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# Understanding Multidirectional Climate Change Impacts on Local Livelihoods through the Lens of Local Ecological Knowledge: A Study in Western Amazonia

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**ABSTRACT**

Climate-related changes taking place in Amazonia substantially impact social-ecological systems, affecting local livelihoods strongly reliant on natural resources. Here, we investigate climate change impacts on different livelihood activities in western Amazonia, through the lens of local ecological knowledge. We conducted semi-structured interviews and surveys with ~400 residents from 24 communities spread across a ~600 km stretch of the Juruá River. Residents reported a vast set of changes, many referring to changes in the atmospheric system (e.g., more summer rainfall), but with cascading effects in physical, biological, and human systems. Different livelihood activities are impacted with different intensities and by different climate-related changes. While most changes have negative impacts, residents recognize some positive impacts of climate-driven changes (e.g., large river floods positively impact fishing). Beyond demonstrating the manifold and multidirectional climate change impacts, our findings highlight the contribution of local ecological knowledge in identifying vulnerable livelihood activities and biodiversity-based value chains.

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Climate change; local communities; local ecological knowledge; local perceptions; social-ecological systems

## Introduction

Climate change represents one of the greatest challenges in Amazonia. Predicted climatic changes in the region will likely shift forest environments into a bioclimatic scenario typical of savannas (Alves de Oliveira et al. 2021) and lead to pronounced changes in river dynamics—particularly an increase in large river floods and droughts (Thomas et al. 2004; Schmidhuber and Tubiello 2007; Rockström et al. 2014; Marengo and Souza 2018). Climate change impacts are further aggravated by the enduring occurrence of forest fires and climatic instabilities arising from phenomena such as El Niño and La Niña (Marengo et al. 2008; da Silva Abel et al. 2021). Although seasonal climatic

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variability and extreme events have historically occurred in the region, the frequency and intensity of anomalies have increased, representing a substantial challenge for Indigenous peoples and local communities (Menezes et al. 2018).

Given Amazonian wide geographical extent and large cultural and biological diversity, the intensity and type of climate change impacts on local livelihoods can vary substantially. A vast portion of the region is formed by mosaics of flooded environments, inserted in a matrix of non-flooded upland forests. Flooded areas are subject to a predictable annual flood pulse (Marengo et al. 2011b; Hawes et al. 2012; Zulkafli et al. 2016; Bredin et al. 2020; da Silva Abel et al. 2021) that shapes the life of biological and human communities that have adapted to this dynamic environment (Schöngart and Junk 2007; Junk et al. 2018). Given their strict dependence on the annual flood pulse, Amazonian floodplains social-ecological systems are considered particularly vulnerable to the increased incidence of extreme weather events that affect the flood pulse (Cochrane and Barber 2009; Barros and Albernaz 2014; Sorribas et al. 2016).

Climate change also differently impacts different species, including those that contribute to local wellbeing (e.g., Evangelista-Vale et al. 2021), therefore different livelihood activities may be differently impacted depending on the extent to which the species on which these activities are based are affected. The understanding of climate change impacts on local livelihoods is still incipient in Amazonia (but see e.g. Funatsu et al. 2019; Evangelista-Vale et al. 2021), in spite its large geographic extent, its socio-ecological diversity, and its exposure to different climate change impacts. Moreover, although local communities in Amazonia typically engage with multiple livelihood activities, differential impacts on different livelihood activities still constitute an important knowledge gap. Jointly considering climate change impacts on the diversity of environments and livelihood activities can be useful, for example, to identify vulnerable livelihood activities and biodiversity-based value chains. This is particularly important in Brazilian Amazonia, where comprehensive public policies addressing climate change impacts on local livelihoods are lacking, despite the growing body of evidence showing the proximity of an ecological tipping point with dramatic ecological and social consequences (Lovejoy and Nobre 2018).

Recent works have demonstrated the potential of Local Ecological knowledge (LEK) to understand how climate change impact local livelihoods (Hopping, Yangzong, and Klein 2016; Savo et al. 2016; Removed by SNR). Through their long-term relationship with nature, local communities have developed detailed LEK that they apply in the use and management of the local resources, and based on which they also identify (and react to) changes (Hou, Han, and Li 2012; Rodriguez, Eakin, and de Freitas Dewes 2017; Lemahieu et al. 2018; Yager et al. 2019). Indeed, previous research in the Amazon has relied on LEK to capture local perceptions of risk, vulnerability, and adaptation to climate-driven changes in the hydrological regime, agricultural practices, wildfires, and extreme weather events (Brondízio and Moran 2008; Camacho Guerreiro, Ladle, and da Silva Batista 2016; Oviedo et al. 2016; Fernández-Llamazares et al. 2017; Ruiz-Mallén, Fernández-Llamazares, and Reyes-García 2017; Funatsu et al. 2019).

