annual flood pulse of large rivers in Amazonia is caused by the seasonal variation of precipitation in their drainage basins (Junk 1989; Schöngart and Junk 2007), which is currently being influenced by climate change. One of the main documented changes is the greater intensity and frequency of extreme floods (Marengo *et al.* 2013), which mainly impact low-lying areas along rivers. Extreme droughts are also recorded and affect not only river dynamics, but also *terra firme* areas (Funatsu *et al.* 2019; Pinho *et al.* 2015). The occurrence of these extreme events has been linked to phenomena such as El Niño (extreme droughts) and La Niña (extreme floods) (Schöngart and Junk 2007), and have profound impacts in Amazonian socio-ecological systems (Barichivich *et al.* 2018; Marengo *et al.* 2011).

The extent to which local communities are impacted by these extreme events depends on their adaptive capacity, or the set of preconditions that allow individuals or groups to respond to changes (Olsson and Folke 2001). Local adaptive capacity focuses on the local context (Rout *et al.* 2020), and includes both intentional and unintended choices (Athayde and Silva-Lugo 2018). LEK is the basis of adaptive strategies that allow local communities to manage resources in the face of the natural variability of ecosystems, as well as in interpreting and responding to feedbacks from the environment (Berkes *et al.* 2000; Gómez-Baggethun and Reyes-García 2013; McMillen *et al.* 2017; Schlingmann *et al.* 2021). For example, to avoid hailstorms in the Mexican highlands, producers intensify late sowing (Arredondo *et al.* 2020), and in Malawi farmers increase crop and livestock diversification to adapt to climatic uncertainty (Nkomwa *et al.* 2014).

Historically, the repertoire of LEK in Amazonia has included practices associated with landscape domestication (Arroyo-Kalin 2016; Clement and Cassino 2018). Legacies of past landscape domestication often persist through time and are often used, managed and transformed by current local communities (Arroyo-Kalin 2016; Clement and Cassino 2018). Examples of domesticated landscapes in Amazonia include artificial islands and terraces built on flooded areas, Amazonian Dark Earths (ADE - dark-colored soils, formed because of the concentration of organic refuse), enhanced densities of useful species (Arroyo-Kalin 2016; Levis *et al.* 2017), and management practices that lead to plant domestication and to the creation and maintenance of agrobiodiversity (Clement 1999; Levis *et al.* 2018).

Given the ongoing changes in climate and its cascading effects in multiple elements of local socio-ecological systems, local communities are also changing the way as they use and manage resources, including how legacies of past landscape domestication are used, transformed and maintained for future use (Arroyo-Kalin 2016; Clement and Cassino 2018). Assessing how management practices are maintained or adapted can enhance the understanding of the socioecological impacts and consequences of climate change, particularly in environments that are more directly exposed to the effects of climate change, such as floodplains. Hence, our study had the following objectives: 1) to characterize climate patterns and to identify changes in climate and in livelihood activities in two Amazonian floodplain ecosystems (*várzeas* and *paleovárzeas*); 2) to identify how local communities and their management activities are affected by extreme climatic events; and 3) to identify adaptive management strategies for these new climatic contexts.

Methodology

Study area

We conducted this study in six *ribeirinho* communities (three in *várzea* and three in *paleovárzea*) in the mid-Solimões River basin, Amazonas State, Brazil (Figure 8). *Ribeirinhos* are inhabitants of communities located along the banks of rivers and lakes, and who organize their life and work routines according to the seasonal variation of water levels (CNPCT 2016). They emerged as a social group in the aftermath of Portuguese colonialism and the rubber era, and descend from diverse groups, including Indigenous, African and European peoples (Adams *et al.* 2009; Harris 2000; Lima Ayres 1992). *Ribeirinho* communities produce food that supplies the smaller interior towns in the region and many large Amazonian cities (such as Iquitos, Leticia, Manaus, Santarém, Belém and Macapá).

The *várzea* communities included in this study are located within the Mamirauá Sustainable Development Reserve (RDSM), which has a total area of 1,124,000 hectares of periodically-flooded forests and about 11,000 inhabitants, distributed among 204 communities (IDSM 2019) inhabited by *ribeirinhos* and Indigenous groups (Cocama, Ticuna, Miranha and Omágua) (Alencar 2010). *Paleovárzea* communities are located in the Amanã Sustainable Development Reserve (RDSA), which has an area of 2,350,000 hectares (Queiroz 2005), including areas of *várzea*, *terra firme* (Ayres 2006) and *paleovárzea* (Irion *et al.* 2010). The RDSA is inhabited by *ribeirinhos* and Indigenous groups (Miranha and Mura) with a total of 5,458 people distributed in 133 communities (SEMMA 2019). Both in the RDSM and in the RDSA, the main economic activities practiced by local communities are small-scale farming and fishing (Peralta and Lima 2014; SEMMA 2019; Queiroz 2005).

According to the Köppen-Geiger system, the region's climate is classified as tropical rainforest (Af) (Peel *et al.* 2007), with monthly rainfall exceeding 100 mm throughout the year (National Water Agency 2021), and an average annual rainfall of 2,200 mm (Ayres 2006). The annual average temperature is 24-26 °C (INPE 2007). In ´winter´ (i.e., the rainy season, lasting from December to June), the mean daily temperature ranges between 19 and 32 ºC and the sky is overcast for 86 % of the time. In May it rains on average 306 mm (National Water Agency 2021), and the river is at its highest level, reaching up to 38.5 m a.s.l. (Ramalho *et al.* 2010). In ´summer´ (i.e., the dry season, lasting from July to November), the temperature ranges between 20 and 33 ºC, the sky is overcast 14 % of the time. August receives an average of 136 mm of rain (National Water Agency 2021) and the river water is at its lowest level, decreasing to 21.7 m a.s.l. (Ramalho *et al.* 2010). During ´normal´ years, the level of the Solimões River in the study region varies by an average of 10.6 m between the minimum and maximum levels (Ramalho *et al.* 2010) and, when flooding is more severe, this might reach 15 to 17 meters (Ayres 2006; Ramalho *et al.* 2010).

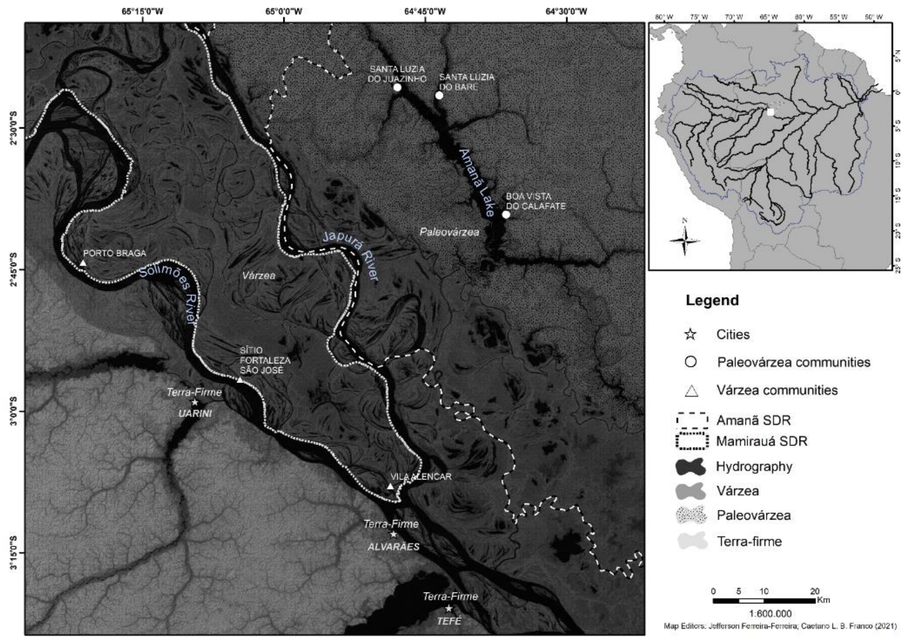

Figure 8. Map of the study area, showing the várzea and paleovárzea communities where this study was conducted. Tefé, Alvarães and Uarini are urban centers.

During annual floods, the areas of *várzea,* where *ribeirinhos* live and cultivate, is often covered by water for at least 1 to 2 months (Steward *et al.* in press). *Paleovárzea* communities rarely have their houses and cultivation areas flooded, except during extreme floods. During extreme floods, most cultivation areas located on the higher *várzea* are covered by water, while in the *paleovárzea* only some cultivation areas are affected by extreme flooding.

Studied communities

The communities who participated in this study settled in the area mainly in the 1940s and 1950s (Alencar 2010). Santa Luzia do Juazinho is the most recently established community, settled a little over 30 years ago, and Porto Braga is oldest, settled in the early 20^{th} century. The three *várzea* communities, Vila Alencar, Sítio Fortaleza and Porto Braga, were composed of 13, 14 and

33 families, respectively. Among these, the Porto Braga community is the least affected by water level changes, being located in a higher *várzea* area. The three *paleovárzea* communities, Santa Luzia do Juazinho, Bom Jesus do Calafate and Santa Luzia do Baré, were composed of 23, 15 and 6 families, respectively (SIMDE 2018).

Agricultural production in the Central Amazon region is based on swidden cultivation, combining the cultivation of manioc (*Manihot esculenta* Crantz) in small fields with the cultivation of squash (*Cucurbita* spp.), beans (*Phaseolus vulgaris* L.), banana (*Musa* spp.), watermelon (*Citrullus lanatus* (Thunb.) Matsum and Nakai), as well as a number of native and exotic fruit trees managed in communal areas, homegardens and secondary forests (Rognant and Steward 2015). Intra and interspecific agrobiodiversity is the most prominent legacy in these communities, present in homegardens, swiddens, agroforests and secondary forests of all families, as well as in forests managed around the communities. In the *paleovárzea*, swidden cultivation occurs mainly in the higher areas, where long-maturing manioc varieties and more perennial species can be grown with little exposure to flooding. In the *várzea*, the low-lying *várzea* is cultivated with short-cycle crops, while the higher *várzea*s tend to be cultivated with more perennial crops that tolerate flooding to a certain degree. Table 8 of the supplementary material characterizes and compares in detail the cultivation systems and manioc varieties grown in these two environments.

Data collection and analysis

Fieldwork was carried out between August 2017 and May 2019 and included different methods for data collection: participant observation, semi-structured interviews and workshops with local residents. Following Bernard (2011), participant observation involved extended visits to selected communities (15-20 days) to understand how families organize resource management and production in a variety of regional contexts. In the context of this research, I participated in the manioc swidden management, production of manioc flours, production of *açaí* and *bacaba* wine and production of regional handicrafts. Events, observations and perceptions were written in a field diary, following Albuquerque *et al.* (2014).

Semi-structured interviews were designed to build a baseline of climatic conditions and of seasonal activities, to record the perceived changes in climatic conditions, and to document changes in resource management practices (particularly those related with plant cultivation and management) in response to extreme climatic events in two ecosystems: *várzea* and *paleovárzea*.

Semi-structured interviews also included some basic questions on socio-economic characteristics of the respondents, such as age, level of formal education and main sources of monetary income. We interviewed one household head per family, until all families of a community were sampled. Who was interviewed varied according to the availability of the heads of the family, with a total of 59 residents from the *várzea* (68 % female, 32 % male) and 42 from the *paleovárzea* communities (33 % female, 67 % male). The age of the respondents varied from 18 to 94 years. More details about interviewees are available in Table 9 of the Supplementary Material.

To build a baseline to assess changes, we created seasonal calendars with each family during the semi-structured interviews. We asked respondents to describe the ´normal´ seasonal variation in rainfall, temperature and river level, to indicate the time of the year when specific weather events are expected (e.g., cold spells), and to indicate the timing of different plant cultivation and management activities in relation to this seasonal calendar. Subsequently, we invited respondents to describe their own perceptions of climate change and the effects of these changes – particularly those related with extreme events - on plant cultivation and management. Specifically, we asked respondents the following questions: what signs are used to predict weather conditions, and do these signs still work? What has changed in plant cultivation and management over time, and why? What years experienced extreme events? How do extreme events influence livelihoods? What do households do in response to extreme events?

Following the semi-structured interviews, we held workshops with participants, with the goal of discussing, complementing and validating the information obtained in the individual interviews. We conducted one workshop per community, and these were attended by approximately 20 people. During these events, we created a space for community members to learn about events observed in other communities and ecosystems and discuss the different points of view.

Data was analyzed qualitatively, focusing on the perceived changes in climate (particularly regarding the occurrence of extreme events), on the impacts of these changes in local livelihoods and on the adaptation strategies that were more frequently mentioned in the semi-structured interviews and collectively validated in the workshops. Additionally, we compiled a list of the indicators that are used to predict weather conditions and indicated their current accuracy based on local perceptions. We also discuss the contrasts and similarities between *várzea* and *paleovárzea* regarding the baseline conditions, the perceived changes and adaptations mentioned by local residents. Finally, we summarize the adaptation practices to extreme events reported by residents from *várzea* and *paleovárzea*, and we classify the adaptations into categories of management practices historically used by Amazonian populations, as defined by Levis *et al.* (2018).

