



Research

"We saw fish in the cocoa farm": local observations of the impacts of climate change on biodiversity and livelihoods in the Lac Télé Community Reserve, Congo Basin

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ABSTRACT. In the second-largest continuous tropical rainforest in the world, the Congo Basin, climate change affects biodiversity as well as forest-dependent local communities. In the region, the lack of historical biophysical data prevents a comprehensive analysis of climate change impacts on its biophysical systems. In this context, local ecological knowledge, building on local communities' long history of interactions with their environment, can improve the understanding of interwoven environmental changes linked with climate change and biodiversity loss. This study focused on four villages, ranging from seasonally flooded to terra firma forests, involved 80 semi-structured interviews, 111 structured interviews, and eight focus groups to document local climatic changes, biophysical impacts, and perceived drivers of change through the knowledge of local communities. We also classified adaptation strategies into different categories according to their potential impacts on biodiversity. Results suggest that a wide range of climate change impacts are already apparent in the area, including changes in temperature and precipitation and the intensification of flooding events. Associated impacts on local biodiversity have also been observed, ranging from increased tree mortality, disrupted fish reproduction, disrupted migratory patterns in mammal species, and reduced fruit production. Our study filled an important knowledge gap, investigating both the direct impacts of climate change on biophysical systems, and its indirect impacts arising from adaptation in human behavior. Our results highlight the importance of integrating local ecological knowledge in rapid biodiversity change assessments.

Key Words: *Central Africa; Indigenous Peoples and local communities; local ecological knowledge; traditional ecological knowledge; tropical floodplain ecosystem; species*

INTRODUCTION

Along with other drivers of change such as land-use change and the overexploitation of natural resources, climate change increasingly appears as a primary threat to biodiversity conservation (IPBES 2019) with effects on all biodiversity organizational levels, from genes to biomes, and across most ecological processes fundamental to ecosystem functioning (Bellard et al. 2012, Scheffers et al. 2016). In addition to those direct impacts, climate change also has indirect impacts on biodiversity through adaptation in human behavior—referred to as indirect impacts of climate change on biodiversity—that can amplify other threats (e.g., increased hunting in response to crop failure) and create new risks for biodiversity conservation, notably within the Congo Basin (Segan et al. 2015).

As the world's second-largest continuous tropical rainforest, the Congo Basin plays a crucial role in global climate mitigation and acts as a key center of global biodiversity, hosting 282 threatened species (IUCN 2024). Spanning across six countries (Cameroon, Central African Republic, Democratic Republic of the Congo [DRC], Equatorial Guinea, Gabon, and the Republic of Congo), the rainforests of the Congo Basin support approximately 100 million Indigenous Peoples' and local communities' (IP&LC) members who rely on forest resources for their livelihoods and cultural and spiritual traditions (Eba'a Atyi et al. 2022). Those rainforests are, however, threatened by a combination of factors, including illegal wildlife trade, deforestation and forest

degradation driven by small-scale and industrial agriculture, extractive industries, infrastructure development, and road construction (Shapiro et al. 2021), which are expected to be further exacerbated by climate change.

Despite its global significance, the Congo Basin remains largely understudied, with limited research and climate data. This is specifically driven by the absence of long-term records and the many temporal and spatial gaps in instrumental measurements (Beekmann et al. 2024). Data unavailability impedes the quantification of global and climate change impacts, the identification of emerging trends linked with ecosystem dynamics, and the prediction of future patterns associated with climate change and biodiversity loss. Consequently, there is a lack of consensus over future regional rainfall trends, which are a critical determinant of future ecosystem dynamics: some studies indicate a long-term drying trend (Zhou et al. 2014) whereas others project a slight increase in precipitation (Creese et al. 2019).

Local ecological knowledge is defined by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) as "knowledge about nature, including organisms (animals and plants), ecosystems, and ecological interactions, held by local people who interact with and use natural resources" (IPBES 2022:930). It can be crucial in detecting overlooked trends linked to climate and biodiversity. Because of their historical relationships with plant and animal species, as well as abiotic factors within their landscapes, IP&LCs are well placed to detect

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changes in ecological processes within biophysical systems that underpin their livelihoods (Reyes-García et al. 2024). Local ecological knowledge is particularly useful in remote, data-deficient sites and plays a valuable role in elucidating the interconnections between ecosystem changes, providing insights into the underlying drivers and highlighting effects on IP&LC livelihoods and sociocultural conditions (Berkes et al. 2000).

Whereas a number of studies have relied on local ecological knowledge to characterize climate change, monitor impacts on ecosystem dynamics, and document adaptation response, relatively few have focused on the Congo Basin (e.g., Nyadzi et al. 2021, Savo et al. 2016). Among the available studies, Few et al. (2017) assessed social-ecological vulnerability to climate stressors and IP&LC responses in the Tri-National de la Sangha (Cameroon) and Monte Alen-Mont Cristal (Equatorial Guinea). In Cameroon, Tieminie et al. (2021, 2023) examined perceptions of climate change and the role of non-timber forest products (NTFPs) in adaptation. In the DRC, Mangaza et al. (2021) evaluated the impacts of climate change on agricultural activities within the Yangambi landscape. Multiple studies (Amani et al. 2022, Baderha et al. 2024 [which also covered Cameroon's Bamboutos mountains], Cuni-Sanchez et al. 2025) have focused on the Itombwe mountains to investigate perceptions of climate change, adaptation strategies, and drivers and barriers to adaptation. Batumike et al. (2021) examined similar dynamics on Mt. Kahuzi. Sonwa et al. (2020) compared local observations with rainfall data across three watersheds in the Central African Republic, Cameroon, and the DRC. In Congo Basin's seasonally flooded forests and floodplain socio-ecosystems, local ecological knowledge of current climatic and ecological changes remains insufficiently documented.

In this context, our research goal was to characterize the direct and indirect impacts of climate change on biodiversity on a site of the Congo Basin, the Lac Télé Community Reserve, Republic of Congo, through the observations of local communities. Part of the largest transboundary Ramsar site in the world (shared with the DRC), the Lac Télé Community Reserve hosts a rich biodiversity and is home to 48 ethnic groups (Devers et al. 2006, Poulsen and Clark 2002). We addressed the following research questions: What are the observed local climate changes and impacts on biophysical systems?, What adaptation strategies are adopted by local people in response to global change impacts on their livelihoods?, and What are the indirect impacts of climate change on biodiversity?

METHODS

Study site

The 4600 km² Lac Télé Community Reserve (hereafter, the Reserve) is a Category VI protected area (i.e., a protected area with sustainable use of natural resource according to IUCN; Dudley et al. 2008). It is managed by the Congolese Ministry of Forest Economy and the Wildlife Conservation Society (WCS). It is characterized by high microhabitat variability, including swamp forests, seasonally inundated forests, seasonally inundated savannas, riparian forests, and patches of terra firma forests (Poulsen and Clark 2002). It is located within the Cuvette Centrale, the largest tropical peatland complex worldwide (Crezee et al. 2022). The Reserve experiences 1600–1800 mm of annual

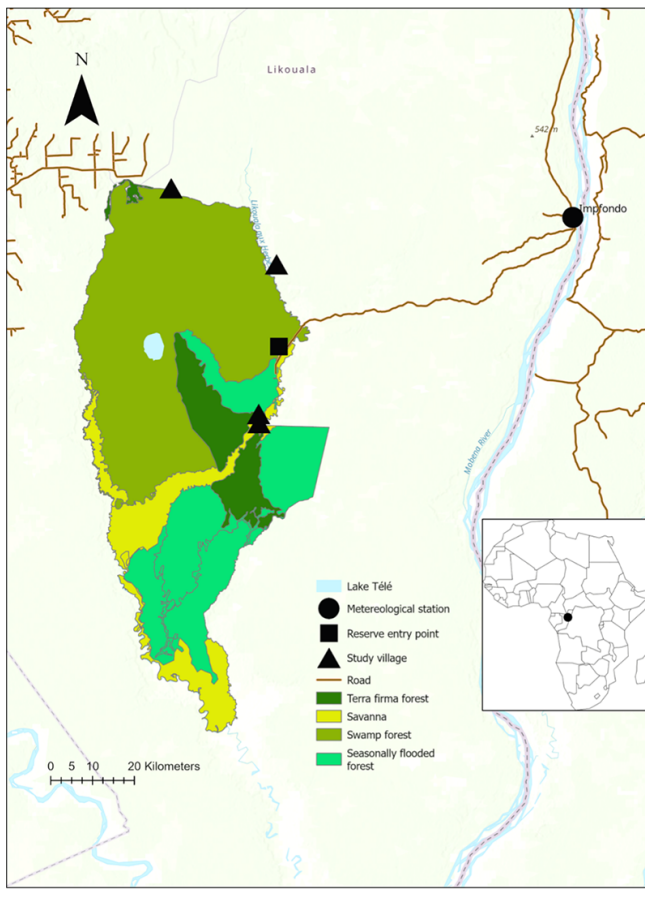
rainfall and an average temperature of 25.6 °C (Bondeko et al. 2016). The area has a bimodal rainfall pattern (Appendix 1), with a long dry season (December–March), a short rainy season (April–May), a short dry season (June–July) and a long rainy season (August–November). The Reserve exhibits pronounced seasonal hydrological fluctuations, with significant changes in water level in the Sangha, Oubangui, and Likouala-aux-herbes rivers and their tributaries (Rainy and Twagirashyaka 2010). However, the site's flooding regime, although a key driver of ecosystem dynamics (e.g., peat formation or nutrient cycling), is poorly known (Hawthorne et al. 2023, Ifo et al. 2019).

The Reserve harbors over 350 animal species, including diverse avifauna (e.g., the Anhinga, *Anhinga rufa*, and the Purple Heron, *Ardea purpurea*) and herpetofauna (e.g., the African dwarf crocodile, *Osteolaemus tetraspis*). It also supports important populations of central chimpanzee (*Pan troglodytes troglodytes*) and of western lowland gorillas (*Gorilla gorilla gorilla*), respectively classified as endangered and critically endangered on the IUCN Red List of Threatened Species (Poulsen and Clark 2004). The Reserve has approximately 20,000 inhabitants distributed in 27 villages, predominantly consisting of Bomitaba people of Bantu origin, along with minority hunter-gatherer groups such as Ba'aka and Bakouyou communities (Faustin et al. 2007, Moukouyou et al. 2015). It has a low estimated average human population density of 3.8 inhabitants/km² (Bondeko et al. 2016). Local communities have developed a varied activity portfolio, relying on rainfed subsistence agriculture (cassava being the main staple), fishing, subsistence hunting (using traps and sometimes guns), and the collection of NTFP. In some villages with better market access, cocoa is also cultivated for commercial purposes. Traditionally, farming and fishing are the main activities during the long dry season, whereas hunting is practiced mostly during the long rainy season when most seasonally flooded forests are inundated. There is no access to electricity or health centers in any of the villages studied, and the main market town is Epéna (the Reserve entry point; Fig. 1). Because of its isolation, deforestation trends in the Reserve were estimated at 1.3 percent in 2000–2023 (Global Forest Watch 2024). Decreasing trends in abundance of large mammals and certain fish species have been reported (Ndzana Biloa et al. 2024, Poulsen and Clark 2004).

Ethics

Research activities were authorized by the Congolese Ministry of Higher Education, Scientific Research and Technological Innovation, and data collection protocols received approval from the University of Sapienza Ethics Committee for Transdisciplinary Research (ID 9/2022). Explicit consent for conducting research activities was sought through local administrative and customary leadership. Free, Prior, and Informed Consent (FPIC) protocols were upheld during the entirety of the fieldwork. Participants were informed that participation was voluntary and that anonymized data would be used for analysis and publication. They signed a consent form acknowledging the research objectives, and those who were unable to read provided oral consent. Village chiefs and community members were informed of their opportunity to participate in the decision-making process regarding the organization of research activities. A benefit-sharing mechanism was discussed in villages, and, in many instances, leadership requested a non-academic activity report in French after fieldwork completion.

Fig. 1. Map of the Lac Télé Community Reserve. Source: Wildlife Conservation Society (WCS).



Data collection

We selected four villages to represent habitat variability and market access: swamp forest (village 1), terra firma forest with market access (village 2, which had cocoa farms), seasonally flooded forests (village 3), and terra firma forest without market access (village 4; Fig. 1). Villages also differed in their degree of exposure to seasonal floods, shaped by micro-scale climatic and topographic conditions, with exposure levels ranging from highest to lowest as follows: villages 2, 4, 3, and 1. All selected villages had between 150–300 inhabitants, ensuring that the integration of authors M. B. and C. M. M. into daily community life was feasible, and were mostly inhabited by Bomitaba communities, with Ba'aka families present in village 2. We adapted data collection methods from the standardized protocol developed by Reyes-García et al. (2023) for the project Local Indicators of Climate Change Impacts (LICCI). The data collection protocol aimed at compiling a comprehensive inventory of indicators of change and associated adaptation strategies. It included four steps in each village: (1) an exploratory focus group discussion (FDG), (2) semi-structured interviews, (3) a validation FDG, and (4) quantitative surveys (Fig. 2).

The Lingala language was used in most interviews and FDGs, with occasional use of Bomitaba terms, and answers were translated into French by C. M. M. In village 2, 19 interviews were conducted in Ba'aka, with the help of an additional interpreter. In total, 196 interviews and 11 focus group discussions were conducted (questionnaires included in Appendix 1). In all villages, additional observations were collected by M. B and C. M. M while accompanying study participants in daily subsistence activities (including farming and fishing). Monthly maximum, mean, and minimum temperatures and monthly rainfall data from the Impfondo meteorological station (for the period 1990–2023) were obtained from the National Civil Aviation Agency of Congo.

Data analysis

We used villages as the main unit of analysis. To investigate observed changes in the local climate and impacts on the Lac Télé Community Reserve biophysical system, we translated interviews into English and created codes for each respondent following this format: village number-F (female) or M (male)-individual number. We systematically coded each change observation into a standardized indicator of change with directional change (e.g., decreased fog intensity), assigned each indicator to the atmospheric, biophysical, or human system (following Reyes-García et al. 2023), and counted the total number of citations (per village and across all villages) of indicators. We removed indicators not validated by at least one FDG ($n = 7$ not validated). To examine whether a small subset of respondents disproportionately contributed to the total number of reported indicators, we computed a per-respondent variable (number of indicators of change) and summarized its distribution.

We performed linear regression analyses on meteorological data, using monthly mean, minimum, and maximum temperatures; monthly rainfall values; and 10-year running mean as dependent variables and the time series as the independent variable. We applied mean imputation (i.e., replacing missing values with yearly average) to fill data gaps; years with data gaps exceeding four months were excluded from the time series ($n = 1$ for mean temperature, minimum temperature, and rainfall; $n = 4$ for maximum temperature). To investigate decadal changes in seasonal patterns, we displayed temperature (minimum and maximum) and rainfall in each of the four seasons (long dry season, short rainy season, short dry season, and long rainy season). To assess the correspondence between indicators of change reported by respondents and instrumental records, we qualitatively compared each indicator with available meteorological data.

To assess adaptation strategies adopted by Lac Télé Community Reserve inhabitants and potential indirect impacts on biodiversity, we classified study participants according to their self-identification of main personal subsistence activities: farming ($n = 113$), fishing ($n = 86$), hunting ($n = 28$), and NTFP collection (and affiliated activities). The latter was further disaggregated into subcategories: edible plant collection ($n = 54$), *Raphia* spp. collection for house construction and basketry ($n = 39$), wild honey collection ($n = 34$), and dugout canoe construction ($n = 33$). We then used descriptive statistics to evaluate the distribution of the adoption of adaptation strategies among the surveyed groups.