Here, we investigate how riverine communities in western Amazonia experience climate change impacts on different livelihood activities. We address the following research questions: (i) Which are the main climate-related changes reported[1] by local communities? (ii) What are the livelihood activities most impacted by climate-related changes, particularly by extreme climatic events, according to local communities? (iii) How does the impacts of extreme climatic events vary across livelihood activities and environments? We discuss these results highlighting the potential of LEK to elucidate the complexities of climate change effects on socio-ecological systems, and to inform public policies aiming to mitigate and adapt to climate change impacts.

## Study Area and Socioecological Context

The study was carried out along the middle section of the Juruá River (Figure S1, Supplementary Information), an important white-water tributary of the Amazon River. The Juruá River comprises more than 3000 km in length, from its source in Peru until it flows into the Solimões River in Brazil, being the most meandering river in the Amazon and one of the largest rivers in the world (Souza 2010; Sousa and Oliveira 2016). Through its journey, the river carries a large amount of nutrient-rich Andean alluvial sediments that are deposited during the annual flooding in the floodplains (Hawes et al. 2012; da Silva Abel et al. 2021).

The middle Juruá is inserted in the Amazonian floristic region, with predominance of dense Ombrophilous forest. The climate is humid equatorial, with yearly rainfall ranging from 1800 to 2200 mm, average temperatures around 29 °C, and relative humidity generally above 90% (Hawes and Peres 2016; da Silva Abel et al. 2021). Seasons are marked by the hydric dynamics of the river, alternating periods of high ("floods") and low ("drought") river water levels. The rainy season starts in November, reaching its peak between January and April. The wet and the dry seasons coincide with periods of high (January–June) and low river water levels (August–November), respectively (Souza 2010; Alvares et al. 2013). River fluctuation also determines the availability and use of natural resources, thus directly affecting the livelihood activities of riverine populations (Souza 2010; Junk et al. 2018).

The Juruá region is composed of flooded environments and non-flooded upland forests (Hawes et al. 2012; da Silva Abel et al. 2021). The region was occupied almost exclusively by Indigenous groups until the middle of the 19th century when it witnessed the arrival of traders and explorers from other areas. The first and second rubber cycles (during the late 19th century and the middle of the 20th century) led to a large influx of migrants from northeastern Brazil who came to work as rubber tappers (Souza 2010). After the Second World War, with the decline of the Amazon rubber economy, many rubber tappers migrated to urban areas and those remaining intensified the extraction of timber resources, agriculture and fisheries for subsistence (ICMBio 2012).

Currently, the main livelihood activities practiced by riverine communities along the middle Juruá River include the extraction of forest products (timber and non-timber), agriculture, and fishing (Newton, Endo, and Peres 2012; ICMBio 2012). Local communities conduct several livelihood activities (Figure S2, Supplementary Information), including upland and floodplain agriculture (focused on manioc production), homegardens and agroforestry systems, carpentry (Newton, Endo, and Peres 2012), fishing (Campos-Silva et al. 2021), hunting (Abrahams, Peres, and Costa 2017), and extraction of several non-timber forest resources including rubber (*Hevea brasiliensis*), açaí

(*Euterpe precatoria*), andiroba (*Carapa guianensis*), muru-muru (*Astrocaryum murumuru*), and ucuúba (*Virola surinamensis*). Manioc is the main source of carbohydrate for local communities and one of the main sources of cash income through the sale of flour (Newton, Endo, and Peres 2012), while fishing and hunting are crucial for protein intake (Sarti et al. 2015; Endo, Peres, and Haugaasen 2016).

Territorial governance within the Juruá River represents a polycentric governance model, which includes a multiplicity of decision-making environments governing a resource under defined boundaries, different organizations, scales, autonomies, and processes (Campos-Silva et al. 2021). The decision-making instances are composed of multiple actors from individuals to a wide set of organizations, including grassroots associations, NGOs, universities, government, and private entities (Campos-Silva et al. 2021).

## Materials and Methods

### *Site Selection*

We conducted research within two sustainable-use protected areas (PAs), the Extractive Reserve of Médio Juruá (hereafter RESEX) and the Uacari Sustainable Development Reserve (hereafter RDS), both located in the municipality of Carauari, Amazonas state (Souza 2010). These two PAs cover a total of 11,331.67 $km^2$. Local populations in the area are spread in small communities located on the margins of the Juruá or its tributaries. The RESEX was created in 1997 and currently has 1921 residents distributed in 338 families and 24 communities; the RDS was created in 2005 and currently houses ~1300 people, distributed in 234 families and 33 communities (ICMBio 2012; SEMA 2019). The categories of "extractive reserves" and "sustainable development reserves" were created in Brazil in the 1990s and 2000s to align the aspirations of both biodiversity conservation and local social development, hence they are PAs focused on the sustainable resource management by local communities (Campos-Silva et al. 2021). In spite of differences in administration (RESEX is federal and RDS is state-managed), these PAs are very similar regarding their socio-ecological characteristics.