This research was approved by the Human Research Ethics Committee of the Mamirauá Institute (CEP) (authorization number: 2.964.758) and registered in the National System for the Management of Genetic Heritage and Traditional Knowledge (CGEN) (A494ADE). We obtained free, prior and informed consent from all community representatives and individuals interviewed. Authorization from the Biodiversity and Information System (SISBIO) (65374-1) was also obtained.

Results

Local understanding of climatic patterns and changes

Ribeirinhos in both *várzea* and *paleovárzea* ecosystems recognize two seasons: winter (the second half of December to the first half of June), with milder temperatures due to the greater presence of clouds and greater rainfall, and rising river water levels; and summer (the second half of June to the first half of December), with high temperatures due to fewer clouds and less rainfall and receding river water levels (Figure 9a,b). All cultivation activities are finely tuned to these seasonal fluctuations in rainfall and in river water levels. Both *várzea* and *paleovárzea ribeirinhos* also recognize the existence of a short dry period of about 2 weeks that occurs during the winter (usually between February and March), called "*Mari* summer". In the *paleovárzea, ribeirinhos* use this period to conduct some activities normally performed in the summer (clearing, burning/re-burning or planting manioc, squash, corn and watermelon). *Ribeirinhos* from *várzea* communities, in contrast, do not carry out specific agricultural practices during the *Mari* summer, since they say that if they plant crops during this time, there would not be enough time for them to mature before their cultivation areas are flooded.

a)

b)

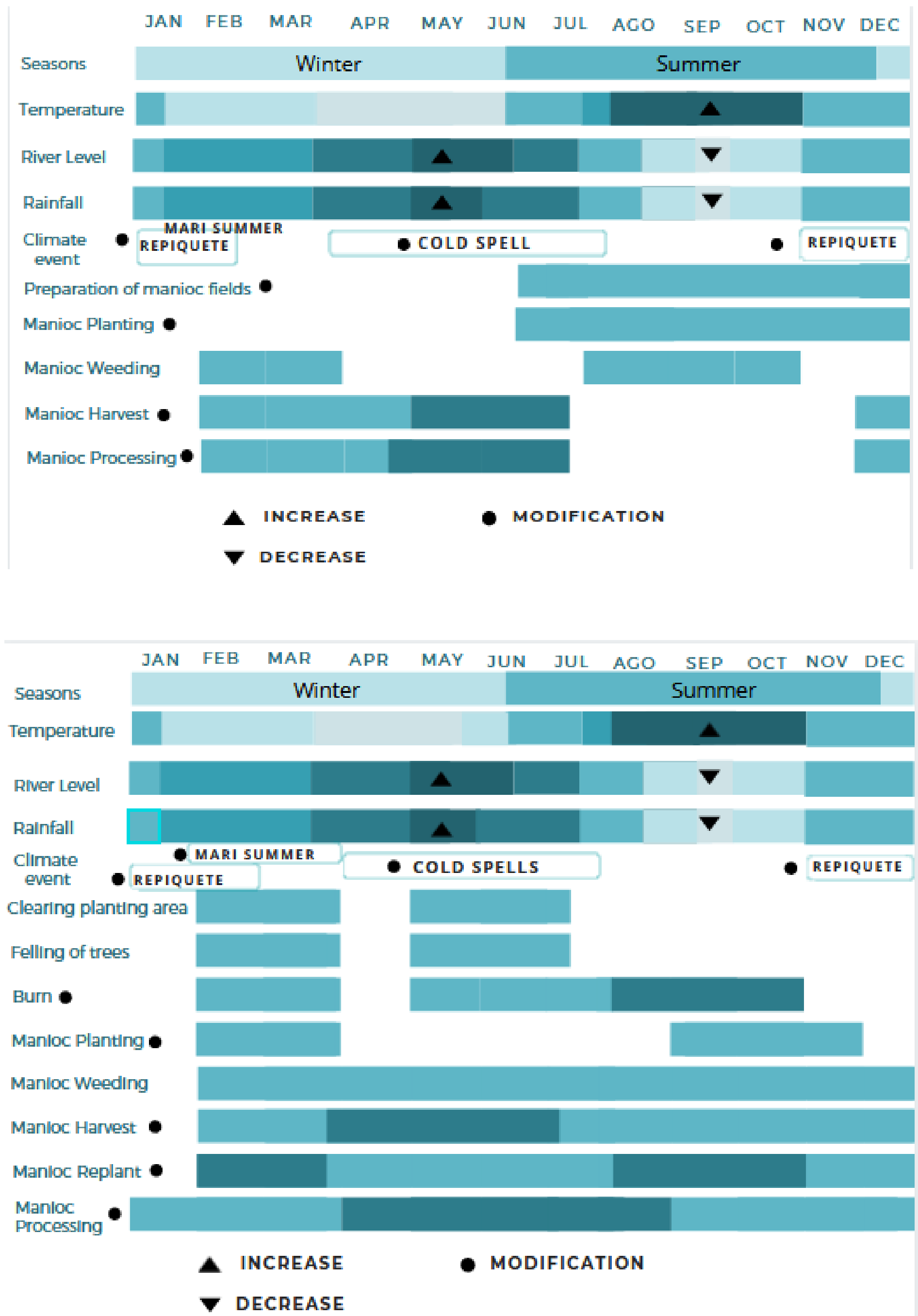

Figure 9. Seasonal calendar of climatic cycles and cultivation activities in ribeirinho communities located on (a) várzea and (b) paleovárzea in the middle Solimões River. Annual rise or ebb of the water level in rivers, lakes and streams occurs gradually. During repiquetes this gradual change is interrupted by more abrupt changes in the opposite direction. *Mari summer* is a short dry period of about two weeks that occurs during the winter. Darker colors indicate higher temperatures, river water level, amount of rainfall or intensity of cultivation activity. Arrows indicate changes in temperature, river level and rainfall reported by local residents. Dark circles indicate reported changes in climatic events (cold spells, Mari summer, *repiquetes*) or in cultivation practices (e.g., harvesting, planting).

In both ecosystems, *ribeirinhos* mentioned that the annual rise or ebb of the water level in rivers, lakes and streams occurs gradually, but this gradual change sometimes is interrupted by more abrupt changes in the opposite direction. These events are called *repiquetes*, and naturally occur between November and January (Figure 9a,b). For many *ribeirinhos*, the absence of *repiquetes* is an important indicator of future flooding levels. Specifically, residents report that if three *repiquetes* do not occur between the end of summer and the beginning of winter, there is a larger possibility of extreme flooding.

Extreme floods are recognized by *ribeirinhos* as those when the water from rivers/lakes rises excessively and comes very close to or enters their homes. Extreme droughts are identified by a pronounced decrease in the water level, so that certain streams or stretches of rivers/lakes dry out and become difficult to access by canoe. According to *ribeirinhos*, extreme floods previously occurred at intervals of about 10 years, with events reported for 1990, 1999 and 2009. However, this frequency has increased substantially, with four large floods reported between 2009 and 2019 (2009, 2012, 2015 and 2019). The largest floods locally remembered occurred in 1953 and 2015, with the particularity that in 2015 the flood started 2 months earlier than expected. Extreme droughts (which previously also occurred at longer intervals) were identified in 1999, 2006, 2009, 2012 and 2016, with 2009 being the most severe drought interviewees remembered. Several residents pointed out that some extreme floods are followed or preceded by an extreme drought (as in the years 1999, 2009, 2012, 2015, 2016) (see timeline in Supplementary material Figure 10). Memories of extreme events coincide with river level data from hydrological stations near the study area (see Supplementary Material Figure 10).

Besides these changes in the frequency of extreme floods and droughts, the *ribeirinhos* also reported other changes in climatic cycles, particularly an increase in temperatures and in the amount of rainfall during summer, as well as an overall understanding that summer rains have become more unpredictable with time. The *Mari* summer, they say, is starting late and its alterations have generated delays in swidden cycles. According to interviewees, rains are more torrential and unpredictable in the summer and less rain is occurring during some winters than it did in the past. The cold spells, which are times when the air temperature decreases and winds rise, are associated with polar air masses that expand along the Andes (Bueno *et al.* 2019, Junk and Krambeck 2000), with 1 to 3 days of strong winds, accompanied by a drop in temperature below 20 °C (Junk and Krambeck 2000). However, cold spells are reported to have become less intense or shorter than before. The *ribeirinhos* also mentioned changes in the occurrence of *repiquetes*, which have become absent in some years of large floods.

Ribeirinhos identify several "indicators" that help them to predict future weather conditions and river water levels, which are observed in many different ways, such as the behavior of animals, plants and in the dynamics of the river waters themselves (Supplementary Material Table 10). With the increased occurrence of extreme events, *ribeirinhos* are in the process of adapting their knowledge and practices to new climatic contexts. Today, several local indicators used to predict seasonal cycles are no longer reliable, as they say that rainfall and river level fluctuation patterns are now much more unpredictable. Nevertheless, some indicators are still considered reliable, such as the absence of *repiquetes* and the unusually high fruit production of some trees, especially camu-camu (*Myrciaria dubia* (Kunth) McVaugh), both of which are considered indicators of future extreme floods.

Impacts of climate change on cultivation systems and agrobiodiversity

During extreme flooding events, *ribeirinhos* say that cultivated areas are flooded suddenly and simultaneously, and so they must harvest their crops quickly and often before their maturation time, resulting in low-quality manioc flour or widespread crop losses. This is particularly important in the low-lying areas that are more exposed to flooding (such as the *várzea*), where extreme floods significantly shorten the window of time available for planting and maturation of manioc and other species in the following season. Local residents also mention that during these extreme events everyone is concerned with their own crops and it becomes more difficult to organize traditional collective work (*ajuris*) to harvest and process of manioc.

Compared to extreme flooding, extreme droughts are perceived to have less impacts on crops. Still, local residents mentioned that during extreme droughts, small creeks that are used to access cultivated areas by canoe dry out, and thus they need to walk long distances to access their fields. In addition, during years of extreme drought, larger rivers may also dry-out partially or completely, and the transportation from communities to cities - where residents' products are sold - can double in both time and fuel expenditure. Consequently, during extreme droughts many *ribeirinhos* prefer to harvest only for consumption or sell at a lower price to middlemen.

Ribeirinhos say that, although planting manioc occurs during the dryer period of the year (´summer´; Figure 9), some rain is necessary to prevent drying of manioc cuttings (*manivas*). But, they also say that planting cannot be followed by periods of intense rain or very hot temperatures, as very humid hot soil can "cook" the recently planted *manivas*. Since rains during the hottest part of the year (summer) are more torrential and unpredictable now, *ribeirinhos* say this has been leading to increased mortality of manioc. Additionally, this overall unpredictability of rains is associated with the occurrence of strong storms, which can damage plant stems, such as those of bananas and palms. During periods of more severe river drought that sometimes is followed by a rain shortage, *ribeirinhos* say that they also irrigate some of their more water-demanding crops (such as watermelon, melon and squash), which is not required during normal years. They also mentioned that in these periods there is an increased use of ash and decomposing wood (to improve soil moisture and fertility). Both these strategies, however, tend to be used much more commonly in homegardens than in their larger swiddens.

Young plants are mentioned to be particularly vulnerable to flooding. Seedlings of wild and cultivated species may not survive extreme floods, reducing recruitment rates of plants already adapted to the normal seasonal cycles in different areas of *várzea* and *paleovárzea*. Also, some *ribeirinhos* report that after extreme flooding, some species may not produce fruits or reduce fruit production for one or more years. This is the case for two species such as cupuaçú (*Theobroma grandiflorum* (Willd. ex Spreng.) K. Schum.) and Brazil nut (*Bertholletia excelsa* Bonpl)).

Local adaptation strategies in the face of extreme climatic events

Several practices and changes in cultivation systems are put in place in response to extreme events, many of which are analogous to historical practices of landscape management used by native Amazonian populations (Table 11 of Supplementary Materials). While most of these practices were reported both in the *várzea* and *paleovárzea*, some of them were mentioned exclusively in the *várzea*, given that these areas are more exposed to extreme floods. For example, the building of small soil mounds for cultivation in homegardens was only reported in the *várzea*, as a strategy to prevent movement, exposure or damage to plant root systems caused by extreme floods, and also to reduce the amount of time plants are exposed to flooding. These small mounds are then maintained and/or expanded and cultivated during the following seasons. Indeed, practices to protect root systems against floods were frequently reported by local residents in both *várzea* and *paleovárzea*, such as the creation of small enclosures around stems, built with wooden stakes. Additionally, local residents mention that when trees are flooded, they avoid climbing on them to harvest fruits; instead, they position canoes below the trees to catch naturally falling fruits or, when the water rises further, to harvest fruits from the canoe.

