Extreme hydroclimatic events in rural communities of the Brazilian Amazon: local perceptions of change, impacts, and adaptation

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Abstract

The Intergovernmental Panel on Climate Change Fifth Assessment Report reveals vast evidence of increasing climate variability and a higher frequency and intensity of extreme events. Vulnerable regions to such disturbances have been widely studied in some areas, but considerably less is known about other vulnerable regions that are key to global climatic regulation, such as Amazonia. In terms of the human dimensions of climate impacts, rural and indigenous communities in developing regions are among the most vulnerable due to their limited economic capital and direct reliance on natural resources. The purpose of this research was to reveal local perceptions about the impacts of, and adaptations to, recent climatic and associated hydrological changes caused by extreme events in the Brazilian Amazon. We worked in severely impacted rural Amazonian riverine communities utilizing a qualitative case study approach that included interviews, observation while living in the community, and participatory mapping. Our results indicate that participants perceived that there has been an increased occurrence and intensity of hydroclimatic events in the last decade, especially extreme floods. Findings also show that the repeated occurrence of extreme floods resulted in severe impacts, including some that had never been experienced by the local communities, such as the complete loss of perennials. We found that a wide range of locally devised responses was implemented, despite incipient governmental support. Data also showed that responses have evolved significantly over time due to local experience with repeated extreme events. A variety of factors also affected participants' abilities to respond to hydroclimatic changes, notably information exchange among farmers and access to technological advancements.

Keywords Climate change · Community-based adaptations · Vulnerability · Drivers of change · Rural communities · Brazilian Amazon

Introduction

Climate change (CC) is considered one of the main challenges to humanity in the twenty-first century (e.g., Fedele et al. 2020). Much of the associated research has focused on two general areas: the physical aspects (IPCC 2013) and

the human dimensions (IPCC 2014a, b). Recent Intergovernmental Panel on Climate Change (IPCC) reports have shown clear evidence of increasing climate variability and a higher frequency and intensity of extreme events (IPCC 2018; 2019a). Vulnerable regions to such disturbances have been widely studied in some areas, such as the Canadian Arctic (e.g., Stroeve et al. 2012) and small island states (e.g., Klöck and Nunn 2019). Considerably, less is known about other vulnerable regions, such as Amazonia, that are key to global climatic regulation (Snyder 2010). For instance, little can be found in AR5 about the sequence of extreme flooding and hydrological droughts that have affected the region during the last decade (IPCC 2014b; Marengo and Espinoza 2016).

Regarding human dimensions, recent research on the effect of CC indicates that it has caused severe impacts on rural communities all over the world (IPCC 2019a; Ahmed et al. 2021). In fact, rural and indigenous communities in

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Fig. 1 Conceptual model for community-based adaptation to climate change

developing regions are identified as being among the most vulnerable due to their direct reliance on natural resources, limited economic capital (Moftakhari et al. 2021), marginalization in decision-making, and, in many cases, “absence of recognized rights over their territories and resources” (Nakashima et al. 2012:8). Climate change impacts on human systems are common in three dimensions: human health, infrastructure, and livelihoods (Dasgupta et al. 2014). A review of over 400 case studies on how CC affects indigenous people demonstrated that impacts on livelihood are the most common (Galloway McLean 2010). Rural communities typically have limited access to goods and services, and impacts on their livelihoods tend to be quite harmful (IPCC 2019b), often leading to poverty traps (Olsson et al. 2014).

Although vulnerable to CC, rural communities are also usually well-equipped to respond to changes due to their history of adaptation, often grounded in local knowledge (Adger 2006). Underscoring this, AR5 partially shifts away from a focus on engineering structures for CC mitigation to considering the social dimension of responses, including community-based adaptations (CBA) (Noble et al. 2014). A local community-driven approach to adaptation “takes context, culture, knowledge, agency, and preferences of communities as strengths” (IPCC 2014b:1762). It focuses on the locally devised and implemented adaptations based on a bottom-up and learning-by-doing paradigm (McNamara et al. 2020). In this context, community self-organization is defined as the bottom-up process through which groups and communities in civil society organize to take collective action, thus aiming to advance their own agendas as opposed to market or government-oriented approaches (Atkinson et al. 2017). CBA allows for taking advantage of local epistemologies and experiences to explore new and expand already-tested solutions. “Given that climate change impacts, appropriate responses, and, to some extent, adaptive capacity, are location-specific, adaptation at the community level is

critical to the process of adaptation” (Bryan and Behrman 2013:2).

Human adaptation occurs in response to a variety of changes that are very much context-specific (Heffernan 2012). For this reason, CBA has increasingly considered socio-economic drivers of vulnerability together with climatic risks (Jamero et al. 2018). Klein et al. (2014:902) indicate that adaptations are influenced by “the rate of climate change as well as rates of economic development, demographic change, ecosystem alteration, and technological innovation.” The existence of multiple stressors is often more harmful to rural communities than the impacts of CC and, therefore, should not be overlooked (Räsänen et al. 2020). As CC is only one of many drivers of change, accounting for the context is essential for identifying how other forces constrain, enable, or make adaptation more flexible (Nakashima et al. 2012). The purpose of this research was to reveal local perceptions about the impacts of, and adaptations to, recent climatic and associated hydrological changes caused by extreme events in the Brazilian Amazon. Our approach considers social and ecological context within communities by accounting for how current drivers of change function as barriers and facilitators for adaptation.