Fig. 2. Graphical representation of the methodological approach used in each village, adopted from Reyes-García et al. (2023). Although we aimed to include new participants at each step, local customs required the participation of certain community leaders (notably, elderly leaders) in multiple activities, resulting in a small overlap (> 10% of respondents).

<p>1) Exploratory focus groups (participants n = 15-20)</p> <ul style="list-style-type: none"> • Focus groups were organized upon arrival in each village. • Using open-ended questions, we guided a discussion on livelihood practices, the village's seasonal calendar, and its historical timeline (including significant events such as past hazards or infrastructure development). This allowed a preliminary understanding of changes at play. • We used a convenience quota sampling associated with gender (male/female), age (30-50/50-90 years old), and livelihoods (farming/fishing/hunting/non-timber forest product collection). After dividing the village population into gender, age, and livelihood quotas, we selected participants based on availability and interest and in discussion with village leadership. 	<p>2) Semi-structured interviews (n = 20)</p> <ul style="list-style-type: none"> • Using preset open-ended questions, we conducted semi-structured interviews. • Semi-structured interviews were used to collect observations of change recorded by local communities. In this context, "observation of change" refer to indications of change in the local climate and biophysical system. • A significant event widely recognized in the village was used as a common historical reference point to delineate changes. • We used a convenience quota sampling associated with gender, age and livelihood groups (see step 1). We included a minimum of 3 participants per quota, depending on the saturation of information. • Participants were ≥30 years old to ensure ≥20 years of observed climate or biophysical changes.
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We classified the adaptation strategies reported by respondents according to potential impacts on biodiversity following a classification derived from the IPBES-IPCC Co-Sponsored Workshop on Biodiversity and Climate Change, which considers the following categories: biodiversity positive, biodiversity neutral, biodiversity possible risk or benefit, and biodiversity negative (Pörtner et al. 2021). We based classifications on available ecological data and, where applicable, on respondents' own perceptions of indirect impacts. When insufficient information was available to determine net outcomes, we categorized strategies as possible risk or benefit to acknowledge uncertainty. Words and species names in Lingala or Bomitaba language are italicized.

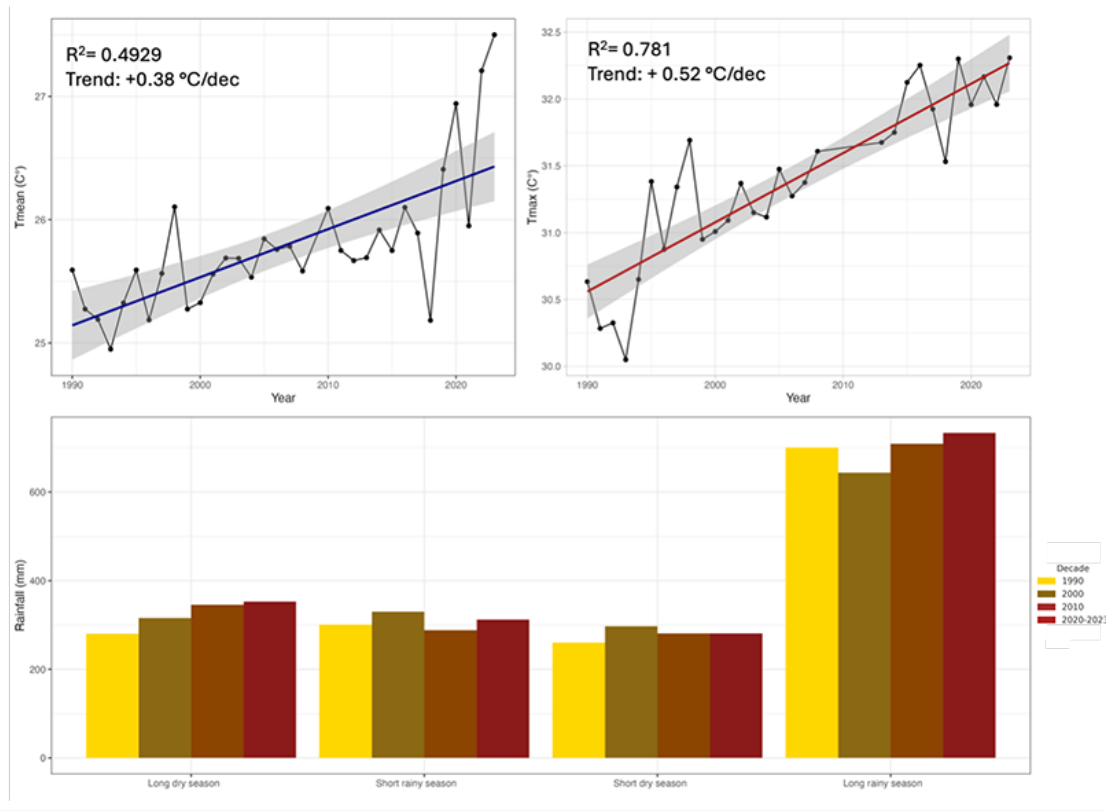
We performed a Mann-Whitney U test (Mann and Whitney 1947) to determine if the responses of the Ba'aka respondents differed significantly from those of the Bomitaba respondents within village 2 and complemented this analysis with two measures of effect size: the rank-biserial correlation (Cureton 1956) and Cohen's d (Cohen 1988). Because the results did not show significant difference between the two groups (Appendix 1), responses from both ethnic groups were combined.

Study limitations

Our study approach has certain limitations. First, only four villages were included per ethnic group, with just one village hosting two ethnic groups. This restricts the extent to which ethnic differences can be disentangled from village-level effects. However, this limitation is partly mitigated by the fact that the

main group studied is the dominant one across the Reserve and thus broadly representative of local social-ecological dynamics. Furthermore, villages of the same group present similar socioeconomic contexts (e.g., in market access or exposure to external change agents). Second, indicators of change reported by local communities may have been influenced by the 2023 extreme flooding event (at the time of data collection), potentially biasing observations toward floods while underrepresenting other possible indicators. Responses related to hunting and fishing activities may have been influenced by hesitancy to discuss them in detail because these activities are restricted within the Reserve. Because we used semi-structured interviews with open-ended questions to document a detailed inventory of indicators, the absence of a mention does not imply that an indicator was unnoticed. A useful future step would be a closed-ended survey based on reported indicators to quantify their frequency, although this was beyond the scope of our present study given the large number of indicators identified. In contrast, we used a closed questions questionnaire to investigate the prevalence of adopted adaptation measures in each village, a feasible approach considering the more limited set of measures. Last, although our primary focus is on climate change, adaptations to climate change are likely influenced by other drivers of change, such as rising costs of living. We were unable to obtain detailed information on adaptation measures related to cocoa farming, which should be investigated in future work.

Fig. 3. Linear trend of annual mean temperature (top right), linear trend of annual maximum temperature (top left), and decadal seasonal rainfall (bottom) at the Impfondo meteorological station. Data source: Agence Nationale de l'Aviation Civile du Congo.



RESULTS

Meteorological data

Our linear regression analysis (Fig. 3) indicated a statistically significant increase of annual mean temperature during the 1990–2023 period ($+1.29\text{ }^{\circ}\text{C} \pm 0.007\text{ SE}$, $p < 0.001$), corresponding to $0.39\text{ }^{\circ}\text{C} (\pm 0.007\text{ SE})$ per decade, where SE denotes the standard error of the estimate. Annual maximum temperature showed a larger increase of $+1.71\text{ }^{\circ}\text{C}$ during the same period ($\pm 0.005\text{ SE}$, $p < 0.001$). The seasonal temperature evaluation based on the 10-year running mean showed a significant but small increase of both minimum temperature in the long dry season ($+0.13\text{ }^{\circ}\text{C}$, $\pm 0.014\text{ SE}$, $p < 0.05$) and short rainy season ($+0.55\text{ }^{\circ}\text{C}$, $\pm 0.059\text{ SE}$, $p < 0.05$), and maximum temperature during the short rainy season ($+0.27\text{ }^{\circ}\text{C}$, $\pm 0.05\text{ SE}$, $p < 0.05$), and long rainy season ($+0.47\text{ }^{\circ}\text{C}$, $\pm 0.07\text{ SE}$, $p < 0.05$). Regarding rainfall, no significant long-term trend was observed in the annual average, although interannual variability increased over the study period (Appendix 1). A small increase of $26.4\text{ mm} (\pm 0.46\text{ SE}$, $p < 0.05$) per decade was found in the long dry season based on the 10-year running mean.

Observations of change in the local atmospheric, biophysical, and human systems

In total, respondents reported 364 indicators of change: 25 in the atmospheric system, 295 in the biophysical system, and 44 in the human system, the majority of which being associated with climate change (Appendix 1). The number of indicators of change reported per respondent was broadly distributed (range: 5–50,

mean ≈ 25.2 , median = 24.0, SD ≈ 9.0), with no evidence of concentration among a limited number of respondents. In the atmospheric system (Fig. 4), most of the indicators of change reported pertained to increasing temperature ($n = 30$), specifically during the dry season ($n = 10$), as well as increased ($n = 28$) or disrupted rainfall distribution ($n = 18$). Twenty-four respondents reported a decrease in fog intensity during the dry season. We found convergence (full or partial) between respondent observations and instrumental records for nine variables and no convergence for five variables; eight could not be assessed because of limitations in meteorological data availability (Table A1.1).

Significant shifts in the Reserve's flooding regime were consistently reported across all villages (Fig. 5). Respondents described increased occurrences of floods of magnitude and durations previously unexperienced ($n = 56$). Whether in villages, agricultural fields, or forested areas, water levels were described as the highest recorded in human memory: “the whole village has been flooded, [and] up to 45 km or even 60 km into the forest is accessible by pirogue ... the entire area is flooded” (1-M-1). Thirty respondents highlighted that the floods penetrated deeper into the forests than previously observed. Respondents reported disrupted seasonal flooding patterns ($n = 20$), with an onset in March instead of September ($n = 26$). Although the floods occurred early, their extent in September was unusually low, specifically in forested areas. Respondents described a significant decrease in the depth of the Likouala-aux-herbes River during the dry season ($n = 41$ respondents), one declared that “the river has changed; it used to be deep, but it's not anymore” (3-M-11).

Fig. 4. Indicators of change reported by respondents in the atmospheric system, $n = 20$ respondents per village. Village 1 corresponds to swamp forest, village 2 to terra firma forest with market access, village 3 to seasonally flooded forests, and village 4 to terra firma forest without market access. Villages are ranked according to exposure to floods (Appendix 1 provides additional details on indicators).

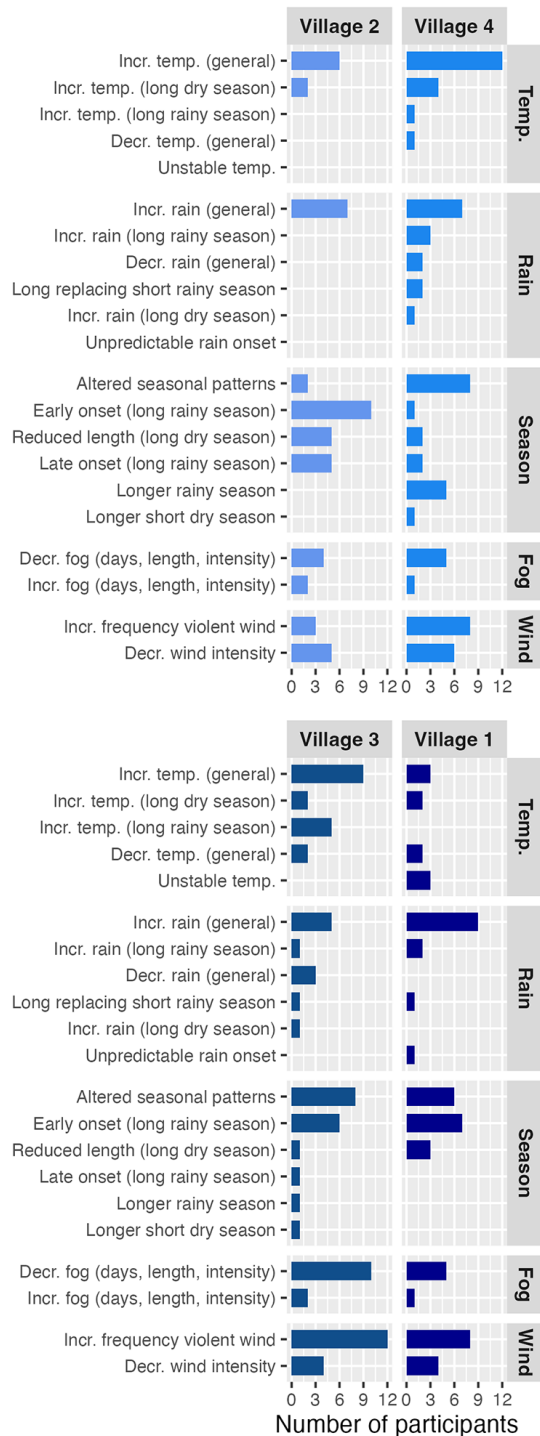
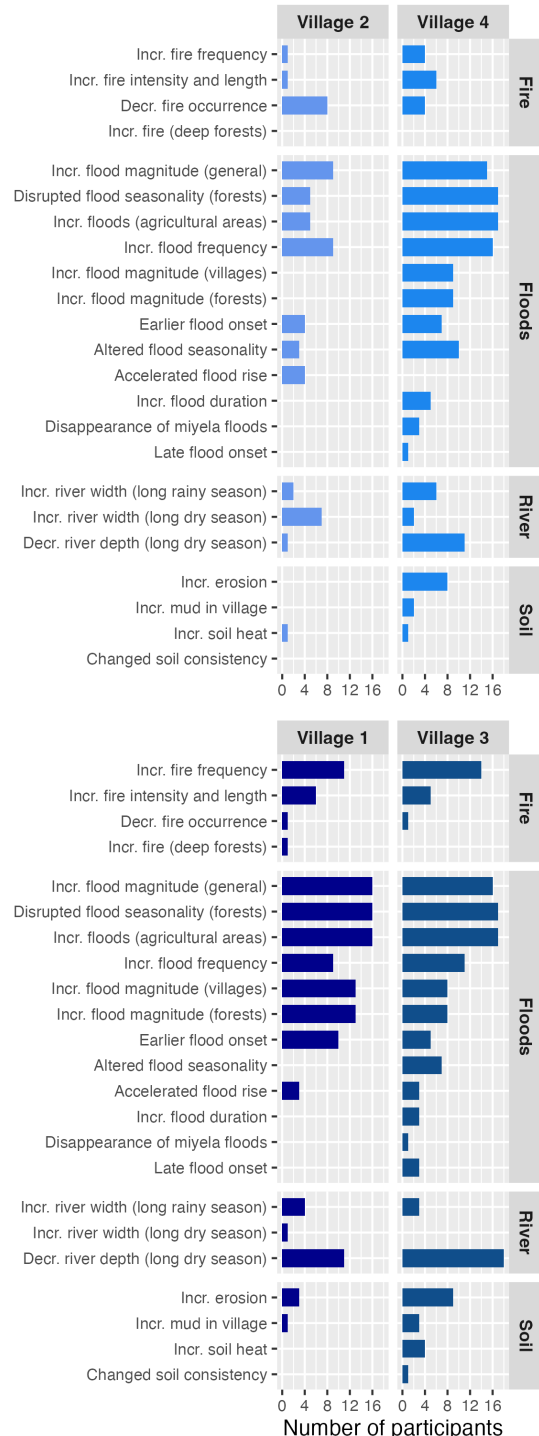


Fig. 5. Indicators of change in the biophysical system as reported by respondents ($n = 20$ respondents per village). Village 1 corresponds to swamp forest, village 2 to terra firma forest with market access, village 3 to seasonally flooded forests, and village 4 to terra firma forest without market access. Villages are ranked according to exposure to floods (Appendix 1 provides further details on indicators).