Research communities were selected to ensure the representation of different environments (i.e., floodplains and non-flooded uplands) and livelihood activities. Although fishing, homegardens/agroforestry systems, extractivism, hunting and carpentry are carried out in all communities, some activities are more prominent in certain communities than in others due to differences in landscape characteristics, access to resources and cultural background.

Before starting our research, we obtained research permits to access the RESEX and RDS according to the Brazilian legislation. We also obtained ethical authorizations from the Ethics Committee of the Universitat Autònoma de Barcelona (CEEAH—4935), and from the Brazilian National Ethics Committee (CAAE—26800819.1.0000.5013). From each participant interviewed, we obtained oral and/or written free, prior, and informed consent. This study is part of a wider project (LICCI—Local Indicators of Climate Change Impacts; https://licci.eu/) designed to increase our understanding of reported climate change impacts, an endeavor to bring Indigenous and local knowledge into policy-making processes and influence international climate change negotiations.

### *Data Collection*

We collected different sets of data to answer the different research questions. To obtain information on observed climate-related changes and how different livelihood activities are affected by them, we conducted 42 semi-structured interviews with local residents from eight communities in March 2020 (i.e., before the COVID-19 pandemic hit the area). We selected people locally recognized as knowledgeable about the environment, environmental changes, and local livelihoods. We selected participants using the snowball method and considered a balanced number of women and men of different ages.

During semi-structured interviews, we asked participants about any change that they had observed in the environment since their early adulthood. Initially, we asked about all observed changes, regardless of whether they were climate-related or not. After the interviewee stopped mentioning environmental changes, we asked about changes in specific elements of the atmospheric, the biophysical, and the human systems, including changes in rainfall, temperature, river dynamics, wind, wild plants, crops, livestock, wild animals, fish or human health. To better understand whether the change was only or mainly attributed to climate change, for each change reported, we also asked about the cause (driver) of change.

In each community, after finishing the semi-structured interviews, we conducted a focus group discussion (FGD). FGD were intended to provide collective validation of changes mentioned during semi-structured interviews and to record additional changes. Participants in FGD numbered between 4 and 14, adding up to a total of 85 participants in eight FGD (see details in Table S1, Supplementary Information). Most FGD participants had not participated in semi-structured interviews. Participants were diverse in terms of sex, age, and livelihood activities performed in the community.

To evaluate the impact of extreme climatic events on different livelihood activities, we conducted individual surveys with 317 residents from 21 communities from March to April 2018 (see details in Table S2, Supplementary Information). To select participants, we used a convenience sampling strategy, approaching people who were available during our visit to the community, but trying to keep a gender balance and to interview people engaged in different livelihood activities. We focused on the impacts of three types of extreme events related with changes in the river dynamics: large river floods, small river floods, and large river droughts. We focused on these types of events based on previous information obtained from local leaders, who indicated that these were the most common extreme events they experienced. While the understanding of "extreme event" may vary between respondents, it generally refers to remarkable events where the river water level at a particular time differs considerably from a historical average. We started interviews by asking participants about their main livelihood activity and the environment where this activity was conducted (upland or floodplains). Then, we asked if the activity had been negatively impacted by the last occurrence of each of the extreme events selected. Specifically, we asked: "Did you suffer any production loss during the [last large river flood/small river flood/large river drought] that you remember?"

### *Data Analysis*

We used descriptive statistics from data obtained in semi-structured interviews to quantify the most (1) frequently mentioned climatic-related changes, (2) impacted livelihood activities, and (3) frequent climatic drivers leading to reported changes. Given our emphasis on climate-related changes, in the analysis we focus on observed changes on elements of the atmospheric system (e.g., changes in rainfall) or directly driven by changes in elements of the atmospheric system (e.g., changes in crop growth driven by changes in rainfall). We did not include changes not linked to the atmospheric system by any of the respondents who mentioned them.

Each change reported during semi-structured interviews and/or FGD (hereafter "observation") was classified into a category of Local Indicators of Climate Change Impacts (LICCI), using a hierarchical system devised to categorize observations of climate change impacts made by local communities (Removed by SNR). LICCIs are grouped into the following higher categories: atmospheric (observations related to changes in temperature, clouds, and rain), physical (observations related to changes in rivers, and soil), biological (observations related to changes in species abundance, phenology, etc.) and human (observations related to changes in cropping systems, human health). For each reported change, we also coded if the respondent made an explicit association with impacts on specific livelihood activities, and the perceived direction of such impact (i.e., positive, negative, neutral). The livelihood activities considered were: andiroba seed harvesting, açaí extraction, fishing, hunting, manioc cultivation, murumuru seed harvesting, homegardens/agroforestry systems, rubber extraction, turtle management, and ucuúba seed harvesting. Changes that had both positive and negative impacts or unclear impacts were classified as "neutral." Finally, we classified the drivers of impacts associated with specific livelihood activities as "large river drought," "large river flood," "small river flood," "change in frequency of flooding," "change in rainfall," or "change in temperature." For example, the observation "large floods are killing the andiroba trees in the floodplains" was associated with the livelihood activity "andiroba harvesting," with the direction "negative," and with the driver "large river flood."