Conceptual model

In order to present our data and explore outcomes related to our purpose, we have developed a conceptual model based on our consideration of the literature, as outlined in Fig. 1. Starting with a climate change event, such as extreme flooding, the model suggests the interactions among key CBA concepts with the solid black arrows indicating the relations that were the focus of this study. For instance, although adaptive actions feedback into climatic changes (white arrows), due to scope limitation, we chose not to focus on those relations but rather on how changes in climate and other drivers triggered adaptive actions (black arrows).

Perceptions of changes in the climate and river cycle were used as an entry point for our discussions with participants. Based on the IPCC's (2018:557) definition of "risk perception," we consider "perceptions of change" as "the subjective judgment that people make about the characteristics and severity of changes." Local perceptions are a common theme in the literature on CC in Amazonia and elsewhere (e.g., Altea 2020; Platt et al. 2021), and like Hasan and Kumar (2019), we recognize that these perceptions of change and impacts are necessary precursors of adaptation.

For the purpose of this study, impacts are defined as the consequences, outcomes, or effects of climatic and associated hydrological changes and extreme events on natural and human systems, based on IPCC 2019a. We focused on the impacts on livelihoods, infrastructure, and human health, all recognized in the literature as relevant impact areas (Dasgupta et al. 2014; IPCC 2019a). A vulnerability lens was used to explain the differential impacts among communities and households based on their adaptive capacity, exposure, and sensitivity to changes (Adger 2006). A system's vulnerability to change is defined as the "propensity or predisposition to be adversely affected" (IPCC 2019b:826) which is a function of the character, magnitude, and speed of changes (Adger 1999).

Human adaptation to CC is central to our conceptual framework. Adaptation to CC is defined as "the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities" (IPCC 2019a: 678). We draw on the CBA approach (Noble et al. 2014) to focus on locally devised adaptations implemented at the household and community levels. This approach gives attention to the short-term and long-term responses that offer enhanced resilience (Wilson 2012) and sustainable livelihood thinking (Scoones 1998).

Additional internal and external drivers of change either reinforce or soften community vulnerability to hydroclimatic changes by, for example, acting as barriers to and facilitators of adaptation. We define barriers as "factors that make it harder to plan and implement adaptation actions... [and] restrict the variety and effectiveness of options for actors to secure their existing objectives," and facilitators as "factors that make it easier to plan and implement adaptation actions, that expand adaptation options or that provide ancillary co-benefits" (Klein et al. 2014: 907). Accounting for the constraining and enabling factors of adaptation is key to understand climatic change contexts (Piggott-McKellar et al. 2019).

Choice of the study area

Magrin et al. (2014) point out vast evidence of increases in extreme climatic events in South America. In Amazonia,

studies have pointed out that river level variability has been increasing since the 1970s (e.g., Satyamurty et al. 2013), with both hydrological analyses and local observations indicating that variability has increased with higher intensity and frequency of extreme hydroclimatic events in the last two decades (e.g., Marengo et al. 2018). Extreme flooding and hydrological droughts have recently severely impacted rural Amazonian *ribeirinho* communities (Marengo and Espinoza 2016). For example, in 2010, the Manaus gauge station registered the lowest river level since records started to be kept in 1902 (Lewis et al. 2011) and, only two years later, recorded its highest level (Marengo et al. 2013). The second-highest level was registered in 2009 (Chen et al. 2010). In addition, the three floods from 2013 to 2015 were also among the nine highest on record at that point (Marengo and Espinoza 2016; ANA 2021), and 2005 registered the eighth-lowest nadir since 1902 (ANA 2021). Such extreme events were previously predicted to happen only once per century (Marengo and Espinoza 2016).

Eleven municipalities on the margins of the Amazonas River, Central Amazon, were selected for this study using several criteria: location in a productive rural region; suffering considerable impacts of hydroclimatic variability in the last decade; providing a mix of floodplain and upland environments, allowing comparison between those environments; providing relatively easy access to Manaus – the Amazonas State capital. The municipalities considered have a combined estimated population of 455,372 people in 2020 (IBGE 2021), with the most recent national census indicating that 45% of the population lived in rural areas, mostly in riverine communities, which was the focus of our research. When searching for communities within the study area to participate in research, we considered those that had higher levels of community self-organization, were willing to participate, had at least 30 households, and had accommodation availability with a good level of personal security. These criteria together with the availability of individual accommodation and personal security for the leading author led to the selection of the two villages described below.

