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Consistency in climate change impact reports among indigenous peoples and local communities depends on site contexts

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Indigenous Peoples and local communities are heavily affected by climatic changes. Investigating local understandings of climate change impacts, and their patterned distribution, is essential to effectively support monitoring and adaptation strategies. In this study, we aimed to understand the consistency in climate change impact reports and factors influencing consistency at site and individual levels. We conducted cross-cultural research among iTaukei (Fiji), Dagomba (Ghana), fisherfolks (Tanzania), Tsimane' (Bolivia), Bassari (Senegal), ribeirinhos (Brazil), Mapuche (Chile), Mongolian (China), Tibetan (China) and Daasanach (Kenya) communities using semi-structured interviews, focus groups, and surveys among 1860 individuals. We found that cross-culturally more than two-thirds of individual reports of climate change impacts match site-confirmed reports. Consistency in reports is higher for changes related to pastoralism than crop production and wild plant gathering. Individual's experience with nature, Indigenous and local knowledge, and local family roots are not significantly associated with consistency across sites, but site-specific associations are prevalent. Despite high average consistency among sites, there is considerable variation caused by site-specific factors, including livelihood activities, socio-cultural settings, and environmental conditions. Site contexts and related consistency in climate change impact reports need to be taken into account for climate change monitoring and adaptation planning.

Climate change is a major driver of changes in nature¹ that heavily affects nature-dependent Indigenous Peoples (IP) and local communities (LC) around the globe^{2,3}. IP and LC observe and report these climatic changes and their impacts on physical and life systems in their surroundings^{4–6}. In particular, they monitor changes in the atmospheric system and on biophysical elements that support their livelihood activities⁷ and take measures to address the effects of these impacts by modifying their livelihood strategies^{8,9}. Therefore, documenting IP and LC climate change impact

reports enhances understanding of localised past and ongoing atmospheric and socio-environmental changes and their impacts on communities and can provide support for culturally-relevant adaptation strategies^{10–12}.

Besides documentation, assessing how climate change impact reports are patterned among community members is essential to understand communities' adaptive capacities and how to effectively support adaptation in given sites^{13,14}. These reports are contingent on both site- and individual-level factors influencing the cognition of community members^{15,16}. Site level

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factors that might affect climate change impact reports include community histories, local cultures, values, worldviews, and religion, which can lead to the same events being interpreted in different ways. For example, due to distinct worldviews, community members in Stilfs, Italy, attribute glacier retreat to natural processes, while community members in Carhuaz, Peru, perceive themselves as the cause of glacier retreat¹⁷. Moreover, climate change impact reports depend largely on environmental settings, varying for example across climate zones and topography^{15,17}, as seen among Tibetans, where climate change impact reports from community members are closely connected to the elevation and exposure of the villages they inhabit¹⁸.

At the individual level, climate change impact reports are associated with socio-demographic characteristics, including types of livelihood activities pursued. For example, case studies indicate that the number of individual climate change impact reports is associated with age, showing first an increase, and then a decline among older individuals, which could be explained by their advanced age and reduced involvement in subsistence-oriented activities^{19–21}. Moreover, older individuals perceive climate change impacts differently than younger individuals, particularly if they experienced stable climatic periods in their youth, an experience younger community members lack²². The types of livelihood activities pursued and the degree of dependence on these activities also seems to pattern climate change impact reports. For example, in Sierra Nevada, Spain, shepherds and ranchers consistently report more climate change impacts on pastures and livestock than arable farmers and community members not engaged in farming²¹. Similarly, Tibetan pastoralists consistently report delayed summers, whereas non-pastoralist community members have varied views²³. However, other case studies challenge such relationships between socio-demographic variables and livelihood activities and climate change impact reports. For instance, age was unrelated to climate change impact reports in Tibet and Alaska^{18,24}, and employment status and experience were unrelated to climate change impact reports in Alaska²⁴. Overall, to date, case study results highlight the complex relationships between climate change impact reports and socio-cultural and environmental factors operating at multiple scales, from site to individual levels.

The extent to which there is a shared understanding of climate change impacts in a given area can be analysed using cultural consensus, a theory developed to assess the degree of agreement in cultural knowledge within cultural groups^{25,26}. Cultural consensus theory has been used to estimate culturally correct information among a group of respondents and assess their level of cultural consistency while enabling the evaluation of individual knowledge by examining the degree of overlap between individual's and culturally correct responses^{25,26}. Cultural consensus theory is particularly well suited to analyse the patterned distribution of knowledge in communities. In the context of climate change research, cultural consensus analysis has, for example, highlighted that local communities may hold different perceptions of climatic threats and appropriate adaptation measures than external researchers and state representatives, as is the case of local residents in rural coastal Maryland²⁷. Moreover, cultural consensus analysis has shown that some climate change impact reports tend to be agreed upon across communities, while others are disputed²⁴, and that a selection of climate change impact reports are acknowledged cross-culturally²⁸. This variance in agreements underscores the complexity of climate change impact reports and emphasises the need for nuanced approaches to understand them effectively. Moreover, it highlights the importance of considering diverse perspectives within the climate change discourse.

In this study, we draw on the notion from cultural consensus theory that culture manifests through agreement to understand the consistency of climate change impact reports among IP and LC. While we did not follow the heavily structured formal cultural consensus analytical approach (i.e., as proposed by^{25,26}), we look for site-level and individual-level agreement in climate change impact reports and the factors influencing report patterns. Our work is cross-cultural, as we explore ten sites on four continents, which goes beyond the usual focus on case studies

and allows understanding if some of the patterns identified in case studies can also be encountered on larger scales. We organise our work around two research questions (i) How consistent are climate change impact reports by IP and LC across sites and individuals?, and (ii) Which factors influence the consistency in climate change impact reports at site and individual levels? At the site level, we focused on understanding the relationship of the climate change impact report consistency with types of livelihood activities pursued. At the individual level, we explored the association between climate change impact report consistency and (1) experience with nature-dependent livelihood activities, (2) self-assessed level of Indigenous and local knowledge (ILK) in nature-dependent livelihood activities, and (3) family roots in the study area. We focused on these variables because, although they can potentially shape climate change impact reports^{21,23}, they are less commonly studied than socio-demographic variables. On both levels, we studied climate change impact report consistency regarding impacts in the atmospheric system and on biophysical elements supporting livelihood activities.

