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Indigenous Peoples and local communities report ongoing and widespread climate change impacts on local social-ecological systems

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The effects of climate change depend on specific local circumstances, posing a challenge for worldwide research to comprehensively encompass the diverse impacts on various local social-ecological systems. Here we use a place-specific but cross-culturally comparable protocol to document climate change indicators and impacts as locally experienced and analyze their distribution. We collected first-hand data in 48 sites inhabited by Indigenous Peoples and local communities and covering all climate zones and nature-dependent livelihoods. We documented 1,661 site-agreed reports of change corresponding to 369 indicators. Reports of change vary according to climate zone and livelihood activity. We provide compelling evidence that climate change impacts on Indigenous Peoples and local communities are ongoing, tangible, widespread, and affect multiple elements of their social-ecological systems. Beyond potentially informing contextualized adaptation plans, our results show that local reports could help identify economic and non-economic loss and damage related to climate change impacts suffered by Indigenous Peoples and local communities.

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Climate change is a global phenomenon, but its impacts on biophysical and sociocultural systems are governed by local conditions[1,2]. Modeling work shows that some world regions will experience higher temperature increase than others, and that some regions will receive more rainfall while others will experience more frequent droughts[3]. Regional changes will also have differentiated impacts on human societies, with nature-dependent communities being more prone to be directly affected by, e.g., droughts or other extreme weather events, than communities less immediately dependent on nature for their livelihood[4,5]. In addition, climate change may be differently perceived and experienced across social groups, as societies have developed unique cultural and epistemological frameworks for understanding and interacting with the world[6]. Consequently, a comprehensive understanding of climate change and its impacts should consider not only spatial heterogeneity, but also variations derived from how climate change and its impacts are experienced and understood by people affected by them.

Current research streams face different challenges in presenting a global picture of climate change and its impacts. On the one hand, research based on instrumental measurements, while fundamental to our comprehension of the global impacts of climate change on physical and biological systems[3,7], falls short in providing a comprehensive view of how climate change and its impacts are locally experienced. Predictive models constructed using instrumental measurements[8] lose accuracy and precision when downscaled, particularly in areas with scarce ground data[9]. For example, since meteorological stations are sparsely distributed in areas inhabited by Indigenous Peoples and local communities[10], predictions for such areas have low accuracy[11,12]. In addition to their coarse resolution, predictive models focus on a few variables, typically defined by the scientific community, often overlooking locally important phenomena or concerns. For example, modeling work forecasting climate change impacts on agriculture focuses on the world's most common cereal crops (e.g., wheat, maize, rice)[13–15], neglecting crops critical to food sovereignty, economic security, and cultural identity in many local food systems[16]. Finally, instrumental measures are unable to capture the diverse and complex ways in which people understand, experience, and relate to the environment, which limits their suitability for risk analysis and adaptation planning[6,17]. For instance, instrumental measurements might capture changes in rainfall patterns but miss crucial relationships between climate change awareness, sensitivity, and vulnerability[18].

On the other hand, the growing body of research relying on grounded information from Indigenous Peoples and local communities, while successfully emphasizing the idiosyncrasies of climate change impacts, does not provide globally comparable information, thus hampering our ability to discern general trends and patterns and to upscale local research results to global climate change research[19,20]. Following calls from the 2014 Intergovernmental Panel on Climate Change (IPCC) report to develop the evidence base for the potential contribution of local knowledge to climate change research[21], the last decade has seen an increase in the number of works examining the intricate knowledge systems that allow Indigenous Peoples and local communities to identify changes in natural systems, the drivers of such changes, and the local responses to them[10,22]. These works provide rich, multi-sited, qualitative, and place-based information on locally experienced climate impacts, although they have limited capacity to discern general trends because they do not rely on a common strategy to gather globally comparable information.

Here, we present the results of a large, globally coordinated study including 48 Indigenous Peoples and local communities on all inhabited continents. The study, which used a place-specific but cross-culturally comparable research protocol[23], documents observations of climate change and its impacts as locally experienced and examines their distribution across climate zones and livelihood activities. We provide compelling evidence that climate change impacts on Indigenous Peoples and local communities are ongoing, tangible, widespread, and affect multiple elements of their social-ecological systems and that reports of change vary according to climate zone and livelihood activity. Our analysis deliberately adopts a global quantitative perspective, oriented to leverage the inclusion of Indigenous Peoples and local communities and their knowledge into climate change research and policy. This work relies on the wealth of qualitative information collected across case studies and published elsewhere[24]. We emphasize the importance of working with both quantitative and qualitative data to identify common trends as well as idiosyncrasies – both of which are important to understand global trends and the myriad of climate change impacts across the world[25].