Research approach and methods

Being exploratory research, we utilized a qualitative case study approach in order to gain a broad understanding of complex issues in a relatively limited amount of time without attempting to manipulate the phenomenon of interest (Creswell and Creswell 2018). Fieldwork was carried out in two phases over a 10-month period. Phase one lasted for approximately 3 months, with data collection beginning in November 2015. We conducted 56 interviews in this phase:

Fig. 2 Two study communities within the larger (gray) study area in Amazonas, Brazil

17 Amazonas State Rural extensionists,¹ 22 community members, eight other government representatives, four farmer and fisher labor unions or association representatives, four NGO employees, and one federal university professor. We sought agents and employees that worked closely with the communities for participation. Due to their close relationship and constant presence in the field, their accounts were considered as an additive to our understanding of how communities perceive change. Community elders, representatives, leaders, and knowledgeable members were also sought for participation. Interviews took between one and one and a half hours, with the data provided by participants compiled in field notebooks.

Two of the 19 communities visited in the first phase were selected as case studies for the second phase, namely Ajaratuba and Ilha do Baixo (Fig. 2). Both communities are relatively isolated, being reachable only through water access, and are around 4 h and 18 h away respectively from Manaus by regular boat transportation. Except for having a church and a primary school, the communities lack other facilities. Like other rural Amazonian communities, they also rely on diverse and non-specialized livelihoods (Adams et al. 2009). We found that their livelihoods involve various combinations

of small-scale family-based crop and animal husbandry, fisheries, and the extraction of timber and non-timber forest products (see also Moran 1984; Nugent 2009).

Phase two relied more heavily on participant and non-participant observation carried out by the lead author who lived in the communities for 7 months. A participant observation guide was used to assist in keeping track of activities observed, such as participants altering their means of transportation and increasing their reliance on fisheries during the flood period. In phase two, 17 community members of Ajaratuba and 20 from Ilha do Baixo were interviewed. Participatory mapping exercises with six participants in each community were carried out to increase understanding of the spatial distribution of impacts and adaptations.

Semi-structured interviews, participant observation guides, and participatory mapping exercises were designed to explore participants' perceptions of hydroclimatic changes and associated impacts on their livelihoods, infrastructure, and health, following our conceptual model. For instance, community participants were asked whether they noticed changes in the weather and river levels over the last few years (especially from 2009 on) and what were the impacts of those changes on their lives and livelihoods. Institutional agents were asked similar questions, aiming to understand the views of the communities they worked with. The complete interview guides are available in Appendices 1 to 3. Data-gathering procedures also investigated the locally devised short-term and long-term

¹ Amazonas State Agency of Technical Assistance and Rural Extension (IDAM, in the Portuguese acronym).

Table 1 Percentage of phase one interviewees mentioning hydroclimatic changes

Hydroclimatic changes	Total (n = 54)	Community members (n = 22)	Government officials (n = 24)	Others (NGO, university, fisher agric. org.) (n = 8)
Extreme flood	70%	77%	67%	63%
Stronger summer	48%	55%	42%	50%
Unpredictability	19%	27%	8%	25%
Extreme drought	15%	18%	13%	13%
Intense storm	7%	9%	8%	0%
Lack of <i>repique</i> *	6%	5%	4%	13%
Quick river drop	6%	5%	8%	0%
Lack of <i>friagem</i> **	4%	0%	8%	0%

*Repique: hydrological phenomenon in that the river level stops rising or receding and does the opposite for a short period, typically for 1 or 2 weeks

**Friagem: climatic phenomenon in which the temperature drops suddenly for a few days (around 3°C or 4°C for about 5 days in Amazonas State)

adaptations and their role in decreasing vulnerability to hydroclimatic changes. The barriers and facilitators to adaptation were taken into consideration to increase our understanding of relevant drivers of change affecting communities and their vulnerability to changes.

A validation workshop was conducted in each community at the end of the fieldwork, where preliminary findings and analyses were presented, followed by a discussion, allowing participants to ask questions and provide further feedback. The workshops lasted for approximately two and a half hours each, with 31 participants in Ajaratuba and 45 in Ilha do Baixo. Findings were also validated through member-checking, prolonged engagement in the field, data source, and methods triangulation, and detailed thick descriptions (Creswell and Poth 2018).

All interviews were fully transcribed, and the data were analyzed for themes and patterns using NVivo 11 Starter software. The data were first analyzed according to the categories drawn from theory (e.g., short- and long-term responses) and then in themes that emerged from the data. Data analysis was accomplished following the steps proposed by Creswell and Poth (2018) for the scrutiny of qualitative data, which included (1) organizing and reading through the data; (2) detailed analysis with data coding; (3) description and representation of findings, with the use of quotes and tables, examples; and (4) interpretation of findings in relation to research objective and the relevant literature.

Research findings in relation to the regional context

Perception of hydroclimatic changes

Participants were asked in phase one about changes in the climate and river cycle (i.e., hydroclimatic changes). Table 1

presents the percentage of participants that mentioned each of the eight grounded categories noted. Although our intent was not to quantify participants' perceptions of change, the proportion of participants who mentioned each change does provide a good picture of the changes that are perceived as being most relevant locally. The perceptions of phase 1 community and non-community members did not differ significantly and were also aligned with phase 2 participants' perceptions. Based on these answers, we focused our investigation of impacts and responses on the three of the most mentioned changes, i.e., extreme floods, extreme droughts, and hotter, drier summers.