Results

Consistency of climate change impact reports across sites

Across sites, respondents' reports of climate change impacts in the atmospheric system matched the site-confirmed reports at an average of 68%. Yet, climate change impact report consistencies (CCIC) differed significantly between atmospheric subsystems ($p = 0.003$), as indicated by a linear model, and were highest for changes related to seasons and temperature (75% each), followed by precipitation (71%) and air masses (52%). When comparing across sites, CCIC in the atmospheric system was lowest for fisherfolks in Mafia Island (Tanzania) (34%) and highest for Mongolian pastoralists in Mu Us Desert (Ordos, China) (94%) and iTaukei fisherfolks in Ba (Fiji) (98%) (Fig. 1, Supplementary Table 1). For instance, for the six changes in the atmospheric system examined among the iTaukei fisherfolks, an arithmetic mean of 98% of individual reports were in agreement with the site-confirmed reports. The variations in CCIC in the atmospheric system ranged from the lowest variation observed among iTaukei fisherfolks ($SD = 2\%$) to the highest variation among Tibetan agropastoralists in Shangri-la county (China) ($SD = 32\%$) and Dagomba agriculturalists in Kumbungu (Ghana) ($SD = 29\%$).

Respondents' reports of climate change impacts on biophysical elements supporting livelihood activities aligned with site-confirmed impacts at an average of 69%. However, CCIC differed significantly across livelihood activities ($p = 0.012$). We observed the highest CCIC in pastoralism (76%), followed by crop production (71%), and gathering (60%). In some sites, the CCIC deviated considerably from these arithmetic means. For instance, the CCIC for Mafia Island fisherfolks was only 36%, whereas for iTaukei fisherfolks it was 93% and for Mongolian pastoralists 97% (Supplementary Table 2). The mean CCIC variation across sites was highest for crop production ($SD = 25\%$), followed by pastoralism ($SD = 20\%$) and gathering ($SD = 14\%$). The variation of CCIC is higher across than within sites (crop production ($SD = 12\%$), pastoralism ($SD = 13\%$), gathering ($SD = 11\%$)). Within sites, the CCIC variation spanned from low among Tsimane' people in the Tsimane' Indigenous territory (Bolivia), Daasanach agropastoralists in Ileret Ward (Kenya), Mafia Island fisherfolks, and Mongolian pastoralists (each $SD = 1–6\%$) to high among Tibetan agropastoralists ($SD = 32\%$) and Dagomba agriculturalists ($SD = 34\%$).

Consistency of climate change impact reports among individuals

When considering which variables were associated with variation in individual reports of changes in the atmospheric system, we found that *local family roots* were not significantly related to *CCIC atmospheric* in any of the sites. The average level of ILK across livelihood activities (*ILK average*) was related to *CCIC atmospheric* in three out of ten sites. Specifically, for Bassari agriculturalists (Senegal), Mafia Island fisherfolks and Tibetan agropastoralists, individuals with above-average knowledge of nature-dependent livelihood activities were more likely to have high CCIC than those with

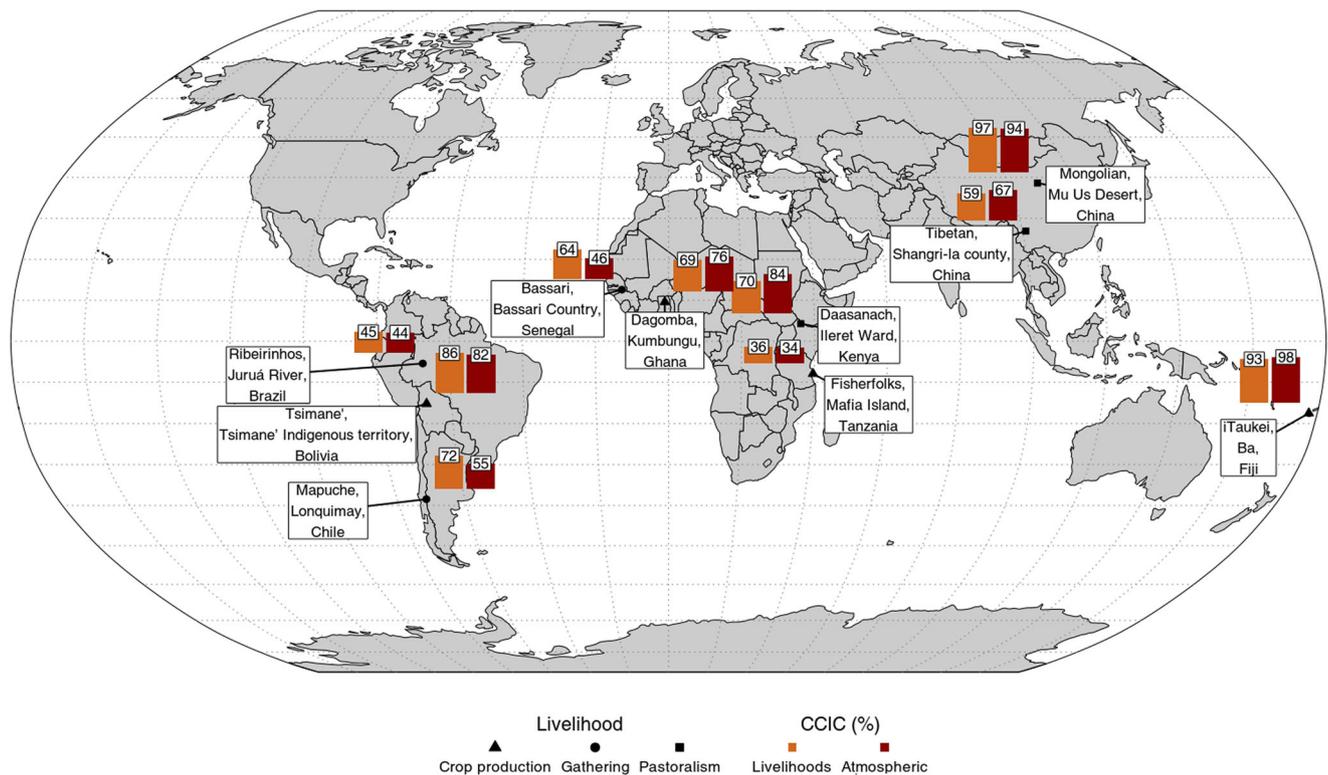


Fig. 1 | Overview of climate change impact consistencies in sites. Site-level climate change impact report consistency (CCIC) for biophysical elements supporting livelihood activities and in the atmospheric system for ten sites ($n = 1860$).

below average knowledge. The general experience with nature-dependent livelihood activities (*NEX general*) was related to *CCIC atmospheric* for the Daasanach agropastoralists, but unrelated in the other sites. Meta-analyses across all ten sites did not reveal significant associations between the explanatory variables and *CCIC atmospheric* (Fig. 2, Supplementary Table 3).

