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

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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 communities of the mid-Solimões River basin (Amazonas, Brazil). Our questions were designed to construct seasonal calendars with residents (*ribeirinhos*) 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 local 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.

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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 1). *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).

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 20th 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 & 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 1 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. 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 %

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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 2 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.

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Results

The 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 1). 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.

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 2). 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 1). Memories of extreme events coincide with river level data from hydrological stations near the study area (see Supplementary Material Figure 1).

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 (Figure 2), 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 3). 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 2), 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,

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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 4 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* sp.), 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 4 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.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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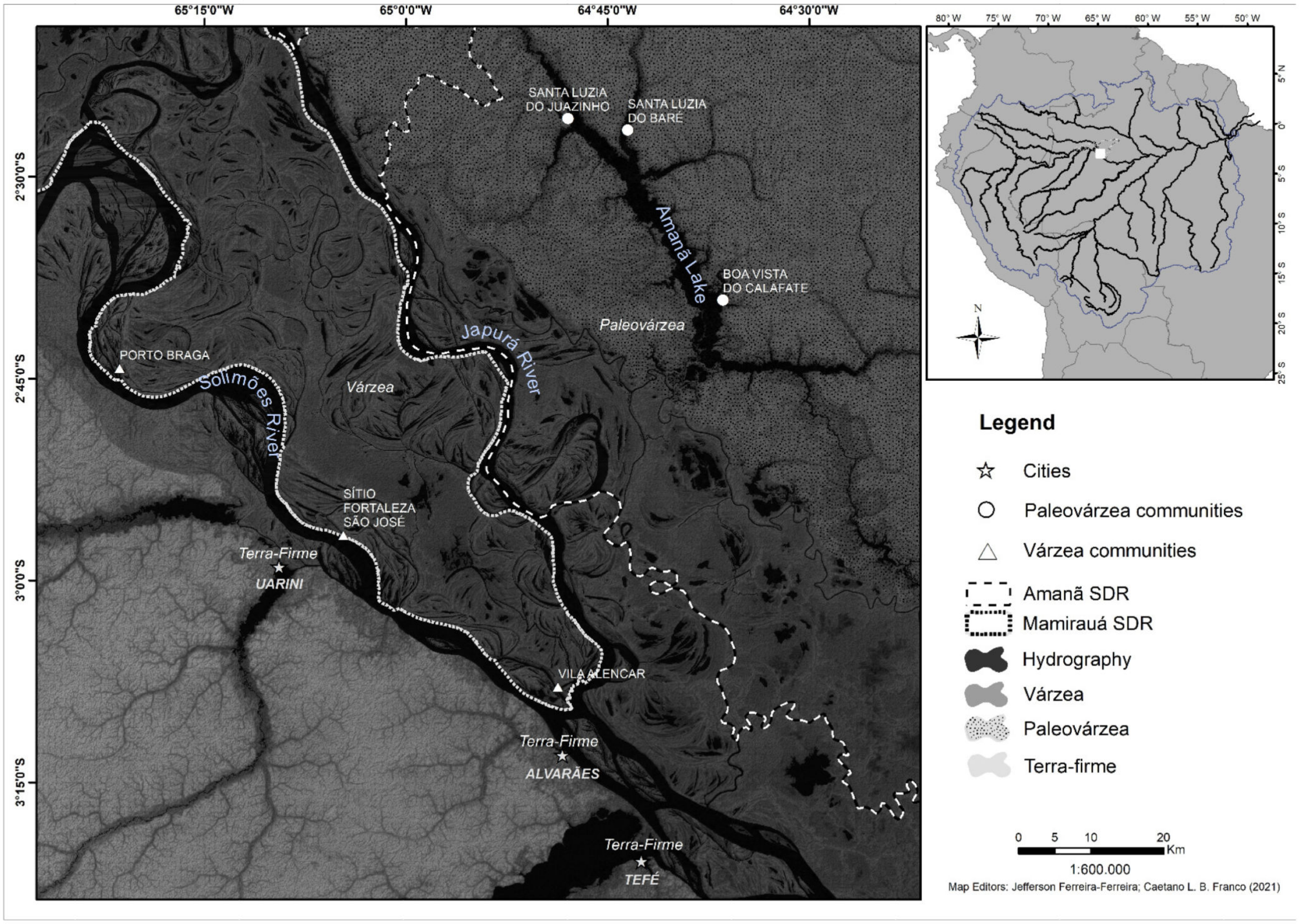

Figure 1.

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

Figure 2.

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. Marisummer 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).

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