Extreme floods were by far the extreme hydroclimatic event mentioned most often by interviewees. The extreme floods occurring from 2009 on were often cited by participants, and their identification of these events agreed with the physical data reported above. Changes noted included that high² floods are reaching even higher levels, occurring at a greater speed from the onset, taking longer to recede, becoming more recurrent, and ending in overall higher water levels (i.e., high water levels during the ebb phase). These themes crossed all the sectors that we interviewed, with a widespread agreement in the data. There was also agreement among participants that the last four floods at the time of data collection, from 2012 to 2015, were extreme floods.

Interviewees in phase one also widely cited 2005 and 2010 as extreme hydrological droughts, also corroborating the physical data and literature. Official data demonstrates that, in fact, river levels in these years were among the lowest ever recorded in the Manaus gauge station: 2010 was the very lowest and 2005 was the 8th lowest river level, reaching respectively 13.63 m and 14.75 m (ANA 2021). Participants

² High floods are those reaching higher than average levels but not enough to be considered an extreme event.

Table 2 Impacts of the main hydroclimatic changes and extreme events on rural communities

Livelihoods	Freq	Infrastructure	Freq	Health	Freq
Extreme flooding					
Loss of crops, seeds, propagules	High	Deterioration of houses/buildings	High	Dangerous wildlife (snakes)	Low
Shorter crop season	High	Loss of furniture and appliances	High	Lack of food and clean water	Low
Animals loss, lower productivity	Med	Damage of materials due to high humidity	Med	Increase in skin infections	Low
Perennials loss, lower productivity	Med	Electricity grid affected	Low	Migraine, headache, back pain	Low
Increased fish stocks	Med	Land loss due to riverbank slumps	Low	Drowning	Low
Extreme hydrological droughts					
Fish mortality (in lakes, channels)	High	Difficult access and transportation	Med	Lack of potable water	Low
Produce loss (difficult transport)	High	Increased costs of merchandise	Med	Difficult transport of patients	Low
Cattle death (due to lack of water)	Med	Stranded boats, speed boat crashes	Med	Dangerous wildlife (alligator)	Low
Difficult access to timber/NTFP	Med	Damage to fishing gear	Low	Accidents with speed boats	Low
Difficult access to fishing areas	Med	Damage to floating houses on dry land	Low	Diarrhea (polluted water)	Low
Drier and hotter summers					
Reduced crop productivity	High	Burned house and crop in uplands	Med	Headache, uneasiness, fatigue	Low
Unable to grow green vegetables	High	Material losses to fire	Med	Respiratory diseases	Low
Lower pasture productivity	Med	Loss of productive material to fire	Med	Eye infection due to smoke	Low
Fish mortality (in aquaculture)	Med	Loss of houses to fire	Low	Emotionally shaken due to fire	Low
Loss of trees (also due to floods)	Low	Contributes to impacts of droughts	Low	Insolation	Low

of phase two corroborated the results of phase one and added that 2015 was also a severe drought. Participants in both research phases also mentioned that storms (i.e., heavy rain with strong winds) are becoming more common and more intense. Such perceptions of extreme events fell in line with what others have reported in the regional literature (e.g., Camacho Guerreiro et al. 2016; Oviedo et al. 2016) and corroborated physical science data (e.g., Marengo and Espinoza 2016).

The second most mentioned change in phase one was that summers are gradually becoming “stronger.” In other words, the seasons have been presenting a combination of lack of rain and high temperatures beyond what participants perceived as average. Several participants mentioned 2015 as one of the strongest summers they experienced in the last decades. This corroborates the literature in that 2015 was the hottest year, with the lowest precipitation levels, since 1986 (D’Avila Junior and Vieira 2019). Participants also mentioned the unusual number of accidental fires happening in 2015, corroborating the Civil Defense reporting. Participants in phase two supported these views, and most mentioned that the climate has been changing toward stronger summers more noticeably in the last 10 to 20 years. “I remember that ten years ago the sun was not this hot, we would work until 11:00 a.m. and then go back to work at 1:00 p.m. We were used to that. Now, when it is 3:00 p.m. we still cannot get out of the house” (Josivan). Participants also noted that summers used to be windier which, together with the decrease in shade area

due to deforestation, there is an increase in the “feels-like” temperature.

Participants in both phases commonly mentioned that climatic events are becoming more variable, with a higher range of intensity within shorter timeframes: “the river is unpredictable. We observe, we live here the whole life by the river, but you don’t have an experience that works...” (José Rubens). The timing of rainy and dry seasons, rising and receding river levels, were presented as being harder to predict in the last years: “No one can predict how the next flood will be anymore” (Edmilson). There was no exact point in time which participants identified as being a turning point, but in general, they agreed that they already started to notice changes in the second half of the 1990s, intensified during the 2000s and reached their peak more recently. *Ribeirinhos* elsewhere have also widely reported their perception of lower hydroclimatic predictability (Pinho et al. 2015; Oviedo et al. 2016).