When considering which variables were associated with variation in individual reports of climate change impacts on biophysical elements supporting livelihood activities, we found that *local family roots* were related to CCIC in three out of ten sites. Particularly, Dagomba agriculturalists, Tsimane' People, and iTaukei fisherfolks who had three or four grandparents living in the area were more likely to report climate change impacts on biophysical elements supporting livelihood activities than people in the same site who had zero, one, or two grandparents living locally. *ILK specific* was positively associated with CCIC among Mafia Island fisherfolks and Tibetan agropastoralists, and *NEX specific* was positively associated with CCIC among Mapuche agropastoralists in Lonquimay (Chile), iTaukei fisherfolks, and Daasanach agropastoralists. Yet, meta-analyses across sites with the same livelihood activities showed no significant associations between the explanatory variables – *local family roots*, *ILK specific*, *NEX specific*—and *CCIC crop production*, *CCIC pastoralism*, and *CCIC gathering*. Similarly, the meta-analyses across all ten sites underscores the absence of statistically significant associations among the three explanatory variables and *CCIC livelihoods* (Supplementary Table 4). Thus, considering all sites together, individuals with more experience in a livelihood activity, more knowledgeable about a livelihood activity, or having stronger *local family roots* in the area were no more consistent with the site-confirmed climate change impact reports on biophysical elements that relate to their livelihoods than individuals lacking these characteristics.

Meta-analyses across all ten sites showed that age exhibited a near-significant association with *CCIC atmospheric* ($p = 0.062$) and a positive association with *CCIC livelihoods* ($p = 0.030$). Overall, older respondents were more consistent with the culturally correct climate change impacts of the sites than younger respondents (Supplementary Table 4).

Discussion

In this study, we aimed to understand the consistency in climate change impact reports and examine potential factors shaping its variation. We found that: (i) the interviewed 1860 community members of ten IP and LC agree with more than two-thirds of the culturally correct climate change impacts in the atmospheric system and on biophysical elements supporting their livelihoods, (ii) consistency is differently associated with crop production, pastoralism, gathering and different atmospheric subsystems, (iii) experience in nature-dependent livelihood activities, ILK, and local family roots do not cross-culturally explain individual variation in consistency. Overall, our results point at large agreement and livelihood-specific and site-specific patterns of variation rather than cross-cultural ones.

Before delving into these results, we must consider four methodological caveats. First, when designing the survey, we applied random sampling to select 15 climate change impact reports from all site-confirmed reports at each site. This approach resulted in the inclusion of two to nine climate change impact reports relating to the atmospheric system and biophysical elements supporting livelihood activities in the site-specific surveys. Our approach therefore included only a subset of the total climate change impacts reported and led to an unbalanced number of survey questions across sites, posing constraints to the analysis and interpretation of the results. Moreover, we acknowledge that survey questions are not sufficient to represent the complexity of ILK about climate change impacts, which in some cases may have led to confusion among respondents when answering the questions. Yet, as the selection of items to be included in the survey was random and as the main results show unequivocal patterns, we argue that they are pertinent. Second, when constructing the surveys, we intentionally selected site-confirmed climate change impact reports rather than selecting reports from the full pool of reports provided by individuals. Our selection of climate change impact reports was thus biased towards widely acknowledged ones. This approach was appropriate in the context of our research, which focused on tapping into IP and LC social memory to understand climate change impacts. However, we acknowledge that it may have resulted in higher consistency rates than a selection from the full pool