The higher frequency of extreme flooding events, according to the *ribeirinhos*, is also leading to changes in the crops being cultivated, both in *várzea* and *paleovárzea*. The havesting of flood-tolerant perennial plants, such as açaí do mato (*Euterpe precatoria* Mart.), camu-camu and buriti (*Mauritia flexuosa* L. f.), is increasing, as well as the cultivation of fast-growing crops, such as some short-cycle landraces of bitter and sweet manioc, yam (*Dioscorea* spp.), watermelon and melon, Overall, *ribeirinhos* mention that this is leading to a substantial reduction in the diversity of crop species and landraces; residents in the communities most impacted by the 2015 flood (Vila Alencar and Sítio Fortaleza), for example, estimate that they lost about half of their crops, including fruits, vegetables and manioc. Such crops may not be replanted - either because plants that survived are preferred or as a precaution given climatic uncertainties. As a result, residents do not plant immediately, so as not to lose more of the same varieties, or because they were unable to maintain seedlings and/or collect seeds. Other *ribeirinhos* believe that two extreme floods never occur consecutively, and immediately resume the cultivation of both short and long-cycle species after a large flood.

Events of extreme floods and droughts are also associated with immediate and long-term changes in the spatial configuration of cultivation areas. Following extreme floods, areas that were not affected or less impacted tend to be selected for cultivation, changing the spatial configuration of cultivation areas. Residents of the *várzea* communities of Vila Alencar and Sítio Fortaleza (more exposed to flooding) mentioned that during extreme floods they cultivate temporarily in upland (*terra firme*) areas, rented or borrowed from neighbors or relatives. During extreme droughts, areas closer to larger rivers or houses tend to be preferred, as they can be more easily accessed. In the long run, the higher frequency of extreme floods and droughts is leading to an increase in the preference for areas that are more accessible and/or that are located in higher elevations – and thus less exposed to floods.

Other reported short-term strategies in response to the occurrence of extreme floods refer to changes in the processing and storage of manioc, and intensification in seed storage. Manioc is processed at the *casas de farinha*, small shacks where manioc flour is made. In *várzea* areas such sites can flood annually, while in the *paleovárzea casas de farinha* are inundated only during extreme flooding events. When water invades them, they are dismantled and rebuilt when river waters recede. Some residents, mostly in *várzea* areas, build floating *casas de farinha*. During extreme floods, there is high demand for the use of these floating *casas de farinha*, since all *ribeirinhos* need to process manioc into flour promptly. In response to this shortage, some *ribeirinhos* use techniques for storing raw manioc roots for later processing. This involves placing semi-prepared manioc in a tightly closed bag which is immersed in water, but without contact with the soil. In these semi-anaerobic conditions, manioc does not rot and can be processed later. *Ribeirinhos* also mention that in years of extreme floods they have to be particularly careful with the storage of manioc cuttings that are used for planting, storing their cuttings in high ground or inside the floating flour-processing facilities.

With respect to fire management, *paleovárzea* residents in particular reported that extreme floods bring an increased deposition of freshwater sponges (cf. *Tubella reticulata* and cf. *Parnula betesil*), which are highly flamable and are associated with increased risk of wildfires. Hence, experienced *ribeirinhos* tend to be more cautious with the use of fire following extreme flood events, increasing the use of firebreaks (*aceiros*) or avoiding opening and burning new swiddens. According to the *ribeirinhos*, these practices tend to be intensified in years where the extreme floods are followed by periods of scarce rainfall, as the dry vegetation is considered a significant risk for fires escaping.

Changes caused by extreme events in cultivation systems are also understood by *ribeirinhos* to have indirect consequences for other livelihood activities, such as fishing and hunting. For example, local residents report that during extreme floods there are more fruits from cultivated trees that fall in the water and attract fish, making fishing near the houses an option. During extreme droughts, many fruits are not harvested because of the difficulties of transporting them to the market. Subsequently, these also attract terrestrial dispersers, such as tapirs (*Tapirus terrestris*), pacas (*Cuniculus paca*) and agoutis (*Myoproct*a cf. *acouchy*), and local residents mention that these can then be hunted more easily and closer to the communities.

Lastly, the *ribeirinhos* strongly emphasized during the interviews the importance of family and reciprocity ties for maintaining their livelihoods and food security during extreme events. During the largest extreme flood (2015), communities received government support: one basic food basket and wooden planks to raise the floors of the houses. Still, when asked about food availability during extreme floods or droughts, respondents pointed out that in spite the diverse impacts of these events to their livelihoods, their food security was mostly assured through the support of other members of the community and family, and through the varied sources of food available. The exchange of food, fuel, work, and accommodation between close/distant kin and neighbors helps families to keep up with the demands and difficulties that intensify during extreme events.

Discussion

Local understanding of climatic patterns and changes

Our results contribute to the understanding that local Amazonian communities have a detailed understanding of climatic patterns and changes, developed through an intimate long-term interaction with their environment, and that is finely tuned with their livelihood activities. Elsewhere in Amazonia, local communities also rely on seasonal river and/or rainfall regimes to identify seasonal patterns and plan subsistence practices (Funatsu *et al.* 2019; Harris 2019; Orlove 2003; Pinho *et al.* 2015; Steward *et al.* in press), and in regions of the Peruvian Amazon, water entering homes is also the most common way of classifying floods as extreme (Langill and Abizaid 2020). *Ribeirinhos* in the Manaus region also predict the timing and intensity of seasonal changes by assessing the behavior of animals, fruits and river water level during the year (Pereira 2007).

Our results also echo patterns from other regions in Amazonia showing that local residents report changes in flooding and rainfall patterns, that the climate is more unpredictable, and that the indicators used for understanding the climate are becoming less accurate than in the past (e.g., Funatsu *et al.* 2019; Marengo *et al.* 2013; Pereira 2007; Pinho *et al.* 2015). While the local understanding of changes in climate stems from direct empirical observations, other researchers also report that LEK concerning the regional weather is increasingly combined with weather forecasts transmitted by radio or television (Funatsu *et al.* 2019). Still, it is based on this refined and ever-evolving knowledge that local communities in Amazonia can detect, react and adapt to climate change, by implementing various modifications in cultivation practices and other livelihood activities.

Impacts of climate change on cultivation systems and agrobiodiversity

We showed that local residents recognize that changing climatic patterns, particularly the increasing frequency and intensity of extreme floods and droughts, have numerous consequences for their cultivation systems and associated agrobiodiversity, especially in the low-lying *várzea* areas. Among these, some of the most important reported consequences of extreme floods are the high mortality of perennial crops (mostly in *paleovárzea*, where these crops are more frequently grown), crop losses, and changes in harvesting time of annual crops (which must be harvested earlier). In the low/middle *várzea*, where cultivation is focused on annual root crops and vegetables, these crops need be harvested earlier (or not harvested at all) during extreme floods. Impacts on species productivity and phenology were also reported as a consequence of extreme floods, mostly in the low-lying *várzea* areas.

Other authors have emphasized the impact of extreme event on crops and cultivation systems in Amazonia (Fraser *et al.* 2012; Langill and Abizaid 2020; List *et al.* 2019; Martins *et al.* 2018), including how extreme floods can affect crop root systems (Schmidt 2003), as well as impacts on natural forest plant communities (Gloor *et al.* 2015; Guimarães *et al.* 2018; Wittmann *et al.* 2004). The zoning observed in this study, with higher elevation areas being devoted to perennial crops, is consistent with observations in the Amazon Delta (Vogt *et al.* 2016), in Amazonian Peru (Denevan 1984), and near Manaus (Guimarães *et al.* 2018). Areas that are more exposed to extreme floods are already becoming increasingly marginalized for crop cultivation, and are likely to become even more so in the context of future climate change. Comparable changes in land-use have also been identified in the Brazilian state of Pará (Brondizio and Moran 2008), and in the Amazon Delta, where farming plots are now primarily located in *terra firme* areas (Vogt *et al.* 2016).

Ongoing and future climate change can weaken food security and compromise livelihood options for many rural Amazonian inhabitants (Brondizio and Moran 2008; Guimarães *et al.* 2018; Harris 2019; Langill and Abizaid 2020; Marengo *et al.* 2013; Steward *et al.* in press; Tregidgo *et al.* 2020), particularly those that inhabit vulnerable areas such as the *várzeas* and *paleovárzeas*. In this context, strong social networks and reciprocity ties are crucial in the response to resource shortages (Brondizio and Moran 2008), which also emerged as a unanimous understanding from the *ribeirinhos* themselves. Still, as extreme events become more frequent and intense in the future, maintaining food and economic security will likely become more challenging for the *ribeirinhos* despite the existence of these strong social structures.

Local adaptation strategies in the face of extreme climatic events

We show that floodplain communities put in practice numerous adaptation strategies in response to extreme events, relying on their LEK, on the management of agrobiodiversity and on the diversified use of their landscape, and that some of their adaptation strategies are rooted on historical practices of resource use and management (Levis *et al.* 2018; Table 11 of Supplemental Material). To protect useful plants, we documented strategies such as the storage of propagules and/or roots of manioc, as well as harvesting from canoes to avoid root damage, which was also reported during extreme flooding in Amazonian Peru (Langill and Abizaid 2020). Despite the strategies used to store and transport crop seeds and propagules, the difficulty of moving them during extreme climatic events may lead to a reduction in crop diversity at the specific and infra-specific levels, as also observed in the Peruvian Amazon (Langill and Abizaid 2020; Sherman *et al.* 2015).

Regarding phenotypic selection, we identified the inclusion of fast-growing species and crop abandonment, which were also reported by Funatsu *et al.* (2019) and Szlafsztein (2014) as strategies for dealing with the effects of climate change in areas of the Brazilian and Peruvian Amazon, respectively. We also reported changes in preferred areas for cultivation following extreme floods, echoing patterns observed by Guimarães *et al.* (2018) in the region of Manaus, in Central Amazonia. As with the current study, following extreme floods in the region of Manaus, areas that were less or not affected by water were later selected for cultivation (Guimarães *et al.* 2018). Following extreme droughts, cultivation of areas closer to rivers or houses tend to be preferred, as these have better access and can also be irrigated more easily. Considering that both floods and extreme droughts are expected to occur more frequently, changes in crop assemblages and in preferred areas for plant cultivation are likely to occur in other regions across Amazonia.

Fire is traditionally used for opening swidden areas and providing a flush of nutrients for cultivation (Levis *et al.* 2018). Various studies have observed that great care is necessary for the use of fire after extreme droughts (Brondizio and Moran 2008; Carmenta *et al.* 2019; Marengo and Espinoza 2016; Milhorance and Bursztyn 2019; Nobre *et al.* 2016; Oviedo *et al.* 2016). *Ribeirinhos* from *várzea* and *paleovárzea* communities recognize that the use of fire following extreme droughts requires care, and they report specific changes in management practices to prevent its spread. This consists of a strategy for resource use and management that is finely tuned to the dynamics of the environment, and is an illustrative example of how LEK can shed light on practices that can contribute to the development of resilient socio-ecological systems.

Building mounds in homegardens to plant trees above the maximum water level has historically been important in flooded ecosystems in Amazonia (Arroyo-Kalin 2016; Harris 2019; Padoch and Pinedo-Vasquez 1999). We show that building mounds is a practice that is still recurrent among *ribeirinho* communities in floodplains as a strategy to avoid flood-driven plant mortality, particularly during extreme floods. Additionally, we show that during extreme floods *ribeirinhos* put in place practices to store manioc roots for future processing that are analogous to pre-Columbian techniques (Mendes dos Santos *et al.* 2021). Together, these examples suggest that the body of knowledge and practices with which Amazonian communities have historically shaped their ecosystems can also provide useful insights to address more ´recent´ issues such as climate change.

Conclusions

Ribeirinhos have historically dealt with the strong environmental contrasts driven by the annual flood pulse; they have also experienced extreme events and developed different strategies to deal with them. We show that these local populations have a detailed understanding of climatic patterns and changes. They also acknowledge that these changes, particularly the higher frequency and intensity of extreme river floods and droughts, have numerous consequences for their cultivation systems and associated agrobiodiversity, varying according to the degree of exposure of different environments to extreme events. In response to these changing climatic conditions, *ribeirinhos* are implementing and modifying historical practices related to resource use and management, relying on their LEK, associated management of agrobiodiversity, and on strong social networks.

Impacts of extreme events on local communities are expected to increase, particularly in environments more exposed to flooding, such as the *várzea* and *paleovárzea*. *Ribeirinhos* are increasingly in need of support to enhance their resilience in this changing climatic scenario. Documenting and disseminating adaptation strategies, such as techniques for storing seeds and propagules, building soil mounds for fruit trees, and cautious use of fire, could help promote food security, maintain agrobiodiversity and prevent further losses during extreme events. In this changing climatic context, further dissemination of these strategies through kin and other local social learning processes is a promising strategy.