The impacts of hydroclimatic variability

Participants of both study phases reported a wide range of impacts in relation to the parent themes of livelihoods, infrastructure, and health (Table 2). We have considered low (1–25%), medium (26–50%), and high (51% and above) frequency of answers in relation to our themes, as reflected in Tables 2, 3 and 4, keeping in mind that this was a qualitative research undertaking. Questions focused on the three most cited hydroclimatic changes: extreme floods, extreme

Table 3 Short-term and long-term responses to hydroclimatic variability

Short-term responses	Freq	Long-term responses	Freq
Extreme flooding			
Improvised second floor on house	High	Focus on fast-growing crops	High
Increase fishing for subsistence	High	Focus on flood-resistant crops	Med
Harvest unripe crops	High	Uplift houses and community buildings	Med
Platforms on stilts for storage	High	Reduce or extinguish herds	Med
Transport cattle to rented upland fields	High	Increase number of floating houses	Low
Exchange of labor to harvest quickly	Med	Migrate to uplands or urban areas	Low
Small softwood planting beds on stilts	Med	Large hardwood planting beds on stilts	Low
Board dikes to delay inundation	Low	Acquire upland fields to transport cattle	Low
Extreme hydrological droughts			
Produce lighter crops (easier to transport)	Med	Pump potable water from uplands	Med
Switch fishing techniques	Med	Collect rain water (government program)	Low
Alternative routes (motorcycle + boats)	Med	Build embankment bridges	Low
Switch from lake fishing to river fishing	Low	Dig proper wells or holes by the riverbank	Low
Fishers switching to crop agriculture	Low	Collectively building dikes in creeks	Low
Treat the river water (hypochlorite, sieve, boil) or buy potable water	Low	<i>Bolinete</i> (device to pull boats to the land)	Low
Collectively dig ditches on silted lakes for school boats to transport students	Low		
Drier and hotter summers			
Reduce working hours	High	Irrigation system for fast-growing crops	High
Quit planting in summer without irrigation	High	Fast-growing crops under shadow screen	High
Wait to plant (soil correction after rain)	High	Fan and air conditioner	Med
Use more pesticides for caterpillar plague	High	More resistant varieties (e.g. plantain)	Low
Leave the uncovered area for breaking fire	High	Switch from cattle to buffalo	Low
Quit sensitive crops (e.g., cucumber)	Med	Introduce aerators to fish ponds	Low
Provide corn ration to cattle	Med		

Table 4 Drivers of change influence on adaptation to hydroclimatic variability

Driver	Strength	Influence on adaptation
Internal drivers of change		
Self-organizing and social cohesion	High	Enable collective responses and facilitate access to governmental programs (+) Enable mutual household support and social learning (+)
Capitalization	High	Financial resources allow for a wider range of responses (+) Lack of resources limits some responses (−)
Religion and spirituality	Medium	Faith counteracts action when denied real changes evidence (−) Faith and hope are associated with serenity to overcome losses and braveness to innovate (+)
Culture, habits, and mindsets	Medium	Relying on paternalistic policies limits some responses (−) Culture is closely related to the local environment, making them prone to find solutions to stay rather than migrating (+)
External drivers of change		
Access to market	High	Proximity to large markets enables a wider responses range (+) Difficult produce trade is a relevant bottleneck for action (−)
Technology	Medium	Access to technology enables learning and innovation (+) Reliance on technology erodes some traditional knowledge (−)
Government programs	Medium	Lack of programs to decrease vulnerability to extreme events (−) Emergency aid enables households to cope with flood impacts(+)
Social networks	Medium	Exchange of materials and knowledge among farmers and with governmental agents fosters learning and enable responses (+)

(+) facilitator; (−) barrier.

hydrological droughts, and stronger summers. Impacts of extreme floods were mentioned the most by participants, reflecting the repeated occurrence of such events in the last 10 years. In general, participants spontaneously mentioned livelihood impacts the most and health impacts the least, likely indicating their perception of the relative importance of such impacts. Plus, health impacts are usually idiosyncratic, while livelihood and infrastructure impacts, for the most part, often affect several households at once.

The data demonstrate that the perception of impacts reflected the vulnerability of communities to hydroclimatic changes, but this depended mostly on their geographic location and sources of livelihood. Geographic location determined the exposure to changes, with communities located in uplands suffering the most with the occurrence of strong summers and the least with hydrological droughts. Communities located by the main river stem did not suffer impacts of hydrological droughts as much as those located on the margins of lakes and river arms. Communities and households located on lower floodplain areas were the most exposed to extreme floods but also were more prepared to handle these events. Differential impacts were also determined by livelihood sources. As most participants relied on crop agriculture, extreme flooding and stronger summers were seen as important hazards. Those that relied mostly on fisheries were more concerned about the impacts of extreme hydrological droughts, while they felt that extreme floods actually brought positive impacts.

The setting of new records for river nadir and zenith in the last decade together with the increase in the occurrence of extreme events established a considerably higher severity of impacts on the local population. Impacts that were commonly observed in years of regular flooding became considerably more severe, such as the damage and even loss of houses, due to more intense currents and river waves. Moreover, new types of impacts were observed in some regions. “After the big floods new types of weeds that we didn’t know showed up” (Nerinho). The higher severity of impacts was also determined by the combination of hostile conditions. For example, extreme floods caused the siltation of bodies of water, which made fish stocks more vulnerable to the occurrence of more intense hydraulic droughts. Extreme floods also pushed the starting of the planting season to the peak of summer, which caused crops not to sprout well due to hotter and drier conditions.