Results

We selected 48 field sites across all inhabited continents. Sites covered four climate zones of the Köppen-Geiger climate classification[26] (i.e., tropical, arid, temperate, and snow/polar), with a slight predominance of tropical climates sites ($n = 16$) and the lowest number in snow/polar climates ($n = 7$) (Fig. 1; Supplementary Table 1). All the sites, except the Tsimane' Indigenous territory (Bolivia, Site_ID 24), are in areas with increasing average decadal temperature (see Methods), most of them ($n = 20$) experiencing a medium average increase (i.e., 0.15 to 0.3 °C/decade). The predominant livelihood activities in studied sites were agropastoralism ($n = 16$), agriculture ($n = 13$), and fishing ($n = 12$). Pastoralism ($n = 4$) and other nature-dependent livelihoods (e.g., hunting and non-timber forest product collection, hereafter 'other NRD'; $n = 3$) were less common.

Reports of climate change and its impacts. Across the 48 sites, we documented 1,661 observations of climate change and its impacts, although the number of citations largely varied across sites (Supplementary Fig. 1). For each site, only observations for which there was agreement across focus group discussions were considered (see Methods). Across sites, observations of changes in elements of the atmospheric system, i.e., indicators of climate change, were most frequently cited (accounting for 46.4% of all observations; Fig. 2), with observations of changes in the subsystems precipitation (20.4%) and temperature (13.0%) being predominant. Observations of changes in the physical and life systems, i.e., climate change impacts, were less cited. In particular, climate change impacts in the physical system were the least frequently cited (19.6%), with observations of changes in the subsystem freshwater (9.1%) being the most common observations in this system. Changes in the life system accounted for about one third of all the observations (33.9%), with observations of changes in the subsystems plant cultivation (9.9%) and terrestrial flora (7.9%) being the most predominant.

Site-agreed observations of climate change and its impacts were classified in 369 local indicators of climate change impacts (LICCI), corresponding to 94 indicators of climate change (i.e., reports of change in elements of the atmospheric system) and 275 indicators of climate change impacts (i.e., reports of change in elements of the physical and the life systems) (see Methods).

The most frequently reported indicators of climate change include changes in mean temperature (45 citations, 2.7%) and changes in mean temperature in a season (34 citations, 2.0%), whereas the most frequently reported indicators of climate change impacts include changes in crop productivity (52 citations, 3.1% of the 1,661 observations documented) and