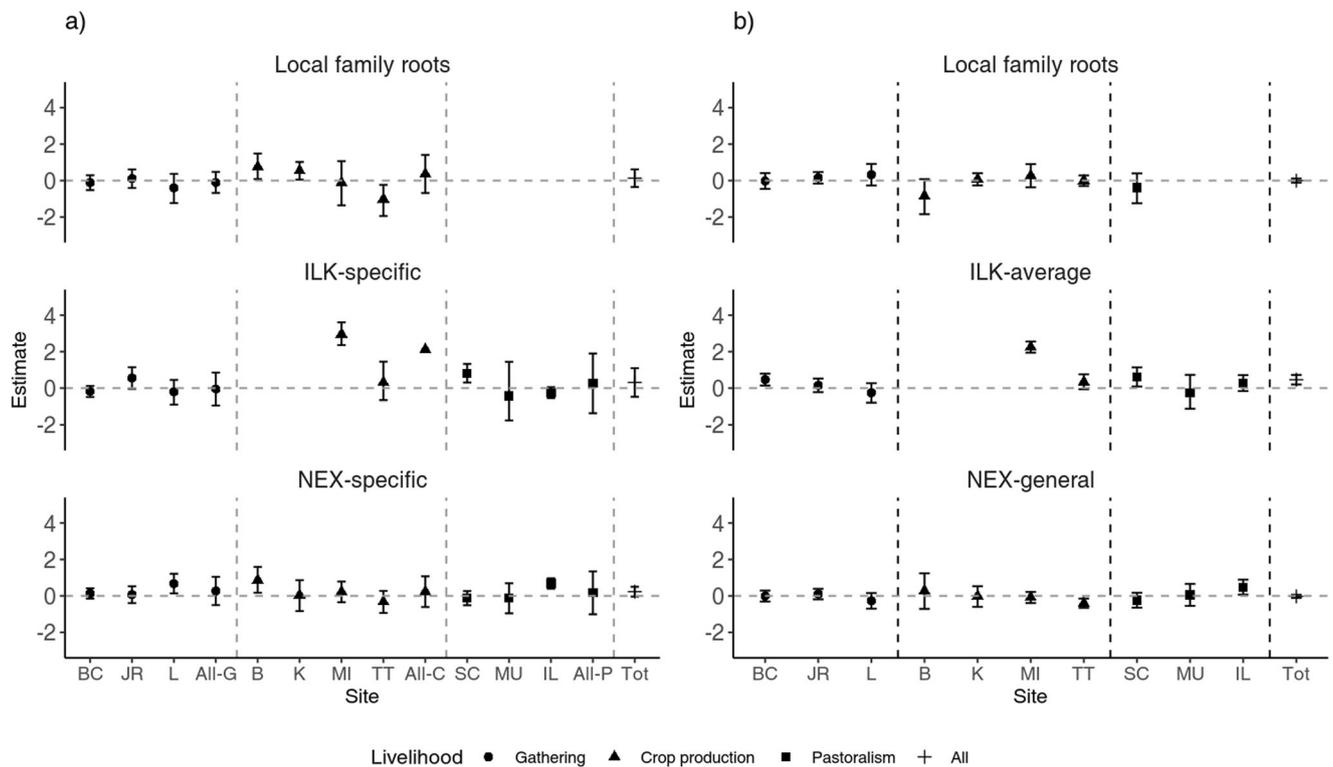


Fig. 2 | Effects of local family roots, indigenous and local knowledge (ILK) and experience with nature-dependent livelihood activities (NEX) on consistency in climate change impact reports. Estimates and confidence intervals are shown for effects on consistency in climate change impact reports relating to (a) biophysical elements supporting livelihood activities, and (b) the atmospheric system (missing values are due to lack of data (local family roots: IL, MU) and lack of variation of

variables (local family roots: SC; ILK specific: K, B)) ($n = 1860$); BC Bassari country (Bolivia), JR Juruá River (Brazil), L Lonquimay (Chile), All-G All sites selected for gathering, B Ba (Fiji), K Kumbungu (Ghana), MI Mafia Island (Tanzania), TT Tsimane' Indigenous territory, All-C All sites selected for crop production, SC Shangri-la county (China), MU Mu Us Desert (China), IL Ileret Ward (Kenya), All-P All sites selected for pastoralism, Tot total.

of reports. Even though the pool of site-confirmed impact reports was high, averaging 38 per site, all results must therefore be interpreted against this background. Third, the site level results are based on a small sample of ten sites in the Global South, for which site level results cannot be considered representative of the large diversity of IP and LC. Nevertheless, the cross-cultural selection of sites from four continents is the most far-reaching effort to understand consistency in climate change impact reports we know of. Fourth, the methodological set-up of the study may have influenced the individual level results. In our study, as in cultural consensus theory, knowledge is conceptualised as matching of individual reports with culturally correct information, which is well suited to analyse patterns of agreement. However, this understanding of knowledge tends to neglect idiosyncratic expert knowledge of individuals²⁹ and may have led to covering knowledge differences in the sample that may have appeared when measuring knowledge in different ways³⁰. Future research on individual variation of climate change impact reports could better circumvent the strengths and weaknesses of particular methods by measuring knowledge in multiple ways.

The considerable consistency in climate change impact reports within sites indicates that there is a significant body of perceptions of change that are shared among IP and LC living on a specific area. This consistency can be explained by the fact that, in a given site, community members are exposed to similar environmental changes and observations of climate change impacts are exchanged and discussed among community members to cross-check individual experiences and ensure mutual learning, especially when the impacts have practical relevance for the collective continuance of livelihood activities³¹. For example, in Lonquimay, Mapuche agropastoralists organised community meetings to exchange information about environmental change and their impacts on livelihood activities as a reaction to increased public discussion on climate change in the course of preparations

for the United Nations Climate Change Conference in Chile in 2019. Such knowledge exchange and social learning may increase consistency in climate change impact reports and are also key ingredients to enhance community resilience to climate change^{32,33}.

Yet, despite this high consistency within sites, inter-site variations of consistency levels are also evident. Part of these variations can be explained by the livelihood activities pursued. Consistency is highest for pastoralism, followed by crop production, and finally wild plant and mushroom gathering. This variation in consistency might emanate from pastoralism's higher socio-cultural homogeneity in the chosen sites, fostering a sense of shared understanding of climate change impacts, in contrast to the more diverse nature of crop production and wild plant and mushroom gathering. In the studied sites, pastoralism is mostly related to the same livestock species, with pastures and even flocks being communal resources governed through customary law. For instance, Tibetan agropastoralists in Shangri-la county (China), who graze mainly cattle and yak, and Daasanach agropastoralists in Ileret Ward (Kenya), who pasture mainly cattle, sheep and goats, utilise pasturelands communally. Among Tibetan and Daasanach agropastoralists, grazing is often conducted jointly by herders, similarly to Mongolian pastoralists in Mu Us Desert (Ordos, China), who also used to graze cattle and sheep on communal pastures until this changed to individual uses of pasture patches in the 1980s. The communal nature of pastoralism in the studied sites contrasts crop production and gathering, where a range of species are usually grown and collected in different locations, potentially leading to higher variation of knowledge and experience of individuals. For example, among *ribeirinhos* in Juruá River (Brazil), in spite gatherers tend to have a diverse resource base and gather several different products, there is some level of specialisation in collecting specific products, like açai fruits (*Euterpe precatoria*), rubber tree (*Hevea brasiliensis*) or murumuru (*Astrocaryum murumuru*)³⁴. Similarly, among Bassari agriculturalists,

many species are gathered only by specialised community members, whereas only some abundant species like shea (*Vitellaria paradoxa*) and African baobab (*Adansonia digitata*) are widely gathered. Thus, different individuals might have observed more closely climate change impacts related with the specific species and agro-ecosystems they regularly interact with than related with those they interact less. This specialisation might lead to a lower consistency in climate change impact reports relating to crop production and gathering than pastoralism. These results suggest that different livelihood activities are not only associated with reports of different climate change impacts^{7,21}, but also with different levels of consistency in their reports.