The regional literature reported similar impacts of extreme floods on small-scale agriculture and fisheries, including loss of crops (Sherman et al. 2015) and lower crop, livestock and short-term fisheries productivity (Brondízio and Moran 2008; Pinho et al. 2015). Our findings of positive correlations between extreme floods and an increase in fishery yields in the following years also corroborate Castello et al. (2015). Findings related to property loss and damage

are also underscored by Marengo et al. (2012) and Maru et al. (2014). We found a scarce reference in the regional literature about the health impacts of extreme flooding. Examples of indirect health impacts were increased food insecurity (Pinho et al. 2015) and lower quality of potable water (Brondízio et al. 2009), which were also reported by our participants.

Regionally, we heard reports of increased fish mortality, underscoring Castello et al. (2015) and Röpke et al. (2017), and decreased captures due to difficulty accessing fishing grounds, as also found by Anderson et al. (2011) and Tomasella et al. (2013). The literature presents plenty of infrastructure impacts of extreme droughts including navigation interruption, stranded boats, and isolated communities (Pinho 2016), as we also found.

Adaptation to hydroclimatic variability

A wide range of responses to recent hydroclimatic changes was reported by participants in both study phases (Table 3). Although *ribeirinho*’s lives are already adapted to the river cycles (Arce-Nazario 2011), our findings indicate that there are continual fine adjustments to the interannual flood-pulse variability (see also, Pinedo-Vasquez et al. 2002; Smith 2011). The frequency of the responses we found regarding adaptation is likely related to the recent repetition of extreme floods since the last extreme droughts occurred long ago (see “[Perception of hydroclimatic changes](#)”). Findings also demonstrate the higher number and frequency of short-term responses in comparison to long-term responses. Most responses were related to avoiding and overcoming livelihood impacts, although responses to infrastructure and health impacts were also reported, such as building higher houses to avoid inundation and reducing working hours to avoid higher temperatures. The overwhelming majority of responses were devised at the household level and did not rely on governmental or other kinds of external support. An exception was gutters installed through a program of the Ministry of Social Development to gather rainwater in water tanks. Examples of community-based responses included gatherings to fight accidental fire in upland communities and protests against speed boats passing by flooded residential areas that were causing severe impacts to houses and community infrastructure due to the boat waves created.

Adaptations to extreme flooding found both in our case studies and by others included transporting cattle to uplands (Oviedo et al. 2016), building planting beds on stilts (Nascimento 2017), focusing on fast-growing crops and cultivars (Osuna et al. 2014; Sherman et al. 2015) and flood-resistant crops (Vogt et al. 2015), reducing herds (Nascimento 2017), increasing the rate of migration (Adams et al. 2009; Sherman et al. 2015), building improvised second floors (Padoch and Pinedo-Vasquez 1991; Sherman et al. 2016), increasing

the number of floating houses (Alencar et al. 2014), and increasing fishing for subsistence (Takasaki et al. 2010; Drapeau et al. 2011). Nevertheless, some of the participant adaptations, such as building dikes to protect crops from rising waters and uplifting houses using hydraulic jacks, have not been reported elsewhere, representing innovations that have only recently been implemented in the study area.

Participants' reports revealed that responses to extreme flooding have evolved significantly during the last decade as a result of the repetition of impacts. In the 2009 extreme flooding, for example, many households did not store plantain pseudostems, as they were expected to sprout spontaneously after regular floods. However, keeping these propagules on top of rafts and platforms on stilts turned into common practice as extreme floods became more frequent so that they would sprout. Households also started to become better prepared by keeping boards to be used in a variety of responses (e.g., putting planting beds on stilts and temporary improvised floors), renting upland fields in advance to keep their herds, and acquiring food for the cattle. The building of board dikes is an emblematic example of response improvement. "There were many changes along the time. Dikes started being made with logs coming down the river and water grass" (Nerinho). With increased experience, they tested and improved dikes with the use of sewed boards, sturdier stakes, and plastic tarpaulin to build higher and more resistant dikes.

Adaptations to extreme droughts and to hotter and drier summers are not well documented in the regional literature. In fact, the vast majority of examples informed by our participants have not been reported elsewhere. A possible reason for that is the higher severity of impacts of the last sequence of extreme flooding in comparison to the impacts of extreme droughts and stronger summers in the study communities. Adaptations that our participants reported and we in some cases observed included leaving clean areas around burn sites to avoid the spread of accidental fire (Emilio et al. 2006; Brondízio and Moran 2008; Carmenta Saskia et al. 2013), building water reservoirs, and switching crops (Emilio et al. 2006).

Drivers of change: barriers to and facilitators of adaptation

Participants were asked about the main drivers of change influencing adaptation to hydroclimatic variability. Table 4 presents the positive and negative drivers that are internal and external to the communities. The strength of drivers was determined not only by the frequency of answers but also by a qualitative analysis of participants' accounts of each. Communities with a higher degree of self-organization and social cohesion were found to implement collective responses that were not seen in other communities, such as

the protest against the impacts of river waves created by speed boats. They were also able to both request governmental support more efficiently and to access environmental programs and aid resources. Community self-organization and social cohesion were usually strengthened by the presence of strong local institutions. "Our community has always been a reference because when we plan something important in the community, all the community organizations work together" (Nei).