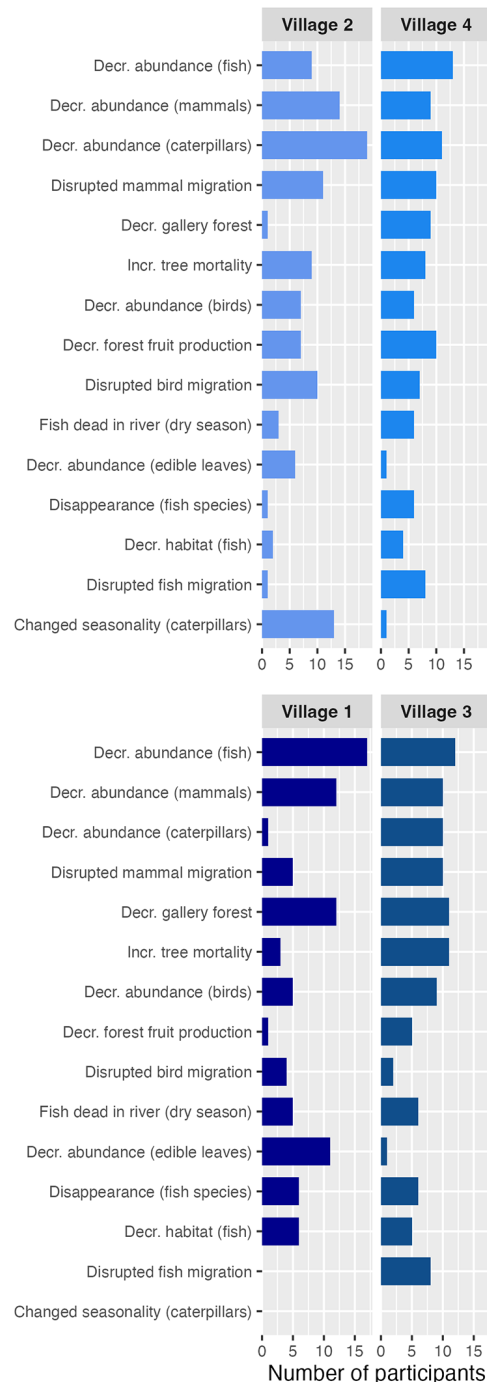
Increased soil erosion ($n = 20$) was described “as if the ground is changing, it is leaving, the erosion is pulling the earth; in one plot, a palm tree fell into the water, it is dangerous” (1-M-19). Another noted, “in my opinion, the soil is breaking up because it was under [flood] water, and with the heat of the [dry season], it dries out, it breaks up, and erosion progresses” (3-F-18). Thirty respondents mentioned an increased frequency of fire events (attributed to both changes in fire management practices, such as reduced adherence to traditional methods, and rising temperatures), and 18 others also described an increased intensity (including length) of fire events. Increasing fire events were associated with the disappearance of gallery forests ($n = 33$ respondents) and encroachment into the forest periphery ($n = 22$), identified as one of the most substantial changes in the landscape. One respondent said, “the forests along the river have disappeared in front of my very eyes. In times of drought, they burn and burn and burn” (4-F-10).

The annual hydrological cycle exerts a strong influence on people’s livelihoods, and, historically, local communities have developed a seasonal activity portfolio adapted to floods (M. Beekmann, *personal observation*). With disrupted flood patterns, respondents reported wide-scale impacts of climate change on their livelihoods and well-being. In 2023, agricultural fields were flooded in all villages studied, including areas typically not subject to severe flooding, and near-total crop loss in others. A respondent declared, “I harvested cassava with water up to my chest ... I had to plunge my head into the water. We suffered a lot I had to harvest early, because normally floods *pela* arrive in November, and that is when we harvest I have lost my three fields” (3-F-7). In one terra firma village, only 13% of fields (Appendix 1) were affected, but this was also considered alarming given that such floods had never occurred there before. One respondent stated, “we saw fish in the cocoa fields [for the first time]” (2-M-2). In village 1, the untimely floods also caused a disruption of the main fishing season and a loss of income for 57% of respondents. In village 3, 83% of respondents reported a decrease in food availability due to the extreme floods, and 63% reported increased cases of the African cassava mosaic virus.

Observations of change linked with Lac T  le Community Reserve biodiversity

Overall, the indicators of change related to fish ($n = 121$), plants ($n = 73$), mammals ($n = 64$), caterpillars ($n = 55$), and bird species ($n = 47$) were the most common. In Fig. 6, we present a summary of indicators most reported. Respondents depicted multifaceted impacts of climate change on fish populations. A commonly expressed opinion was that floods of large magnitude usually had a positive effect on fish reproduction and stocks ($n = 11$ respondents). Respondents declared that “water is like a village for the fish” (3-M-15), and “the fish reproduce well when the water goes far into the forest and enters ponds” (4-F-9). However, respondents mentioned being perplexed by the impacts of disrupted cyclicity on fish stocks. One person stated, “the fish weren’t able to enter the forest at a time when they should normally be there, normally the second half of October ... so they are waiting in the river” (4-M-8). There was disagreement between villages regarding the reproduction success of fish species amidst flood disruption. One group (village 3) stated,

Fig. 6. Summary of the 15 most observed indicators of biodiversity change in Lac T  le Community Reserve biodiversity, $n = 20$ respondents per village. Village 1 corresponds to swamp forest, village 2 to terra firma forest with market access, village 3 to seasonally flooded forests, and village 4 to terra firma forest without market access. Villages are ranked according to exposure to floods (Appendix 1 provides further details on indicators).



In the same way that we humans were surprised by the water, the fish were too. In April, we didn't see the youngs of the mounoussou (Paraphiocephalus obscurus). In April, the fish had no eggs in their abdomens. The eggs were seen in the bellies of the fish when the water level dropped. The fish are disturbed.

Another group declared, “we don't know whether the fish are reproducing, perhaps we'll have to wait until the dry season to find out We don't really know to what extent they have been disturbed” (village 2). Moreover, respondents (n = 20) mentioned the more frequent occurrence of floating dead individuals during the long dry season, frequently citing *mounoussou* (*Paraphiocephalus obscurus*).

Respondents reported a significant increase in tree mortality due to the effects of extreme floods (n = 30; Fig. 7). Tree species adapted to terra firma habitats or to regular seasonal flood cycles were identified as vulnerable to prolonged exposure to water, for example, *eyeyi* (*Macaranga brunensis*). Recruitment rates were also considered to be negatively affected by changing flood patterns, with observations including tree seedlings in terra firma habitats. In addition, we recorded 23 observations of reduced fructification of several species, *malombo* (*Saba senegalensis*) being the most frequently mentioned (n = 17). The effects of increasing dry season duration and intensity on plant species were also discussed. One respondent mentioned, “it's too hot nowadays, it even stings the skin. The leaves on the trees are thinning [i.e., reducing in abundance], even the fruits [are] thinning, even the *Raphia* palm fruits *mbila* are small. The fruits [in the village] don't reproduce well. The orange trees have disappeared because of the heat” (3-M-11).

Respondents also emphasized the effects of floods on altered migratory patterns for mammal species (n = 36). In 2023, the altered pattern and increased duration of annual floods appeared to disrupt typical migratory patterns, rendering, in some cases, the usual response ineffective. One respondent stated,

you could say that the animals are disturbed; some cannot tolerate water. Small duikers (mboloko), hedgehogs (ngoumba) flee to find dry land They endure or go elsewhere like men. Each year, they adapt. Before, the forest didn't flood like it does now. It was just in the corners. It's difficult for them too” (4-M-4).

Increased abundance of *Gorilla gorilla gorilla* was reported during the flooded period near village 2 (terra firma forests), for example: “before, when I went fishing, I didn't see many gorilla nests. This time, there were a lot, and I was even scared to go fishing Maybe because they've had lots of youngs or they've fled because of the water in search for food” (2-M-5). Increased mortality among small-sized species, for which long-distance displacement is more challenging, was also reported, although infrequently (n = 2; focus group agreement). For example, “I have seen 16 dead porcupines. They probably got stuck and ran out of food” (2-M-23). Increased heat was also described as a concern for mammals: “the sun ... is difficult for animals too. When the heat is too much, the animal will be bothered. If the sun breaks through and gets to where he is, it will push him to go somewhere else where it's cooler to rest” (3-M-9).

Fig. 7. 1) Fallen trees resulting from extreme flood-induced impacts. 2) The Likouala-aux-herbes River becomes large during extreme floods. 3) Flooded village. 4) Gallery forest fire. 5) Flooded terra firma forest. Pictures taken by M. B. in June–December 2023.

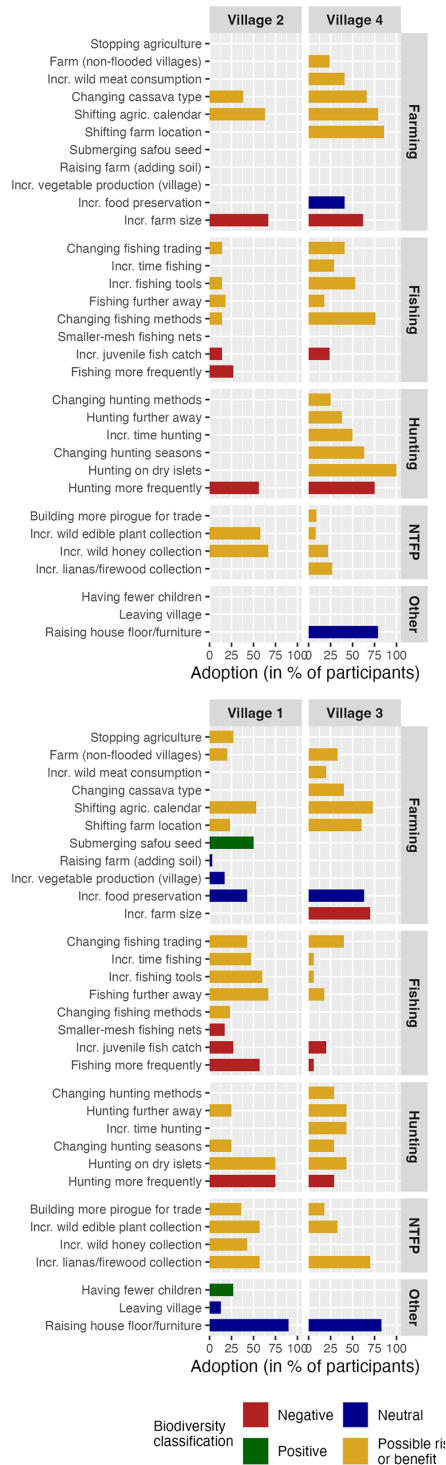


The alteration in flood timing appears to affect migratory bird population (n = 23). Marabout Storks (*Leptoptilos crumenifer*) were reported to arrive in large groups during the dry season, exploiting shallow water bodies to feed on small fish. A respondent observed that “the storks *Marabouts* arrive in March ... they come to eat the fish They didn't eat much because the dry season *mwanga* didn't go all the way, [they] left just afterwards” (2-F-11). Reduced food source was also identified as a problem for other bird species, such as the heron, *mwangalaka* (*Ardea purpurea* and *Ardea melanocephala*) and the African Drafter, *ediedi* (*Anhinga rufa*; n = 5). Other observations mentioned less frequently included reports of damaged reptile eggs (n = 2; focus group agreement), asynchrony between reptile species' reproductive strategies and flood timing (n = 1), and the effect of increased heat on reptile physiology (n = 1).

Local communities' adaptation strategies

Our respondents reported 33 adaptation strategies, with variability across villages (Fig. 8). Adaptations related to all subsistence activities (farming, fishing, hunting, and NTFP collection), shelter, and living strategies (e.g., reproduction and migration to other Reserve villages). The most recorded strategies included shifting agricultural calendars, increasing fishing material, and hunting more frequently. Other adaptation strategies, such as permanent emigration or having fewer children, were only considered in one village. Most adaptation strategies were linked to flood impacts on respondents' livelihoods, although many were concomitantly associated with other factors (e.g., reduced fish stocks). All recorded strategies were household-driven rather than being initiated by institutional or non-governmental stakeholders.

Fig. 8. Adoption rate of reported adaptation strategies across villages and potential indirect impact on biodiversity (n = 111). Village 1 corresponds to swamp forest, village 2 to terra firma forest with market access, village 3 to seasonally flooded forests, and village 4 to terra firma forest without market access. Villages are ranked according to exposure to floods.



In the agricultural sector, shifting agricultural calendars were reported in all villages (from 53% in village 1 to 79% in village 4). Most respondents (e.g., 70% of the respondents in village 3) reported increasing agricultural surface, with a respondent noting “I need to make a bigger field on dry land, because it doesn't flood” (3-F-2). Some respondents also relocated agricultural fields to previously unexploited terra firma forests, especially in village 4 (86%), where local authorities decided to allocate a portion of previously unused forested land to agriculture to mitigate the impact of floods on crop yields. In areas where terra firma forests were not easily accessible, villagers moved agricultural activities to locations less affected by floods, such as small zones of higher elevation. Increased heat during the dry season led villagers to advance their planting dates, which was viewed as a measure to counter African cassava mosaic virus. It also prompted villagers to increase agricultural efforts, e.g., by expanding the number of fields, as indicated by this respondent's statement: “before, our parents only did the fields once, but now we have to do it twice because of the disease” (3-F-10).

We noted variations in adaptation strategies related to fishing depending on villages. In village 1, where floods severely affected crop yields, there has been a subsistence shift toward fishing: 53% of respondents reported an increase in fishing efforts, 67% practiced fishing in new forested fishing grounds made accessible through the high flood levels, and 60% of respondents acquired more fishing material. Village 1 also had the highest juvenile fishing catch report, and many residents reported an increased proportion of their fishing efforts dedicated to sales, as follows: “the share of sales has changed; you have to buy more cassava because there are no fields [anymore]; the floods has changed [our] management” (1-F-21). In other villages, where agriculture plays a more prominent role, the focus on fishing in response to floods was less pronounced. Villagers prioritized preserving cassava production over increasing fishing efforts. Still, a respondent in village 3 indicated that “the disruption caused by the [untimely] floods in the forest gave an advantage Because flood occurrence increased, fishing is encouraged, and young people have been able to go more into the forest to [fish]” (3-M-7).

Regarding hunting, changes in frequency and in period of the year were most reported, followed by hunting further away or for a longer period. In village 1, 75% of respondents reported more frequent hunting compared to a typical flooding season (October–November), for example, because flood levels facilitated pirogue access to more remote forested areas. In village 4, a respondent stated, “this year [2023, the floods] rose very strongly ... hunting was easy” (4-M-11). Several respondents, however, reported ceasing hunting activities during periods of excessively high or rapid flooding because it made walking in the forest more difficult and rendered certain techniques, such as using traps, impractical. Several others reported a decreasing interest in hunting activities, regardless of the potential increased success rate driven by high flood levels, citing their arduous nature, the discouraging presence of eco-guards, and the higher profitability of other subsistence activities (including fishing), considering the costs of material such as cartridges.