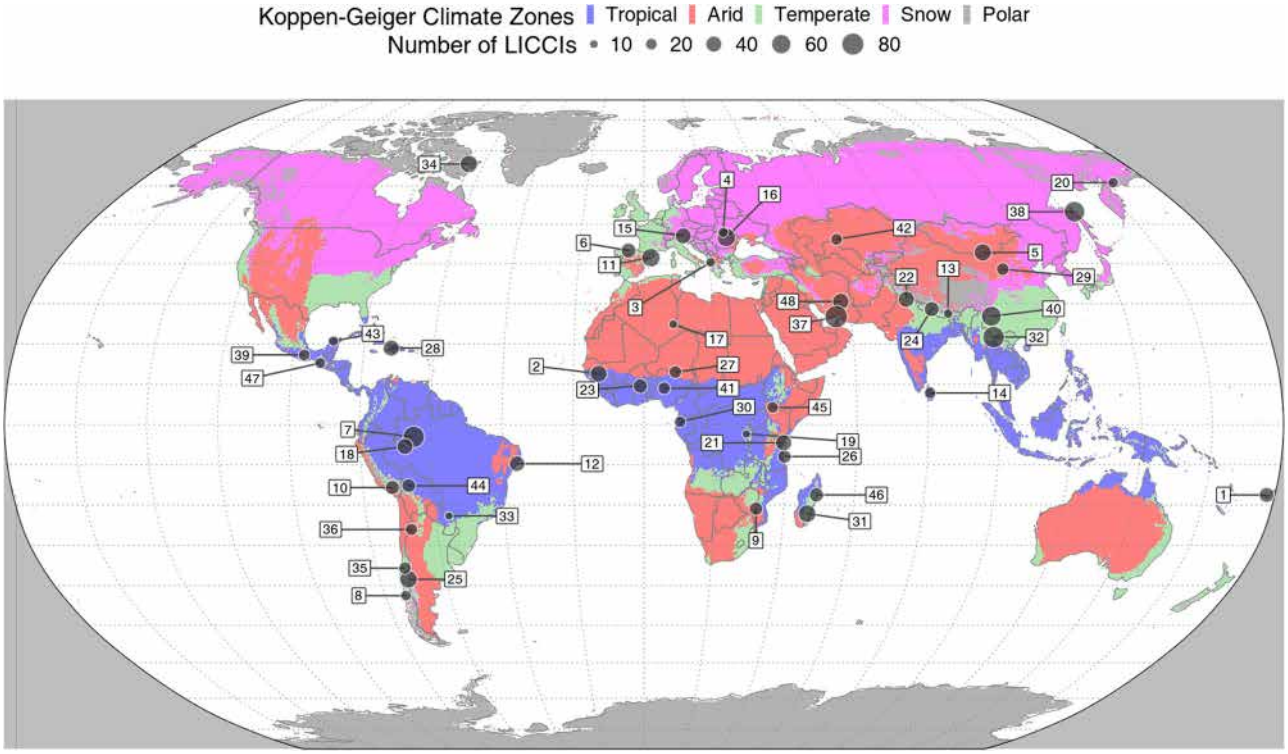

Fig. 1 Site distribution across climate zones. Site labels correspond to Site_ID in Supplementary Table 1, which also contains site characterization. Dot size indicates the number of local indicators of climate change impacts reported in a site (see Online Methods). Climate zones were adapted from the Köppen-Geiger climate classification[26], differentiating tropical, arid, temperate, snow and polar climates.

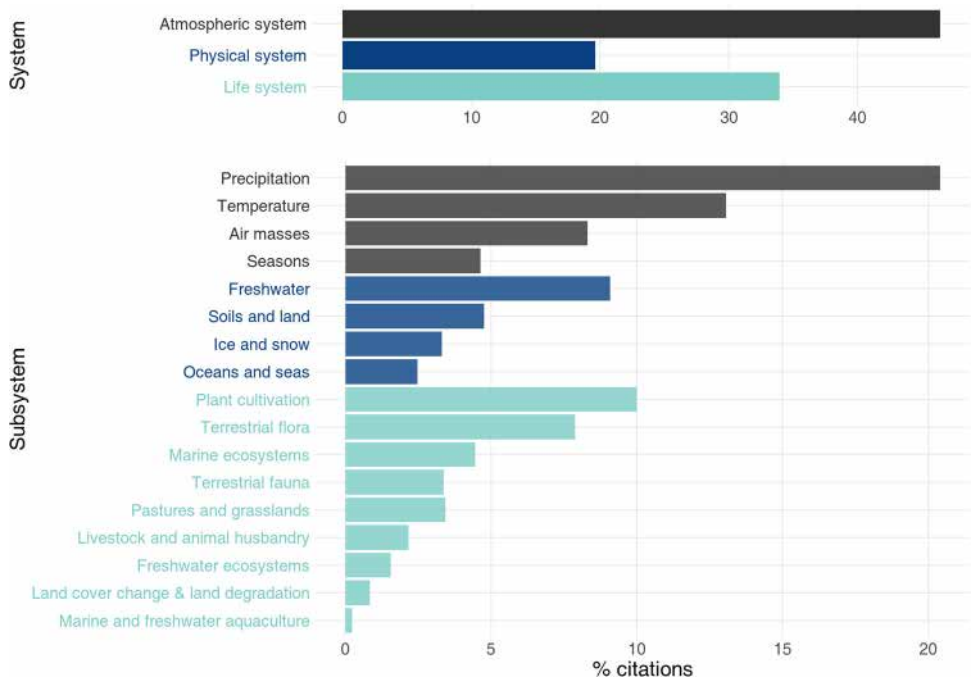

Fig. 2 Percentage of observations of climate change and its impacts on the physical and life system ($n = 1{,}661$ site-agreed observations, $n = 48$ sites). Subsystems in black refer to the atmospheric system, in blue to the physical system, and in green to the life system.

changes in the abundance or density of wild plant or fungi species (33 citations, 2.0%).

This classification conceals the complex, nuanced, and integrated nature of the reported observations of climate change and local explanations of its impacts. For example, reports classified as changes in mean temperature conceal very different observations and explanations of change across sites. For instance, Dagomba-Gur agriculturalists (Kumbungu, Ghana, Site_ID 23) report a general temperature increase which they attribute to a warmer Harmattan (dry wind blowing from the Sahara), whereas farmers in Chiloé (Chile, Site_ID 8), while also reporting a general temperature increase, attribute it to a

precipitation and streamflow decrease. In a similar way, Bassari farmers (Bassari Country, Senegal, Site_ID 2) report changes in the productivity of sorghum long-cycle landraces, which they attribute to the shortening of precipitation cycles, whereas Csángó farmers (Gyimes, Romania, Site_ID 16) report declining potatoes yields due to pests' infestations, which they relate to warmer winters that allow pests to breed over winter.

Distribution of reports of climate change and its impacts. While our classification masks nuanced observations of changes, it also allows for a global analysis of the distribution of reports of local climate change and its impacts. The number of site-agreed observations of change (see Methods) showed large variation across sites (avg. = 34.9 LICCIs/site, sd = 18.8, min = 9, max = 84). However, the frequency distribution across systems and subsystems of site-agreed observations of change (Fig. 3, column 'Total') resembles the overall distribution of observations (Fig. 2, subsystems).