Not only we found livelihood-related variation in consistency of climate change impact reports, but also variation of consistency levels across sites where the same livelihood activities predominate. This suggests that variables other than the type of livelihood pursued also contribute to the variation in climate change impact reports. In earlier studies, heterogeneity in the way livelihood activities were pursued was suggested to influence the extent to which community members consistently reported climate change impacts¹⁸. For example, in Alaska, Iñupiat communities who caught and dried white fish in autumn reported increases in precipitation in this time of the year, whereas increases in precipitation were not reported by communities in sites catching salmon in summer²⁴. This explanation also holds relevance in our study. For instance, in Ba (Fiji), where iTaukei fisherfolks cultivate predominantly crops like chilis, cassava, taro, kava, banana, and breadfruit, and in the Tsimane' Indigenous territory (Bolivia), where Tsimane' People primarily grow rice, maize, manioc, and plantain, single Indigenous groups - the iTaukei and the Tsimane', respectively - reside and consistency levels are high. In contrast, in Mafia Island (Tanzania), cultural diversity is comparatively high with inhabitants from a range of ethnic groups, including the Matumbi, Ndengereko, Wamwera, Wayao, Wanyasa, Wamakonde, Wasukuma. Each ethnic group might grow different crops in different ways, resulting in low consistency in the site. Moreover, heterogeneity of the natural environments surrounding communities has been suggested to influence consistency²³. For example, in the mountains of Tibet, differences in topography, elevation, and exposure of villages determined the types of climate change impacts reported by community members¹⁸. This explanation is again useful to explain the variation found in our study. *Ribeirinhos* in Juruá River, an ecologically diverse ecosystem, and Tibetan agropastoralists in Shangri-la county, a steep mountainous area, inhabit diverse landscapes and also have comparably low consistency, whereas Daasanach agropastoralists and Mongolian pastoralists inhabit more monotonous landscapes and have comparably high consistency. In other words, results from our study dovetail with findings from earlier case studies^{18,23} with a larger sample: similarity in methods and environments is associated to higher levels of consistency.

Consistency in climate change impact reports also varies in relation to the atmospheric subsystem concerned. Specifically, in our study consistency levels relating to temperature, seasons, and precipitation are higher compared to consistency levels on air masses. Other studies have also found varying consistencies across observations of change in the atmospheric system. For example, among Iñupiat and Athabascan communities in northern Alaska, climate change impacts relating to precipitation yielded less consistency than climate change impacts relating to temperature. This was explained by the fact that precipitation varies more than temperature over small distances and is highly relevant for local livelihood activities, for which it might be more observed, discussed, and consistently reported by community members²⁴. These explanations are also applicable to our results. In particular, variations in precipitation, seasons, and temperature, may be more relevant to crop production, pastoralism and gathering than variation in air masses. For example, precipitation directly influences the growth of crop and pasture species, and thus the availability of food and fodder, and seasonal changes influence seeding and harvesting times^{35,36}. Changes in the direction, frequency, temperature and intensity of wind, however, usually do not have such direct influences on the livelihood activities selected, certainly with the exception of profound changes and

extreme events. For instance, Bassari agriculturalists did not report that wind directly impacts their livelihood activities, whereas precipitation directly influences their rain-fed agricultural systems, the abundance of wild plants for gathering, and water sources for livestock. However, wind is highly relevant for other livelihood activities, as for example variation on air masses is highly relevant for fishers³⁷. Consistency in atmospheric subsystems might thus vary according to specific livelihood activities analysed, with air masses being less relevant for crop production, gathering and pastoralism.

In contrast to these variations at site level, the main individual-level variables used to test variation in consistency in climate change impact reports—*nature experience*, *ILK* and *local family roots*—showed no statistically significant associations in the atmospheric system and for livelihood-related biophysical elements. In other words, across sites, we did not find any evidence that individuals who have spent more time in nature-related livelihood activities, who are more knowledgeable about a livelihood activity, or who have stronger local family roots are more consistent in their reports of climate change impacts than individuals not having these characteristics. Thus, knowledge about climate change impacts is rather evenly distributed across people with and without the characteristics tested, apart from the respective site-specific significant associations. The main explanation of this finding lies in the high level of shared climate change impact reports of community members, and in the generally low within-site variation of consistency. In other words, the fact that on average two-thirds of climate change impact reports in a site match among community members levels out differences between individuals. This phenomenon is similar to the result of a study on hunting among small-scale societies, where cultural practices of sharing prey ensure balanced nutritional status of community members, although individual knowledge, skills and hunting successes vary³⁸. In relation to climate change, a study among Iñupiat and Athabascan communities in northern Alaska also found that individual experience in livelihood activities, a proxy for nature experience and ILK, and duration of residence, a proxy for local family roots, were unrelated with climate change impact reports²⁴.

Among the individual-level variables, only age was significantly positively associated with consistency in climate change impact reports in biophysical elements relating to livelihood activities and almost significantly positively associated with consistency in the atmospheric system across sites. Thus, despite the generally high consistency, older community members have greater agreement with agreed climate change impacts on biophysical elements supporting livelihood activities than younger community members. This result brings further data to the diverging results of earlier case studies, which found that age was associated with climate change impact reports in Spain^{20,21} and the Arctic¹⁹, but that age was not associated with climate change impact reports in Alaska²⁴ and Tibet¹⁸, with broader, cross-cultural insights. In that regard, we note that, although the test turned out cross-culturally significant in our study, it must be taken into account that the site level tests for age were significant in only three out of ten sites and that this number of significant associations at site level is quite similar for *nature experience*, *ILK*, and *local family roots*. Therefore, all these variables can be relevant to understand patterns of climate change impact reports in sites and in-depth studies are needed to clarify the circumstances that lead to them being significantly associated in some sites, whereas insignificant in others. Altogether, our results indicate that climate change impact reports within communities tend to be considerably consistent, with variation between individuals being contingent on local particularities.