A variety of other activities related to NTFP collection were also affected, some even becoming markers of the magnitude of flood impacts. One respondent declared about the collection of *Raphia laurentii* leaves, “I have been there three times this year, previously

it was only once; the rising waters have made it easier for me to go into the forest [using the pirogue]. I would never have gone without *pela* (3-M-1).

Potential impacts of adaptation strategies on biodiversity

Reported adaptation strategies may have differential impacts on Reserve biodiversity (Fig. 9). Among adaptation strategies in the agricultural sector with potential negative impacts on biodiversity, we noted the expansion of agricultural surface area and shifting field location because cropland expansion can lead to increased deforestation and land fragmentation, reducing habitat size and connectivity. Hunting and fishing more frequently also fall in that category. We identified less common adaptation strategies that can positively impact biodiversity, such as enhancing intra-village agrobiodiversity by submerging safou seed (*Dacryodes edulis*) in water before planting it, with the aim of enhancing the resistance of fruiting trees to floods or ceasing agricultural activities entirely.

Most adaptation strategies observed across the Reserve were categorized as possible risk or benefit because of the numerous mediating factors influencing the Reserve's social-ecological system. For instance, in the fishing sector, although the opening of new fishing grounds linked with the fishing further away adaptation strategies could facilitate the increased extraction of natural resources, increased flooding magnitude may lead to a decrease in fish density, potentially reducing overall fishing pressure. Similarly, building more pirogues does not necessarily intensify harvesting impacts given the low human population density, the considerable time required to construct a pirogue (trees are felled manually), the small proportion of men with the necessary skills, and the fact that different tree species are suitable for this craft. In the hunting sector, it is unclear whether hunting for longer is associated with increased catch. Likewise, hunting in new areas does not inherently expand the total hunting range but may simply represent a spatial shift, which does not automatically translate into greater hunting pressure. Traditionally, most hunting occurs during the rainy season, with hunters using local topography to target animals seeking refuge in non-flooded areas. Rising flood levels may increase the hunting pressure on wildlife by driving species migration toward terra firma or higher elevation areas, making animals easier to catch. Many respondents recalled the year 2000 as the last time an extreme flood affected the Reserve, leading to increased hunting efforts and local extirpations of species, such as the African grasscutter (*Thryonomys swinderianus*). However, similar occurrences were not reported during recent large-scale floods.

Furthermore, it seemed that several factors significantly constrain adaptation capacities in local communities within the Reserve. Many respondents simply noted “we are just putting up with it” (1-F-6) or “what can we do?” (1-F-6). This was exemplified in village 1 (swamp forest), where space for agriculture, already limited, is further diminishing because of increasing floods, and where alternative livelihood options are scarce. As a result, overall impacts on local biodiversity appear limited.

DISCUSSION

Observed local climate change and impacts on biophysical systems

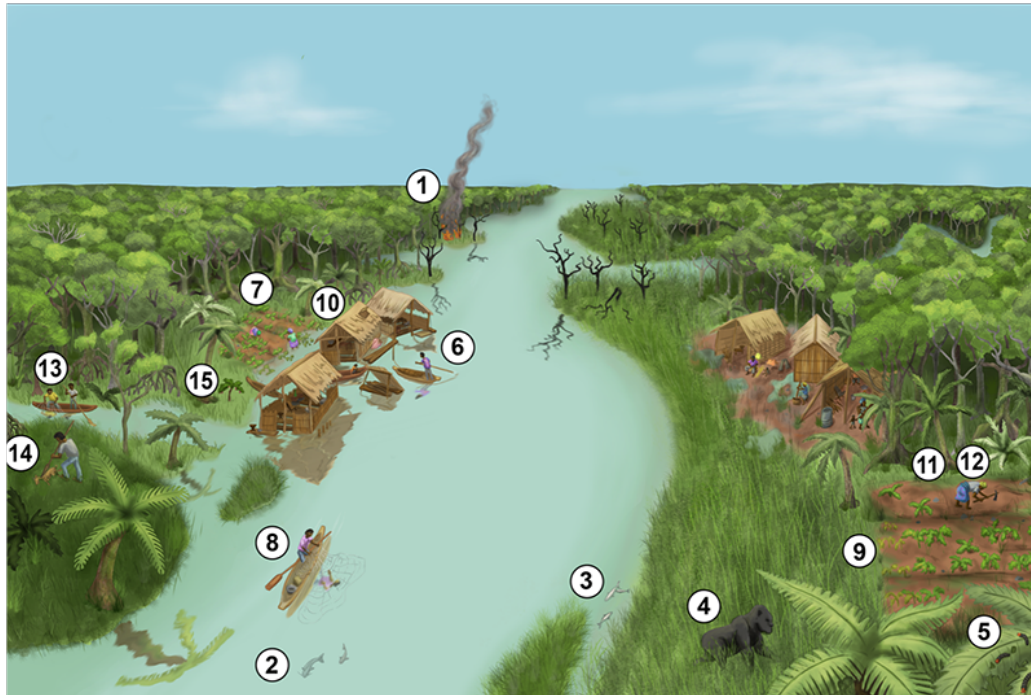
Local communities within the Lac Télé Community Reserve have documented a variety of climatic changes, including increased

temperatures, changing rainfall patterns, and disrupted flooding regimes. Previous literature has shown that local observations of climate changes can often align with meteorological data (Savo et al. 2016). In our study site, although agreement is not uniform across all indicators, several reported indicators correspond with available meteorological data. For instance, increased rainfall during the long dry season, surpassing that of the short rainy season, aligns with reports of unrecognizable rainfall patterns within the Reserve. Most climate changes reported by respondents in this study are also consistent with findings from local communities in other Congo Basin regions; although increasing unpredictability of rainfall and shifting seasonal patterns are reported in Cameroon and Equatorial Guinea (Few et al. 2017), smallholder farmers in the eastern DRC have observed increased temperatures, changing rainfall patterns, reduced fog, and stronger winds (Amani et al. 2022, Batumike et al. 2021). Importantly, detailed insights provided by local communities on changes in flood frequency and magnitude are particularly valuable considering the paucity of instrumental records associated with water level variations, both spatial and temporal, in the Lac Télé Community Reserve and the broader Congo Basin (Alsdorf et al. 2016). The reported shifts in the Reserve flooding regime represent a previously undocumented phenomenon in Congo Basin floodplain ecosystems. This underscores the critical importance of the fine-scale and nuanced hydrological knowledge held by Reserve inhabitants.

The local ecological knowledge held by Reserve inhabitants enabled a rapid, cross-domain assessment of ecological changes, through which respondents documented several significant impacts of climate change on biophysical and human systems. These include disrupted migratory patterns of several mammal, bird, and fish species; decreased production of wild fruits; reduced availability of wild edible caterpillars; increased tree mortality attributed to changes in flooding patterns; and reduced crop yields, a phenomenon frequently documented among Congo Basin smallholders (e.g., in the DRC, Amani et al. 2022 and Batumike et al. 2021; in Cameroon and Equatorial Guinea, Few et al. 2017). Increased soil erosion, floods, and prevalence of African cassava mosaic virus have also been documented in the eastern DRC, where participants attributed the rise in disease prevalence to increased showers during the dry season (Amani et al. 2022). In the Reserve, this was associated with elevated temperatures and heightened flood exposure.

Although we were unable to identify local observations of change in species migratory patterns in other Congo Basin seasonally flooded systems, our findings are consistent with ecological studies in the Amazon. In line with reports from our respondents, seasonal flooding is identified as a significant driver of migration for Amazon floodplain species, with mammals employing strategies such as retreating to higher elevation refuges, temporarily migrating to unflooded areas, or using arboreal pathways within the forest midstory or canopy to cope with periodic flood disturbances and associated habitat and food resource reduction (Ramalho et al. 2021). Amazon fish migrations are closely related to seasonal flooding, with increased flood extent and duration enhancing habitat availability, food resources, and recruitment opportunities (Castello et al. 2019). However, extreme flooding events can adversely affect fish communities, particularly when accompanied by changes in flood timing (Chea et al. 2020).

Fig. 9. Visual summary of the variety of observed changes in the Lac T  l   Community Reserve, including biodiversity changes (1-5), human system impacts (6-10), and adaptation strategies (11-15): 1) gallery forest decrease due to increasing fires, 2) reduced abundance of fish, 3) fish found dead, 4) disrupted mammal species migration, 5) changed seasonality patterns of edible caterpillars, 6) flooded village, 7) flooded agricultural fields, 8) disrupted fishing season, 9) increased cases of African cassava mosaic virus, 10) smaller quantities of food for villagers, 11) villagers shifting agricultural field location, 12) villagers increasing agricultural surface, 13) villagers shifting fishing grounds, 14) hunters using dry islets, 15) submerged safou (*Dacryodes edulis*) seed.



In the Congo Basin, local communities outside seasonally flooded systems, such as in eastern DRC, have reported reductions in wild fruit production and availability of wild edible caterpillars related to climate change (Batumike et al. 2021). Similar declines in edible caterpillars have been observed in Cameroon, attributed to both climate change and logging activities (Ngute et al. 2020). If widespread across the Reserve and the broader Congo Basin, a reduction in wild fruit production could have significant consequences not only for human populations that depend on these resources for consumption and trade, but also for frugivorous wildlife (Bush et al. 2020), including the critically endangered western lowland gorilla found in the Reserve. Evidence from Gabon's Lop   National Park shows that an 80% reduction in wild fruit production over a 32-year period was linked to reduced body mass in African forest elephants (*Loxodonta cyclotis*; Bush et al. 2020). Such severe decline was associated with an increase in minimum decadal temperatures—a trend also observed in the Reserve. Further research on how climate-driven reductions in fruit availability may affect both people and wildlife is urgently needed.

Adaptation strategies

Study participants reported 33 adaptive strategies related to farming, fishing, and hunting practices, as well as in-house adaptation. Among these, certain strategies, such as increasing farm size, emerged as particularly prominent, reflecting responses not only to reduced crop yields, but also rising costs of living.

Given the central role of seasonal floods in structuring livelihoods, shifts in flood regimes—particularly changes in timing—are driving a Reserve-wide reorganization of seasonal calendars and daily life. Importantly, differences in flood exposure across villages play a decisive role in shaping adaptation pathways, intersecting with culturally mediated factors such as gender roles, livelihood specialization, and access to natural resources. Adaptation to climate change impacts within Congo Basin floodplain ecosystems, and notably the globally significant Cuvette centrale, remains virtually undocumented, making these findings an important first contribution to understanding how local communities respond to hydrological shifts. This highlights an emerging research frontier: understanding how climate change-driven shifts in hydrological spatiotemporal variability structure adaptation—reshaping seasonal activity calendars, livelihood strategies, and natural resource use—and how these dynamics extend to other communities across similar floodplain ecosystems in the region.

Across the Congo Basin, expanding farm size and diversifying off-farm activities were also documented in eastern DRC (Batumike et al. 2021), though that study did not focus on seasonally flooded systems. Notably, in contrast to other studies (e.g., in Cameroon or the DRC), we did not observe a pronounced increase in NTFP reliance as a safety net against climate-induced crop failure (Bele et al. 2013). This may be because of the high baseline reliance on NTFP in the communities studied, as

suggested by Batumike et al. (2021). Several adaptive strategies observed in the Reserve are also reported in studies of floodplain local communities in the Amazon. For example, strategies such as harvesting crops in waist-deep water, elevating household items onto platforms, and submerging sealed cassava bags in water for preservation were also noted by Da Cunha Ávila et al. (2021). Interestingly, these authors documented additional biodiversity-friendly adaptations, including constructing stilt houses, using floating boards for agriculture, and minimizing stress on fruit-tree root systems, which were not mentioned by our study participants. Given their biodiversity-friendly nature, these practices could be considered in future discussions with Reserve local communities.

Adaptation strategies' potential impact on biodiversity

Considering the paucity of research on climate change adaptation in Central Africa, our study provides one of the first insights into the indirect impacts of adaptation on biodiversity in the Congo Basin. In light of the current state of knowledge, we found that most adaptation strategies reported by respondents can be classified as possible risk or benefit for biodiversity because their impacts are contingent on multiple contextual factors. Further research is needed to expand on these findings, particularly for adaptation strategies where impacts are still uncertain or for those posing potential conservation risks. Expanding farm size, for instance, may negatively impact biodiversity, particularly if it involves clearing old-growth forest rather than fallow land. This highlights the necessity for continued monitoring of Reserve local communities' adaptation strategies to more effectively identify and implement those that are biodiversity-friendly. One potential approach could involve examining biodiversity-friendly strategies used in other regions, such as Amazon floodplain ecosystems, to assess constraints and opportunities for their adoption, in dialogue with Reserve inhabitants. Rather than recommending best practices, the range of adaptive strategies documented here can serve as a basis for identifying potential approaches for testing in other seasonally flooded areas of the Congo Basin, particularly those that are biodiversity-friendly.

Implications of the findings

The statement, "we saw fish in the cocoa farm," expressed by one of our respondents, highlights the profound severity of climate change impacts and increasing livelihood constraints in an already isolated Congo Basin rainforest context. Such impacts may reinforce challenges to biodiversity conservation within the Lac Télé Community Reserve. This situation likely reflects the realities of many seasonally flooded sites across the region. To effectively reconcile biodiversity conservation and local development objectives in this ecologically critical area, a comprehensive understanding of climate change impacts on both biodiversity and livelihoods is of crucial importance. Indeed, the Congo Basin is projected to experience more extreme floods (Bola et al. 2022, Tshimanga et al. 2016) and droughts (Karam et al. 2022), but the monitoring of climatic variables (Yakusu et al. 2023) and of climate change effects on biodiversity remains insufficient (Beekmann et al. 2024). As our case study demonstrates, the local ecological knowledge of IP&LCs can offer valuable insights into the fine-scale impacts of climate change. Our study hence facilitates an improved understanding of ongoing changes and also contributes to filling an important data gap linked to IP&LC adaptation strategies in Central Africa.

Crucially, an interrogation remains: how to strengthen the resilience of local communities to climate change impacts without compromising biodiversity conservation objectives? Addressing such a question will benefit from enhanced co-production of knowledge among stakeholders, prioritizing science with society over science for society approaches (Steger et al. 2021). This inquiry is vital for the future of the Lac Télé Community Reserve and other floodplain socio-ecosystems within the Congo Basin.

Author Contributions:

Milena Beekmann: conceptualization, methodology, data collection, data curation and analysis, writing—original draft, writing—review and editing, funding acquisition, visualisation. Carlo Rondinini: validation, writing—review and editing, supervision. Célié Moungouya Moukassa: data collection, writing—review and editing. Alain Loumouamou: data collection, writing—review and editing. Andrea Lauti: scientific illustration. Aida Cuni-Sanchez: data analysis, writing—review and editing. Sandrine Gallois: conceptualization, validation, writing—review and editing, supervision.