We tested whether site-agreed observations of change were differently distributed across climate zones using a Poisson general linear model followed by a series of post-hoc tests (Fig. 3). The average number of indicators of climate change/site referring to changes in precipitation, temperature, air masses, and seasons were not statistically different across climate zones. However, in sites in tropical climates, the average number of indicators/site referring to changes in freshwater was higher than in sites in snow/polar climates. Grounded observations exemplify the many ways in which changes in the freshwater subsystem are observed in tropical zones. For example, ribeirinhos from the Juruá River (Brazil, Site_ID 7) reported changes in the river dynamics, including changes in flood duration, height, and sedimentation patterns; farmers in Coastal-Vedda (East region, Sri Lanka, Site_ID 14) reported changes in groundwater quality and lower water levels in village tanks; and agriculturalists in Milot (Haiti, Site_ID 28) reported the drying of lakes, ponds and wells, increasing sediments in rivers, and larger but more erratic floods.

In arid and in snow/polar climates, the average number of LICCIs/site referring to impacts in pastures and grasslands was significantly higher than in tropical climates, while the average number of LICCIs/site referring to impacts in plant cultivation was lower than in temperate climates.

Finally, in snow/polar and temperate climates, the average number of LICCIs/site referring to impacts in ice and snow was higher than in arid and tropical climates, where ice and snow are unusual, and the average number of LICCIs/site referring to impacts in terrestrial fauna was also higher in snow/polar and temperate climates than in tropical climates.

We followed a similar approach to test whether reports of change were differently distributed across different levels of exposure to change in decadal temperature (Supplementary Fig. 2). The average number of LICCIs/site referring to impacts in pastures and grasslands was higher in sites experiencing high decadal temperature increases (>0.3 °C/decade) than in sites experiencing medium (0.15 to 0.3 °C/decade) or mild (0 to 0.15 °C/decade) temperature increases. Also, the average number of LICCIs/site referring to land cover change and land degradation was higher in sites experiencing high decadal temperature increases than in sites experiencing medium decadal temperature increases.

We found important differences when using the same approach to test differences in reports of climate change and its impacts across site's main livelihood activity (Fig. 4). Where agriculture predominates, the average number of indicators of climate change/site referring to changes in *precipitation* was higher than where other NRD livelihoods predominate and the average number of indicators of climate change/site referring to changes in *temperature* was higher than in predominantly pastoralist sites. Additionally, the average number of LICCIs/site referring to impacts in *freshwater* and *soils* was also higher than where agropastoralism predominates. For example, Akha farmers (Nannuoshan, China, Site_ID 31) report decreasing levels of water in mountain creeks and rivers and Gurung farmers (Laprak, Nepal, Site_ID 24) report increased soil erosion due to heavier rains during the monsoon season.

Where fishing predominates, we found higher average number of indicators of climate change/site referring to changes in *air masses* (relative to sites where agriculture, agropastoralism, or pastoralism predominate), higher number of impacts in *oceans and seas* (relative to agropastoralism and other NRD), and higher number of impacts in *marine ecosystems* (relative to agriculture). For example, iTaukei fishers (Ba, Fiji, Site_ID 1) report an increase in the intensity of tropical cyclones, Catalan fishers (Costa Brava, Spain, Site_ID 11) report changes in coastal storms with fast winds and strong waves, and Swahili fishers (South coast, Kenya, Site_ID 21) report an increase in sea water temperature during the Kaskazi (wind) season resulting in increased shell mortality.

Where pastoralism predominates, the average number of LICCIs/site referring to impacts in *pastures and grasslands* and *land cover change and land degradation* was higher than in sites with any other livelihood activity. For example, Kolla-Atacameños pastoralists (Puna, Argentina, Site_ID 36) report a decrease in pasture productivity related to decreasing rainfall and Mongolian pastoralists (Mu Us Desert, Ordos, China, Site_ID 32) report the increased presence of non-edible grasses which displace edible pastures under drier conditions.

Finally, in sites where other NRD livelihoods predominate, the average number of LICCIs/site referring to impacts in *ice and snow* was higher than in all other sites, although the difference was not statistically significant. In fact, this high average seems to be largely driven by reports from Inuit (Baffin Island, Canada, Site_ID 34), who reported numerous impacts, such as slower freezing and faster melting of sea ice, more ice break-ups, and changing thickness of the sea ice.

In a final analysis, we used a multivariate approach to investigate how the assemblage of LICCIs reported in a site, including the type of LICCI and the frequency in which they are reported (hereafter *LICCI composition*, see Methods) relates to the site (i) climate zone, (ii) change in decadal temperature, and (iii) main livelihood activity. We found that LICCI composition was significantly related with both the climate zone where a site is located (NPMANOVA $F_{3,47} = 1.8$, $p < .01$, Supplementary Table 2) and the site's main livelihood activity (NPMANOVA $F_{4,47} = 1.2$, $p = .04$), but not to the change in decadal temperature. In other words, the distribution of LICCIs reported in a site is related with both the site's climate zone and the way people use the resources of their environment through their main livelihood activity.