During the last hydroclimatic extreme events reported in this study, there were no governmental programs in place to increase the adaptive capacity of rural communities. There was also no warning system to inform locals about the probability of extreme events and their characteristics, such as the expected duration. As a response to extreme events in Amazonia, the federal and state governments repeatedly provided millions of dollars in short-term aid, instead of addressing the factors that cause the system's vulnerability (Borma et al. 2013). One of the reasons for governments to focus on readily observable measures is that those often benefit political and election structures (Adger et al. 2011). Participants felt that, despite the palliative nature of government measures, families did benefit from the provision of groceries, wood, and cash during the flood period. A common participants' complaint was the poor rural technical assistance provided by governmental agencies: "When farmers try a new technique in here, we always get a punch first because there is none to instruct us on the right way of doing it" (Jesiel). One of the main ways participants filled this gap was by exchanging information with farmers from other communities. This has allowed participants to learn, for example, about technological improvements to agriculture such as machinery, irrigation systems, and more productive crop varieties.

Interactions within our conceptual model

We highlight here five interactions within our conceptual model that were revealed by the data. The first interaction of note is between "perception of change and impacts," as there was a strong association between the severity of social impacts and the perception of the intensity of changes. Pinho et al. (2015:651) also found that remote communities of the Brazilian Amazon, in fact, perceived flooding events as extreme "on the basis of powerful social impacts." Similar results were also found for Bangladeshi and Peruvian Amazon flood-prone communities (Sherman et al. 2015; Alam et al. 2017). Our data suggest that the households located in high floodplain areas perceived the last extreme floods as more severe than low floodplain households did. A plausible explanation is that these households had never had their houses inundated in earlier floods, while low floodplain

households were used to inundation even in regular flooding events. Crop farmers and ranchers tended to consider the flooding events more extreme while fishers considered drought events more threatening, also due to the severity of impacts suffered (see also Castello et al. 2013).

The second interaction is between “adaptation and perception of change.” Considering this interaction in the model allowed us to identify that perception of change and of associated impacts significantly influence whether and how adaptation occurs, which has also been identified in the literature (Hasan and Kumar 2019). Participants’ accounts indicated that during the extreme flooding events of 2009 and 2012, most riverine families actioned almost exclusively only short-term responses to overcome flooding impacts, believing that such extreme events would take longer to happen again. This was supported by the fact that elders knew and taught that the last extreme flood of such proportions and similar impacts had taken place back in 1953. In fact, the perception that future risks are too far away was shown to, in general, prevent long-term responses (Michetti and Ghinoi 2020). Nevertheless, as extreme floods continued happening in the following years, long-term responses became more common. The benefits of long-term adaptation were then considered worth their higher costs by participants because a future extreme event seemed more probable to them, a rationale that can also be found in the literature (Bustos and Vicuña 2016).

The third interaction we highlight is between “impacts and adaptation.” New types of impacts and significantly higher-intensity impacts require novel and, in some cases, transformative adaptation (Wilson et al. 2020). The innovative responses presented in “Adaptation to hydroclimatic variability,” for example, would probably not have been carried out had extreme hydroclimatic events not happened. This is in line with the regional literature that presents novel responses stemming from impacts to “degrees outside living experience” (Pinho et al. 2015: 651). Some of these new responses we found included switching to fast-growing crops on riverbeds, cultivating flood-tolerant plantain varieties (see also Sherman et al. 2015, 2016), and planting grasses to protect houses from river waves (see also Oviedo et al. 2016).

The fourth interaction we considered was between “adaptation and vulnerability.” Most long-term adaptive measures presented in “Adaptation to hydroclimatic variability” led to lowering community vulnerability to extreme hydroclimatic events. These included switching to flood-resistant crops to decrease sensitivity and lifting houses to reduce exposure to extreme floods. Although adaptive measures usually result in vulnerability reduction, our conceptual model led us to realize that adaptation may rather increase vulnerability. In fact, maladaptive measures usually decrease specific vulnerability while increasing a system’s overall

sensitivity or exposure to hazards (Juhola et al. 2016). For example, we found that farmers who cut ties with the floodplain – by selling their house and lands – are free from flooding impacts but often are not able to gain a livelihood in upland or town areas due to lack of specific knowledge, lack of employment opportunities, and scarce financial resources. The literature corroborates that migration as an emergency response to environmental hazards usually increases overall household vulnerability (e.g., McNamara et al. 2018).

Interaction between “drivers of change and adaptation” is the fifth analytical link we highlight. Community self-organization and social cohesion were found to be strong internal drivers of change, determining a wider range of community-based adaptation. For example, crops were saved due to actioning community task forces to harvest fields about to be flooded, and community groups united to provide assistance through labor – to rebuild houses that fell apart—and for food donation to families that experienced major material losses. The literature notes that communities with such cooperative capacity were better equipped to adapt and therefore less vulnerable to hydroclimatic impacts than their lesser self-organized counterparts (e.g., Barnes et al. 2020), which could be at play here as well. Access to economic capital was also stressed by participants as an important driver of change supporting adaptive capacity, corroborating social sciences CC literature (e.g., Moftakhari et al. 2021). For example, the households that we were able to acquire upland property without having to sell their floodplain lands were better off when coping with extreme floods both in terms of housing safety and secure livelihood sources, as our data shows.