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Data Availability:

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

LITERATURE CITED

- Alsdorf, D., E. Beighley, A. Laraque, H. Lee, R. Tshimanga, F. O'Loughlin, G. Mahé, B. Dinga, G. Moukandi, and R. G. M. Spencer. 2016. Opportunities for hydrologic research in the Congo Basin. *Reviews of Geophysics* 54(2):378-409. <https://doi.org/10.1002/2016RG000517>
- Amani, R. K., B. Riera, G. Imani, R. Batumike, N. Zafra-Calvo, and A. Cuni-Sanchez. 2022. Climate change perceptions and adaptations among smallholder farmers in the mountains of Eastern Democratic Republic of Congo. *Land* 11(5):628. <https://doi.org/10.3390/land11050628>
- Baderha, G. R., R. O. K. Tchoffo, A. S. K. Ngute, G. Imani, R. Batumike, N. Zafra-Calvo, and A. Cuni-Sanchez. 2024.

- Comparative study of climate change adaptation practices. *Mountain Research and Development* 44(2):20-27. <https://doi.org/10.1659/mrd.2023.00014>
- Batumike, R., F. Bulonvu, G. Imani, D. Akonkwa, A. Gahigi, J. A. Klein, R. Marchant, and A. Cuni-Sanchez. 2021. Climate change and hunter-gatherers in montane eastern DR Congo. *Climate and Development* 14(5):431-442. <https://doi.org/10.1080/17565529.2021.1930987>
- Beekmann, M., S. Gallois, and C. Rondinini. 2024. Uncertain future for Congo Basin biodiversity: a systematic review of climate change impacts. *Biological Conservation* 297:110730. <https://doi.org/10.1016/j.biocon.2024.110730>
- Bele, M. Y., D. J. Sonwa, and A. M. Tiani. 2013. Supporting local adaptive capacity to climate change in the Congo basin forest of Cameroon: a participatory action research approach. *International Journal of Climate Change Strategies and Management* 5(2):181-197. <https://doi.org/10.1108/17568691311327587>
- Bellard, C., C. Bertelsmeier, P. Leadley, W. Thuiller, and F. Courchamp. 2012. Impacts of climate change on the future of biodiversity. *Ecology Letters* 15(4):365. <https://doi.org/10.1111/j.1461-0248.2011.01736.x>
- Berkes, F., J. Colding, and C. Folke. 2000. Rediscovery of traditional ecological knowledge as adaptive management. *Ecological Applications* 10(5):1251. [https://doi.org/10.1890/1051-0761\(2000\)010\[1251:ROTEKA\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2000)010[1251:ROTEKA]2.0.CO;2)
- Bola, G. B., R. M. Tshimanga, J. Neal, M. A. Trigg, L. Hawker, V. M. Lukanda, and P. Bates. 2022. Understanding flood seasonality and flood regime shift in the Congo River Basin. *Hydrological Sciences Journal* 67(10):1496-1515. <https://doi.org/10.1080/02626667.2022.2083966>
- Bondeko, G., R. Mobongo, A. G. Bassouama, M. Boboto, R. Mossaba, and M. Yoko. 2016. Paysage Lac Télé- Lac Tumba. Rapport de l'étude économique de la Réserve communautaire du Lac Télé. Wildlife Conservation Society.
- Bush, E. R., R. C. Whytock, L. Bahaa-El-din, S. Bourgeois, N. Bunnefeld, A. W. Cardoso, J. T. Dikangadissi, P. Dimbonda, E. Dimoto, J. E. Ndong, K. J. Jeffery, D. Lehmann, L. Makaga, B. Momboua, L. R. W. Momont, C. E. G. Tutin, L. J. T. White, A. Whittaker, and K. Abernethy. 2020. Long-term collapse in fruit availability threatens Central African forest megafauna. *Science* 370(6521):1219-1222. <https://doi.org/10.1126/science.abc7791>
- Castello, P., P. B. Bayley, N. Nidia, Á. V. S. Fabr , and N. N. Batista. 2019. Flooding effects on abundance of an exploited, long-lived fish population in river-floodplains of the Amazon. *Reviews in Fish Biology and Fisheries*, 29(1):67-78. <https://doi.org/10.1007/s11160-019-09559-x>
- Chea, R., T. K. Pool, M. Chevalier, P. Ngor, N. So, K. O. Winemiller, S. Lek, and G. Grenouillet. 2020. Impact of seasonal hydrological variation on tropical fish assemblages: abrupt shift following an extreme flood event. *Ecosphere* 11(12):e03303. <https://doi.org/10.1002/ecs2.3303>
- Cohen, J. 1988. Statistical power analysis for the behavioral sciences. Second edition. Routledge, New York, New York, USA.
- Creese, A., R. Washington, and C. Munday. 2019. The plausibility of September–November Congo Basin rainfall change in coupled climate models. *Journal of Geophysical Research: Atmospheres* 124(11):5822-5846. <https://doi.org/10.1029/2018JD029847>
- Crezee, B., G. C. Dargie, C. E. N. Ewango, E. T. A. Mitchard, B. O. Emba, J. T. Kanyama, P. Bola, J. B. N. Ndjango, N. T. Girkin, Y. E. Bocko, S. A. Ifo, W. Hubau, D. Seidensticker, R. Batumike, G. Imani, A. Cuni-Sanchez, C. A. Kiahtipes, J. Lebamba, H. P. Wotzka, H. Bean, T. R. Baker, A. J. Baird, A. Boom, P. J. Morris, S. E. Page, I. T. Lawson, and S. L. Lewis. 2022. Mapping peat thickness and carbon stocks of the central Congo Basin using field data. *Nature Geoscience* 15(8):639-644. <https://doi.org/10.1038/S41561-022-00966-7>
- Cuni-Sanchez, A., A. B. Aneseyee, G. K. R. Baderha, R. Batumike, R. Bitariho, G. Imani, N. Jha, K. R. Kaganzi, B. A. Kaplin, J. A. Klein, A. Leite, R. A. Marchant, E. H. Martin, F. Mcharazo, B. Mwangi, A. S. K. Ngute, J. Nkengurutse, A. Nkurunziza, L. Olaka, T. Soromessa, R. O. K. Tchoffo, J. P. R. Thorn, I. Twinomuhangi, M. J. P. Sullivan, and N. Zafra-Calvo. 2025. Perceived climate change impacts and adaptation responses in ten African mountain regions. *Nature climate change* 15:153-161. <https://doi.org/10.1038/s41558-024-02221-w>
- Cureton, E. E. 1956. Rank-biserial correlation. *Psychometrika* 3:287-290. <https://doi.org/10.1007/BF02289138>
- Da Cunha Ávila, J. V., C. R. Clement, A. B. Junqueira, T. Ticktin, and A. M. Steward. 2021. Adaptive management strategies of local communities in two Amazonian floodplain ecosystems in the face of extreme climate events. *Journal of Ethnobiology* 41(3):409. <https://doi.org/10.2993/0278-0771-41.3.409>
- Devers, D., J. P. Vande Weghe, A. Billand, B. Cassagne, J. Doucet, R. Nasi, T. Tr fon, and C. E. G. Tutin. 2006. The forests of the Congo Basin: state of the forests 2006. Congo Basin Forest Partnership. https://pfbc-cbfp.org/fileadmin/user_upload/pfbc-cbfp/Thematiques/Etat_des_Forets/EDF2006_EN.pdf
- Dudley, N., editor. 2008. Guidelines for applying protected area management categories. International Union for Conservation of Nature, Gland, Switzerland. <https://doi.org/10.2305/IUCN.CH.2008.PAPS.2.en>
- Eba'a Atyi, R., F. Hiol Hiol, G. Lescuyer, P. Mayaux, P. Defourny, N. Bayol, F. Saracco, D. Pokem, R. Sufo Kankeu, and R. Nasi. 2022. Les for ts du Bassin du Congo:  tat des for ts 2021. CIFOR, Bogor, Indonesia. https://www.cifor-icraf.org/wp-content/uploads/sites/35/2024/06/Factsheet-Etat_des_forets_du_Bassin_du_Congo-2021-FR.pdf
- Faustin, O., G. Bondeko, and R. Mobongo. 2007. Projet de la R serve communautaire du Lac T l  (PRCLT). Wildlife Conservation Society, Washington D.C., USA.
- Few, R., A. Martin, and N. Gross-Camp. 2017. Trade-offs in linking adaptation and mitigation in the forests of the Congo Basin. *Regional Environmental Change* 17(3):851-863. <https://doi.org/10.1007/s10113-016-1080-6>
- Global Forest Watch. 2024. Forest monitoring designed for action. <https://www.globalforestwatch.org/>

- Hawthorne, D., I. T. Lawson, G. C. Dargie, Y. E. Bocko, S. A. Ifo, Y. Garcin, E. Schefuß, W. Hiles, A. J. Jovani-Sancho, G. Tyrell, G. E. Biddulph, A. Boom, B. M. Chase, P. Gulliver, S. E. Page, K. H. Roucoux, S. Sjögersten, D. M. Young, and S. L. Lewis. 2023. Genesis and development of an interfluvial peatland in the central Congo Basin since the Late Pleistocene. *Quaternary Science Reviews* 305:107992. <https://doi.org/10.1016/j.quascirev.2023.107992>
- Ifo, S. A., S. Binsangou, I. Ibocko Ngala, M. P. N. Madingou, and A. Cuni-Sanchez. 2019. Seasonally flooded, and terra firme in northern Congo: insights on their structure, diversity and biomass. *African Journal of Ecology* 57(1). <https://doi.org/10.1111/aje.12555>
- Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). 2019. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. IPBES 7, Paris, France. <https://doi.org/10.5281/zenodo.3553579>
- Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). 2022. The thematic assessment report on the sustainable use of wild species of the intergovernmental science-policy platform on biodiversity and ecosystem services. In J. M. Fromentin, M. R. Emery, J. Donaldson, M. C. Danner, A. Hallosserie, D. Kieling, G. Balachander, E. S. Barron, R. P. Chaudhary, M. Gasalla, M. Halmy, C. Hicks, M. S. Park, B. Parlee, J. Rice, T. Ticktin, and D. Tittensor, editors. IPBES Secretariat, Bonn, Germany. <https://doi.org/10.5281/zenodo.6425599>
- IUCN Red List of Threatened Species. Version 2024.1. <https://www.iucnredlist.org/>
- Karam, S., O. Seidou, N. Nagabhatla, D. Perera, and R. M. Tshimanga. 2022. Assessing the impacts of climate change on climatic extremes in the Congo River Basin. *Climatic Change* 170:1-24. <https://doi.org/10.1007/s10584-022-03326-x>
- Mangaza, L., D. J. Sonwa, G. Batsi, J. Ebuy, and J. M. Kahindo. 2021. Building a framework towards climate-smart agriculture in the Yangambi landscape, Democratic Republic of Congo (DRC). *International Journal of Climate Change Strategies and Management* 13(3):320-338. <https://doi.org/10.1108/IJCCSM-08-2020-0084>
- Mann, H. B., and D. R. Whitney. 1947. On a test of whether one of two random variables is stochastically larger than the other. *Annals of Mathematical Statistics* 18:50-60. <https://doi.org/10.1214/aoms/1177730491>
- Moukoyou, P., J. L. Kasali, J. Diamouangana, and F. Nsonsi. 2015. Gestion participative dans les aires protégées du Congo, mythe ou réalité: cas de la Réserve communautaire du Lac Télé. *Tropicultura* 33:24-32.
- Ndzana Biloa, E. B., V. Mamonekene, and J. C. Micha. 2024. Characterization of fish spawning grounds near the Likouala-Aux-Herbes River, Lac Tele Community Reserve (LTCR), Republic of Congo, for sustainable wetland management. *Sustainability* 16(8):3353. <https://doi.org/10.3390/su16083353>
- Ngute, A. S. K., M. A. K. Dongmo, J. A. M. Effa, E. M. Ambombo Onguene, J. Fomekong Lontchi, and A. Cuni-Sanchez. 2020. Edible caterpillars in central Cameroon: host plants, value, harvesting, and availability. *Forests, Trees and Livelihoods* 29(1):16-33. <https://doi.org/10.1080/14728028.2019.1678526>
- Nyadzi, E., O. C. Ajayi, and F. Ludwig. 2021. Indigenous knowledge and climate change adaptation in Africa: A systematic review. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources* 16(29). <https://doi.org/10.1079/PAVSNNR202116029>
- Pörtner, H. O., R. J. Scholes, J. Agard, E. Archer, A. Arneth, X. Bai, D. Barnes, M. Burrows, L. Chan, W. L. Cheung, S. Diamond, C. Donatti, C. Duarte, N. Eisenhauer, W. Foden, M. A. Gasalla, C. Handa, T. Hickler, O. Hoegh-Guldberg, K. Ichii, U. Jacob, G. Insarov, W. Kiessling, P. Leadley, R. Leemans, L. Levin, M. Lim, S. Maharaj, S. Managi, P. A. Marquet, P. McElwee, G. Midgley, T. Oberdorff, D. Obura, B. Osman Elasha, R. Pandit, U. Pascual, A. P. F. Pires, A. Popp, V. Reyes-García, M. Sankaran, J. Settele, Y. J. Shin, D. W. Sintayehu, P. Smith, N. Steiner, B. Strassburg, R. Sukumar, C. Trios, A. L. Val, J. Wu, E. Aldrian, C. Parmesan, R. Pichs-Madruga, D. C. Roberts, A. D. Rogers, S. Díaz, M. Fischer, S. Hashimoto, S. Lavorel, N. Wu, and H. T. Ngo. 2021. Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change. IPBES Secretariat. <https://doi.org/10.5281/zenodo.4782538>
- Poulsen, J. R., and C. J. Clark. 2002. Feasibility study of the Lac Télé Community Reserve. Wildlife Conservation Society, Washington, USA.
- Poulsen, J. R., and C. J. Clark. 2004. Densities, distributions, and seasonal movements of gorillas and chimpanzees in swamp forest in northern Congo. *International Journal of Primatology* 25 (2):285-306. <https://doi.org/10.1023/B:IJOP.0000019153.50161.58>
- Rainy, H., and F. Twagirashyaka. 2010. Community-based natural resource management land-use planning: lessons learned from the Lac Télé Community Reserve. Pages 2427-2441 in D. Yanggen, K. Angu Angu, and N. Tchamou. Landscape-scale conservation in the Congo Basin: lessons learned from the Central Africa Regional Program for the Environment (CARPE). United States Agency for International Development (USAID), Washington, D. C., USA.
- Ramallo, E. E., M. B. Main, G. C. Alvarenga, and L. G. R. Oliveira-Santos. 2021. Walking on water: the unexpected evolution of arboreal lifestyle in a large top predator in the Amazon flooded forests. *Ecology* 102(5):e03286. <https://doi.org/10.1002/ecy.3286>
- Reyes-García, V., S. Álvarez-Fernández, P. Benyei, D. Garciadel-Amo, A. B. Junqueira, V. Labeyrie, X. Li, V. Porcher, A. Porcuna-Ferrer, A. Schlingmann, and R. Soleymani. 2023. Local indicators of climate change impacts described by Indigenous Peoples and local communities: study protocol. *PLoS ONE* 18(1):e0279847. <https://doi.org/10.1371/journal.pone.0279847>
- Reyes-García, V., D. García-del-Amo, S. Álvarez-Fernández, P. Benyei, L. Calvet-Mir, A. B. Junqueira, V. Labeyrie, X. Li, S. Miñarro, V. Porcher, A. Porcuna-Ferrer, A. Schlingmann, C. Schunko, R. Soleymani, A. Tofighi-Niaki, M. Abazeri, E. M. N. A. N. Attah, A. Ayanlade, J. V. D. C. Ávila, B. Babai, R. C. Bulamah, J. Campos-Silva, R. Carmona, J. Caviedes, R. Chakauya, M. Chambon, Z. Chen, F. Chengula, E. Conde, A.