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Appendix - Supplemental material chapter 2

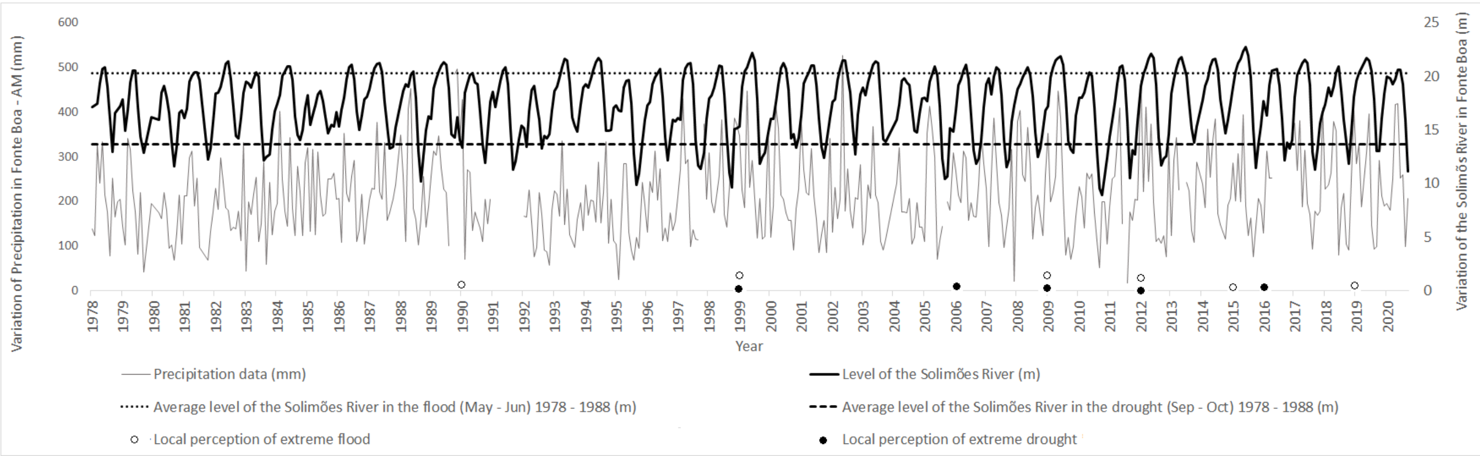

Figure 10. Extreme events remembered by local ribeirinhos and variation of the average quota of the Solimões River and variation of precipitation in the municipality of Fonte Boa (AM), 180 km northwest of Tefé, for the period 1978-2020 (Source: Prepared by the authors with data from the National Water Agency, https://www.gov.br/ana/pt-br, accessed date: 05/01/2021).

Table 8. Characteristics of local cultivation systems on floodplains of the Middle Solimões.

	Várzea	**Paleovárzea**
Influence of water under normal flooding	- The soil is covered by water for 1 to 2 months	- Most cultivation and dwelling areas do not flood, making agricultural management more flexible. - Because they are in higher areas than the "high *várzea*", *paleovárzea* areas are only affected by extreme flooding.
Swiddens (*Roças*) (area of cultivation of species of short cycle, such as manioc, sweet manioc, pumpkins, corn, cane, watermelon, pepper)	- Planting of manioc and sweet manioc is carried out on the riverbanks in areas of high levees ("*restingas*") and sandy areas ("*praias*") and mudflats ("*lamas"*). The latter two are only exposed during the annual lowering of the water, which usually occurs in July.	- Areas of forest or young secondary forest (*capoeira*) are cut down each year to plant swiddens in areas that do not flood annually. - After the capoeira is felled, farmers wait for period of 15 to 30 days so that the vegetation can dry; they then set fire to the debris (in areas of forest or older capoeira, the wait is from 30 to 90 days). - Subsequently, prepare swidden areas, by gathering and burning logs and other remains from first burning. - The need to prepare fields during the period when there is less rain means that *ribeirinhos* in the *paleovárzea* will be planting mainly between September and October, since the months with the least rainfall occur are August, September and October.
Multi-species orchards/ Agroforests (*Sítios*)	- Agroforests are made in the "high *várzea*" areas, where floodplains are forested.	- Agroforests are enriched forests and fallows from the *roça* system, where inhabitants choose areas of high fertility to plant species of interest and guide the natural selection of native species in a dynamic management system.

	Várzea	Paleovárzea
(area of greatest cultivation of woody perennial crops)	- *Ribeirinhos* will open up area with or without the aid of fire, removing native trees of little interest from the forest and growing perennial trees for use as food/medicine/income generation.	
Varieties of bitter and sweet manioc	- Manioc varieties planted in the *várzea* require between 5 and 10 months to reach maturation - Harvesting of manioc in the *várzea* begins in December (5-6 months after planting), but peaks May and June, when water encroaches on cropped areas (facilitating product transport).	- Most cultivated manioc varieties require from 10 to 18 months to mature and can remain in the soil for up to 2 years. - Many families maintain manioc plants at different stages of development and can then harvest and make farinha throughout the year, responding to family or market demands. - Flood months are those when harvesting manioc and making *farinha* most commonly occur, due to the reduced distance from cultivation areas, sales points and homes.

Table 9. Socioeconomic characterization of the *Várzea* and *Paleovárzea* communities visited during the study in the Mamirauá (*várzea*) and Amanã (*paleovárzea*) RDS on the middle Solimões River, Amazonas, Brazil. (total number of respondents = 101 interviews, 59 being interviewed in the *várzea* (Vila Alencar = 13, Sítio Fortaleza = 14, Porto Braga = 32), and 42 interviews in the *paleovárzea* (Santa Luzia do Baré = 5, Santa Luzia do Juazinho = 23 and Bom Jesus do Calafate = 14).

Interview Location	Female	Male			
Várzea	68%	32%			
Paleovárzea	33%	67%			
Age of Interviewee	18-30 yrs	31-40 yrs	41-50 yrs	50-60 yrs	More than 60 yrs
Várzea	32%	29%	14%	12%	14%
Paleovárzea	38%	21%	21%	10%	10%
Education level of Interviewee	Did not study/Not literate	Elementary School	High School	Higher Education	
Várzea	8%	42%	47%	2%	
Paleovárzea	33%	50%	17%	0	
Principal source of family income	Government assistance /retired	Fishing	Agriculture	Other paid work (Cook, teacher, etc.)	
Várzea	46%	27%	8%	25%	
Paleovárzea	19%	2%	76%	2%	

Table 10. Historical indicators ("signals") of climate used by ribeirinhos. "Widely shared" was shared by more than 50 % members during community meetings, "Shared" was share by less than 50% and "Little shared" was shared by few meaning only 1-2 participants.

Signal	**What the signal indicates about the weather**	**Does it work (according to respondents)?**	**Associated with an extreme event?**	**Locally recognized as shared between community members during community meetings**
Lack of *repiquetes* (river level oscillations)	Strong flooding likely	Appears to do so	Yes	Widely shared
As water levels drop (vazante) they do so slowly. Any repiquete oscillations are minor.	Strong flooding likely	Appears to do so	Yes	Little shared
Increased appearance of venomous animals seeking shelter in people´s houses	Strong flooding likely	Sometimes	No	Little shared
Várzea fruit trees crop unusually heavily (camu-camu is the main indicator)	Strong flooding likely	Sometimes	No	Shared
River level remains relatively high during dry (low water) season	Strong flooding likely	Sometimes	Yes	Shared
Extreme drought ("when the drought is very strong, the food is also great ")	Strong flooding likely	Sometimes	Yes	Shared
Height at which Uruá (a freshwater snail: *Pomacea canaliculata* Lam.) lays its egg masses on *várzea* tree-trunks	Flood level	Sometimes	Yes	Little shared
When the protective bract (*capemba*) of the jauari palm (*Astrocaryum jauari* Mart.) inflorescence	Big flood	Sometimes	No	Shared

looks like a canoe when it falls to the ground				
Jauari capemba looks like a canoe turned-over, and beached (*emborcada*)	Big drought	Sometimes	No	Shared
Cattle eat lots of capim murim /muriru (Poaceae)	Strong flooding likely	Sometimes	Yes	Little shared
Periodicity (for example, 5 times in 5 years)	Strong flooding likely	Sometimes	Yes	Shared
A very rainy winter	Strong flooding likely	Sometimes	Yes	Shared
When the undulated tinamou (*Crypturellus undulatus* [Temminck, 1815]: Macucaua-da-*várzea*) flies from the *várzea* in towards the terra firme	Strong flooding likely	Sometimes	Yes	Little shared
Cocoa trees produce large crops	Strong flooding likely	Sometimes	Yes	Little shared
Black-fronted nunbird (*Monasa nigrifrons* [von Spix, 1824]: *Bico de brasa)* calls (note: other common name *choro-chuva*, means ´rain crier´)	(Normal) flooding about to start	Sometimes	No	Little shared
Catfish jump in the middle of the river in the direction of the bank	(Normal) flooding about to start	Sometimes	No	Little shared
Catfish near the river bank jump in the direction of middle of the river	(Normal) water level decline about to start	Sometimes	No	Little shared
Longer rains and more clouds	Start of winter	Sometimes	No	Shared
Sunny, little rain, few clouds	Start of summer	Sometimes	No	Shared
Listening to the radio for news of the river level in Tabatinga	Beginning and peak of river high-	Sometimes	Yes	Little shared

	water and low-water			
Place from where the frog sings	Highest level to which the water will reach during flooding	Sometimes	Yes	Little shared
Every year asking an expert elder in the community (there is no way to learn, only with time)	Level of the highest and lowest waters	Sometimes	Yes	Shared
Saint Anthony´s Day (12th of June)	Highest water levels	Sometimes	No	Shared
Weight of river water (collect the same volume of water from the river/lake on December 31 and January 01. Whichever water weighs most indicates which year had/will have the greatest flood	Flood level (indicates whether highest water level will be greater or lesser than that of the previous year)	Sometimes	No	Shared
Presence of yellow butterflies (family Pieridae)	Start of the dry (low water) season	Yes	No	Shared
River does not fill greatly during flooding season	Extensive dry season	Sometimes	Yes	Shared
Start of flooding delayed	Extensive dry season	Sometimes	Yes	Little shared
Extreme flood ("when the flood is very big, the drought will also be large")	Extensive dry season	Sometimes	Yes	Shared
River water very high during flood season	Short dry season	Sometimes	Yes	Shared
Scattered clouds in the sky as summer nears	Very strong summer	Sometimes	No	Little shared
A cold spell (*friagem*) a few days long, when	Summer is coming	Rarely occurs every year	No	Shared

temperatures fall below 20 °C				
Low-lying mist and cloud (*Serração*)	Summer is coming	Rarely occurs every year	No	Shared
Strong, rapid, thunderstorm, with more wind and lightning than at other times	Summer is coming	Sometimes	No	Shared
Elders' knowledge (*Dom dos antigos*)	Levels of highest and lowest water	Sometimes	No	Shared
Large numbers of mosquitoes (*carapanã/ pernilongo*) and blackfly (*pium*).	When the rains will Start?	Sometimes	No	Little shared
Várzea forest trees produce flowers	Extreme event	Sometimes	No	Little shared
Bees buzz loudly and persistently (*faz zuada*)	Extreme event	Sometimes	No	Little shared
Monkey makes a " Swidden" in the juarizal (breaks leaves of the juarizal in the middle)	Strong summer (good to open a forested area to make a swidden)	Sometimes	No	Little shared
Vultures singing	Start of the summer	Sometimes	No	Little shared
Sungrebe (*Heliornis fulica* [Boddaert, 1783]: *Patinha do igapó* or *Picaparra*) sings/calls	Sign of winter (rain/ milder temperature)	Sometimes	No	Little shared
When the path of the sun changes	Start of the rainy season	Yes	No	Little shared
New moon	2-3 days of rain	Sometimes	No	Little shared
Mist rises	Rain	Sometimes	No	Little shared
Mist descends	Sun	Sometimes	No	Little shared
Morning dew (*Sereno*)	Sun the following day	Sometimes	No	Little shared

When the new moon has the form of the letter “c"	Sun	Sometimes	No	Little shared
When the new moon has the form of the letter “u”	Rain	Sometimes	No	Little shared

Table 11. Cultivation management practices carried out by local ribeirinhos, and adaptations to extreme floods and droughts. Practices are classified according to the framework of Levis *et al.* (2018). VZ = recorded in the várzea; PVZ = recorded in the paleovárzea