Discussion

The results of this large global effort add to the growing evidence that Indigenous Peoples and local communities observe climate change and that the impacts of climate change on them are ongoing, tangible, and pervasive[1]. They also suggest that, despite idiosyncrasies, there are important patterns in how Indigenous Peoples and local communities experience and report climate change and its impacts.

Before discussing these findings, we examine three important caveats of our work. First, our method cannot discern whether reported impacts can be fully attributed to climate change, as

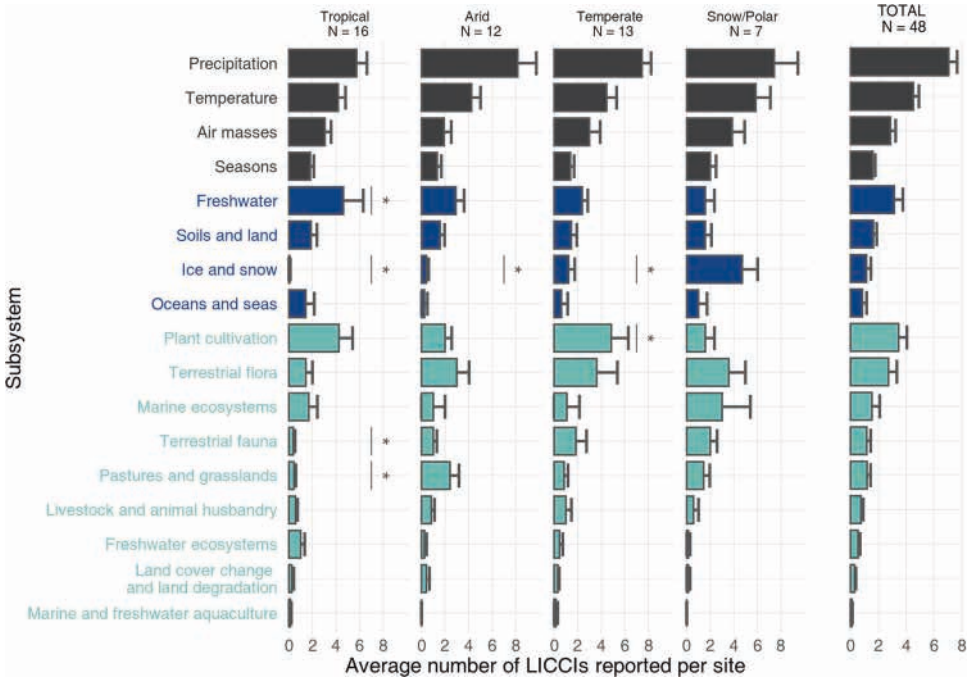

Fig. 3 Average number of LICCIs/site, by climate zone. Subsystems in black refer to the atmospheric system, in blue to the physical system, and in green to the life system. The error bars represent the standard error of the mean (SEM). * at the end of a column indicates a statistically significant difference ($p < 0.05$) in the average number of LICCIs/site in the subsystem between the climate zone indicated in the header and the snow/polar climate (category of comparison) in a Poisson general linear model. The error bars represent the standard error of the mean.