- Cuni-Sanchez, C. Demichelis, E. Dudina, Á. Fernández-Llamazares, E. K. Galappaththi, C. Geffner-Fuenmayor, D. Gerkey, M. Glauser, E. Hirsch, T. Huanca, J. T. Ibarra, A. E. Izquierdo, L. Junsberg, M. Lanker, Y. López-Maldonado, J. Mariel, G. Mattalia, M. D. Miara, M. Torrents-Ticó, M. Salimi, A. Samakov, R. Seidler, V. Sharakhmatova, U. B. Shrestha, A. Sharma, P. Singh, T. Ulambayar, R. Wu, and I. S. Zakari. 2024. Indigenous Peoples and local communities report ongoing and widespread climate change impacts on local social-ecological systems. *Communications Earth & Environment* 5(1):1-10. <https://doi.org/10.1038/s43247-023-01164-y>
- Savo, V., D. Lepofsky, J. P. Benner, K. E. Kohfeld, J. Bailey, and K. Lertzman. 2016. Observations of climate change among subsistence-oriented communities around the world. *Nature Climate Change* 6(5):462-473. <https://doi.org/10.1038/nclimate2958>
- Scheffers, B. R., L. De Meester, T. C. L. Bridge, A. A. Hoffmann, J. M. Pandolfi, R. T. Corlett, S. H. M. Butchart, P. Pearce-Kelly, K. M. Kovacs, D. Dudgeon, M. Pacifici, C. Rondinini, W. B. Foden, T. G. Martin, C. Mora, D. Bickford, and J. E. M. Watson. 2016. The broad footprint of climate change from genes to biomes to people. *Science* 354(6313):aaf7671. <https://doi.org/10.1126/science.aaf7671>
- Segan, D. B., D. G. Hole, C. I. Donatti, C. Zganjar, S. Martin, S. H. M. Butchart, and J. E. M. Watson. 2015. Considering the impact of climate change on human communities significantly alters the outcome of species and site-based vulnerability assessments. *Diversity and Distributions* 21(9):1101-1111. <https://doi.org/10.1111/ddi.12355>
- Shapiro, A. C., H. S. Grantham, N. Aguilar-Amuchastegui, N. J. Murray, V. Gond, D. Bonfils, and O. Rickenbach. 2021. Forest condition in the Congo Basin for the assessment of ecosystem conservation status. *Ecological Indicators* 122:107268. <https://doi.org/10.1016/j.ecolind.2020.107268>
- Sonwa, D. J., M. O. Farikou, G. Martial, and F. L. Félix. 2020. Living under a fluctuating climate and a drying Congo basin. *Sustainability* 12(7):1-22. <https://doi.org/10.3390/su12072936>
- Steger, C., J. A. Klein, R. S. Reid, S. Lavorel, C. Tucker, K. A. Hopping, R. Marchant, T. Teel, A. Cuni-Sanchez, T. Dorji, G. Greenwood, R. Huber, K. A. Kassam, D. Kreuer, A. Nolin, A. Russell, J. L. Sharp, M. Šmid Hribar, J. P. R. Thorn, G. Grant, M. Mahdi, M. Moreno, and D. Waiswa. 2021. Science with society: evidence-based guidance for best practices in environmental transdisciplinary work. *Global Environmental Change* 68:102240. <https://doi.org/10.1016/j.gloenvcha.2021.102240>
- Tieminie, R. N., E. L. Chia, J. C. Tieguhong, and F. L. Awamba. 2023. Perceptions of climate change and local responses on livelihoods: the case of people around the Mambioko community forest. *GeoJournal* 88:3969-3984. <https://doi.org/10.1007/s10708-023-10849-y>
- Tieminie, R. N., C. E. Loh, J. C. Tieguhong, F. Nghobuoche, S. Piabuo, and M. Tieguhong. 2021. Non-timber forest products and climate change adaptation among forest dependent communities in Bamboko forest reserve, Southwest region of Cameroon. *Environmental Systems Research* 10:20. <https://doi.org/10.1186/s40068-020-00215-z>
- Tshimanga, R. M., J. M. Tshitenge, P. Kabuya, D. Alsdorf, G. Mahe, G. Kibukusa, and V. Lukanda. 2016. A regional perspective of flood forecasting and disaster management systems for the Congo River Basin. Pages 87-124 in T. W. Adams and T. C. Pagano, editors. *Flood Forecasting*. <https://doi.org/10.1016/b978-0-12-801884-2.00004-9>
- Yakusu, E. K., J. Van Acker, H. Van de Vyver, N. Bourland, J. Mbifo Ndiapo, T. Besango Likwela, M. Lokonda Wa Kipifo, A. Mbuya Kankolongo, J. Van den Bulcke, H. Beeckman, M. Bauters, P. Boeckx, H. Verbeeck, K. Jacobsen, G. Demarée, F. Gellens-Meulenberghs, and W. Hubau. 2023. Ground-based climate data show evidence of warming and intensification of the seasonal rainfall cycle during the 1960-2020 period in Yangambi, Central Congo Basin. *Climatic Change* 176(10):142. <https://doi.org/10.1007/s10584-023-03606-0>
- Zhou, L., Y. Tian, R. B. Myneni, P. Ciais, S. Saatchi, Y. Y. Liu, S. Piao, H. Chen, E. F. Vermote, C. Song, and T. Hwang. 2014. Widespread decline of Congo rainforest greenness in the past decade. *Nature* 509(7498):86-90. <https://doi.org/10.1038/nature13265>

Appendix 1

Table A1.1 Number of local indicators and observations of changes reported by study participants (n=80), across systems and sub-systems.

System	Sub-system	Number of indicators	Number of observations				
			Village 1 (swamp forest)	Village 2 (<i>terra firma</i> forest)	Village 3 (seasonally flooded forest)	Village 4 (<i>terra firma</i> forest)	Total
Atmospheric system	Temperature	7	15	12	18	18	63
	Seasons	6	16	22	18	19	75
	Rainfall	8	17	10	20	19	66
	Fog	2	6	6	12	6	30
	Wind	2	12	8	16	14	50
	Total	25	66	58	84	76	284
Biophysical system	River	4	16	10	22	19	67
	Floods	14	77	45	85	107	314
	Soil	4	4	1	17	11	33
	Fire	6	19	14	21	15	69
	Forest	5	21	18	20	11	70
	Forest trees	46	16	35	36	34	121
	Fish	61	71	33	56	47	207
	Mammals	95	55	87	66	77	284
	Birds	50	20	31	19	28	98
	Non-timber forest products	10	23	54	20	21	118
	Total	295	344	384	404	400	1531

Human system	Agriculture	14	38	27	39	39	143
	Health	10	36	6	36	33	111
	Village trees	20	44	21	32	17	114
	Total	44	125	70	119	93	407
TOTAL		364	554	537	618	585	2293

Table A1.2 Indicators of change reported by respondents in the atmospheric system (n= 80 respondents), including agreement with meteorological data, and respondent quotes. “N/A” denotes absence of meteorological data linked with the corresponding indicator.

Indicator of change	Total number of citations	Agreement with meteorological data	Quotes
Increased temperature (in general)	30	YES	<i>“Things have changed. I can't leave my house when it's hot. And yet I used to work in the sun. The sun is very uncomfortable [...] when you stay in the sun, you get dizzy. I used to work in the fields under the sun.”</i>
Increased temperature (long dry season)	10	YES	<i>“The heat has increased, especially in the dry season [mwanga]. The heat even stings the nostrils when it's so hot. Every day, the children go straight to the water after school, even the adults go to cool off there [...] even drinking is difficult, as the water in the wells heats up and looks like it's been heated. The water in the river is getting hot.”</i>
Increased temperature (long rainy season)	6	YES	<i>“We're in pela and it's hot, everyone says ‘oh, it's hot’. Normally, the really strong suns are in the dry season [mwanga], but now they're also in the rainy season [pela], because of climate change.”</i>
Decreased temperature (in general)	5	NO	<i>“It's cooler, because of the winds that come from the savanna. There are no longer trees to protect us and the wind blows into the village and breaks the trees.”</i>
Unstable temperature (in general)	3	N/A	<i>“Now, in periods of heat, there is less stability, it can change by a week or a day.”</i>
Increased rainfall (in general)	28	YES	<i>“Generally speaking, there is more rain, and it is more frequent and more intense, especially this year.”</i>
Increased rainfall (long rainy season)	6	YES	<i>“The rains have exceeded. It rains without rest. In the rainy season [pela], it rains morning and night. It wasn't like that before.”</i>
Reduced rainfall (in general)	5	NO	<i>“Before, it used to rain all day in the rainy season [pela], from morning until 5pm, even flooding the plot, but now it doesn't rain like that [...] anymore. The rains threaten, they come with wind, but they come with less intensity than before.”</i>

Long rainy season in lieu of short rainy season	4	PARTIAL	<i>"It's the first time that a short rainy season has caused people to flood, the calendar we had before has changed, it's the first time we've seen this [...] there's upheaval even in our heads."</i>
Increased rainfall (long dry season)	2	YES	<i>"There used to be no rain in in the dry season [mwanga], only from May onwards. The rains are more intense now than they used to be. Before, if there was heavy rain, it meant that the rainy season was starting. But now it rains as early as March."</i>
Unpredictable onset of rainfall	1	N/A	<i>"The rains have changed. Today there are rains that fall suddenly with no warning signs. Before there were signs in the sky like black clouds and thunder before the rains."</i>
Altered seasonal patterns	24	YES	<i>"The calendar has been turned upside down. We no longer use the calendar. As soon as there's sun, we take advantage of it to burn the fields because there's a change in the rains." "We ask ourselves: is it the rainy season [pela]? Is it the dry season [mwanga]? It's hard to tell the seasons apart."</i>
Early onset of the long rainy season	24	N/A	<i>"The rains have changed. They used to start in August. This year, they started from March".</i>
Reduced length of long dry season	11	PARTIAL	<i>"The dry season is becoming shorter, at least in recent years."</i>
Late onset of the long rainy season	8	N/A	<i>"In the past, at this time of year [in October], it would have rained, but now there's sunshine instead of rain, the water doesn't push anymore."</i>
Longer duration of long rainy season	6	PARTIAL	<i>"Normally [...] at the end of August, the long rainy season [pela] begins, lasting until September-October-November. This year, since June, is it [pela]. The water only recedes a little, then rises again."</i>
Longer duration of short dry season	2	NO	<i>"Often, the dry season [mwanga] is extended, from December to July, instead of 6 months dry season. This creates major changes in society. Fish have the same problem: for them to circulate, they need water that corresponds to their body, otherwise they can't eat properly, they stay put, even if the bait is in front of them, they</i>

			<i>don't eat, they're not healthy. That's why sometimes there are no fish in the net or on the hook."</i>
Decreased fog (#days, length, intensity)	24	N/A	<i>"The fog is no longer intense. Before, for even a week you could see blurred. Now it's less intense. It's now down [only] at 5am, 6am. From 7am, you can see over the river. It only disappears for 5 days. It used to last for 2 weeks, all day long, the sunlight down [would] turn as white as the moon."</i>
Increased fog (#days, length, intensity)	6	N/A	<i>"You can see the fog when the water goes down [at the end of the flooding season]. It's much cooler now than it used to be."</i>
Increased frequency of violent wind (in general)	31	N/A	<i>"Some people flooded with their canoe while crossing [the river], the winds pushed them out of the canoe, the waves came in and the cassava fell into the water crossing [...]. The wind has been increasing like this for two years." "There is lot more wind because we've cut down too many trees. It's the trees that stop the wind."</i>
Decreased intensity wind (across seasons)	6	N/A	<i>"Some winds are intense, others not. Lately, the winds have not been so intense."</i>

Table A1.3 Indicators of change reported by respondents in the biophysical system (n= 80 respondent), including respondent quotes.

Indicator of change	Total number of citations	Quotes
Increased flood magnitude (in general)	56	<i>"The waters came after the dry season [mwanga], it pushed on dry land really strongly, the trees near the river were flooded, there were even fish on dry land."</i>
Disrupted seasonality of floods in forests	5	<i>"The water is late in the forest, and the old man who spoke of the changing of the trimesters, without us believing him, was right."</i>
Increased floods in agricultural areas	30	<i>"Before, the fields would flood at the corners and a part would remain intact, but now it's the whole field that's flooded."</i>
Increased frequency of flooding events	45	<i>"This year, it is a total upheaval. There are possibly three floods for the first time. Before, there was not so much flooding, just in the corners. We can't move the village, where can we go?"</i>

Increased floods in village	55	<i>"In May, the villages were flooded [...] all the villages in the North were flooded. They used dugout canoes in the village. People took refuge in the forest during the floods."</i>
Increased flood magnitude in forests	42	<i>"The water has pushed up a lot in the forest, it's made a mess of things. The water has [...] at noon on 11 March. The water washed away our nets and hooks. At noon, I saw that the water had risen in 2 hours over 200 meters. I was at the ancestors' camp. It's a big river and I've never seen the water rise like that."</i>
Earlier onset of flooding events	26	<i>"This year, the flooding started in March. The floods used to arrive in August."</i>
Altered seasonal flooding regime	20	<i>"There's upheaval even in our heads. The real high-water season is now, but we can already see that the water is not going to rise much, there are too many variations."</i>
Accelerated rise in flood levels	10	<i>"There was a strong current and the water rose quickly in one day. I went back to the village to leave the child and the next day I went back into the forest, the water had already advanced a long way. We thought it was the end of the world, we were scared."</i>
Increased duration of flooding events	8	<i>"We are not used for the floods to be so long".</i>
Disappearance of flood patterns called "miyela"	4	<i>"Miyela [referring to subtle shifts in water flow observed in the Likouala-aux-herbes river, traditionally signaling the onset of the short rainy season] was in April; there are none now."</i>
Late onset of flooding events	4	<i>"Things aren't as they used to be. At the moment, there should be plenty of water in the forest, but the young people who go fishing say that it's drying up."</i>
Reduced river depth (long dry season)	41	<i>"In the dry season, when the water goes down, it can be at the level of your calves or ankles because there is too much sand. Before there was depth, you could dive in completely."</i>
Increased river width (long rainy season)	15	<i>"In the rainy season [pela], again because of the disappearing trees, you can forget your way, the river has become very wide, you can end up in Epéna by mistake."</i>
Increased river width (long dry season)	10	<i>"Before during the dry season [mwanga], the water dried completely. Now, it doesn't dry as well as it used"</i>

		<i>to. It's bad because you don't find many fish. It's getting wider than it used to be on dry land."</i>
Increased erosion (riverbank or in village)	20	<i>"In [my] opinion, the soil is breaking up because it was under water, and with the heat, it dries out, breaks up and erosion progresses, causing the trees along the river to fall. The river becomes open, in front of the village and elsewhere."</i>
Increased occurrence of mud in village	6	<i>"The ground has really changed. Before, even after it rained, you could move around. There was no mud. Now, after a little rain, there's mud and the water stagnates in the village."</i>
Increased soil heat in village	6	<i>"The ground is very hot, even walking in the street is difficult, there are not many trees or fruits."</i>
Increased frequency of fire events	29	<i>"In the old days, the elders respected the seasons [...] Now, very early on, around February or March, the savannas are burnt. When this happens, it creates disturbances and seasonal variations. Before, we used to wait until May to burn [...] the timetable is no longer respected because of extreme poverty."</i>
Increased intensity (including length) of fire events Reduced occurrence of fire events	18	<i>"Now, [we do] a little fire, and it burns from the savanna to the forest. I realized it's because of the stronger sun. Even the trees with the green leaves burn."</i>
Increased occurrence of fire events in forested areas	6	<i>"The new fishermen go into the camps and no longer clean up the debris before setting fire to it. Now they directly set fires in the forest."</i>

Table A1.4 Summary of the 15 most observed indicators of biodiversity change in Lac Télé Community Reserve (n= 80 respondents), including respondent quotes.