	Traditional management practices	**Adaptations to extreme floods**	**Adaptations to extreme droughts**	**Adaptations to rain shortages**
Protection of useful plants	Care of fruit tree seedlings and adult plants. Use of non-destructive harvesting practices. Construction of suspended beds.	Intensify root systems protection. [VZ, PVZ] Create soil mounds or surround stems with wood stumps. [VZ] Reinforced and raised suspended beds. [VZ, PVZ]	Intensify irrigation. [VZ, PVZ]	Intensify irrigation [VZ, PVZ]
Attraction of non-human dispersers of useful plants	Some fruits left under trees for animals.	Many fruits not harvested intensify fish and other disperser-attraction. [VZ, PVZ]	Many fruits not harvested intensify disperser-attraction. [VZ, PVZ]	
Human transportation	People intentionally transport seeds, seedlings and clones of useful plants.	Intensify seed and seedlings storage. [VZ, PVZ]	-	
Phenotypic selection of useful plants	Selection practices are motivated by human preferences for specific phenotypes (fruits with larger sizes or higher contents of desirable products, such as sugar, starch and oil).	Prioritize flood resistant and short-cycle plants. [VZ, PVZ]	-	
Fire management	Fire is used to open new planting areas.	More cautious with fire. [VZ, PVZ]	More cautious with fire. [VZ, PVZ]	More cautious with fire [VZ, PVZ]

	Traditional management practices	**Adaptations to extreme floods**	**Adaptations to extreme droughts**	**Adaptations to rain shortages**
Planting	Take care of seedlings after planting.	Temporarily cultivate in leased areas or relatives' land *in terra firme*. [VZ] Prioritize non-flood areas to replant. [VZ, PVZ]	Prioritize areas closer to the river to replant. [VZ, PVZ]	
Soil improvement	People use ash and decomposing wood as compost in swiddens and gardens.	-	Intensify fertilizing [VZ, PVZ]	Intensify fertilizing

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Interview script (translated from Portuguese)

Interviewer name: ______________________________________Date:____________

Community:___________________________ Code:__________________

Socioeconomic Questionnaire
1.. Name 2. Gender: ________ 3. Age:__________ 4. Education level
5. Place of birth and where you have lived

6. Community residence time 7. Nº of residents 8. Nº of children
9. What are your sources of family income?

10. What is your main source of income today?

11. Did you ever receive another source of income? What and when?

12. How long have you been working in agriculture?

13. Currently, you receive: (check "Y" or "N")
Pension S N Retirement S N Bolsa Floresta S N Bolsa família S N
Bolsa Verde S N Other social benefits

14. What is your current monthly income? R$

Ethnobotanical questionnaire

1. Do you notice any changes regarding the cultivation of plants from the time of your parents / grandparents to now? Which changes specifically?

2. How are the areas managed today? How was management in the past? Who manages cultivation areas? At what times?

3. How many swiddens / agroforest / capoeira do you take care of (manage)? How large are they?

4. Has you observed changes compared to the time of your parents / grandparents regarding the location / size / number of cultivated areas?

5. How much time in fallow do you leave your agricultural areas? Why? And, your parents and grandparents? In the case of a change: Why do you think these changes ocurred?

6. What is the best type of area to cultivate?

7. Are mature forest areas currently opened to establish swiddens? (note periodicity and size)

Did your parents use forests?
Did your grandparents?

8. How did the extreme flood and drought affect your cultivation areas (describe for each of the following: homegarden, swiddens, raised garden beds, agroforest, others)? What changes in management occurred during these times?

9. Did anything change related to your crops after extreme events? (what?, how?, where?, by whom?, time)

10. Which plants produced poorly or did not produce because of extreme flood / drought? Did any plants produce better?

11. Which plants that you did not have before did you start to plant or planted in greater quantity after a large flood / drought?

12. Which plants did you have before extreme events and how were they affected? Which plants do you have now? (free listing)

13. How was your family's food supply during these times of heavy floods and droughts?

14. How has income from agricultural products been affected by the flood/droughts?

15. In your opinion, did the Bolsa Floresta or Bolsa Família programs change anything regarding the way agriculture happens in the region, compared to the old days? Do you consider it good or bad?

16. Are any chemicals "medicine" used in dealing with plants? For what purpose? Which products specifically?

17. In which locations are cultivated / collected products sold?

18. What types of transportation are used to take the products to the city? How much time do you spend to get there per each type?
A (winter) Amount of time: B (summer) Amount of time:
During climate change situation

19. Is there a “sign” that helps you to understand the climate? Are these signs common knowledge in the community? Do you do something when you see these signs?
20. In the 2015 flood, how deep is the water in cultivation areas? And in the houses?

21. Did you receive any government support during extreme flood/drought? What would it take?
of Amont of Time:

22. Seasonal Calendar

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Chapter 3

Ávila, J.V.C., Lima, A.M.A., Junqueira, A.B., Steward, A.M., Mendes dos Santos, G., Clement, C.R., 2022. Adaptations of pre-Columbian manioc storage techniques as a strategy to adapt to extreme climatic events in Amazonia. *Human Ecology*. p. 1-11, 2022.

Chapter 3: Adaptations of pre-Columbian manioc storage techniques as strategies to adapt to extreme climatic events in Amazonian floodplains

Abstract

In Amazonian floodplains, manioc flour is the main plant food product and source of income for local populations. In the context of climate change, extreme flooding is more frequent and intense, making it difficult to cultivate and process manioc. As local knowledge is dynamic and fundamental to adapt in critical times, we studied local techniques for storing manioc roots, which allow them to be processed later. We conducted semi-structured interviews in three floodplain (*várzea*) communities (52 families) and three paleofloodplain (*paleovárzea*; 1-3 m higher) communities (36 families) in the middle Solimões River basin (Brazil). Residents mention four techniques for storage of fresh manioc; two also cited in archaeological or ethnographic studies (burial and basketing) and two not cited before on the region (bagging and *kanaká*). In the paleovárzea, where manioc production is more important as a source of income, residents have more knowledge of manioc storage techniques, however, this knowledge also persists in areas where manioc has less importance for income generation. Residents of the study area express a demand for the dissemination of these practices, as they can contribute to adaptation in critical periods.

Key words: *Ribeirinhos*, Traditional Ecological Knowledge, adaptive strategies, Indian bread.

Introduction

In local communities in Amazonia, the diet is based on fresh foods, from fishing, hunting and harvesting wild or cultivated fruits and vegetables (Alencar, 2010; Dufour *et al.*, 2016; Posey, 1985). In addition, local communities use traditional food processing, storage and preservation techniques, such as the production of manioc flour (*Manihot esculenta* Crantz) (Denevan, 1996; Lentz, 2000), the main plant food of current Amazonian populations and an important food source for past populations (Dufour, 1995; Dufour *et al.*, 2016). In climate change scenarios, where extreme floods have become more frequent and intense (Cai *et al.*, 2014; Marengo *et al.*, 2013), local communities' livelihoods and diets have suffered changes (Ávila *et al.*, 2021; Dubreuil *et al.*, 2017; Funatsu *et al.*, 2019; Langill and Abizaid, 2020; Tregidgo *et al.*, 2020). In this study, we seek to identify the strategies that are used for manioc storage in the context of extreme floods in Amazonian *várzea* and *paleovárzea* ecosystems.

Dry manioc flour is a primary source of carbohydrates (Dufour *et al.*, 2016) in the Amazonian *várzeas* and *paleovárzeas* of the middle Solimões River basin. Dry flour is also the main form of manioc storage by local populations (Lima *et al.*, 2012). A diversity of methods for processing and consuming manioc has already been documented in the region (Venturato and Pereira, 2010). After harvest, the manioc flour produced is most often the basis of family food security throughout the year; additionally, surpluses are sold locally (Adams *et al.*, 2009; Fraser *et al.*, 2012). The durability of manioc flour is also advantageous, given that in much of Amazonia refrigerating food is not viable (Tregidgo *et al.*, 2020); limitations include the high costs of electricity, coming mainly from generators powered by fossil fuels and, rarely, with solar energy (Penteado *et al.*, 2019; Valer *et al.*, 2014), and refrigerators and freezers.

In Amazonia, the *várzeas* are flooded annually by white water rivers, while the *paleovárzeas* are only inundated in extreme flood years (Irion *et al.*, 2010) because they are 1-3 m above the *várzeas*. Hence, the impacts of large floods between the *várzea* and *paleovárzea* agroecosystems are different and more intense in the latter environment (Ávila *et al.*, 2021). Because manioc plants cannot withstand flooding for many days (Langill and Abizaid, 2020), local producers seek to quickly process the roots in local flour mills, but these processing areas can also be flooded. Even if manioc flour mills are mounted on floating rafts, the community demand may be too high for everyone to process (Ávila *et al.*, 2021).

Archaeological and ethnographic studies carried out in *terra firme* (non-flooded) regions highlight the importance of pre-Columbian food storage techniques (Furquim, 2018; Mendes dos Santos, 2016; Mendes dos Santos *et al.*, 2021), especially for manioc (Fausto and Neves, 2018). One of the products, popularly called Indian bread (*pão de índio* or *pães de indio*), is currently found by chance or in excavations of archaeological sites (Mendes dos Santos *et al.*, 2021). Many techniques are historically used to produce *pães de índio*. *Pães de índio* are ways of preserving edible plant biomass for a period, especially starch-rich fruits and/or roots. When made with manioc roots, they first processed the manioc to remove anti-nutritional factors (such as prussic acid) and transformed the manioc into a dough, either cooked or raw; fruit mesocarps or seeds were ground into dough. The dough is shaped, toasted/smoked or not, wrapped in waxy leaves and buried. Depending upon treatment, *pão de índio* can last for months or years (Mendes dos Santos *et al.*, 2021).

In addition, ceramics are historically used in Amazonia for both preparation and storage of food (Costa *et al.*, 2011). Because ceramics resist degradation in tropical climates, they are more easily found in archaeological sites (Neves, 2011). On the other hand, leaves, sticks and vines rot quickly, which makes them difficult to be record in archaeological sites, but were certainly widely used, especially in emergency contexts, such as during extreme floods. Early reports of *pão de indio* considered it to be a colony of fungi (Araújo and Souza, 1978; Aguiar and Sousa, 1981) or a production of fungus for food purposes (Santos *et al.*, 2014). However, more recent compositional analyzes identified plant materials, mainly edible roots and fruits that are rich in starch, and its functionality as a form of food storage was confirmed (Mendes dos Santos *et al.*, 2021). Similar to observations in Amazonia, other tropical countries where the manioc is an important component of local diets have different forms of short, medium or long-term storage (Knoth, 1993).

There are reports of manioc conservation through burials (Affran, 1968; Anon, 1944; Balagopalan, 2000; Knoth, 1993; Irvine, 1969), covering with various leaves or sawdust (Fadeyibi, 2011; Knoth, 1993; Osei-Opare, 1990; Rickard and Coursey, 1981), and in plastic bags (Gallat *et al.*, 1998; Knoth, 1993; Rickard and Coursey, 1981; Westby *et al.*, 1999). Manioc storage techniques are believed to be a derivative of the common practice of leaving the roots stored in the field (unharvested) for several months after reaching maturity (Ingram and Humphries, 1972; Rickard and Coursey, 1981). Archeological studies in Amazonia demonstrate that *food storage* techniques were part of ancient local ecological knowledge (LEK) in the region (Furquim, 2018; Neves *et al.*, 2014; Schmidt *et al.*, 2014).

The knowledge about food storage, such as *pães de índio*, is useful today, keeps changing and can contribute to the future of local communities (Avila *et al.*, 2021). Furthermore, it is important to highlight those changing scenarios, with different social, economic, political and environmental/ecological pressures, can result in loss (Reyes-Garcia *et al.* 2013; Aswani *et al.* 2018) or changes of LEK (Reyes-Garcia *et al.* 2014). These pressures influence the dynamics of LEK, which is a major area of study in ethnoecology (Gaoue *et al.*, 2017). To manage flood risk, modern adaptations of techniques can replace LEK about older techniques (Haughton *et al.,* 2015). In the case of manioc storage, some techniques seem to be in disuse, such as *pão de índio* (Mendes dos Santos, 2021), while modern techniques with the same propose can be taking their place. However, the existence of different techniques can enhance the resilience of local communities in the context of social, economic and environmental change (Walker *et al.*, 2004).

Recognizing the great importance of manioc as a source of food and income for *várzea* and *paleovárzea* communities, how extreme flooding can make processing difficult and the importance of the dynamics of local knowledge in critical moments, we investigated 1) the techniques known and/or used by local communities in the *várzea* and *paleovárzea* for storage of manioc roots that allow for further processing and consumption when water recedes, and 2) whether *várzea* communities know more techniques for storing manioc than *paleovárzea* communities. Our hypotheses are that 1) local communities from both ecosystems know and/or use traditional (exclusively made using natural components from local ecosystems, such as fibers, sticks and leaves, and mentioned in archeological studies about practices and knowledge of Pre-Columbian populations of Amazonia) and modern techniques, that use synthetic components (such as plastic bags) to store the manioc mass, and 2) because várzea is more frequently and intensely influenced by flooding, residents in these ecosystems know and use more techniques for storing manioc roots than residents living in the paleovárzea .