Results from this study have implications for climate change monitoring and designing adaptation strategies for, in and by nature-dependent societies. First, the considerable consistency of climate change impact reports across sites confirms that IP and LC closely monitor, reliably report, and calibrate with each other changes in their local environments. Local community members thus hold significant knowledge about climate change impacts, which could be treated as an essential source of evidence to understand past damages and loss and to potentially anticipate future impacts. Therefore, it is extremely important to involve IP and LC in local

Table 1 | Sites description

| Site | Group name | Country | Climate zone | Main livelihood activities | Livelihood activity analysed | |
|-------------------------------|-------------|----------|--------------|-----------------------------|------------------------------|--|
| | | | | | Livelihood activity | Main species |
| Ba | iTaukei | Fiji | Tropical | Fishing (crop production) | Crop production | chillis, cassava, taro, kava, banana, breadfruit |
| Kumbungu | Dagomba | Ghana | Tropical | Crop production | Crop production | rice, maize, millet and sorghum |
| Mafia Island | fisherfolks | Tanzania | Tropical | Fishing (crop production) | Crop production | rice, cassava, coconuts, sweet potatoes, maize |
| Tsimane' Indigenous territory | Tsimane | Bolivia | Tropical | Fishing (crop production) | Crop production | rice, maize, manioc, plantain |
| Bassari country | Bassari | Senegal | Tropical | Crop production (gathering) | Gathering | shea, baobab |
| Juruá River | ribeirinhos | Brazil | Tropical | Fishing (gathering) | Gathering | açaí, rubber, muru-muru, andiroba, ucuúba |
| Lonquimay | Mapuche | Chile | Temperate | Agropastoralism (gathering) | Gathering | araucaria pine nuts, morels |
| Mu Us Desert | Mongolians | China | Arid | Pastoralism | Pastoralism | cattle, sheep |
| Shangri-la county | Tibetan | China | Temperate | Agropastoralism | Pastoralism | cattle, yak |
| Ileret Ward | Daasanach | Kenya | Arid | Agropastoralism | Pastoralism | cattle, sheep, goats |

monitoring and adaptation planning in order to identify adequate and culturally appropriate monitoring targets and adaptation pathways. Second, the varying consistency levels of sites shows that the development of adaptation strategies should take into account the local contexts. In sites with high consistency, climate change monitoring and adaptation strategies can be reasonably discussed and implemented at higher organisational levels, for example site and community levels, because individual community members tend to be affected in similar ways. In contrast, in sites with low consistency, community members are affected by different impacts and in various ways and discussion and implementation of climate change monitoring and adaptation strategies is needed at sub-group and household levels. These results suggest that the heterogeneity of sites—in terms of livelihood activities pursued, socio-cultural groups living in the site, and environmental surroundings – need to be taken into account when designing climate change monitoring and adaptation strategies. At the individual level, our results suggest that consistency is not widely related to socio-demographic and livelihood-related variables. Nevertheless, site-specific significant associations with distinct variables are evident and intra-community consistency patterns are therefore contingent on local contexts rather than universally applicable. We therefore argue that in a given site a broad range of individuals with different characteristics can be knowledgeable about the site's major climate change impacts and should be invited to participate in forums and discussions about climate change impacts and adaptation.

Methods

Research context

In this study, we analysed data from the Local Indicators of Climate Change Impacts (LICCI) project, a collaborative project investigating ILK about climate change impacts to leverage the inclusion of ILK into climate change research and policy (www.licci.eu). For this project, a generally applicable, but locally adaptable, study protocol was developed³⁹. The protocol allowed cross-cultural comparisons. Data were collected by project team members and external collaborators who had long-lasting relationships with the sites where they collected data. Before data collection, Free, Prior and Informed Consent (FPIC) was obtained from all participants³⁹ in writing or, when participants were illiterate or uncomfortable with reading or writing, oral consent was gained and confirmed in writing by a witness. The Ethics Committee of the Autonomous University of Barcelona approved the project (CEEAH 4781), and authorisation from national ethics committees was gained in sites where needed.

Sampling

Research for the LICCI project was conducted in 48 sites, from which ten were selected for this study (find selection criteria in the data analysis section

below) (Table 1). The sites were located in areas deficient in weather records assembled by meteorological stations and were distributed across all climate zones according to the Köppen-Geiger classification system⁴⁰. Moreover, in all sites, IP and LC had long-term relationships with and dependence on nature mainly through crop production, fishing, pastoralism, hunting and gathering. In each site, 3–10 villages that were environmentally and socio-culturally representative and relatively homogeneous for the respective site and had a maximum of 500 households were selected for data collection. First, we used semi-structured interviews with 20–47 respondents per site ($\bar{x}=34$, $SD = 9$) to elicit local perspectives about environmental changes, and their attribution to climate or other drivers of change. To select respondents, we relied on recommendations from key informants, and used quota sampling, interviewing at least three respondents across gender (men and women), different age categories (younger, middle aged, older), and locally relevant livelihood activities. Second, in each site, we organised 1–12 focus group discussions, with 4–12 participants per focus group, to validate information obtained from semi-structured interviews. We selected focus group participants using convenience sampling, ensuring that respondents were diverse in terms of gender, age and livelihood activities. Finally, in 22 of all 48 sites, we conducted a survey to investigate patterns of individual reports of climate change impacts. To select survey respondents, in each site we first applied random sampling to a census of households, and then convenience quota sampling to select survey respondents across gender and age categories from households³⁹. In each of the ten sites selected for this study, we obtained between 75 and 316 responses to surveys ($\bar{x}=186$, $SD = 64$), totalling 1,860 surveys (Supplementary Table 5).

Data collection

The semi-structured interviews were guided by the question “Compared to when you were young, what changes in the environment have you noticed?”, followed by probing questions to elicit further reports of environmental changes. These probing questions were drafted along elements of the systems that potentially experienced changes, i.e., the atmospheric system (e.g., air masses, precipitation, seasons, temperature), physical system (e.g., lakes, rivers, sea, soil), and life system (e.g., aquaculture, crops, livestock, wild flora and fauna)³⁹. For each climate change impact report, respondents were asked about the direction of change and the drivers of change. Environmental changes that were attributed to climate change and consistently reported by respondents—that is, reported by at least 20% of respondents with >90% of reports being in the same direction – were considered as site-confirmed climate change impact reports. Climate change impact reports that were reported in different directions and not always attributed to climate change were taken to focus group discussions. These focus group discussions aimed to determine whether respondents could reach agreement on the types, directions, and/or drivers of change after discussion.