To investigate how the impacts of the selected three extreme events (i.e., large river floods, small river floods, and large river droughts) vary according to livelihood activities and to the environment where they are practiced, we performed Generalized Linear Models (GLMs) using binomial error structures using survey data. The response variable in the GLMs was the presence or absence of reported production losses in the last episode of the extreme event, while the predictors were the main livelihood activity of the respondent and the environment where the livelihood is practiced (floodplains or uplands). Models were fitted using the lmer function from the lme4 package and each model combination was examined using the MuMIn package (Barton 2009). We selected the most parsimonious model with the lowest Akaike Information Criterion, correcting for small sample sizes (AICc). $\Delta$ AICc is calculated as the difference between each model's AICc and the lowest AICc, with a $\Delta$ AICc $< 2$ interpreted as substantial support that the model belongs to the set of best models (Burnham and Anderson 2004). After model selection, we calculated a model average, which considers the beta average of all variables included in parsimonious models (Table S4, Supplementary Information). As the variables were standardized (*z*-scores), we compared the relative effect size of all variables. All assumptions were examined before analyses, including linear relations, correlations between explanatory factors, homoscedasticity, and distribution of residuals (Zuur, Ieno, and Elphick 2010). All analyses were performed within the R platform.

Before presenting our results, we acknowledge some important limitations of our work. First, we recognize that LEK is holistic in nature, a characteristic that is not properly reflected in the classifications used in this work (e.g., "atmospheric," "biological," "physical," and "human" systems). While admittedly an over-simplification, we argue that these can be useful in summarizing the complexities of LEK and in favoring dialogues with western scientific knowledge. Second, none of us are members of the local communities represented in this work, nor speak on their behalf. Thus, it is possible that some of the interpretations presented here do not match those of local residents (in spite our efforts to avoid it). Third, we recognize that some of the livelihood activities analyzed here are less important in some sampled communities that in others, for which people might not have referred to them during interviews. Fourth, we acknowledge that reliance on memory to report on past events can bias respondents' responses, as extreme weather events that have recently occurred tend to be more often mentioned by respondents. Finally, although climate change can impact human activities but also be affected by it in a feedback loop (e.g., Pires and Costa 2013), we decided to focus solely on the former pathway.

## Results

### *The Diversity of Reported Climate-Driven Changes*

During semi-structured interviews and FGD, respondents mentioned 477 reports of climate-driven changes (hereafter "observations"), which were classified into 53 Local Indicators of Climate Change Impacts (LICCIs). More than one third ($n = 183$; 38.5%) of those observations referred to changes in elements of the atmospheric system, including changes in temperature (e.g., "today is hotter than in the past") and in rainfall (e.g., "nowadays, we have more rainfall during the summer"). Changes in elements of the physical system were mentioned 126 times (26.5%), including seasonal changes in the river water level (e.g., "the river level now is much lower during the dry season"), changes in the intensity of sedimentation of the river or lakes (e.g., "large floods are depositing a lot of soil in the várzea [floodplains]"), and changes in the speed of seasonal fluctuation in the river water level (e.g., "the river now rises faster"). Changes in elements of the human system were mentioned 89 times (18.5%), referring mostly to changes in crop mortality or productivity (e.g., "manioc is dying more now"), and changes in the incidence of human diseases (e.g., "we get more flu because of this strong heat"). Changes in elements of the biological system were mentioned 79 times (16.5%), and included changes in the mortality of wild plants (e.g., "the aterro [sediment] brought by the floods is killing all the andiroba trees"), changes in the abundance of freshwater fish (e.g., "there is less fish now"), and changes in vegetation dynamics (e.g., "the várzea forest is getting denser now"; Table 1; see full LICCI list in Table S2 in Supplementary Information).