Methodology

Study area

This study was conducted in the middle Solimões River basin (Amazonas, Brazil) between August 2017 and May 2019. Local communities are considered *ribeirinhos*, local populations that historically inhabit the banks of rivers and experience the seasonal variation of waters in their daily lives (CNPCT, 2016).

The *várzeas* originated in the Holocene and are periodically flooded in regular annual cycles, in which soils are covered for up to six months with river waters rich in sediments with a high content of nutrients from the Andes (Ayres, 2006; Junk *et al.*, 1989). *Paleovárzeas*, on the other hand, originated in the Late Pleistocene, and are positioned in the landscape a few meters above the *várzeas*, although this difference is greater in regions closer to the mouth of the Amazon River (Irion *et al.*, 2010). Thus, during the annual flood cycle, the *várzea* areas where *ribeirinhos* live and cultivate are usually covered by water for at least 1 to 2 months (Steward *et al.*, in press). On the other hand, the agricultural and living areas of *paleovárzea* communities are rarely flooded. During extreme flooding, most of the high *várzea* cultivation areas are covered by water, while in the *paleovárzea* some cultivation areas are affected and others are less affected.

The *várzea* communities in this study are within the *Mamirauá* Sustainable Development Reserve (RDSM) and the *paleovárzea* communities are within the *Amanã* Sustainable Development Reserve (RDSA) (Figure 11). According to the Köppen-Geiger system, the region's climate is tropical rainforest (Af), monthly rainfall is greater than 60 mm throughout the year (Peel *et al.*, 2007) and the average rainfall is 2.200 mm (Ayres, 2006). The flood season (winter) is from December to May and the dry season (summer) from June to November (Bueno *et al.*, 2019). In normal years, the water level of the Solimões River in the study region rises an average of 10.6 m during the flood season, and may rise by 15-17 m in more severe floods (Ramalho *et al.*, 2010).

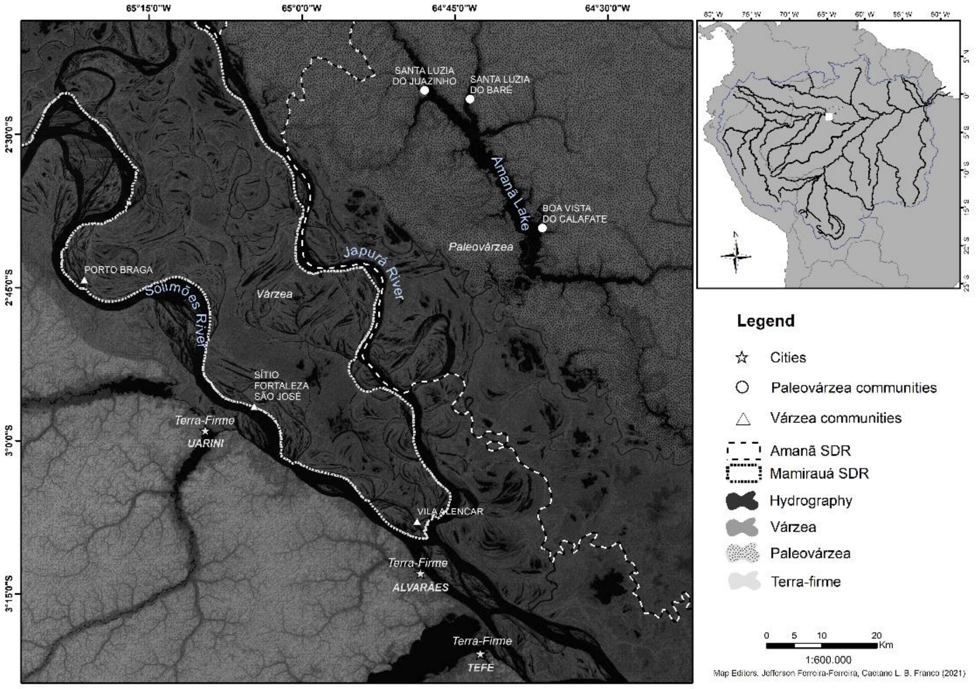

Figure 11. Map of the study area, identifying the várzea and paleovárzea communities in the middle Solimões River region, Amazonas, Brazil

This study took place in six communities, three *ribeirinho várzea* communities (*Vila Alencar* (composed by 13 families), *Sítio Fortaleza* (14 families) and *Porto Braga* (33 families) and three *ribeirinho paleovárzea* communities (*Santa Luzia do Juazinho* (23 families), *Bom Jesus do Calafate* (15 families) and *Santa Luzia do Baré* (6 families)). Information on the socioeconomic characteristics of the residents can be obtained from Ávila *et al.* (2021). Planting in the region is based on the cultivation of manioc in small areas, combined with the cultivation of other annual and perennial crops (Rognant and Steward, 2015).

Data collection

We conducted semi-structured interviews with one household head per house, until all available families were sampled, totaling 52 *ribeirinhos* in the *várzea* and 36 *ribeirinhos* in the *paleovárzea*. We interviewed one man or woman, more than 18 years old, per family unit. The semi-structured interviews focused on the storage of manioc in years of extreme flooding. For this, we asked if *ribeirinhos* knew any technique for storing manioc. In the case of a positive answer, we asked which techniques they know and some specific questions to understand the permanence or continuity of these techniques: a) whether the *ribeirinho* only knew about the technique, but did not know how to perform it, b) whether the *ribeirinho* knew the technique sufficiently to perform it, and c) whether the *ribeirinho* had already performed the technique (currently or in the past).

Data analysis

Information about known and used storage techniques was categorized and analyzed using descriptive statistics. We used a generalized linear model using the program R (R Development Core Team, 2020) , to verify if there are statistical differences in the *ribeirinhos*' knowledge about manioc storage between the *várzea* and *paleovárze*a ecosystems.

Results

Manioc storage techniques

In both the *paleovárzea* and the *várzea*, people from all communities reported that during major floods they employ various storage techniques to store raw peeled manioc roots (locally called *massa da mandioca/*manioc mass) during the flood and process it into flour when waters recede. They say that these techniques have been practiced historically and were learned from their grandparents and indigenous peoples. The guiding principle of most manioc storage techniques is the creation of an anoxic environment into order to eliminate or reduce oxygen. Four techniques were described in the study area: burial of manioc mass, basketing of manioc mass, bagging of manioc mass and *kanaká* of manioc *puba.*

The first technique uses soil and leaves to create a more anoxic environment, called *enterrar a massa da mandioca* (burial of manioc mass). It consists of *ribeirinhos* burying the fresh peeled roots in pits excavated in the soil, which will remain submerged during the flood period. This is a technique recognized by the interviewees as a widespread and ancient technique, practiced both in the *várzea* and *paleovárzea*. The technique follows these steps: 1) a 1-meter square pit is dug in the ground (depending on the amount of manioc to store it can be larger or smaller), 2) the inner walls of the pit are lined with *cauaçú* (*Calathea lutea* (Aubl.) Schult.) leaves, which serve to prevent the roots from direct contact with the soil (one of the respondents mentioned that *embaúba* (*Cecropia* sp.) leaves may also be used for this purpose), 3) peeled manioc roots are placed in the pit up to the edge of the soil surface, 4) *cauaçú* leaves are used to cover all of the manioc roots, and 5) soil excavated from the pit is piled over the manioc to cover the storage pit (Figure 12.1).

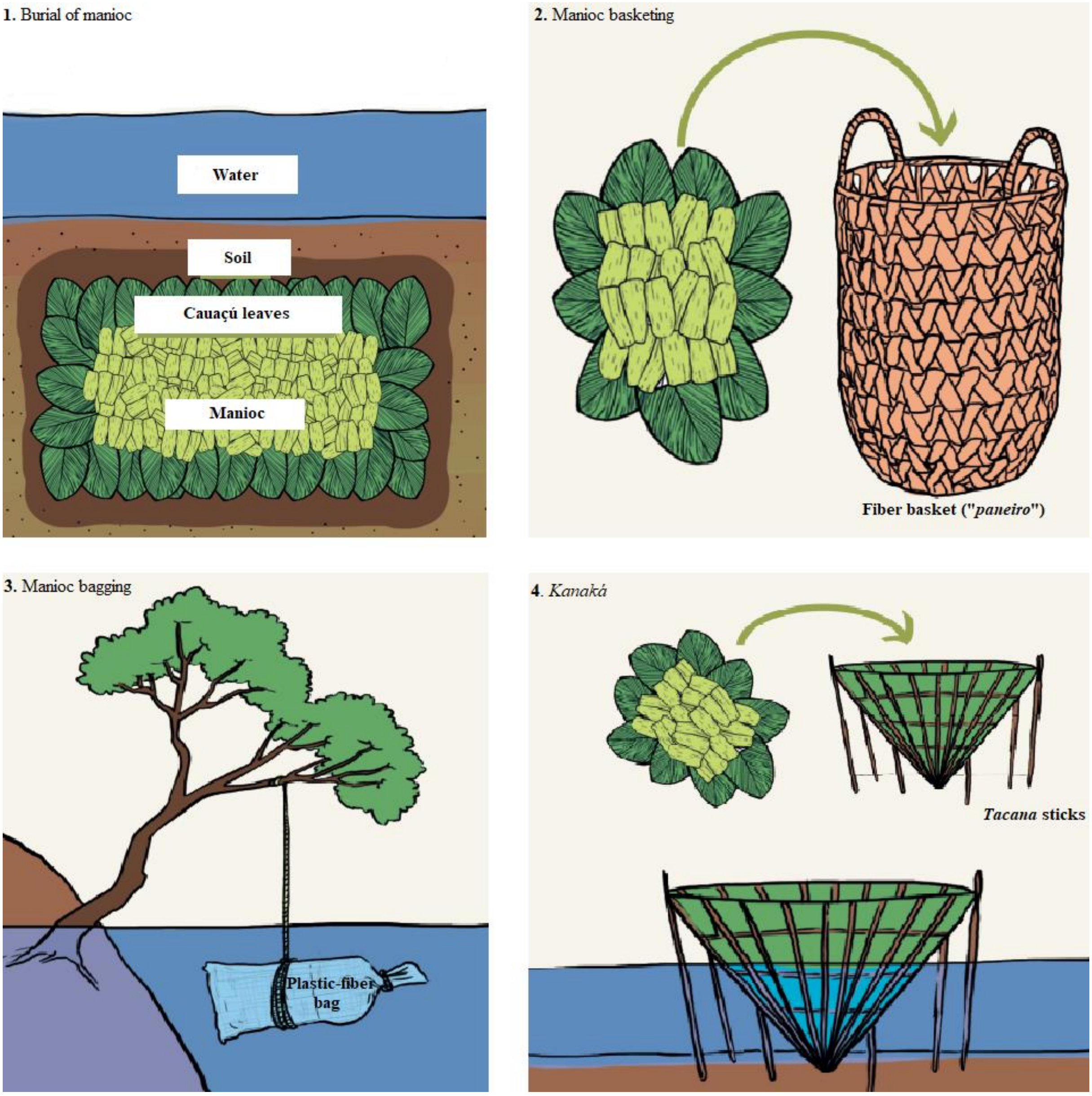

Figure 12. Schematic drawings of techniques used for manioc storage during large floods in *ribeirinho* communities in *várzea* and *paleovárzea* areas in the middle Solimões River region, Amazonas, Brazil. 1. Burial of manioc; 2. Manioc basketing; 3. Manioc bagging; 4. Peeled manioc roots wrapped in *cauaçú* leaves for storage in *Kanaká* and *Kanaká* submerged in water (Figures created by Maurício Afonso).

The second technique, called *empaneirar a massa da mandioca* or *empalhar a massa da mandioca* (basketing or wrapping manioc mass), is also locally recognized as ancient and known in both ecosystems; it is cited as a simplified alternative to the first technique. It consists of: 1) constructing a fiber basket (popularly called *paneiro*) using dry petioles of *cauacú* or some Arecaceae, 2) lining the fiber basket with *cauaçú* leaves or other leaves, such as *pariri* (cf. *Pouteria pariry* (Ducke) Baehni), 3) filling the basket with peeled manioc roots, 4) covering the top of the basket with *cauaçú* leaves, 5) tying the covering tightly with fiber rope (made using hanging aerial roots of *ambé* (cf. *Philodendron* spp.)), and 6) immersing the basket in the water. When employing this technique, the basket must be completely submerged during the entire storage period (Figure 12.2). One of the interviewees also mentioned that the basket can be buried as in the first technique. Other recommended using a rope to support the basket on a tree, without touching the river bottom, because the manioc stored exactly where the fiber basket touches the river may show rotting signs.