Indicator of change	Total number of citations	Quotes
Reduced abundance of fish	56	<i>"Some species of fish have disappeared or become rare. Forest fires are destroying their homes and breeding grounds, and fishing pressure is increasing."</i>
Reduced caterpillar abundance	41	<i>"The caterpillars didn't produce much this year. They came out on time but didn't last. There were only three days during which there were a lot of caterpillars: the other days they came out a little, 30 caterpillars, we call them biffinio which means</i>

		<i>premature. Normally, the period during which we harvest good quantities lasts 2 weeks."</i>
Disrupted mammal migration	36	<i>"When they see the water coming, [animals] go on dry land. During the first [flood], the biggest one, the animals reached the dry land."</i>
Decreased gallery forest area, replaced by savanna areas	33	<i>"Forests are burning down because there are more fires, there is too much sun and less rain in the dry season."</i>
Increased tree mortality	30	<i>"Every year, the trees fall. This year, it looked like a cut field. Even on 1 hectare, the big trees were falling on top of each other. Big and small trees fall. There was water up to your chest. The soil was weakened."</i>
Reduced mammal species abundance	28	<i>"There used to be a lot of animals. We used to kill seven to ten elephants with the spear [assegai]. When it rained, they would go and eat on the edge of the savannah, [and] we would come and surround them [...]. These days, nothing."</i>
Reduced abundance in birds	24	<i>"There was one type of bird which reproduced a lot in the savannah during [pela]. We caught them to eat them. We don't see them anymore. We used to see them all the time [...]. There were lots of them on the palm trees near the river. We used to hear them a lot."</i>
Decreased forest fruit production	23	<i>"Fruits are still producing, but less than before. When I was growing up, it wasn't like that."</i>
Disrupted bird migration	23	<i>"The marabout stock come in large numbers in March, in 2023, March was the rainy season [pela], they came, but left just afterwards. They eat in groups, the water has to go down, they eat all types of fish in the ponds."</i>
Reduced abundance in <i>Gnetum africanum</i>	20	<i>"We used to find them in the fields, behind the houses, but now we don't find them as much as before"; "they were burned by the fire."</i>
Fish found dead	19	<i>"Fish like it cool. A lot of fish has died this year because of the heat."</i>
Reduced habitat for fish	17	<i>"The fish have moved because the water is not deep enough, the river is silted up."; "Their house was burnt down by the fires."</i>
Disrupted fish migration	15	<i>"The [flood] took the fish to the forest and brought them back to the savannah. Instead of leaving them to reproduce properly, they reproduced in disorder. Some mounougoussou (Parachanna obscurus) started to reproduce in the forest, then came back to the savannah with the fry, then went back to the forest again, which upsets them." "Normally, the fish spawn</i>

		<i>in the forest ponds, then emerge into the river as the water rises. The floods in March took the juveniles out of the forest too soon; this year, it is a total disruption.”</i>
Changed seasonality patterns for caterpillars	14	<i>“We observed that they appear with a slight delay of two weeks or even a month.”</i>
Disappearance of fish species	14	<i>“There are many qualities of fish (mboto, souni, nina kombo....) which are no longer seen.”</i>

Table A1.5 Climate change impacts on Lac Télé Community Reserve villages, % of respondents (n= 111). Not applicable indicates that the observation was not reported in the respective village.

System	Impact	Village 1 (swamp forest)	Village 2 (terra firme forest)	Village 3 (seasonally inundated forest)	Village 4 (terra firme forest)
Housing	Flooded houses	100%	Not applicable	43%	59%
Agriculture	Flooded agricultural fields	100%	13%	93%	86%
	Disturbance of seasonal activities	Not applicable	42%	87%	86%
	Smaller quantities of food	73%	83%	60%	21%
	Increase of human-wildlife conflicts	Not applicable	50%	17%	41%
	Increase cases of African cassava mosaic virus	Not applicable	58%	63%	52%
Fishing	Disrupted fishing season	57%	42%	53%	41%

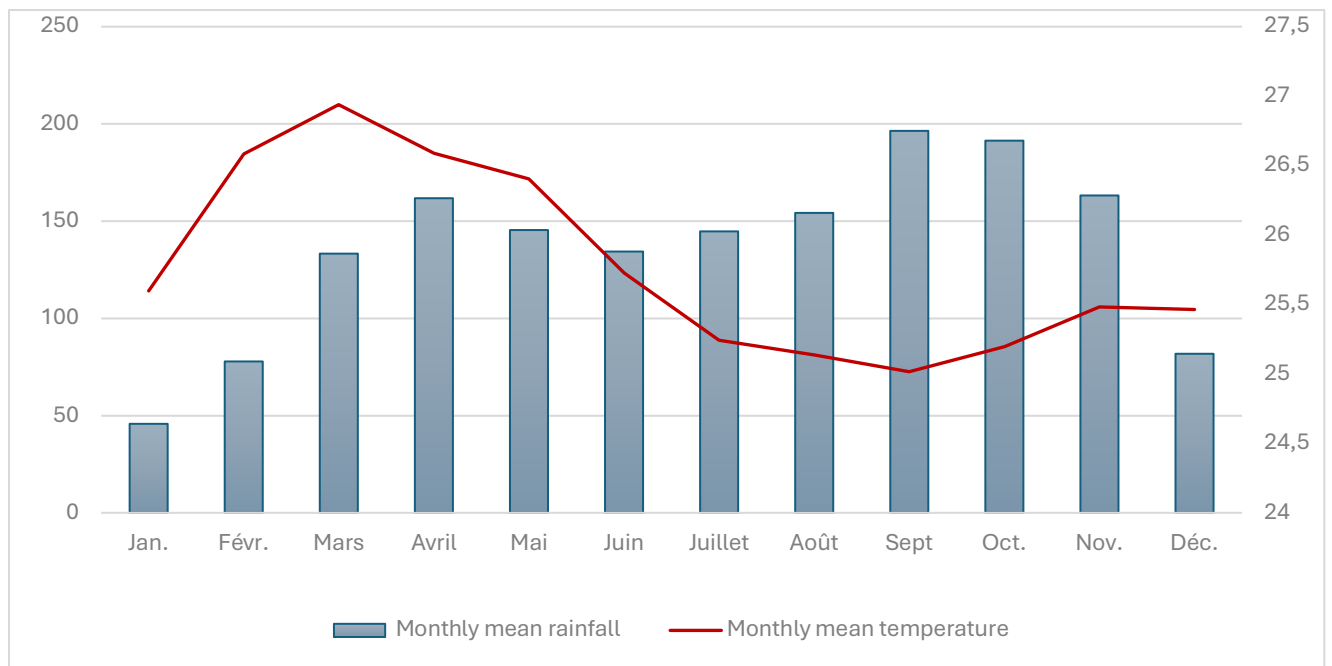


Fig. A1.1 Seasonal variation in temperature and rainfall at the Impfondo meteorological station at the Impfondo Airport. Data source: Agence Nationale de l'Aviation Civile du Congo.

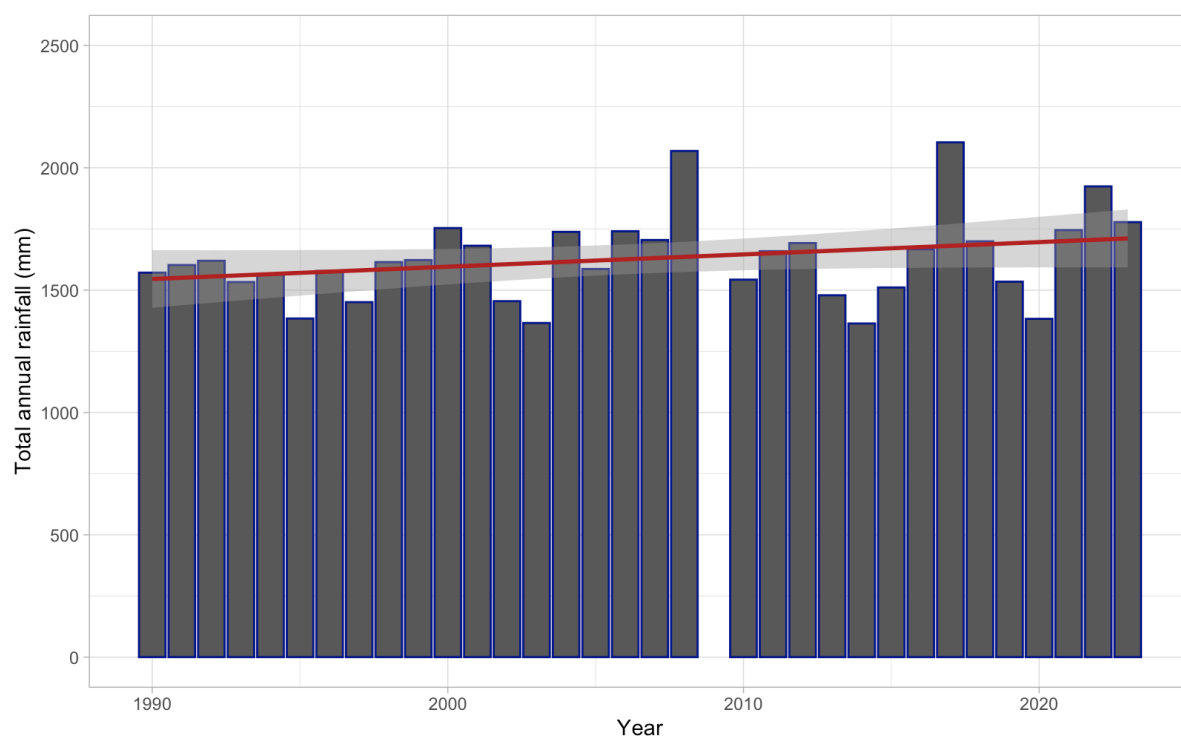


Fig. A1.2 Total annual rainfall for the 1990-2023 period at the Impfondo airport. Data source: Agence Nationale de l'Aviation Civile du Congo.

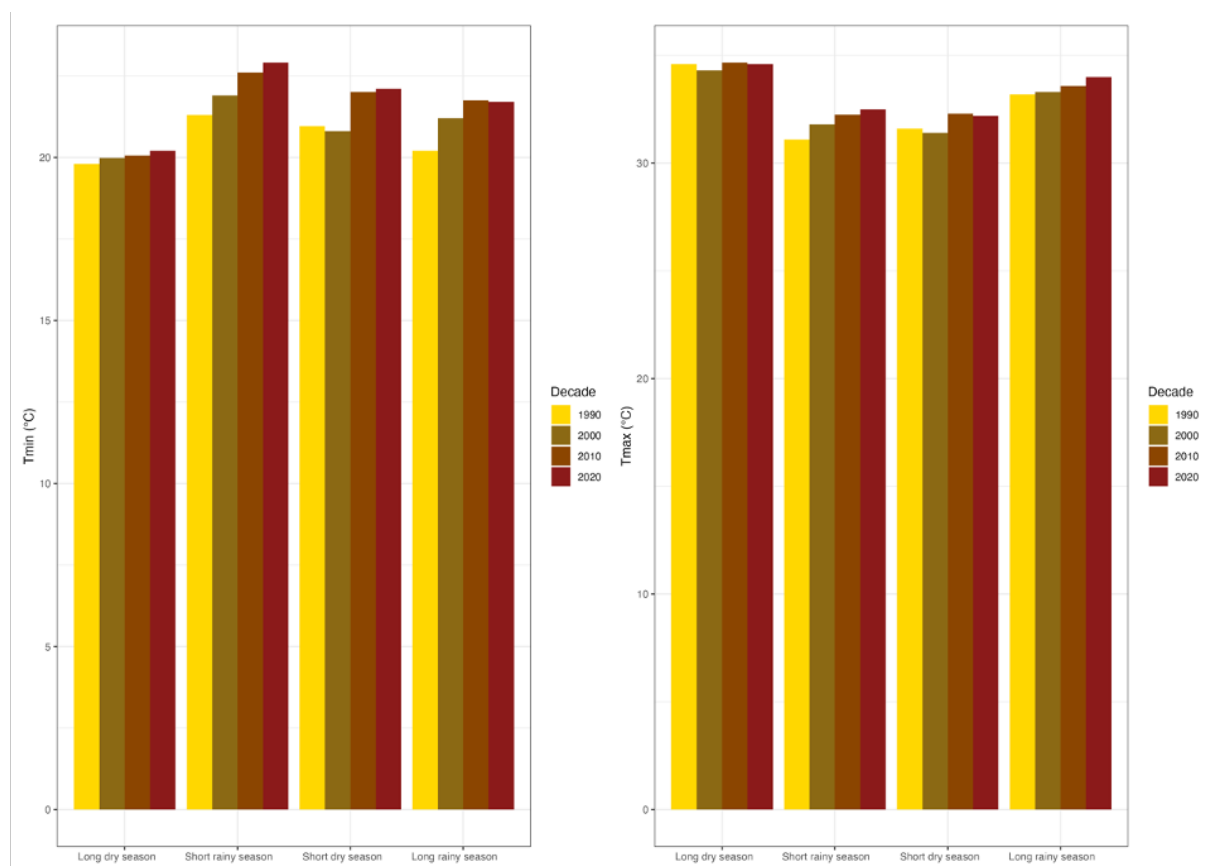


Fig. A1.3 Seasonal minimum temperature (left) and seasonal maximum temperature (right) at the Impfondo airport. Data source: Agence Nationale de l'Aviation Civile du Congo.

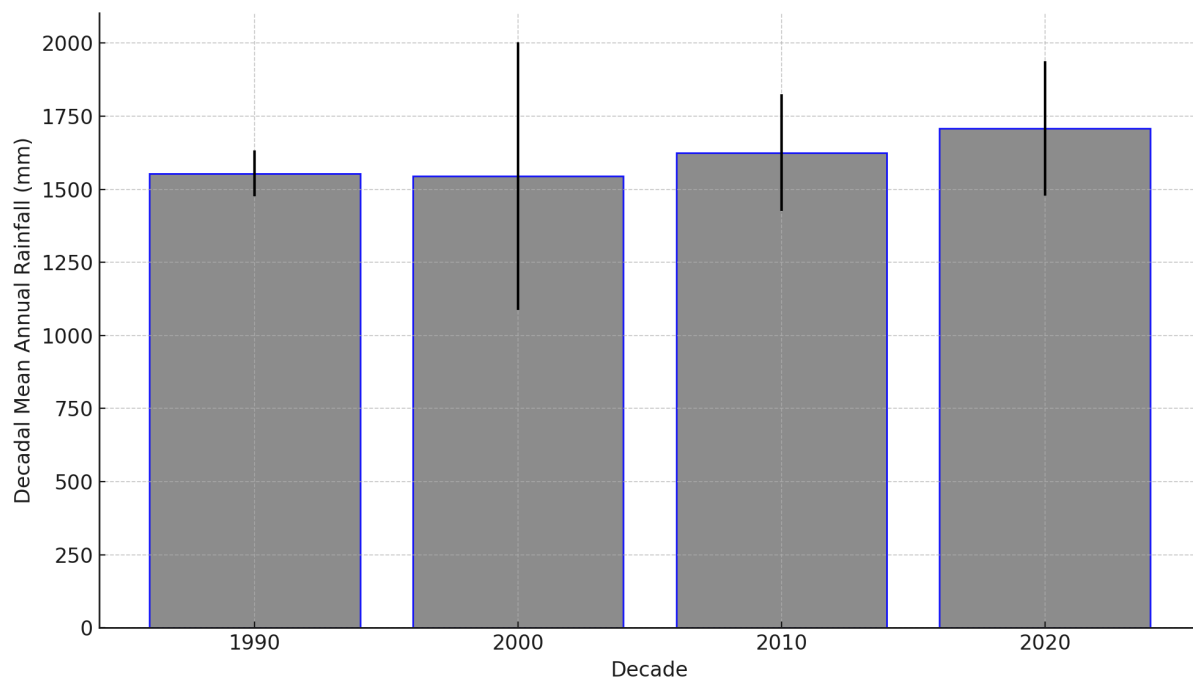


Fig. A1.4 Decadal averages of annual rainfall ($\pm$ standard deviation) for the period 1990-2023 at Impfondo airport. Bars represent decadal averages, and error bars indicate interannual variability within each decade. Data source: Agence Nationale de l'Aviation Civile du Congo.