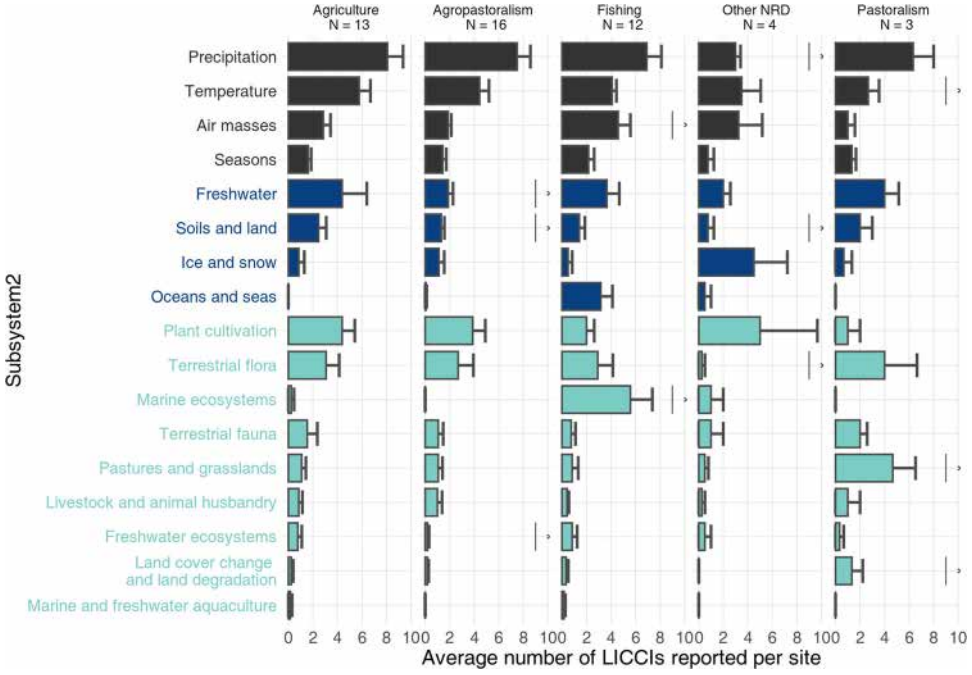

Fig. 4 Average number of LICCI per site, by main livelihood activity. Subsystems in black refer to the atmospheric system, in blue to the physical system, and in green to the life system. The error bars represent the standard error of the mean (SEM). * at the end of a column indicates a statistically significant difference ($p < 0.05$) in the site average number of LICCI in the subsystem between the livelihood activity indicated in the header and agriculture (category of comparison) in a Poisson general linear model. The error bars represent the standard error of the mean.

complexity and confounding drivers of environmental change (e.g., land-use change or overextraction) make attribution difficult[27,28]. While recognizing that reported impacts might not always be driven by climate change, we also argue that, for Indigenous Peoples and local communities, climate change impacts do not occur in isolation from other drivers of change, but rather they often exacerbate situations of environmental change resulting from colonialism, racism, inequality, and environmental injustice[29,30]. Indeed, research increasingly emphasizes that environmental change reflects the outcome of multiple drivers of change and synergistic relations among them[31,32], for which interventions might be more effective if they

consider both social context and climate change interactions with other drivers of change. A second important limitation of our work refers to the fact that our sample of sites is small, geographically biased, and potentially imbalanced as there is some overlap between climate zones and livelihoods. Despite this limitation, this research constitutes the largest global effort to compile, harmonize, and categorize local observations of climate change and its impacts by Indigenous Peoples and local communities. Finally, we also acknowledge challenges common in research with Indigenous Peoples and local communities, including overgeneralizations and misinterpretations deriving from the transformation of locally meaningful information to fit into scientific classifications[32]. While acknowledging ontological differences and positionalities, we argue that the current climatic emergency requires exploring multiple forms of collaboration between knowledge systems aiming towards similar pragmatic goals[33], even if collaboration is based on categorical equivocations[34].

In contrast with narratives analyzing future changes in climate and potential impacts under different scenarios, results from this work emphasize that Indigenous Peoples and local communities report a myriad of indicators of climate change as well as ongoing environmental impacts, which they (fully or partially) attribute to climate change. Changes reported stem from people's close interactions with the environment and include richly described, nuanced, and locally contextualized changes in many elements of the atmospheric systems and their impacts in the physical and the life systems. In that sense, the 369 local indicators of climate change and its impacts documented here, which range from indicators of changes in rainfall or fog, to how these changes impact freshwater availability, soil humidity, abundance and phenology of wild and cultivated plants and terrestrial and aquatic animals, or increases in crop pests, reflect the detailed understanding of changes captured by Indigenous Peoples and local communities. Our findings stress the importance of empirically grounded research to obtain a complete picture of climate change and its impacts. They also provide strong empirical support to perspectives that emphasize the need to enlarge our research focus to account for impacts that change the interwoven relationships between humans and nature at the local scale[35] as well as for diverse perceptions of which impacts matter[36].

In addition to presenting a more complete picture of climate change that includes indicators and impacts as locally experienced, the work presented here also allows to identify general patterns on how Indigenous Peoples and local communities perceive them. For example, our global analysis shows the predominance of reports of changes in precipitation, which represent about 20% of all reports, and their impact on elements of the life system. The finding could be read in terms of the direct and cascading impacts of changes in the water cycle on local social-ecological systems[32]. Results of the global analysis also show that Indigenous Peoples and local communities reports of climate change and its impacts are largely contingent on the climate zone where they live and on their main livelihood activity. For example, changes in precipitation and impacts on freshwater systems were more frequently reported in sites where agriculture predominates, whereas changes in air masses and impacts on marine ecosystems were more frequently reported in sites where fishing predominates and impacts in pastures and grasslands and land cover were more frequent where pastoralism predominates. This finding provides empirical basis to the previously untested hypothesis that the way people interact with the environment -in this case through livelihood activities- is an important predictor of the changes they observe.