### *Climate-Driven Changes Impacts on Livelihood Activities*

Of the 477 observations, 202 (42.3%) were directly related to impacts on specific livelihood activities (see details in Supplementary Information, Table S3). A third of the

**Table 1.** Environmental changes mentioned by local residents from the middle Juruá river are organized according to the system (i.e., atmospheric, physical, human, and biological) and the element (e.g., temperature, precipitation, air masses) where they are observed.

| Type of change | Citations | Percentage |
|---|---|---|
| Atmospheric system | 183 | 38.5% |
| Temperature | 94 | 51.5% |
| Precipitation | 62 | 34% |
| Air masses | 27 | 14.5% |
| Physical system | 126 | 26.5% |
| Freshwater physical systems (continental waters) | 119 | 94.5% |
| Terrestrial physical systems (soil and land) | 7 | 5.5% |
| Human system | 89 | 18.5% |
| Cultivated plant spp (crops, orchards) | 67 | 75% |
| Human health | 20 | 22.5% |
| Livestock | 2 | 2.5% |
| Biological system | 79 | 16.5% |
| Terrestrial wild flora | 54 | 68.5% |
| Freshwater biological system | 18 | 22.5% |
| Terrestrial wild fauna | 5 | 6.5% |
| Land cover change and land degradation | 2 | 2.5% |
| Total | 477 | 100% |

impacts on livelihood activities referred to changes in wild plant or fungi species mortality (64 observations, 31.6%; e.g., "rubber trees are dying in the floodplains"). Other observations included changes in crop mortality rates (37 observations, 18.3%), crop productivity (33 observations, 16.3%; e.g., "maize is not producing well anymore"), the productivity of wild plant species (nine observations, 4.5%), the abundance of freshwater fish (six observations, 3%), wild plant species fruiting time (six observations, 3%), length of crop harvesting time (six observations, 3%), and frequency or occurrence of weed species stated as invasive (six observations, 3%).

The livelihood activities most often cited as impacted by the reported changes were homegardens/agroforestry systems (48 observations, 24%) and manioc cultivation (41 observations, 20%). Andiroba harvesting was also frequently cited as impacted by changes in elements of the atmospheric system (28 observations, 14%) (see details in Table S3 in Supplementary Information) (Figure 1).

For the 202 observations directly associated with livelihood activities, drivers were mentioned 170 times. Of these, 50 (29.5%) were changes in the frequency of river flooding, 34 (20%) were changes in temperature, and 32 (19%) were changes in the rainfall regime. Another 54 of the mentioned drivers were changes in extreme events, of which 48 (28%) referred to large river floods, 4 (2.5%) to small river floods, and 2 (1%) to large river droughts.

Different livelihood activities are reported to be impacted by different drivers (Figure 1c). Manioc cultivation is more impacted by changes in the rainfall regime (26 observations, 57%), while homegardens/agroforestry systems and açaí extraction are more affected by changes in temperature (20 observations, 37.5%; and seven observations, 50%). Changes in large floods and changes in the frequency of flooding are the most frequently cited drivers impacting ucuúba harvesting (14 observations each change, 50%) and hunting (five observations each change, 50%). Changes in the frequency of flooding are the most cited driver impacting muru-muru (15 observations, 52%), andiroba harvesting (24 observations, 50%), and fishing (six observations, 37.5%). Rubber extraction is most impacted by large floods (18 observations, 50%), whereas the