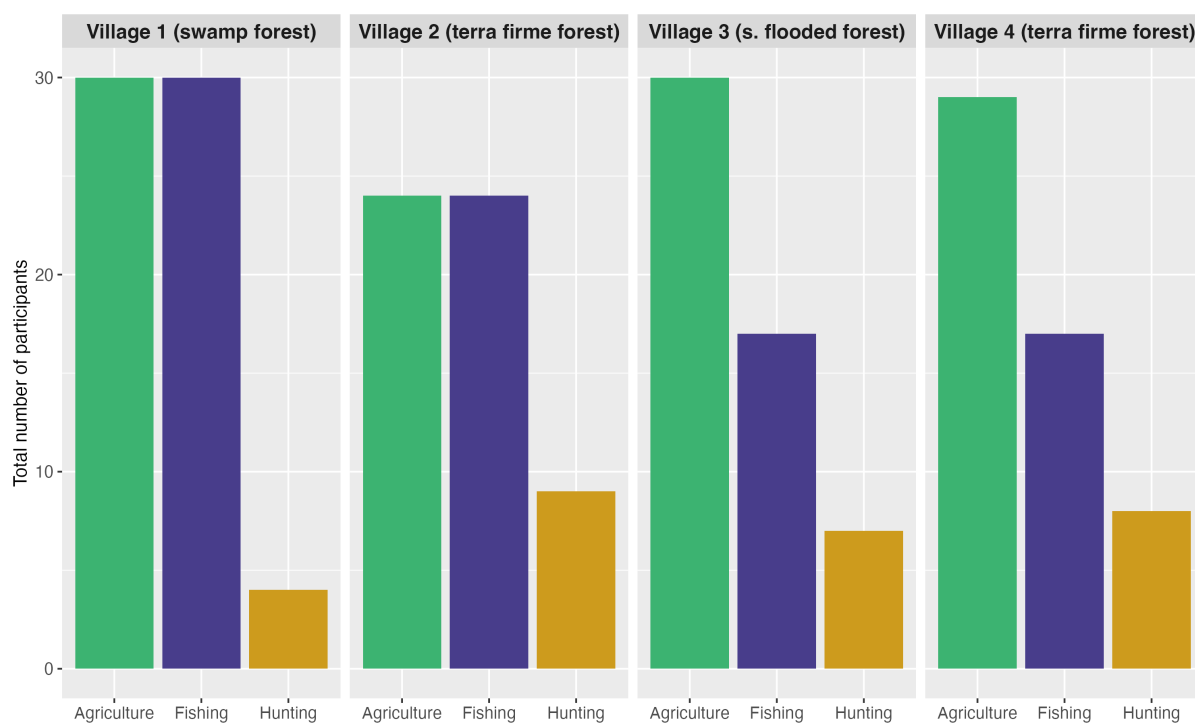


Fig. A1.5 Primary subsistence activities in each village.

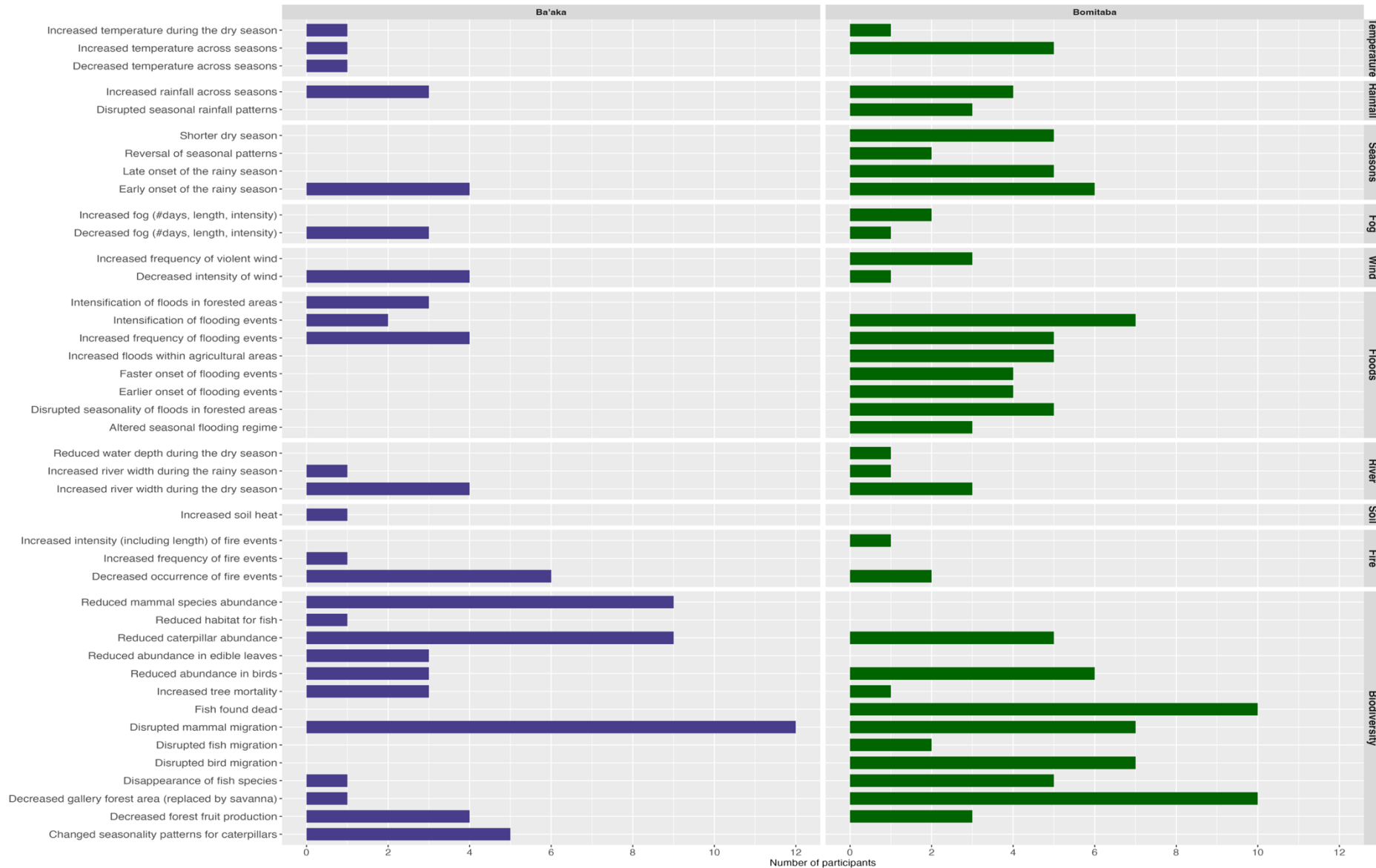


Fig. A1.6 Indicators of change reported by Ba'aka (n=12) and Bomitaba respondents (n=10). No significant difference found between Ba'aka and Bomitaba respondents ($U = 1464.0$, $p = 0.115$), though effect sizes ($r_{rb} = -0.16$; $d = -0.27$) suggest a small tendency for Bomitaba to report more indicators.

Guiding questionnaire used for exploratory focus group discussions:

Seasonal calendar:

Objective: Identify seasonal livelihoods and significant events (rainy seasons and dry seasons, holidays and festivals, agricultural activities including planting, harvesting, and marketing, hunting and fishing, periods of resource scarcity such as food, water, fish, or pastures, the calendar of climatic events such as storms, floods, droughts, and heatwaves).

Materials: Large sheets and colored pens or chalk in different colors.

- What are the main seasons? How do you recognize the change of seasons? What are the local names?
- What are the most important subsistence activities in the community? What are the local names?
- Details on planting: What are the main species cultivated? What techniques are used? In which season? When is the harvest? Where do you carry out these activities? Are there any people/groups of people who have more knowledge about this activity? What are the local names?
- Details on fishing: What are the main species fished? What techniques are used? At what time of the year? Were there times of the year when this activity was not done in the past? Has that changed? Where do you carry out these activities? Are there traditional fishing areas? Are these areas still respected? Are there people/groups of people who have more knowledge about this activity? What are the local names?
- Details on hunting: What are the main species hunted? What techniques are used? At what time of the year? Were there times of the year when this activity was not done in the past? Has that changed? Where do you carry out these activities? Are there traditional hunting areas? Are these areas still respected? Are there people/groups of people who have more knowledge about this activity? What are the local names?
- Details on collecting forest products: What are the main species collected most often? What techniques are used? At what time of the year? Were there times of the year when this activity was not done in the past? Has that changed? Where do you get the best forest products? Are there traditional collection areas? Are these areas still respected? Are there people/groups of people who have more knowledge about this activity? What are the local names? When do you usually get the best forest products?
- When are the major village festivals? What are the local names?
- Compared to when you were young, have there been any changes?
- If someone wants to know something about the forest (plants, animals, and specific areas), who among the villagers is able to explain it?

Historical timeline:

Objective: Establish the history of the village over the past 80-100 years. Relevant information includes: the date of the community's foundation/establishment; demographic changes, migration and settlement patterns; land rights over their territory and their evolution over time; trends in market interaction or changes in subsistence activities; approximate dates/periods when these events started to occur; extreme weather events; key infrastructure or social developments, including past disasters and changes in their nature, intensity, or configuration.

- How long has this village existed?
- Have there been any significant events?
- Has a road been built?
- Has a school been built?
- Has a new local chief arrived?
- Have there been any other significant events?
- Have there been any significant environmental events (e.g., extreme weather events)?

Guiding questionnaire used for the semi-structured interviews and the focus group discussions.

Part 1. Observed changes in climate, biophysical systems and drivers of change

1. Compared with when you were a young child, have the rains changed? (details on how they have changed, amount, duration, dry spells, showers, which seasons)
2. Compared with when you were a young child, has fog changed? (details on how it has changed, which seasons)
3. Compared with when you were a young child, has temperature changed? (details on how it has changed, which seasons)
4. Compared with when you were a young child, has wind changed? (details on how it has changed, which seasons)
5. Compared with when you were a young child, has frost changed? (details on how it has changed, which seasons)
6. Compared with when you were a young child, have hail storms changed? (details on how it has changed, which seasons)
7. Is there anything else you would like to add with regard to changes in local climate?
8. Why do you think the local climate has changed?
9. Compared with when you were a young child, has the environment here changed, e.g. floods, stream flow, landslides, soil erosion? (details on how it has changed)
10. Is there anything else you would like to add with regard to changes in your environment?

Part 2. Changes in the biological domain

11. Compared with when you were a young child, has the abundance of caterpillars, mushrooms or wild honey in the forest changed? (details on how it has changed)
12. Compared with when you were a young child, has the abundance of some trees or animals in the forest changed? (details on how it has changed)

13. Compared with when you were a young child, has the fruiting of some trees changed? (details on how it has changed)
14. Compared with when you were a young child, has the yield of some crops changed? (details on how it has changed)
15. Compared with when you were a young child, has domestic animals' health or number of offspring changed? (details on how it has changed)
16. Is there anything else you would like to add?

Part 3. Adaptive strategies used

17. Because of the changes in local climate you mentioned (e.g. less rainfall), and impacts on crops what have you changed? (details)
18. Was this change driven by a project from an NGO or the government?
19. Is there anything else you would like to add with regard to the things you have done to adapt to changes in climate and its impacts?
20. Is there anything else you would like to add?

Quantitative questionnaire – adaptation strategies and livelihood change (adapted on site)

Sex:

Age group:

Main activity (farmer, fisherman, hunter, etc.):

Agriculture:

1. Are you still involved in agricultural activities? Yes/no/not applicable
2. Have you changed the location of your field? Yes/no/not applicable
3. Have you changed the size of your field? Yes/no/not applicable
4. Have you changed the distance of your field, compared to the village? Yes/no/not applicable
5. Have you changed the duration or frequency of daily agricultural activities? Yes/no/not applicable
6. Have you changed species grown? Yes/no/not applicable
7. Have you changed your agricultural techniques (e.g. cutting, seedlings...)? Yes/no/not applicable
8. Have you changed your soil conservation techniques? Yes/no/not applicable
9. Have you changed your use of fertilizers or pesticides? Yes/no/not applicable
10. Have you changed the amount of irrigation? Yes/no/not applicable
11. Do your fields produce as before? Yes/no/not applicable
12. Have you noticed any seasonal changes in relation to agricultural production? Yes/no/not applicable
13. Have you changed your livestock activities (e.g. more or less cattle)? Yes/no/not applicable
14. Are there any other change related to your agricultural activities that you would like to mention? Yes/no/not applicable

Fishing:

15. Do you catch the same amount of fish as before? Yes/no/not applicable
16. Do you catch the same qualities/species of fish as before? Yes/no/not applicable

17. Do you use the same fishing method as before? Yes/no/not applicable
18. Do you catch more juveniles than before? Yes/no/not applicable
19. Do you fish in the same areas? Do you fish further or less far than before? Yes/no/not applicable
20. Do you fish more than before? Yes/no/not applicable
21. When you go fishing, do you fish longer than before? Yes/no/not applicable
22. Do you fish at the same time as before? Yes/no/not applicable
23. Do you fish deeper than before? Yes/no/not applicable
24. Do you fish in the same season as before? Yes/no/not applicable
25. Are there more fishermen than before? Yes/no/not applicable
26. Are there any other changes related to fishing that you would like to mention?
Yes/no/not applicable

Hunting and collect of NTFP:

27. Do you hunt more than before? Yes/no/not applicable
28. Do you hunt other qualities/species than before? Yes/no/not applicable
29. Do you hunt the same amount of animals as before? Yes/no/not applicable
30. Do you hunt in the same areas as before (further away, less far)? Yes/no/not applicable
31. Do you use the same hunting method as before? Yes/no/not applicable
32. When you go hunting, do you hunt longer than before? Yes/no/not applicable
33. Do you hunt at the same time of the year as before? Yes/no/not applicable
34. Are you collecting more forest products than before (e.g. plant, resin, building or medicinal material)? Yes/no/not applicable
35. Are you collecting more firewood than before? Yes/no/not applicable
36. Are there any other changes related to hunting or collecting forest products than you would like to mention? Yes/no/not applicable