We conclude with three policy recommendations derived from our work. First, Indigenous Peoples and local communities can expand, enrich, and deepen understandings of climate change and its impacts on local social-ecological system. This knowledge can contribute to the formulation of feasible and locally relevant adaptation plans and interventions[37–39]. Our results show that reports of climate change and its impacts are dependent not only on climate zones, but also on main livelihood activities, for which such reports could help made adaptation and mitigation plans more locally meaningful. While several mechanisms have been created to engage Indigenous Peoples' and local community representatives and delegates in climate policy, they mostly have a global character (e.g., the Local Communities and Indigenous Peoples Platform under the UNFCCC[40] or the Local and Indigenous Knowledge Systems (LINKS) program at UNESCO). Parallel actions at the local and national levels are strongly needed, with mechanisms to increase coordination across scales. Second, as discussions on the need to address loss and damage to achieve climate justice are gaining recognition in the academic literature[41,42] and in climate negotiations (e.g., Decision 2/CP.27, UNFCCC. Conference of Parties), our work provides a methodology that allows both the identification of climate change impacts at the local level and the cross-cultural comparison of reported impacts. This methodology has been applied to various tools, including the OpenTEK platform and Oblo, both of which have served to help assess local climate change impacts, either by researchers, citizen scientists, or communities themselves. In this sense, the methodology has the capacity to be applied to existing or new tools and adapted in a way that would inform about the specific economic and non-economic loss and damage related to climate change impacts on local social-ecological systems[43]. By combining the methodology with a climate impact valuation process, as defined either by communities or regional stakeholders, the work has the potential for providing empirical basis for parties to discuss appropriate compensatory measures. This would contribute to a broader recognition of the diverse histories of social, environmental, and ecological harm while opening just pathways into uncertain futures. Finally, considering that the foundations of Indigenous and local knowledge systems are being compromised and disrupted in many places[44], there is a greater need than ever before to support Indigenous Peoples and local communities in mobilizing their knowledge basis to adapt to ongoing impacts and contribute to global mitigation efforts. Our compilation of ethnographic data documenting diverse Indigenous and local expertize about present and future climate change impacts and adaptation plans could inform elite-driven debates about loss and damage, CO2 emissions mitigation, and the turn to renewables. Developing locally specific data ultimately serves the goal of reducing harm to Indigenous Peoples and local communities that comes from both acute climate impacts and top-down climate adaptations.

Online Methods

This research was carried out within the framework of a research project aiming to bring contextualized information from Indigenous Peoples and local communities to climate change research by creating a research network that coordinated data collection[19]. The research network included people with different nationalities, disciplinary backgrounds, and positionalities, who recognized the need to increase the transferability, integration, and scalability of information from Indigenous Peoples and local communities into climate research using standardized methods for the collection and coding of locally relevant but cross-culturally comparable data. We are aware that our framing of local climate change and

its impacts is largely influenced by Western epistemic traditions and that, therefore, the indicators used are situated and partial. We understand that Indigenous Peoples and local communities might assess, conceptualize, and weigh local manifestations of climate change and its impacts differently.

The Ethics Committee of the Universitat Autònoma de Barcelona approved the research protocol used in this project (CEEAH 4781). Before data collection started, we obtained permits from local authorities in each site to conduct research, as well as the Free Prior Informed Consent of all participants. Where necessary, we also obtained authorizations from national ethics committees. Following open science principles, the protocol for the research project is openly available[23] and the team has made available a series of online training materials to facilitate the use of the protocol (https://www.licci.eu/resources/) so here we focus on explaining the methodological aspects that directly relate to this work.

Data collection. We collected first-hand data in 48 field sites with predominantly nature-dependent livelihoods during 2019–2022. A site was defined as a group of villages or households showing relative environmental and socio-cultural homogeneity. We selected sites to maximize variability in climate zones and nature-dependent livelihoods.

In each site, we conducted semi-structured interviews with 15–25 key participants to document climate change, understood as changes in elements of the atmospheric systems, and its impacts on the environment. Our interviews focused on changes registered over decades, and noting the direction (e.g., increase or decrease) and the driver(s) of reported changes. We started by asking, "Compared to your youth, what changes have you noticed in the environment?" and continued asking, "Have you noticed any other change?" Once the participant stopped mentioning changes, we directly asked about changes in temperature, precipitation, wind, seasons, soils, water, and wild and domestic animals or plants. For each change mentioned, we asked about the perceived driver(s) of the change (i.e., "Why do you think this change happened?"). If the participant responded with another environmental change, we asked again for the perceived driver(s) of the latest mentioned change, until the respondent did not identify any additional driver. A full description of the protocol is publicly available[23]. As observations of changes and its drivers came in contextualized narratives, they often included multiple drivers. For example, the observation that "Plants "cook" on the ground. The ground is hot, it rains, and then it is hot again, and this "cooks" the plants" made by Tsimane' informants (Bolivia, Site_ID 24) was classified as a report of "changes in precipitation", "changes in soil temperature", and "changes in crop mortality rates".