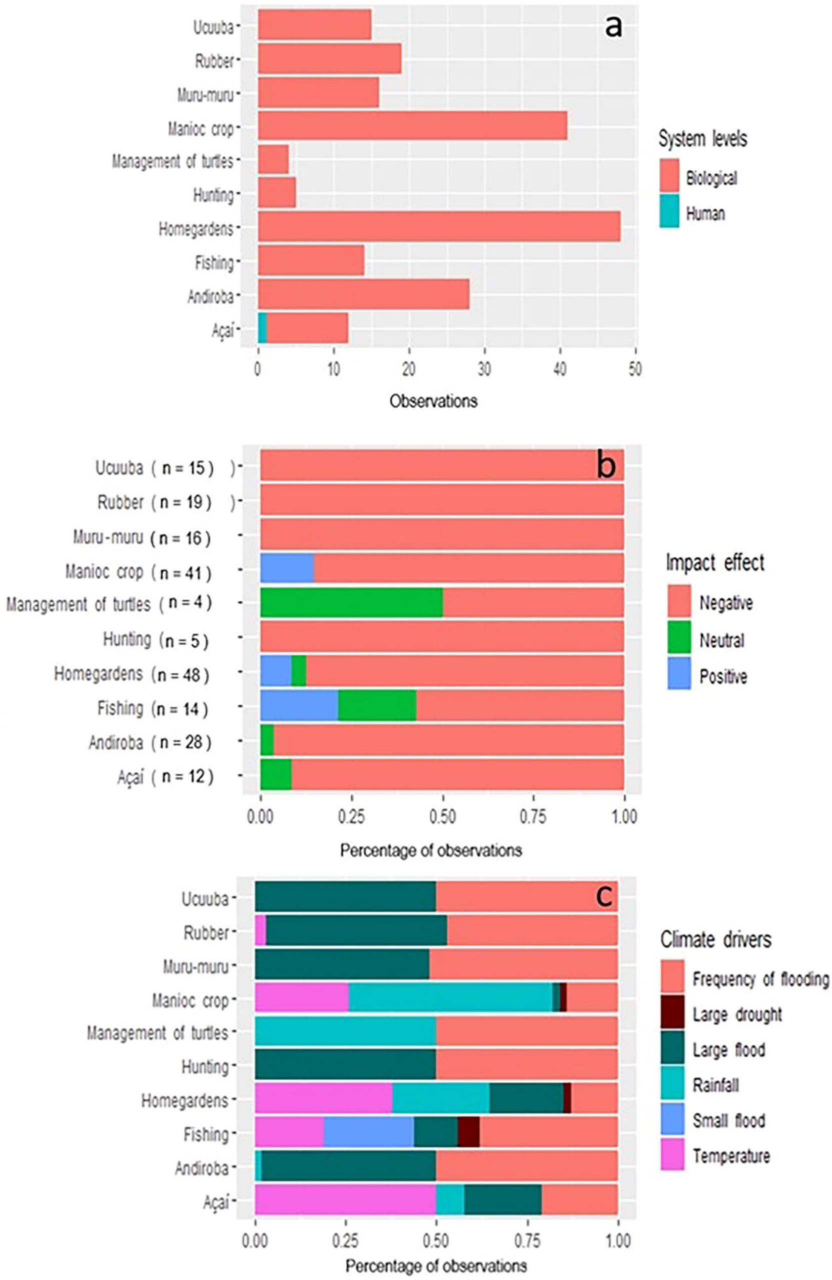


**Figure 1.** (a) Number of Observations of environmental change associated with different livelihood activities, grouped by system levels (biological and human); (b) Negative, neutral, and positive effects of the impacts of changes in elements of the atmospheric system on different livelihood activities along the middle Juruá river. Bars indicate the percentage of observations associated with each livelihood activity that have negative, positive, or neutral impacts; and (c) Percentage of observations of changes in elements of the atmospheric system impacting different livelihood activities according to the perceptions of local residents along the middle Juruá river.

management of turtles is equally impacted by changes in temperature (one observation, 50%) and by changes in the frequency of flooding (one observation, 50%) (Figure 1c).

Most of the 202 observations associated with livelihood activities were reported as having negative effects (180 observations [89%] were associated with negative effects, 13 observations [6.5%] with positive effects, and nine observations [4.5%] were classified as "neutral"). Negative impacts were reported for all livelihood activities, although the described impacts were different for each activity. All of the reported impacts on hunting (five observations), muru-muru harvesting (16 observations), rubber (19 observations), and ucuúba harvesting (15 observations) were negative. Other activities such as andiroba harvesting (28 observations; 96.5% negative, 3.5% neutral), açaí harvesting (12 observations; 91.5% negative, 8.5% neutral), and turtles' management (four observations; 50% negative, 50% neutral) were mostly associated with negative impacts, but some of the impacts were classified as "neutral" (Figure 1b).

Three livelihood activities were reported to be positively impacted by climate-driven changes. Fishing is, proportionally, the livelihood activity associated with the most positive impacts (14 observations; 21.5% positive, 57% negative, 21.5% neutral). As explained by respondents, fish abundance tends to be favored by large flood events and by increases in the frequency of flooding (e.g., "large floods help the fish to grow and reproduce"), and higher temperatures prevent fish from dying during cold waves. Similarly, manioc cultivation (41 observations; 14.5% positive, 85.5% negative) and homegardens/agroforestry systems (48 observations; 8.5% positive, 87.5% negative, 4% neutral) were reported to somehow benefit from changes in the rainfall regime, as increased rainfall in the summer helps plant growth (Figure 1b).

## *Extreme Events Impacts on Livelihood Activities*

River floods and droughts have significant, but differentiated, impacts on the livelihood activities conducted in the area. Our analysis shows a positive association between large floods and muru-muru palm and andiroba production loss, which means that in extremely large floods these activities are economically jeopardized (Figure 2).

On the contrary, we found a negative association between large floods and açaí, ucuúba, and fishing production loss (Figure 2a), which can be understood as an absence or even a positive impact, considering that respondents reported that those activities are benefited from large floods. Small flood events were associated with production losses in ucuúba harvesting and fishing (Figure 2b), whereas large droughts were associated with ucuúba production losses (Figure 2c); both these events were negatively associated with muru-muru production losses, indicating that they can actually benefit this livelihood activity (Figures 2b,c).

We also found that the environment where the livelihood activity is conducted (uplands *versus* floodplains) is associated with the reported impact of large droughts (Figure 2c). Respondents conducting agriculture in floodplains areas were more likely to report the negative impacts of large river droughts in agricultural production losses than their peers conducting agriculture in the uplands. We did not find significant effects of the environment on the impacts of large or small river floods (see details in Table S4 in Supplementary Information).