Because major floods often rise quickly, the considerable work required for mass storage of manioc in pits, baskets or cones may be impractical, so about 30 years ago residents adapted the basketing technique with woven plastic-fiber bags. It is important that the bag be of woven fiber and not solid plastic, since woven fiber bags allow water movement into and out of the bag. This variation is called *ensacamento da massa da mandioca* (bagging of manioc mass). The bagging consists of 1) placing the whole peeled manioc in woven fiber bags, 2) closing the bag with a rope, 3) with another rope, hanging the bag on a tree, so that the bag is completely immersed in the water and does not touch the riverbed during storage (Figure 12.3).

A fourth technique, locally called "*kanaká*" (Figure 12.4), different from the techniques described above, uses ground manioc root mass (locally called *pubar a mandioca*), which is prepared in a sunken canoe along the river edge where the manioc roots are submerged in water for 2-4 days. As *kanaká* uses only natural components for its construction and was cited as used in the past, it was considered an ancient technique to preserve manioc. The *kanaká* steps include: 1) in a region that will be flooded build a cone with *tacana* sticks (cf. Poaceae) fixed to the ground, which are tied with *ambé* vine (cf. *Philodendron* spp.), 2) line the *kanaká* structure with *cauaçú* leaves, 3) place the wet ground manioc mass in the *kanaká*, 4) cover the *kanaká* with *cauaçú* leaves. In this technique, the wet ground manioc mass is isolated from oxygen by the *cauaçú* leaves, allowing storage without oxidation and rot. In a large *kanaká*, manioc from an entire field (about 0,5-1.0 ha) can be stored. After processing, such a *kanaká* yields between 8-10 bags of manioc flour- weighing 60 kg each

The *kanaká* technique was mentioned only by one *ribeirinho* from the *várzea*. He was the oldest man interviewed (63 years) in *Sítio Fortaleza*, with greater traditional knowledge about the community. He was born in a municipality close to the study area (Fonte Boa) and remembers doing these techniques when he was young. However, in other projects conducted by the *Mamirauá* Institute, the *kanaká* practice was observed at other local communities along the middle Solimões River. As our interviews were not conducted at those communities, other mentions about *kanaká* in the region were not included in the results and figures of the present manuscript.

The techniques described above differ in terms of difficulty, speed and cost (Table 12). Manioc bagging is the fastest, easiest and cheapest technique, as it reuses bags that were used to pack manioc flour or other plant products. In the case of burial, the leaves must be collected and there is more physical labor to dig the pit and bury the manioc. The basket, in addition to requiring the collection of leaves, sticks and ties, also demands the ability to weave the fiber basket and sometimes bury or elevate it with a rope. Finally, the most time-consuming and laborious technique is the *kanaká*. It requires the collection of sticks, ties and leaves, the construction of the structure. The manioc mass must also be softened and ground, which takes at least 3 days to prepare.

Table 12. Techniques of manioc storage described in *várzea* and *paleovárzea* communities along the middle Solimões River in Central Amazonia, Brazil.

	Cited in archaeological or ethnographic studies in Amazonia	Material required	Manioc preparation	Labor time	Duration of preservation	Threats, like predation	Capacity	Quality of flour
Burial	Yes	*Cauaçú* leaves	Fresh peeled roots	Intermediate	At least 6 months	Low	High	Low
Basket (touching river bottom)	Yes	Fiber basket, fiber rope and *cauaçú* leaves	Fresh peeled roots	Intermediate	At least 6 months	Intermediate	Low	Low
Basket (free in current)	Yes	Fiber basket, fiber rope and *cauaçú* leaves	Fresh peeled roots	Intermediate	At least 6 months	Intermediate	Low	Intermediate
Bagging (touching river bottom)	No	Woven fiber bags	Fresh peeled roots	Fast	At least 6 months	Intermediate	Low	Low
Bagging (free in current)	No	Woven fiber bags	Fresh peeled roots	Fast	At least 6 months	Intermediate	Low	Intermediate
Kanaká	No	*Tacana* sticks, *ambé* and *cauaçú* leaves	Manioc root mass (manioc "*puba*")	Time consuming	At least 6 months	Intermediate	High	Intermediate

Storage time varies with each technique, spanning the time from when cultivation areas are flooded and the period they need to rebuild the manioc flour houses, which can vary from 1 to 4 months. In the scenario where extreme floods last longer, the *ribeirinhos* confirm that any manioc storage technique mentioned is effective and increasingly necessary.

Ribeirinhos interviewed mention that the flour from the stored roots can turn bitter. Because of this, they adopt specific processing techniques to remove the bitter taste. The main way to do this is to place the previously stored manioc in a sunken canoe near the riverbank, letting the river water soak the roots and wash away the bitterness (in the same way as they traditionally soften manioc to prepare the flour). Another strategy to help to remove the bitterness is to let the rainwater wash it off. Even when done effectively, interviewees mention that the flour produced for stored manioc is mainly reserved for family consumption, as its flavor and color can be less acceptable in the local market.

Distribution of knowledge in different ecosystems

Among the 88 people interviewed, 32 % did not know any technique for storing manioc roots, 20 % knew a little about it, 12 % knew it in detail but had never practiced, and 36 % knew some technique and had performed one in the past. These proportions, however, varied substantially between environments; in the *paleovárzea*, most of the interviewees (58 %) had performed some technique; in the *várzea* most of the interviewees either did not know any technique (46 %) or knew little about it (29 %). In this sense, *ribeirinhos* from *paleovárzea* communities use and know more about traditional techniques (72 %) than those from *várzea* communities (25 %) (Figure 13).

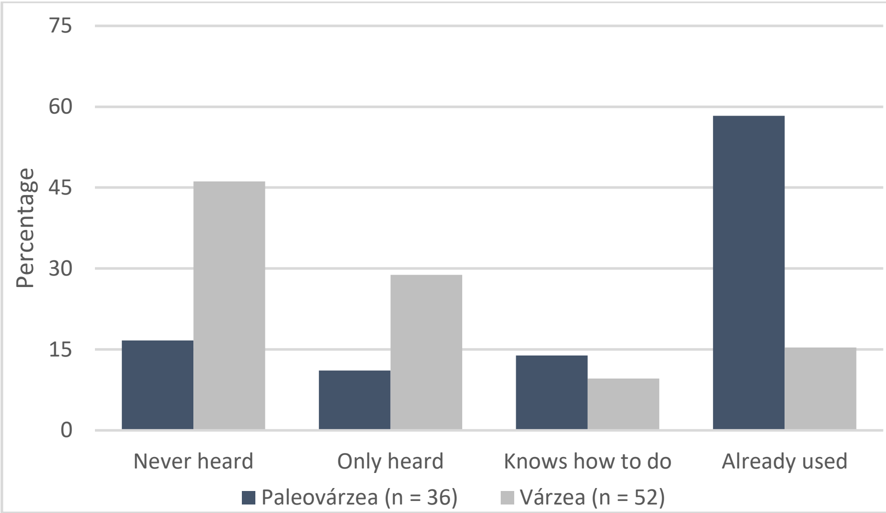

Figure 13. Percentage of *ribeirinhos* from both ecosystems in the middle Solimões River region, Amazonas, Brazil, who know and/or use manioc storage techniques during extreme floods.

In general, *ribeirinhos* from the *paleovárzea* know more about traditional manioc storage techniques (87 %) than those from the *várzea* (59 %) (Figure 14). As for the knowledge of each of the techniques, the bagging technique is the best known, followed by the burial technique, the basketing technique and, finally, the *kanaká*. In the *várzea* they know mainly the burial technique (47 %) and basketing (35 %), while in the *paleovárzea* the bagging technique is better known (64 %) and after the burial technique (29 %).

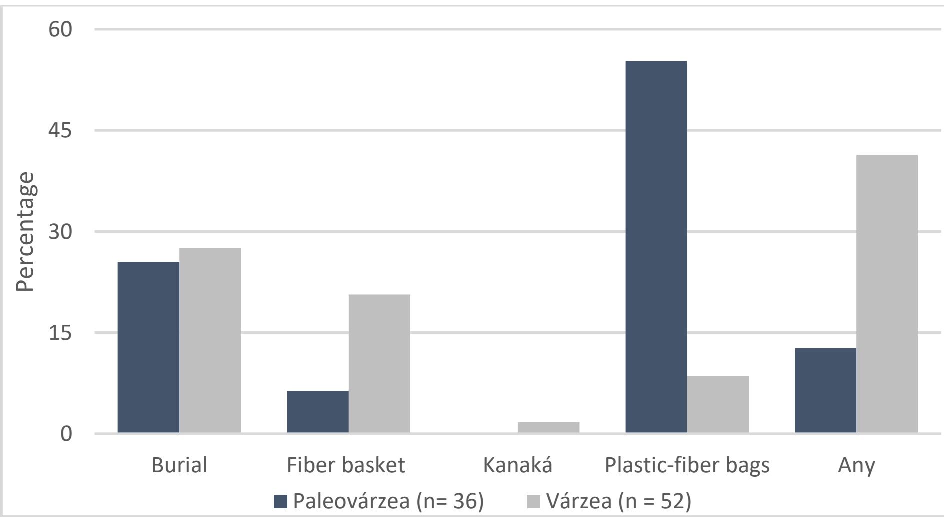

Figure 14. Distribution of knowledge (%) about each manioc storage technique in the study ecosystems in the middle Solimões River region, Amazonas, Brazil.

Among the known techniques, the *kanaká* was mentioned by only one *ribeirinho* in the *várzea*, the burial and basketing techniques are known by at least one *ribeirinho* from each community in both ecosystems. In contrast to what we hypothesized, results of generalized linear model to test the knowledge about manioc storage related to the *várzea* and *paleovárzea* ecosystems indicate that in the *paleovárzea ribeirinhos* know more about storing manioc than *ribeirinhos* in the *várzea* (β = -1.45, SE = 0.53, z = -2.76, p = 0,005).

Discussion

Four manioc storage techniques were cited as useful in case of extreme and unpredictable flooding. Two of these techniques have not yet been described in the literature for the region: *kanaká* and *ensacamento* (bagging). One of them consists of burying manioc roots, the other three consist of ways in which the peeled manioc is stored in different fiber packages (natural or synthetic), which are submerged in water (basketing, bagging and *kanaká*). One technique was exclusively mentioned in the *várzea* (*kanaká*) and only the most recently developed technique (bagging) is currently used in both ecosystems. We found that the greatest dissemination of knowledge and use of manioc root storage occurred in the *paleovárzea*. In the context of climate change, in which extreme flooding is more intense and unpredictable, *ribeirinhos* from both ecosystems who do not know the techniques were very interested in learning about them. In general, those who use the technique considered it more important today given the last extreme flood (2015).

Around the world, local communities also know and use traditional food storage techniques to preserve potatoes, maize, rice, cowpea, millet, quinoa, sorghum etc. For example, they use underground pits, wooden structures/silos or bags (jute, sisal, local grass, cotton or polyethylene) (Tapia and Torre, 1998; Mobolade *et al.*, 2019).

Manioc storage techniques using burials are cited in old (Edmondson, 1922; Lancaster *et al.*, 1982; Monteiro, 1963) and recent studies in Amazonia (Acosta Muñoz *et al.*, 2005; Mendes dos Santos *et al.*, 2021). Archaeological and ethnographic work highlights the long history of this burial technique in the region, which could be used to store starchy plant materials that would be used after the temporary migrations of indigenous groups (Furquim, 2018). Burial is also a technique historically used in Africa (Affran, 1968; Irvine, 1969) and in Mauritius island (Anon, 1944). In the latter case, it is referred to as "Reine's method", where layers of peeled manioc roots are alternated with layers of 7.5 cm of earth and then covered with earth (15 cm deep), allowing storage for more than one year (Anon, 1944). In India, there are also studies of manioc burials, where it was observed that after 2 months in a soil with 15 % moisture, 80-85 % of the roots were undamaged and could be used (Balagopalan, 2000).

As for the basketing technique, use was reported among indigenous groups from others traditional populations of the Solimões River (Sousa *et al.*, 2017) and the upper Negro River (Maia, 2018). In some regions of Hispanic America, where the *cauaçú* also occurs (locally called *bijão*), leaves are used to wrap food and protect it from humidity (Sousa *et al.*, 2017). In addition, in an archaeological study in the Purus River basin, it is believed that the basketing technique was used to produce *pães de índio* found in the interfluve of the Jacareúba-Mucuim Rivers, due to its specific conservation characteristics (Cangussu and Perez, 2017). With respect to the current use of burial and basketing techniques, other studies observed evidence of these practices near the middle Purus River, the upper Negro River and the upper Madeira River, suggesting that these techniques continue to be used, although infrequently (Mendes dos Santos *et al.*, 2021). In addition, the historical importance of the burial and basketing techniques has been highlighted for the storage of other roots (such as the *mairá* potato (*Casimirella* sp.)) and also fruits (such as *pupunha* (*Bactris gasipaes* Kunth) and *buriti* (*Mauritia flexuosa* L. f.) (Lancaster and Coursey, 1984; Mendes dos Santos *et al*, 2021).