Conclusions

This exploratory study contributes to the CC adaptation literature by providing a local perspective grounded in the perceptions of participants that supports and adds to the directions noted in the literature. One contribution relates to demonstrating that the frequency and intensity of extreme climatic events have created new and significantly more severe impacts for local communities. In the worst case, such impacts could even undermine local capacities to react, as Pinho et al. (2015) also noted. Our findings are also relevant in indicating that extreme stresses require innovative and transformative forms of responses, as revealed locally, in addition to the incremental short- and long-term adaptations emphasized by the literature (Novalia and Malekpour 2020). The locally devised responses demonstrated through our cases to have the potential to impact policy-making in the region and elsewhere. Policies that learn from and support local responses have the advantages of being usually low-cost and culturally appropriate in comparison to

external fixes. In addition, governmental policies should, at least partially, focus on strengthening self-sustaining measures for building on any developing community capacity (Robinson and Berkes 2011). Our findings certainly support the IPCC (2019b) indication that the involvement of local stakeholders and the reinforcement of their own attempts at climate adaptation improves the effectiveness of CC governance by maximizing co-benefits and minimizing trade-offs, especially for more vulnerable communities.

Our purpose was to explore local perceptions about changes and impacts due to extreme hydroclimatic events to demonstrate the local responses of riverine communities in the Brazilian Amazon. In this regard, participants established that they did clearly and correctly recognize the increased occurrence and intensity of hydroclimatic events in the last decade, especially extreme floods, as their perceptions were supported by findings of IPCC AR5 and the regional literature (e.g., Brondízio and Moran 2008; Ruiz-Mallén et al. 2017). Findings demonstrate that the repeated occurrence of extreme floods resulted in severe impacts, including some that had never been experienced by the local communities, such as the complete loss of perennial crops. We found that a wide range of locally devised responses was implemented despite the lack of governmental support. Our data also show that many of these responses evolved significantly over the last decade due to local experience with repeated extreme events, a finding that we expect will become more common in other studies, but that has not been noted yet. In fact, locals made investments in longer-term adaptation due to their repeated experiences.

Not surprisingly, we found a variety of factors affected participants' ability to respond to hydroclimatic changes, notably information exchange among farmers of the same or other communities and access to technological advancements such as irrigation systems and more flood-resistant crops. Such findings are valuable and must be tested against new evidence as extreme floods have continued to occur since the conclusion of this research. In 2019, the 6th highest river level at that time was recorded at the Manaus gauge (29.42 m), and in 2021, a new highest level was set (30.02 m), surpassing the 29.97 m registered in 2012 (ANA 2021). Given the ongoing occurrence of such events in the context of the COVID-19 pandemic, future research should consider the extent to which emergency aid provided by the Brazilian government since April 2020 has enabled *ribeirinhos* to improve local responses. Recent research indicates the success of such measures in safeguarding the essential needs of local Amazonian populations (Lopes et al. 2021).

As the field of CBA is still emerging and lacks a well-established analytical framework, our conceptual model is intended to contribute to future research, especially regarding

local communities facing CC impacts. Our model proved valuable for revealing important linkages among key CBA concepts. While we placed emphasis on adaptation as being at the core of the model, the interactions among impacts and adaptations and barriers to adaptation provide a fuller picture of the effects of extreme weather on rural communities and their ability to change. We found, for example, that the capacity to self-organize and community cohesion worked together to help to drive change and adaptation. The model also facilitated our understanding that people's perceptions of change and the kinds of impacts they suffer will determine if, how, and when they may adapt. The model also demonstrated the strength of taking internal and external drivers of change into consideration, something that is now receiving increased recognition within the CC literature (Olsson et al. 2014). As pointed out by Fraser et al. (2011:2): "Taken together...[the] social and ecological context in which climatic problems occur is likely to be as important, if not more so than the climatic shock itself." Our findings in relation to the interaction between adaptation and drivers of change certainly support this view.

Looking into the future development of the CBA field, we envision a need for researchers to further engage with learning approaches and theories. The challenges imposed by CC creates room for "temporal, geographical, political, institutional learning spaces" (Robin et al. 2019:246) including experimentation and innovation (Novalia and Malekpour 2020), which some of our respondents did, at least from their point of view. As new impacts and novel responses are, to a certain extent, beyond the living experience of local populations, there is also room for research to explore the risks and costs of locally devised innovations and transformations. Transformative responses could, in fact, turn out to be maladaptive (i.e., increase vulnerability) by strengthening path-dependencies, for example, Barnett and O'Neil 2010). Finally, future research on CBA should look at the conditions for successfully scaling up local CBA initiatives into higher-level programs and policies where the fit seems right. In line with Kirkby et al. (2017), we believe that the CBA approach needs to gain efficiency by aligning theoretical development with practical lessons to improve the well-being of local communities and others among the most vulnerable to CC.

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