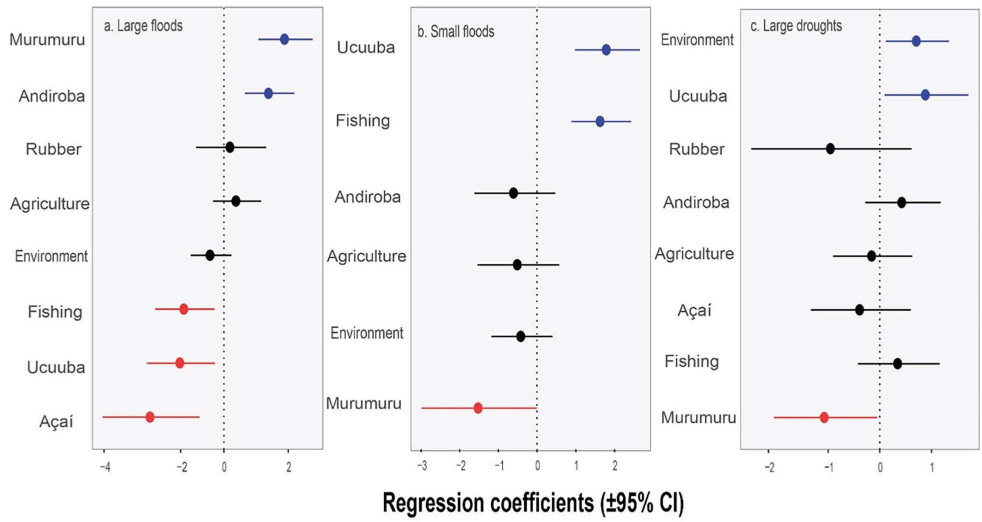


**Figure 2.** Estimates for regression slopes (±95% confidence intervals, CIs) showing the magnitude and direction of the effects of (a) large floods, (b) small floods, and (c) large droughts on production losses for different livelihood activities, according to the perceptions of local residents along the middle Juruá River ($n = XX$). Solid circles indicate the mean estimates and horizontal lines indicate confidence intervals. For significant variables, CIs do not cross the horizontal dotted line at zero. Red and blue symbols represent, respectively, the significant positive and negative association between the predictor and response variable (production loss).

## Discussion

### *The Myriad of Locally Reported Climate-Driven Changes*

In recent decades, different climate change impacts have been documented in Amazonia, such effects often being exacerbated by other drivers of environmental change (Pires and Costa 2013; Silveira et al. 2020; da Silva Abel et al. 2021; Lovejoy and Nobre 2018). Along the Juruá River changes in elements of the atmospheric system, such as warmer temperatures and less predictable rains, while often and almost unanimously reported by local communities, are often reported in conjunction with a vast set of changes in elements of the physical, the human, and the biological systems. This high inter-relatedness of changes suggests that understanding, mitigating, and adapting to climate change impacts on local communities requires approaches that look at changes in socio-ecological systems in a broader and integrated way. Within this complexity, our findings reinforce the idea that LEK can help to identify not only changes in elements of the atmospheric system but also their cascading impacts in multiple elements of social-ecological systems (Oviedo et al. 2016; Junqueira et al. 2021).

Our results also highlight how climate-driven changes impact elements of the biophysical system and substantially affect local livelihoods, a finding that echoes patterns reported for other communities in Amazonia and elsewhere (e.g., Nyima and Hopping 2019; Funatsu et al. 2019). Moreover, we show that while a handful of these impacts are perceived as positive, most of them are perceived as negative, calling the attention to the vulnerability of these communities to ongoing and future climate change impacts.

Regarding climate-driven impacts on elements of the human system, local residents associated some changes in elements of the atmospheric and physical system with an increased incidence of some diseases, such as dengue and filaria (e.g., "now that it is hotter there is more dengue"). This finding is in line with previous studies showing that the increase in temperature and large floods frequency can lead to increases in vector-borne diseases (Iwamura, Guzman-Holst, and Murray 2020; Ryan et al. 2019, Oviedo et al. 2016). This is a reason for concern, considering the relatively precarious access to formal healthcare in most rural Amazonia (Garnelo et al. 2020). Higher temperatures were also often mentioned as a cause of headaches or other types of physical discomfort, leading farmers to shorten their work journeys in their fields, which may have important negative consequences for food and economic security.