In each site, we created a list of local indicators of climate change and its impacts (LICCIs) that were locally agreed upon. The list includes reports of change in elements of the atmospheric system, considered as 'indicators of climate change', and reports of change in elements of the physical and the life systems associated with those, considered as 'indicators of climate change impacts'. As our original question referred to environmental changes, our first step was to remove observations of environmental changes that participants did not consider to be at least partly driven by changes in temperature, precipitation, wind, or seasons. We classified the remaining observations into indicators. Verbatim observations depicting the same change were classified into the same indicator. Indicators were organized using a system with four hierarchical levels. The two highest levels corresponded to the system (i.e., atmospheric, physical, and life systems) and the subsystem in which the change was observed (e.g., precipitation, temperature, air masses, and seasonality are subsystems within the atmospheric system). The third level corresponded to the impacted element (e.g., mean temperature, temperature extremes, seasonal temperature, and sunshine intensity in the temperature subsystem), and the last level to the indicator[23].

In each site, we organized 3–5 focus groups to discuss observations and indicators for which semi-structured interviews resulted in contradictory or unclear information. In this work, we only consider indicators of climate change and indicators of climate change impacts agreed upon focus groups discussions. In sites where we could not conduct focus group discussions due to COVID restrictions, we conducted additional semi-structured interviews to further discuss indicators for which we had found contradictory or unclear information. We considered that there was agreement on an indicator when (*i*) there were no contradictions in reporting a given observation of change in semi-structured interviews or (ii) participants agreed with the reported change in focus group discussions.

In each site, the list of indicators of climate change impacts used in the analysis reflects changes for which participants agreed that are -at least partly- driven by changes in temperature, precipitation, air masses, or seasons, and that reflect temporal depth (i.e., the change refers to "compared to your youth"). The participatory and iterative nature of the data collection process helped identify climate change indicators and impacts that reflect the collective intergenerational knowledge held and owned by Indigenous Peoples and local communities living in close interaction with the local environment.

Each site was assigned to a climate zone using the site location and the Köppen-Geiger climate classification[26]. We differentiated between sites located in tropical, arid, temperate, and snow/polar climates. We combined sites in the snow and polar climates because we only had one site in the polar climate. For each site, we calculated the decadal temperature change using estimates reported by the IPCC[45] and constructed using the CRU-TS dataset that spans 1901 to 2018[46]. We then categorized sites into high positive (>0.3 °C/decade), medium positive (0.15, 0.3 °C/decade), mild positive (0, 0.15 °C/decade), and negative (<0 °C/decade) average decadal temperature change.

We used information gathered through open ended and semi-structured interviews to characterize the main livelihood activity of the communities we worked with. Most communities in this study included households relying in complex livelihood strategies which often combine different capabilities, assets, and activities to make a living[47]. While recognizing this complexity, for the analysis presented here, we only focus on the main livelihood activity, differentiating among sites where the predominant livelihood activity was agropastoralism, agriculture, fishing, pastoralism, and other nature dependent livelihoods (e.g., hunting, gathering, non-timber forest products collection). We note that our classification reflects the current economic activity of the sites, which might differ from group's identity and from previous classifications of some of the groups in the sample.

Data analysis. We started the analysis by providing a description of the local indicators of climate change and its impacts (i.e., LICCIs) reported in the full sample ($n = 48$ sites). We then used the site as a unit of analysis to explore whether the agreed reports of indicators of climate change and its impacts were differently distributed across (*i*) climate zones, (*ii*) decadal temperature change, and (iii) main livelihood activities. We did so by using a set of general linear models (GLM) with Poisson distribution to systematically compare the site average number of LICCI cited in a subsystem with a selected category of comparison (i.e., snow/

polar for climate zones; high positive decadal temperature change; and agriculture for main livelihood activities). When the GLM assessing the average LICCIs in a subsystem showed significant relationships with an explanatory variable, pairwise comparisons between the different levels of the variable were carried out with a Tukey's honest significance test.

In our final analysis, we explored the relative importance of the selected variables in explaining the variation in number and type of LICCI reported at each site. Drawing on methods from community ecology and species composition analysis[48], we created a variable that captured the number and identity of LICCIs reported at a site, named site LICCI composition. To create the variable, we constructed a dissimilarity matrix using the Bray-Curtis dissimilarity index, calculated at the subsystem level and including only impacts on the physical and the life system. The new variable considered both the number and the type of LICCI and compared them between sites. We then explored whether variation in site LICCI composition was associated with climate zone, decadal temperature change, and main livelihood activities by using a non-parametric multivariate analysis of variance (NPMANOVA). Multivariate analysis was performed using the vegan package[49] in R version 4.2.1[50]. GLM analyses were run using the stats package[49] and tukey post-hoc tests were run with the emmeans package[50].

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

Data availability

The datasets generated analyzed during the current study are available in the Dataverse repository, https://doi.org/10.34810/data878.

Code availability

This work did not use any custom computer code or algorithm.

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Competing interests

The authors declare no competing interests.

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