Climate change impact reports that achieved agreement after discussion were then included in the lists of site-confirmed climate change impact reports ($\bar{x}=38$, $SD = 14$, $\min = 21$, $\max = 65$).

We then collected data from individual respondents through a survey³⁹, of which three sections are relevant for this study, in addition to a standard socio-demographic question where we asked the respondents' sex, age, and the number of grandparents who grew up in the area. In the first section, each respondent was presented with 15 climate change impacts, which were randomly selected from the site-specific lists of site-confirmed climate change impacts. For each of the impacts, respondents were asked: (i) whether they had observed the impact, for example, "Compared to your early adulthood, did you observe a change in the frequency of dry spells?", and, if the response was positive, (ii) in which direction they had observed the impact to happen (e.g., less/lower/shorter/earlier, more/higher/longer/ later). In the second section, we employed the pebble distribution method⁴¹ to gather data on respondents' experience with different livelihood activities. We selected the most common site-specific livelihood activities—nature-dependent or not—and asked respondents to allocate a total of 100 pebbles according to their estimations about how much time they had spent on each of the livelihood activities in their lifetimes. We considered nature-dependent livelihood activities as those where individuals directly interacted with nature, such as fishing, hunting, and timber extraction, excluding indirect interactions like carpentry or tourism. In the third section, we utilised self-assessments to gain respondents' estimates of their levels of ILK. We asked, "Compared to [knowledgeable group], who are knowledgeable about [activity], how much of their knowledge about [activity] do you have?". The question was contextualised for each site. Thus, livelihood activities that were relevant in the respective site were filled in at [activity] and groups of people especially knowledgeable about these livelihood activities were filled in at [knowledgeable group]. In each site, this question was posed for three to four locally relevant livelihood activities or related practices. For instance, among the Bassari agriculturalists in Bassari country (Senegal), we asked respondents for self-assessing their knowledge about the activities [crop cultivation], [rain prediction], and [wild plant gathering] in comparison to the knowledge group of [men elders] for men, and [women elders] for women. The answers were coded in a four-step scale, ranging from "I know hardly anything they know about [activity]" (scale rating 1), "I know some things they know about [activity]" (scale rating 2), "I know a lot they know about [activity]" (scale rating 3), to "I know everything they know about [activity]" (scale rating 4).

Data analysis

In this study, we analysed data from 10 of the 48 LICCI sites. The selection criteria for sites were threefold. First, since we analysed only survey data in this study, we selected the 22 LICCI sites where surveys were conducted. Second, we selected sites in which the random sampling of site-confirmed climate change impacts resulted in the inclusion in the survey of at least two changes in the atmospheric system and at least two impacts on biophysical elements that are closely related with nature-dependent livelihood activities, including (i) crops and soils, supporting crop production, (ii) pastures and livestock, supporting pastoralism, or (iii) wild flora and mushrooms, supporting gathering of plant and mushroom species. Thus, in each site, we analysed climate change impacts in the atmospheric system and on one livelihood activity (i.e., crop production, pastoralism or gathering). The third selection criterion was that we selected sites where the arithmetic mean of experience of community members in the chosen livelihood activity was at least 20%, as assessed in the pebble game. This ensured that the selected livelihood activities were locally relevant to communities, although they did not have to be the sites' main livelihood activities.

Four of the ten selected sites are located in Africa, three in Latin America, two in Asia, and one in Oceania. We analysed climate change impacts on the atmospheric system in all ten sites, whereas on only one selected livelihood activity per site: in four sites our analysis focused on climate change impacts on crop production, in three sites on pastoralism, and in another three sites on gathering. In each site, three to nine ($\bar{x}=5.5$,

$SD = 2$) site-confirmed climate change impacts in the atmospheric system, and two to seven ($\bar{x}=3.6$, $SD = 1.6$) impacts on biophysical elements supporting livelihood activities were included in the survey, and thus used for our analyses. All 1860 respondents reported climate change impacts on the atmospheric system, 693 reported climate change impacts on biophysical elements related with crop production, 750 related with pastoralism, and 417 related with gathering.

We conducted data analysis at site and individual levels. The site level climate change impact report consistencies (CCIC) were the arithmetic mean of the individual CCIC of respondents in a given site. We calculated site level CCIC for the atmospheric system, its subsystems (air masses, precipitation, seasons, temperature), and the biophysical elements supporting the livelihood activities crop production, pastoralism, and gathering. We subsequently compared the variation of CCIC between sites descriptively and used linear models to assess differences across sites between CCIC among atmospheric subsystems and livelihood activities.

At the individual level, we assessed CCIC by calculating the level of agreement between individual reports of climate change impacts and site-confirmed reports. For example, if a respondent reported three climate change impacts out of four that were presented to him/her, and noticed them to happen in the same change direction as in the site-confirmed list of climate change impacts, the calculated level of consistency for this individual would be 3/4 (0.75). We calculated individual climate change impact report consistencies in the atmospheric system (*CCIC atmospheric*) and for biophysical elements supporting livelihood activities (*CCIC livelihoods*). To make livelihood-specific analyses, we also divided *CCIC livelihoods* into livelihood-specific variables (*CCIC crop production*, *CCIC pastoralism*, *CCIC gathering*), yielding a total of five dependent variables.