## *The Diverse Impacts of Climate-Driven Changes on Livelihood Activities*

We show that local residents acknowledge that all their livelihood activities are affected by climate change impacts, albeit in different intensities, directions, and by different drivers. Previous research has shown that climate change may have strong impacts on small-scale agriculture (e.g., Labeyrie et al. 2021). These impacts are likely to be stronger for subsistence and smallholder farmers in the tropics, given their fragile socioeconomic and political conditions (Morton 2007). Farmers from the Juruá river acknowledge that their agricultural and agroforestry systems are impacted in different ways by changes in the atmospheric system, and these two livelihood activities were indeed those most often mentioned as impacted by climate change. Although respondents recognized some positive impacts in agriculture or agroforestry (e.g., the increase in rainfall during the summer is perceived as favoring crop growth), most of the perceived impacts in plant cultivation are negative. This is particularly worrisome considering the importance of agriculture for food security and income generation for the communities along the middle Juruá and elsewhere in Amazonia (Newton, Endo, and Peres 2012).

Climate change can strongly affect the distribution of palm and tree species that are culturally and economically important for local communities in Amazonia (Evangelista-Vale et al. 2021). Residents from the middle Juruá reported increased mortality and reduced productivity of açaí, ucuúba, andiroba, and muru-muru, particularly due to greater incidence of large river floods. While some activities such as muru-muru and andiroba harvesting are negatively impacted by large floods (because "large floods spread their seeds and is thus harder to gather them"), others such as açaí and ucuúba harvesting may be favored since large floods improve access to some individuals of these species, temporarily increasing the ability to harvest them. While most of these activities involving the gathering of non-timber forest were reported to be impacted mainly by changes in river dynamics, some of them such as açaí or rubber harvesting are also impacted by changes in temperature or rainfall (e.g., "too much rain in the summer hinders the harvesting of rubber"). Together, these results highlight the complexity and the nuanced climate change impacts on local livelihoods and suggest that the diversification of livelihood activities can be a promising strategy to mitigate climate change impacts.

Changes in the frequency and size of river floods can also impact fish, turtles, and game species abundance, size, and reproduction cycles. Local residents report that large floods increase fish availability and capture in subsequent years. During large floods, aquatic species, especially fish, have a larger area to reproduce and to obtain food resources, contributing to their development and growth (Castello, Isaac, and Thapa 2015; Hurd et al. 2016). On the contrary, small floods are reported to have negative impacts on fishing because the lower availability of flooded habitats harms the reproduction and growth of fish species. Hunting was reported to be negatively impacted by the increased incidence of large floods since during these events game species are restricted to small areas and are more vulnerable. Finally, the community-based management of freshwater turtles was also reported to be negatively impacted by large floods, which can flood the turtles' nests, and by small floods, which can jeopardize their reproduction.

Overall, in spite of the differential impacts of climate-driven changes in different livelihood activities, the combined effects of these changes represent important threats to local communities' income generation, food security, and food sovereignty (Mbow et al. 2019). In addition, these impacts can compromise the social dynamics of such communities and may induce local migrations (Brondízio and Moran 2008; Oviedo et al. 2016). Understanding the complexities of these impacts through the lens of LEK, we argue, is an important step in devising strategies to mitigate and adapt to them.

### *Reported Impacts of Extreme Events on Livelihood Activities*

About one-fourth (24.7%) of the reported changes is driven by extreme events related to river dynamics (large river floods, small river floods, and large river droughts), and these events impact differently different livelihoods. This is particularly evident in the case of large river floods, in which some activities such as fishing are benefited, while others (such as the harvesting of muru-muru) are negatively impacted by these events. These findings highlight the nuanced and multidirectional consequences of climate change impacts. Hence, initiatives aiming to build adaptation capacity/resilience in relation to extreme events in Amazonia should take these multidirectional impacts into consideration. Also, by identifying activities that are most vulnerable to different types of extreme events according to local residents (e.g., muru-muru and andiroba harvesting are vulnerable to large floods; fishing is vulnerable to small floods; ucuúba harvesting is vulnerable to both small floods and large droughts), our results provide support to devising strategies that ensure food and economic security under changing climatic conditions.

## Conclusion

Based on environmental changes reported by local communities from the Juruá River, our study demonstrates the potential of Local Ecological Knowledge to assess the diversity and complexity of the effects of climate change on socio-ecological systems. In particular, we show how local communities recognize the multidimensional impacts of climate change, in which different livelihood activities are impacted in different intensities and by different climate-related changes. Beyond demonstrating the manifold and multidirectional climate change impacts, our findings highlight the contribution of local ecological knowledge in identifying vulnerable livelihood activities and biodiversity-based value chains. From documenting the diversity of perceived impacts, we derive that it is crucial to include local knowledge holders in the formulation of policies and mitigation/adaptation strategies, from local to global levels, not only due to social justice since historically these communities have been relegated to decision-making space but also because their knowledge could help in devising policies to prevent and mitigate climate change impacts in local livelihoods.

## Note

1. In this manuscript we use the term "reports" when referring to specific changes observed/experienced/reported by local people, but it is important to mention that these reports are based (and are part of) LEK (see e.g., Yeh 2016).

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