In relation to the *kanaká*, the *puba* process causes the manioc to ferment. This process is also used for manioc flour preparation (locally called *farinha d´água*); the fermented softened roots facilitate the grinding into a homogenous mass and liberate part of the prussic acid (Lancaster *et al.*, 1982). With respect to the *kanaká* storage technique, some similar methods were observed in Uganda, which use wooden boxes with humid sawdust. The box is coated with plastic to prevent the sawdust from drying out for 4-8 weeks (Nahdy and Odong, 1995). However, in the case of *kanaká* the wooden structure has a cone shape, the plastic is substituted with local leaves, and manioc *puba* is used.

Storage in conical piles was observed in traditional indigenous silos in Colombia. In these a thick layer of straw is placed, and the roots piled up. The mounds, with between 300 and 500 kg of manioc, are covered with straw and earth, with openings left at the bottom for ventilation. The method allows storage for about one month depending on the temperature and rainfall of the season (Rickard and Coursey, 1981). In the Philippines, conical piles are also used to store manioc for 25 days (Baybay, 1922).

In relation to bagging, tightly woven bags without chemical treatment were observed in Ghana (Gallat *et al.*, 1998) and in Tanzania (Westby *et al.*, 1999), allowing 7-10 days of storage. The use of bags to preserve manioc roots is recognized as an extension of traditional storage methods, where plastic bags are used to prevent moisture loss and water stress (Rickard and Coursey, 1981). Polyethylene bags were also used with humid sawdust associated with chemical treatments, preventing post-harvest deterioration and increasing root quality (Carvalho *et al.*, 1985). In Colombia, this type of storage allowed conservation for 14 days (Best, 1990). Comparing the techniques present in the literature with those mentioned in the communities, we can identify that the techniques of bagging and basketing have similarities with the other techniques of storing manioc in water. In comparison to older techniques to store manioc, the bagging technique is easier, fast and effective, and demosntrate the dynamics of local knowledge (Haughton *et al.*, 2015). However, alternatives and old techniques provide options to store manioc and the knowledge about different techniques are important factors to enhance resilience in the context of climate change (Altieri *et al.*, 2015).

Várzeas are at high risk for major periodic flooding (Denevan 1996). In the *várzea* areas studied, *ribeirinhos* emphasized that they do not cultivate as much manioc as they used to because extreme floods are recurrent and unpredictable (Avila *et al.* 2021). Consequently, in *várzea* ecosystems, as there is less manioc to be processed into flour, the need for these storage techniques is smaller compared to the need in the past or compared to the *paleovárzea*. This may be the reason that *várzea ribeirinhos* know less about manioc storage than *ribeirinhos* in the *paleovárzea*.

Conclusion

Ribeirinhos of *várzea* and *paleovárzea* communities are familiar with four techniques for storing fresh manioc. However, in both ecosystems they used only a recently adapted technique (manioc bagging). *Ribeirinhos* from the *paleovárzea* know more about storage techniques than those from the *várzea*. In the *paleovárzea*, crops do not suffer from annual flooding, thus the swiddens are more important for income generation and, consequently, are larger, which could justify that knowledge of this technique is better distributed in this ecosystem. The differences in LEK are due to their histories of interaction with each ecosystem’s environmental characteristics, especially susceptibility to extreme flooding. In addition, many *ribeirinhos* in the study area want to know more about manioc storage techniques to avoid losing their crops. This demand reiterates how traditional and adapted technologies are dynamic, need to be shared and can be important in strengthening food security and sovereignty of communities in critical periods, favoring the resilience of these communities even in the context of climate change.

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Conflict of interests

The authors declare no conflict of interests.

Informed consent

The interviews were conducted after the interviewees signed the informed consent form wherein they agreed to participate in the study and authorized the disclosure of the results. This research was approved by the Ethics Committee for Research with Humans at Mamirauá Institute (CEP authorization number: 2.964.758), registered in the National System for the Management of Genetic Heritage and Traditional Knowledge (SISGEN A494ADE) and obtained authorization from the System of Authorization and Information on Biodiversity (SISBIO 65374-1).

Authors´ contributions

Conceptualization: Julia Vieira da Cunha Ávila, Charles R, Clement, Angela May Steward; Methodology: Julia Vieira da Cunha Ávila, Angela May Steward; Formal analysis and investigation: Julia Vieira da Cunha Ávila, André Braga Junqueira, Tamara Ticktin; Writing - original draft preparation: Julia Vieira da Cunha Ávila, Charles R. Clement; Writing - review and editing: Anderson Márcio Amaral; André Braga Junqueira; Gilton Mendes dos Santos, Tamara Ticktin; Supervision: Angela May Steward, Charles R. Clement.

Data Availability

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

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Synthesis

This thesis, divided into three chapters, investigated the impacts and recovery of *ribeirinhos'* floodplain agroecosystems after an extreme flood occurred in the middle Solimões River. In these chapters, we also verified general perceptions about the climate, how its changes affect daily activities, and identified the strategies *ribeirinhos* developed locally to deal with extreme climatic events.

In the first chapter, we evaluated extreme flood impacts on *ribeirinhos'* agroecosystems in different Amazonian floodplain ecosystems (low *várzea*, high *várzea* and *paleovárzea*), comparing the agrobiodiversity managed immediately before and immediately after the flood, and how this recovered after two years of management. We found that low *várzea* is the most critically impacted ecosystem. Immediately after the extreme flood, there was a reduction in the agrobiodiversity in the low and high *várzea*, which was recovered after two years of management in the high *várzea* and not recovered in the low *várzea*. In addition, manioc ethnovarieties took longer to recover in the low *várzea*. Comparing the agrobiodiversity between ecosystems, before the flood it were similar for both ethnospecies and manioc ethnovarieties. However, in the case of ethnospecies, immediately after the extreme flood and even after two years of local actions, the agrobiodiversity managed between ecosystems was more heterogeneous. Native species, especially palms and trees, tend to have a greater survival in agroecosystems after an extreme flood than non-native species.

In the second chapter, we collected local perceptions about the climate in the past and today, comparing adaptations in local agrobiodiversity management of the *várzea* and *paleovárzea* ecosystems. We verified that in both ecosystems *ribeirinhos* have deep knowledge about the climate, and the strategies to deal with extreme climatic events are in general similar between ecosystems, with the exception of temporary *terra firme* management and the construction of mounds of soil to protect tree roots, exclusively observed in the *várzea*. However, some strategies are still not shared among families of both ecosystems.

In the third chapter, from the adaptive strategies observed in chapter 2, we examined manioc storage techniques in detail, due to the great importance of manioc for local food sovereignty, income generation and cultural identity. These techniques were relevant for allow the processing of manioc as soon as the river water recedes. Previous reports about manioc storage techniques were obtained from ethnographic and archaeological studies, and included laborious techniques, such as the burial and basketing of manioc wrapped in *cauaçú* leaves. This study identified two new techniques: *kanaká* and bagging of manioc. The *kanaká* is more time consuming, but bagging is simple and easy, and news about this is being spread among communities.

This thesis is a contribution to understanding the impacts of extreme climatic events associated with climate change, recording old and current perceptions about climate, and contributing to the sharing of strategies to deal with the challenges arising from those circumstances. In view of the problems observed and the results obtained, it is evident that *ribeirinho* communities are increasingly in need of support to maintain local ways of life in changing climatic scenarios. As the impacts observed resulting from extreme climatic events are not punctual and can last for years, we suggest long-term support and strategic plans, from local to federal government levels, to deal with these scenarios.

For example, in 2015, many *ribeirinho* families received one month of food support from the state government; some also received potable water and wooden boards to raise the floors of their houses. Many *ribeirinho* families remember the state government's 2009 "*Bolsa enchente*" that allowed flexibility and a longer period of support. Extreme climatic events are expected to reoccur and, in these situations, agroecosystem soils can be covered with water for close to three months. As fast-growing plants take about 3-6 months to harvest, the creation of a government reserve fund could direct support to families hit by extreme flooding for up to nine months, reducing the drastic effect from lost crops. In addition, exchange of seeds and manioc cuttings could be promoted in local and regional meetings, favoring the sharing of information about seed storage, preparation of seedlings of recalcitrant species and adaptation strategies still not commonly observed, such as the production of mounds of soils to protect root systems and manioc storage techniques.

Local feedback actions associated with this research

Manioc and seed exchange fair

During the development of field work, we identified the need to strengthen the exchange of local plant varieties. We invited students from the Technological Vocational Center of the Mamirauá Institute to support a mobilization of annual fairs for the exchange of manioc and seeds (Figure 15). As the displacement of residents is very expensive and time-consuming, we found that the best strategy would be to hold fairs during the evening of cultural events associated with the General Assemblies that take place annually in the Mamirauá and Amanã Sustainable Development Reserves and to which all communities are invited to participate. We contributed to three seed exchange fairs (year 2018, 2019 and 2020, before the COVID-19 pandemic).

Figure 15. Photos that illustrate the seed exchange fairs in the RDS Amanã and Mamirauá (years 2018, 2019 and 2020)

Booklets produced in popular language

To share the impacts and main strategies that strengthen the local communities in the context of extreme climate events, as well as important aspects of local culture and agrobiodiversity, we wrote two booklets[4] that have already been printed and are available online (Figure 16). The materials were written with collaborators from the Mamirauá Institute for Sustainable Development and the National Institute for Research in the Amazon and will be delivered to residents and presented at schools in the region.

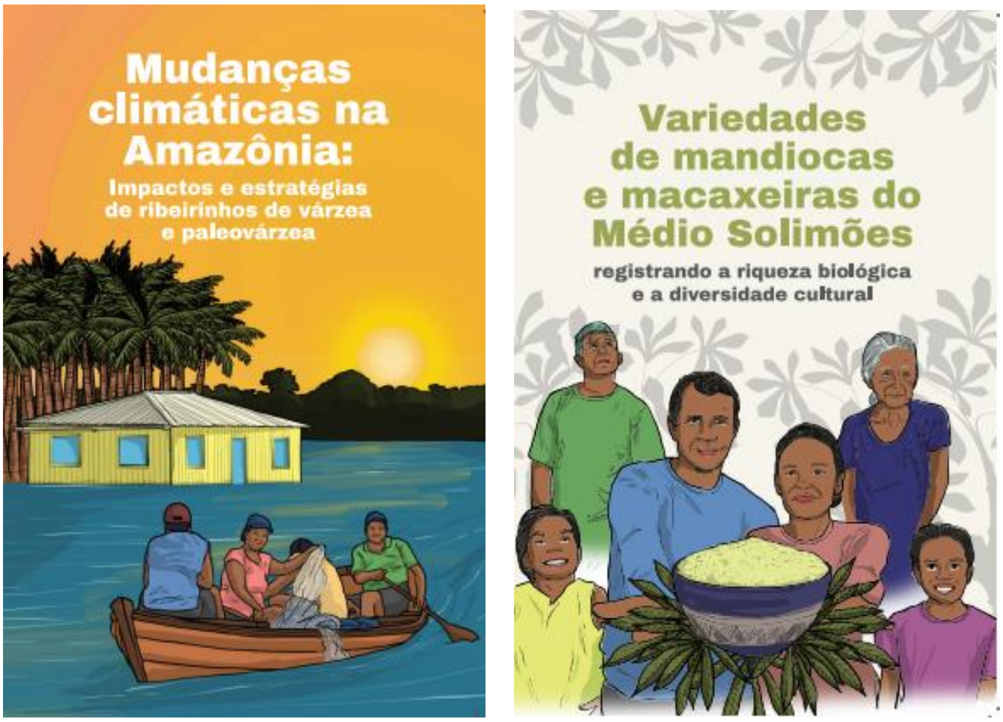

Figure 16. Cover of the books produced in popular language to share the main results and local strategies to face extreme climatic events in the region.

In addition, on June 21, 2021, the results of these booklets were shared on the radio station "*Ligado no Mamirauá*", a program with the theme "Impact of climate change on the Amazon floodplains, a problem aggravated in the context of COVID -19".

[4] ÁVILA, J. V. C.; SANTOS, J. P. G. ; LIMA, A. M. A. ; BERTIN, V. M. ; STEWARD, A. M. . Mudanças climáticas na Amazônia: impactos e estratégias de ribeirinhos de várzea e paleovárzea. 1. ed. Tefé: 2021. 48p. ISBN 978-65-00-54912-6.
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