At the individual level, we then constructed the following explanatory variables (Table 2):

- i. *experience with specific nature-dependent livelihood activities (NEX specific)*, defined as the time individuals have devoted to crop production (four sites), pastoralism (three sites), or gathering of plant and mushroom species (three sites) during their lifetimes, as estimated in the pebble game. We divided respondents in two groups: (i) low NEX specific: respondents who spent less than average time in a site with the selected livelihood activity, and (ii) high NEX specific: respondents who spent an above-average amount of time in a site with the selected livelihood activity;
- ii. *experience with nature-dependent livelihood activities in general (NEX general)*, defined as the share of time individuals have invested in any nature-dependent livelihood activity in their lifetime, as estimated in the pebble game. We divided informants in two groups: (i) low NEX general: respondents who spent less than average amount of time in a site with nature-dependent livelihood activities, and (ii) high NEX general: respondents who spent an above-average amount of time in a site with nature-dependent livelihood activities;
- iii. *livelihood activity-related level of Indigenous and local knowledge (ILK specific)*, defined as the level of ILK in crop production (four sites), pastoralism (three sites), or gathering of plant and mushroom species (three sites) as self-assessed on the four-step scale. We divided respondents in two groups: (i) low ILK specific: scale rating 1–2, and (ii) high ILK specific: scale rating 3–4;
- iv. *average level of Indigenous and local knowledge across livelihood activities (ILK average)*, defined as the arithmetic mean of levels of ILK in three or four locally relevant nature-dependent livelihood activities. We split respondents in two groups: (i) low ILK average: arithmetic mean 1–2.4, and (ii) high ILK average: arithmetic mean 2.5–4;
- v. *local family roots*, defined as the number of grandparents that grew up in the area. We categorised informants in two groups: (i) weak local family roots: 0–2 grandparents from the area; and (ii) strong local family roots: 3–4 grandparents from the area (variable not collected in two sites: among Daasanach agropastoralists (Kenya) and Mongolian pastoralists (China)).

Table 2 | Sample description and summary statistics of explanatory variables

| Livelihood activity site | n | Sex women % | Age x̄ | Local family-roots ^a % | NEX general % | NEX-specific | | | ILK average x̄ ^b | ILK-specific | | |
|-------------------------------|------|----------------|-----------|--------------------------------------|------------------|--------------|------------------|----------------|--------------------------------|--------------------------|--------------------------------|------------------------------|
| | | | | | | Crops % | Pastoralism % | Gathering % | | Crops x̄ ^b | Pastoralism x̄ ^b | Gathering x̄ ^b |
| <i>Crop production</i> | | | | | | | | | | | | |
| Ba | 155 | 56 | 39 | 44 | 58 | 29 | – | – | 1.6 | 2.0 | – | 1.1 |
| Kumbungu | 175 | 43 | 59 | 83 | 99 | 98 | 1 | – | 3.9 | 3.9 | – | 4.0 |
| Mafia Island | 175 | 47 | 38 | 6 | 72 | 27 | 2 | 1 | 2.7 | 2.7 | – | 2.6 |
| Tsimane' Indigenous territory | 188 | 53 | 36 | 75 | 88 | 55 | 0 | 1 | 2.1 | 2.1 | – | 2.0 |
| <i>Pastoralism</i> | | | | | | | | | | | | |
| Mu Us Desert | 316 | 48 | 57 | – | 85 | 23 | 62 | – | 1.8 | – | 1.9 | 1.8 |
| Shangri-la county | 175 | 52 | 52 | 93 | 54 | 22 | 27 | 5 | 3.4 | 3.7 | 3.6 | 2.9 |
| Ileret Ward | 259 | 55 | 35 | – | 98 | 9 | 82 | 0 | 2.5 | – | 2.6 | 2.4 |
| <i>Gathering</i> | | | | | | | | | | | | |
| Bassari country | 177 | 52 | 44 | 85 | 75 | 38 | 14 | 21 | 2.8 | 2.8 | – | 2.8 |
| Juruá River | 165 | 50 | 40 | 27 | 79 | 34 | – | 29 | 2.6 | 2.9 | – | 2.3 |
| Lonquimay | 75 | 52 | 49 | 84 | 78 | 17 | 33 | 27 | 3.1 | 2.9 | 3.0 | 3.3 |
| x̄ | | 50 | 46 | 43 | 77 | 37 | 27 | 12 | 2.7 | 2.9 | 2.8 | 2.5 |
| Total | 1860 | | | | | | | | | | | |

NEX nature experience, ILK indigenous and local knowledge.

^a% of respondents of which 3–4 grandparents grew up in the area.

^bx̄ on 4-step scale ranging from 1 = "I know hardly anything they know about [activity]" to 4 = "I know everything they know about [activity]".

We assessed the relationship between the explanatory variables and the five individual level dependent variables using a two-step approach with generalised linear models (GLM). In the first step, for each site, we calculated GLM using a binomial distribution and a logit link function. The obtained coefficients represented the relationship between the corresponding explanatory variable and the odds ratio of detecting or not detecting climate change impacts, as indicated by the dependent variables. *CCIC atmospheric* was assessed using *NEX general* and *ILK average*, whereas *CCIC crop production*, *CCIC pastoralism*, *CCIC gathering* and *CCIC livelihoods* were assessed using *NEX specific* and *ILK specific*. We included *age* (in two groups per site: elder 50% / younger 50%) and *biological sex* (in two groups: men / women) as control variables. In all cases, we controlled for overdispersion in the model and corrected the estimates and standard errors considering the dispersion parameter as the ratio of residual deviance to residual degrees of freedom⁴². Each site was analysed using the stat package in R version 4.1.2⁴³. In a second step, we adopted a meta-analysis approach—in the sense of conducting a statistical analysis across individual studies for the purpose of integrating results⁴⁴—to identify overarching relationships between the explanatory (*NEX specific*, *NEX general*, *ILK specific*, *ILK average*, *local family roots*) and dependent variables across (i) sites with the same livelihood activities and (ii) all ten sites. To calculate these overall effects, one GLM per livelihood activity (dependent variables: *CCIC crop production*, *CCIC pastoralism*, *CCIC gathering*) and system (dependent variables: *CCIC atmospheric*, *CCIC livelihoods*) was used. These models were weighted based on the standard error of each site-specific variable estimate, ensuring that the variance of each estimate was accounted for in our model. To include the effect of the standard error of the estimates, these models were fitted using the nlme package⁴⁵ in R version 4.1.2⁴³.

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The datasets generated and analysed during the current study are available in the repository CORA. Repositori de Dades de Recerca, <https://doi.org/10.34810/data958>.

Code availability

The underlying code for this study is not publicly available but may be made available to qualified researchers on reasonable request from the corresponding author.

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Competing interests

The authors declare no competing interests.

Additional information

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